NTNU
Norwegian University of
Science and Technology

Back calculation of Debris flow Run-Out & Entrainment Using the Voellmy Rheology

Lemessa Fille Bayissa

Geotechnics and Geohazards
Submission date: June 2017
Supervisor: Arnfinn Emdal, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

NTNU – Trondheim
Norwegian University of
Science and Technology

Back Calculation of Debris Flow Run-Out & Entrainment Using the Voellmy Rheology

Lemessa Fille Bayissa

Geotechnics and Geohazards
Submission date: June 11, 2017
Supervisor: Vikas Thakur, NTNU
Co-supervisor: Ashenafi Leulseged Yifru, NTNU

Norwegian University of Science and Technology
Department of Civil and Transport Engineering

NTNU – Trondheim
Norwegian University of Science and Technology

Faculty of Engineering Science and Technology

Department of Civil and Transport Engineering

Master Thesis

Spring 2017

For

Lemessa Fille Bayissa

Back Calculation of Debris Flow Run-Out & Entrainment Using the Voellmy Rheology

Debris flow is one of the many geo-hazards that cause major damage worldwide. It can cause loss of human lives especially in mountainous regions. Besides, it can cause economic damage by destroying properties and infrastructure. Forecasting and controlling the hazard is still a difficult task that requires qualitative and quantitative analyses. However, the development of numerical dynamic run out models has a major advantage in the study of this processes, as they allow the simulation of possible future scenarios. Some of these numerical models, currently in use for simulating debris flows, are MassMov2D, DAN-3D, FLO-2D and RAMMS.

The main objective of this thesis is to back-calculate debris flow run out including entrainment using numerical models. For this study, it is suggested that the candidate could use the RAMMS run out model. RAMMS is able to model entrainment along the flow path by using rate controlled entrainment method, which regulates the amount of mass being entrained into the debris flow and the time needed to accelerate this mass.

Task Description:

- Conduct literature review on debris flow, entrainment and applications of the available rheological models
- Study the different numerical modelling methods used to analyse debris flow
- Study methods for including entrainment in numerical modelling of debris flow
- Evaluate the effect of the entrainment area on the volume of the flow.
- Back calculate the debris flow that occurred 2016 along Fv.45 Hunnedalsveien, Mjåland & its entrainment using RAMMS run-out model
    - Calibrate the input parameters and evaluate their sensitivity
    - Study the correlations among the input parameters.
    - Study the effect of the resolution of DEM on the quality of the model

For Vikas Thakur
Steinar Nordal

Vikas Thakur
Professor
Geotechnical Division
NTNU

NTNU – Trondheim
Norwegian University of
Science and Technology

Faculty of Engineering Science and Technology

Department of Civil and Transport Engineering

MASTER THESIS 2017

SUBJECT AREA: **GEOTHECHNICS & GEOHAZARDS**	DATE: JUNE 11, 2017	NO. OF PAGES:85

TITLE:

Back Calculation of Debris Flow Run-Out & Entrainment Using the Voellmy Rheology

BY:

Lemessa Fille Bayissa

Abstract

Debris flow is one of the many geo-hazards that cause a major damage worldwide. It can cause loss of human lives especially to those living in mountainous regions. Besides, it can cause economic damage by destroying properties and infrastructure. Forecasting and controlling the hazard associated to this type of mass movements is still a difficult task that requires qualitative and quantitative analyses. However, the development of numerical dynamic run out models has a major advantage in the study of these processes, as they allow the simulation of possible future scenarios. Some of these numerical models currently in use for simulating debris flows are MassMov2D, DAN-3D, FLO-2D and RAMMS.

The main objective of this thesis was to back calculate debris flow run out and its entrainment behavior using numerical model. For this study, the Author uses RAMMS run out model for the back analysis of debris flow mobility. RAMMS is able to model entrainment along the flow path by using rate controlled entrainment method, which regulates the amount of mass being entrained in to the debris flow and the time needed to accelerate this mass to the debris flow velocity.

One Norwegian debris flow, Mjåland debris flow happened in june 2016, was back calculated using RAMMS. The Voellmy rheological model was used first to calibrate the input parameters (friction coefficient, turbulence factor and coefficient of entrainment) and then to test the sensitivity of each parameter. The model is found to be highly sensitive to entrainment coefficient, K, friction coefficient, μ and turbulent friction, ξ.

The result of this study also showed that the velocity and height of the flow with entrainment and high slope is relatively greater than the normal range for debris flow. Although RMMS was able to simulate entrainment, the quality of its output depends on the resolution of digital elevation model (DEM) used as input during modelling.

SUPERVISOR: **Professor VIKAS THAKUR**

OTHER SUPERVISOR(S) : **ASHENAFI LULSEGED YIFRU**

CARRIED OUT AT: **MJÅLAND**

Abstract

Debris flow is one of the many geo-hazards that cause a major damage worldwide. It can cause loss of human lives especially to those living in mountainous regions. Besides, it cause economic damage by destroying properties and infrastructure. Forecasting and controlling the hazard associated to this type of mass movements is still a difficult task that requires qualitative and quantitative analyses. However, the development of numerical dynamic run out models has a major advantage in the study of this processes, as they allow the simulation of possible future scenarios. Some of these numerical models currently in use for simulating debris flows are MassMov2D, DAN-3D, FLO-2D and RAMMS.

The main objective of this thesis was to back calculate debris flow run out and its entrainment behavior using numerical models. For this study, the Author uses RAMMS run out model for the back analysis of debris flow mobility. RAMMS is able to model entrainment along the flow path by using rate controlled entrainment method, which regulates the amount of mass being entrained in to the debris flow and the time needed to accelerate this mass to the debris flow velocity.

One Norwegian debris flow, Mjåland debris flow happened in June 2016, was back calculated using RAMMS. The Voellmy rheological model was used first to calibrate the input parameters (friction coefficient, turbulence factor and entrainment coefficient) and then to test the sensitivity of each parameter. The model is found to be highly sensitive to entrainment coefficient, K, friction coefficient, μ and turbulent friction, ξ.

The result of this study also showed that the velocity and height of the flow with entrainment and slope is relatively greater than the normal range for debris flow. Although RAMMS was able to simulate entrainment, the quality of its output depends on the resolution of digital elevation model (DEM) used as input during modelling.

Preface

This thesis is submitted in partial fulfilment of the requirement for Master's Degree (MSc) in Geotechnics and Geohazards at the department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU). It was carried out in the spring semester of 2017.

I would like to thank Professor Vikas Thakur, my supervisor at NTNU, for his continuous supervision and guidance during my work. He was available when needed with smart approach and the right solution. Also a special thanks to my co-supervisor Ashenafi Leulseged, PhD candidate at NTNU for his continues advice and guidance throughout my work. His depth understanding of the application software (RAMMS) was a great input for my work.

I am also very grateful to Professor Terje MidtbØ (NTNU), Martine Frekhaug (Statens Vegvesen) Radoslar Raqynski and Bigyan Sherchan for their guidance in preparation of digital terrain model (DEM) of the study area.

Table of Contents

List of figures

List of Tables

1. Introduction

1.1 Background

Debris flow is one of the landslides that cause a major damage worldwide. It can cause loss of human lives especially to those living in mountainous regions. Besides, it cause economic damage by destroying properties and infrastructure. Debris flow associated with highly sensitive clays is a typical geo-hazard that pose a serious risk to human lives and infrastructure (Thakur, Nigussie, & Degago, 2014b; Yifru, 2014)

Debris flows and related landslide processes occur in many regions all over Norway and pose a significant hazard to inhabited areas and transportation facilities. During the last 150 years, approximately 2000 peoples have been killed by all kinds of landslides in Norway (Jaedicke, Lied, & Kronholm, 2009). Debris flow associated with highly sensitive clays is a typical geo-hazard that pose a serious risk to human lives and infrastructure in Norway.

The earth flow which occurred at Mjåland in Gjesdal on the 2nd of June 2016 was the latest example which showed the damage caused by debris on highway and other facilities. It closed highway number 45 (Fv.45 Hunnedalsveien) and also caused severe damage on power line of the area.

Large areas in Norway area exposed to all kinds of rapid mass movements. Snow avalanches are common during winter while slush flows are active during early winter and spring. Rock slides and debris flows can occur during the whole year but mainly in periods of heavy rain (Jaedicke et al., 2009). Huge rock slides of several million cubic meters are a threat to a number of Norwegian fjords, where damage caused by flood waves can destroy shore lines and single events might kill a number of peoples (Anda & Blikra, 1998).

Forecasting and controlling the hazard associated to this type of mass movements is still a difficult task that requires qualitative and quantitative analyses. However, the development of numerical dynamic run out models contributed a major factor in the study of this processes, as they allow the simulation of possible future scenarios (Quan, 2012). Some of these numerical models are MassMov2D, DAN-3D, FLO-2D and RAMMS.

For most debris flow, the final volume of the flow is different from the ejected volume. This is mainly due to either detrainment in which the volume decreases due to loss of mass particles or entrainment in which the volume increases due to scouring of bed channels. This study focus on back analysis of the later type of flow.

1.2. Problem statement and Objectives

The main objective of this thesis is back calculation of debris flow with entrainment by using a numerical model called RAMMS. Although there are a number of numerical models used to back analysis such type of debris flow, this study focus on using Rapid Mass Movements (RAMMS) to back analysis a typical debris flow with entrainment. Its application is briefly described in later chapters. In addition, after the model calibration, the sensitivity of the model to the applied release volume and friction parameters will be analyzed.

Back calculation is the most reliable approach to determine the model sensitivity to released volume changes. In this particular study a sufficient run out distance is back analyzed by changing the volume and keeping the other parameters constant. The model sensitivity to the volume change will be evaluated based on the deviations in run out distance and the pick velocity. A simple sensitivity analysis involves determining the model sensitivity to the applied friction parameters. Moreover the effect of changes in the Voellmy coefficients, μ and ξ, on the modelled run out distance and maximum velocity is considered.

To achieve the main objective, a number of sub-objectives have been formulated:

- To calibrate the model input volume in order to obtain sufficient debris flow run outs.
- To calibrate the friction parameters to obtain the required run-out.
- To compare the sensitivity of the model outputs to volume changes
- To consider the results in terms of the cases channelization
- To determine the model's sensitivity to coefficient of friction, μ.
- To determine the model's sensitivity to turbulent coefficient, ξ.
- To determine the model's sensitivity to coefficient of entrainment, K.
- To determine the relations among the input parameters.
- To evaluate the effect of entrainment area on the volume of the flow.
- To evaluate the μ coefficients sensitivity to various debris flows
- To assess if the empirical models predict adequate results compared to the numerical models

1.3. Approach

RAMMS (Rapid Mass Movements Simulation) is an application software which is used for back calculation of the physical modelling of the debris flows. RAMMS is a two-dimensional numerical simulation program that calculates the mass movements of a three-dimensional terrain (Christen, Kowalski, & Bartelt, 2010). It was specially designed to provide geotechnical engineers with a tool that can be applied to analyze problems that cannot be solved with existing one-dimensional models. It is a reliable numerical simulation tool yielding runout distance, flow heights, flow velocities and impact pressure of slow avalanches, hillslope landslides and debris flows. It has been developed by a team of experts at the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Johnson, 1984)

1.4. Description of Task

The first part of the study deals with the mechanics of debris flows, entrainment and mitigation measures. In addition, a brief explanation of different types of numerical models used to back-calculation of debris flow will be presented along with their merits and demerits.

In second part detailed discussion on different characteristics of RAMMS (Rapid Mass Movements Simulation) will be presented. Besides the principles and governing equations of the software are carefully studied to understand how it works followed by the simulation of a physical model.

The final part deals with simulation of a physical model of Mjåland debris flow focusing on entrainment.

1.5. Structure of the Thesis

Chapter 1 deals with the introduction of the thesis explaining the statement of the problem and the research objective.

Chapter 2 deals with the theoretical background of debris flow and types. Different mechanisms of countermeasures of debris flow will be discussed.

Chapter 3 provides detail discussion on different methods of numerical models used in back analyze of debris flow in general and particularly focus on RAMMS.

Chapter 4 deals with the methods and tools used to achieve the goal of the thesis.

Chapter 5 study the analyses, results and discussions of the back-calculation of debris flow event that occurred at Mjåland, Norway.

Chapter 6 summarizes the whole study by presenting the conclusion and limitations of the study.

Chapter 7 give recommendation based on the result of the study and forward some future works.

2. Literature Review

2.1. Terminology

Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction. Both solid and fluid forces played a vital role in influencing its motion which distinguish it from related phenomena such as rock avalanches and sediment-laden water floods (M. Iverson, 1997).

Other criteria for defining debris flows focus on sediment concentrations, grain size distribution, flow front speeds, shear strengths, and shear rates. The most common criteria that differentiate debris flow from the other part of landslide is the interaction between solid and fluid forces. Based on this criteria, they can be identified as : debris slides, debris torrents, debris floods, mudflows, mudslides, mud spates, hyper concentrated flows, and lahars may be regarded as debris flows(Johnson, 1984).

The interaction of solid and fluid forces not only distinguishes debris flows physically but also gives them unique critical power. Like any other types of landslides, debris flows can occur with little warning as a consequence a slope failure in continental and seafloor environments occur which results catastrophic events (M. Iverson, 1997). To mention one, the earthflow which occurred at Mjåland in Norway on 2nd of June 2017 caused the (Fv.45 Hunnedalsveien) to be closed and also damaged the power line (figure 1)(Rese, 2017).

Figure 1. løsmasseskred=earthflow happened on 2/6-2016 near Mjåland, Norway (Rese, 2017)

Debris flows, like floods are cable to travel long distance in channels with modest slopes and to inundate vast areas; large debris flows can exceed 10^9 m^3 in volume and release more than 10^{16} J of potential energy, but even commonplace flows of 10^3 m^3 can cause denude vegetation, clog drainage ways, damage structures, and endanger humans (M. Iverson, 1997).

Debris flows were defined differently by several scholars over years based on different criteria. According to (Hunger, Evans, Bovis, & Hutchinson, 2001) the term 'debris ' refers to a loose of unsorted material of low plasticity which is produced by mass wasting process, weathering, glacier transport, explosive volcanism or human activity. It was also stated as a flow of sediment and water mixture in a manner as if it was a flow of continues fluid driven by gravity, and it attains large mobility from the enlarged void space saturated with water or slurry (Takahashi, 2014).

The North American classification system defined debris as "rapid movements of material as a viscous mass where inter-granular movements predominate over shear surface movements. These can be debris flows, mud flows, rock avalanches, depending upon the nature of the material involved in the movement (Cruden & Varnes, 1996). According to (Hunger et al., 2001), debris flow is very rapidly to extremely rapidly flowing material in a steep channel and it is non-plastic with plasticity index less than 5 percent in sand and finer fractions.

2.2. Mechanics of debris flow

Debris flow occurs when three conditions are fulfilled; failure of mass, water and transformation of energy particularly potential energy to kinetic energy (M. Iverson, 1997). The path of debris flow consist of three zones: an initiation zone, transport zone and deposition zone (figure-2).

There are two causes of debris initiation (Norem & Sanderson, 2012). The first cause is the force coming from the flowing water exceeds the surface resistance of the soil and as a result, the mobilization of the particles takes place with increase of mass. It is the most common type of initiation in Norway.

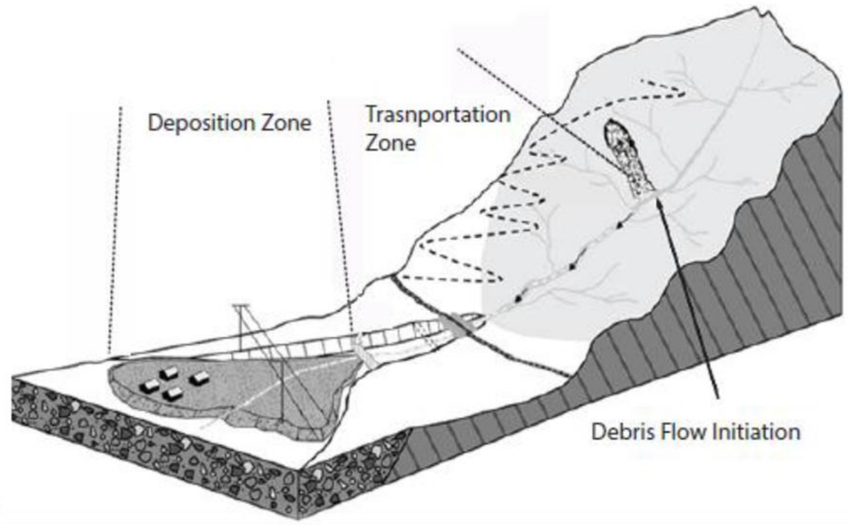


Figure 2 . A typical debris flow path (Schematic diagram from www.dnv.org) (Hussin, 2011)

The other cause might be the pore pressure increase, which gradually weakens the binding force between soil particles, and cause a soil slip as shown in figure 3. The main difference between the two is in the latter case the main initiation is the rise in pore pressure unlike the surface erosion of water(Norem & Sanderson, 2012).

Figure 3. Soil slip caused by a weak layer, Åby in Telemark county, Norway(Håland, 2012)

The middle part of the debris path is referred to as the transportation zone, which usually has a slope angle of more than 10 degrees (Jakob & Hunger, 2005). In this zone the volume of the flow is expected to increase due to the entrainment of the material and it is also the region where the flow reaches its terminal velocity. It can consist of either erodible soil or non-erodible bedrock channels or both; once the slope of the flow path reached the minimum limit for deposition, the debris will star settling down (R. M. Iverson, 2005). This transition usually takes place when the slope interval is between 15 and 20 degrees (Frekhaug, 2015). Structures constructed within this interval are highly susceptible to debris flow hazard; therefore proper risk assessment should be carried out before construction.

2.3. Morphology

Debris flow is commonly distinguished as channelized and hillslope as shown in figure 4. Channelized debris flows are common in large gullies while hillslope debris flows normally occur on open slopes(Glade, 2005).

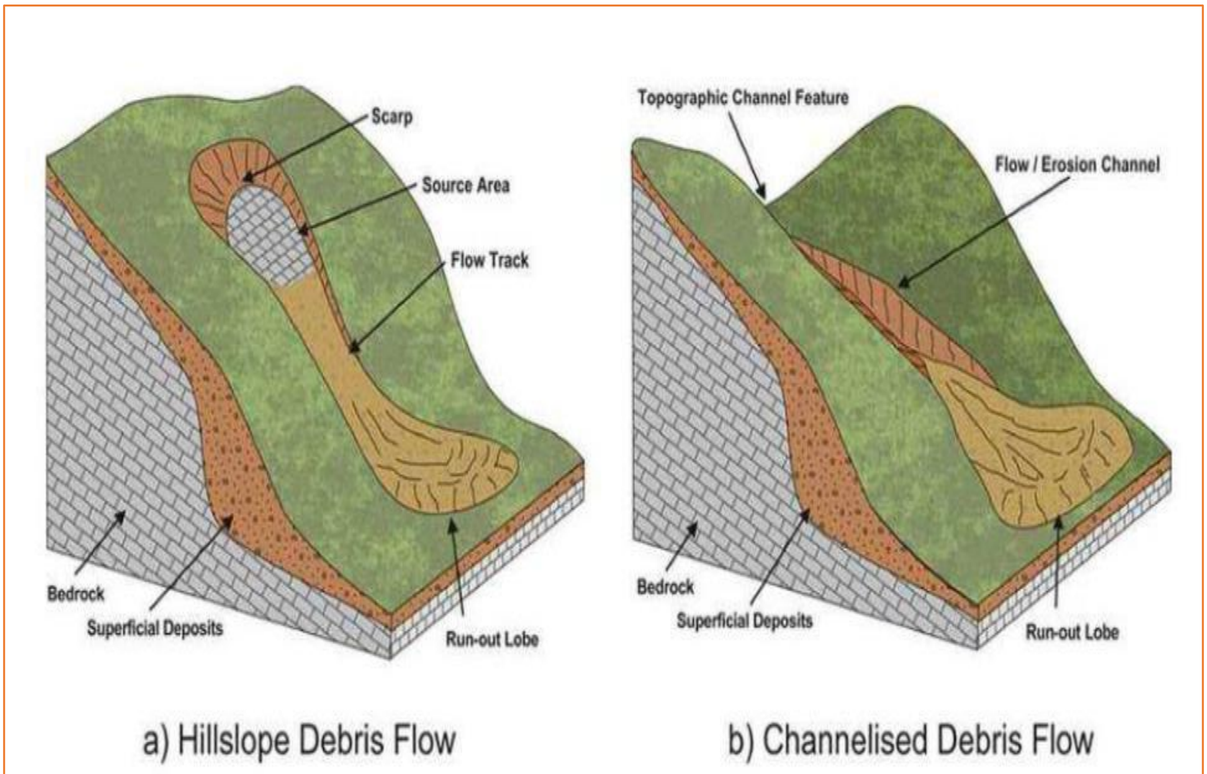


Figure 4. Figure Hillslope and Channelized Debris Flows Nettleton et al. (2005)

2.4. Classification of debris flows

There are different classification of debris flow based on a number of criteria; for instance, based on its appearance debris flow is classified as: stony, turbulent-muddy and viscous debris flow (Takahashi, 2014).

Stony type of debris flow: As its name indicates this type of debris flow is characterized by accumulation of big boulders at the front part of the flow with little water. Generally, this type of debris has the following properties (Okuda et al. 1977):

- The forefront of the debris flow shaped like a bore and the depth of the flow suddenly increases from the preceding flow.
- The biggest stones collect at the front part and it contains only little water.
- The front part lasts only a few seconds and the following part that lasts long looks like a mudflow with a gradually decreasing discharge.

Turbulent –muddy type debris flow: this type of debris flows are mainly comprised of fine ash despite the fact that it contains builders too.

Viscous debris flow: This type of debris flow is considered as the flow of the dispersion of coarse particles in dense slurry, which is usually more than 50%, by volume.

The other base for classification of debris is causes and processes of occurrence.

2.5. Debris flow mechanics

Debris flows include gravity driven motion of solid-fluid mixtures with variable erodible basal surface and composition that may change with both position and time. These complications cause great problems in efforts to understand debris flow mechanics and predict debris flow properties (R. M. Iverson, 2005). It contains a wide range of phenomena intermediate between rock avalanches and sediment-laden water floods. Even though debris flows are largely concentrated with water, it contains sediment suspension.

The interaction between solid and fluids in debris flow is strong unlike the one in rock avalanches where the presence of water is mostly incidental to the dynamics of the avalanches as a whole. This strong interaction is very essential element of the debris flow and its magnitude depends on the flow. Typically, solid grains and inter-granular liquid constitute roughly 30-70% of the volume of a debris flow(R. M. Iverson, 2005).

2.5.1. Debris flow dynamics

Debris flow is treated as fluid in describing its dynamic property and hence fluid dynamic laws are applied. In fact, the resistance to the flow is much higher in debris than pure water because of granular materials that exist in debris flow which have higher friction force (Breien, 2005).

The conservation laws of classical physics provide the basic tools for analysis of debris-flow dynamics. The most important one of these are the law of conservation of mass and the law of conservation of energy (R. M. Iverson, 2005). Regarding debris flow, it starts accelerating when the driving gravity force exceeds the resistance force caused by the frictional force. According to (Norem & Sanderson, 2012) there are two types of friction force in debris flows: coulomb friction and viscous-turbulent friction.

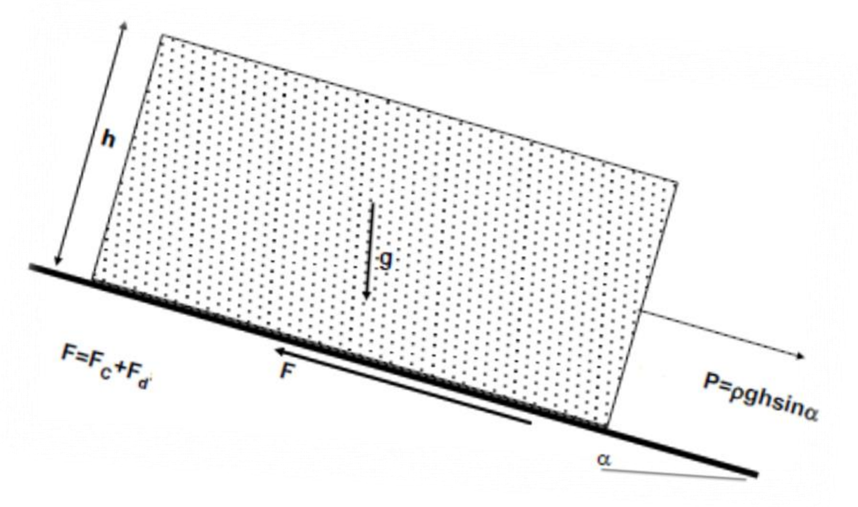


Figure 5. Illustration of the forces acting on a volume moving down a slope (Norem & Sanderson, 2012).

The coulomb friction is velocity independent and it allows the flow to deposit in sloping terrain; on the other hand, viscous-turbulent friction is the velocity dependent friction allows the flow to reach its terminal velocity in steep terrain. A small amount of fine particles with low water content is coinciding with a high viscosity. It also leads to low velocity and short-term run outs. Based on this Newton's second law can be written as follows(Norem & Sanderson, 2012).

$$ma = \rho h \frac{dv}{dt} = P - (Fc + Fd) = \rho g h \sin\alpha - (C + pe\tan\phi + k\frac{v}{h}) \qquad 2.1$$

Where, ρ is the bulk density, g the gravitational acceleration, α the slope of the flow path, C the cohesion, P is the effective stress, tan ϕ is the friction angle (a shear strength parameter) k the viscosity, and v/h is the average velocity gradient (Norem & Sanderson, 2012). It is also shown in figure 5.

According to (Gauer & Harbitz, 2014), the friction parameters are also dependent on rheology. Rheology refers to the study of the deformation and flow of matter (Van Wazer, Lyons, Kim, & Colwell, 1963). It provides a relationship between the shear stress and shear strain. For a Newtonian fluid, there is a linear relation between applied shear stress (τ) and shear rate

($\frac{du}{dy} = \dot{\Upsilon}$) (equation 2.2)(Van Wazer et al., 1963).

$$\tau = \eta \cdot \dot{\Upsilon} \qquad 2.2.$$

Where the η is the coefficient of viscosity of fluid. For the non-Newtonian fluid, it is common to concerned with the relation between shear stress and shear rate which is also known as the flow curve(figure 6).

$$\eta = \eta(\dot{\Upsilon}) \qquad 2.3.$$

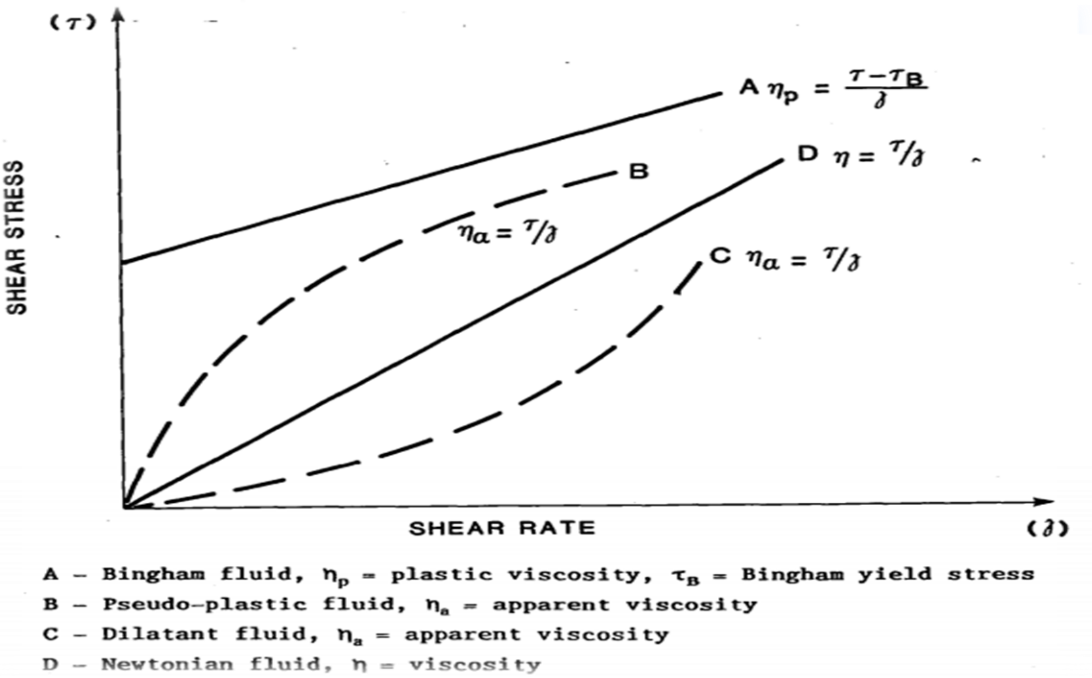


Figure 6. Typical stress-shear rate relationships (flow curves) for fluids (Van Wazer et al., 1963).

2.5.2. Entrainment in debris flow

Entrainment in debris flow can commonly defined as incorporation of solid and fluid boundary material which doesn't significantly change the composition of the flow and mostly resulting from the scouring of the channel bed or banks (M. Iverson, 1997). In most of the debris flow, there is an increase in volume of the flow along its way until it reaches the deposition zone of the flow where its velocity deceases and as a result the flow volume decreases due to deposition. This is especially true in channelized flow with small release area and relatively steep slope.

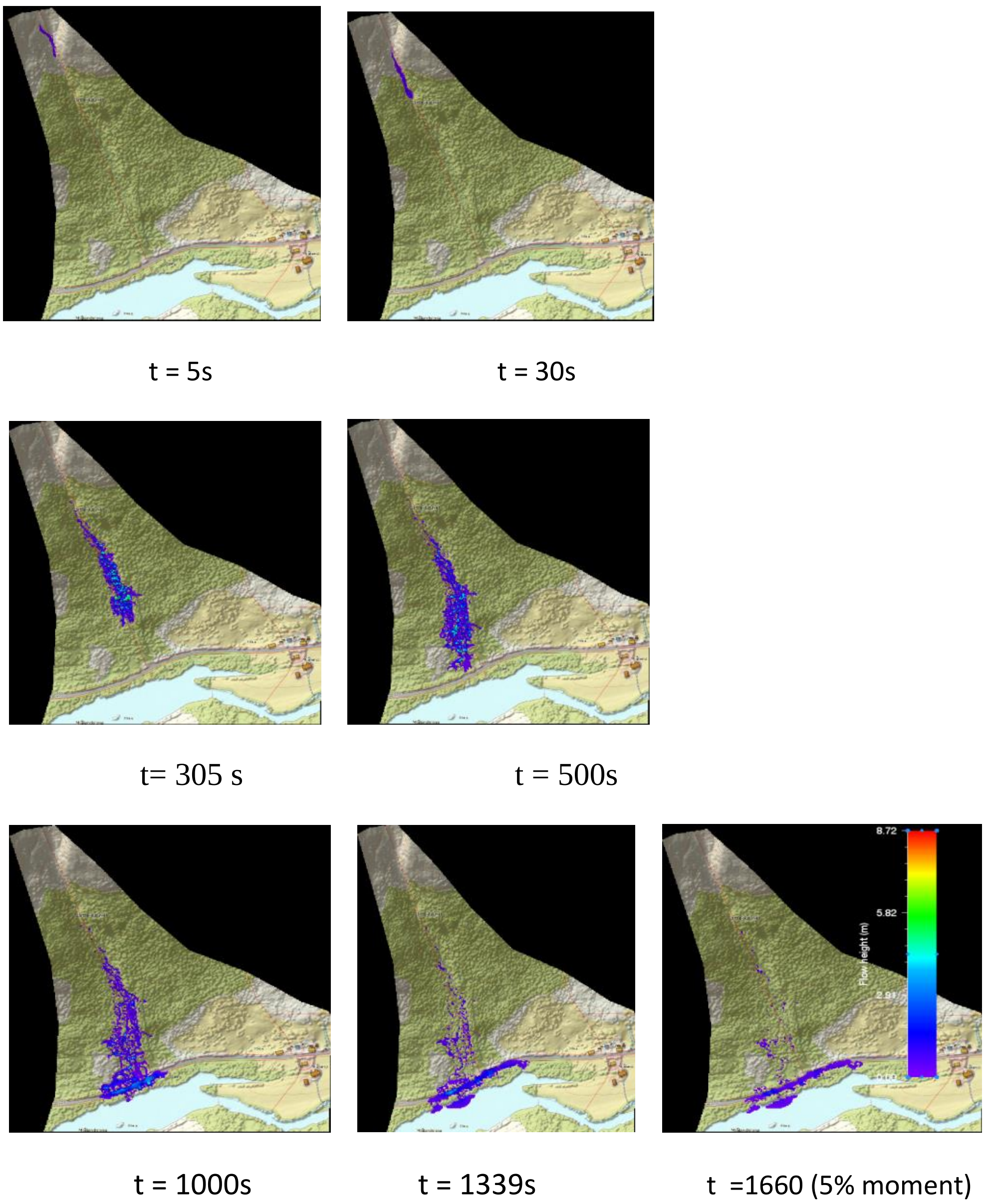


Figure 7. The simulation result of Mjåland debris flow with time

The debris flow which occurred on the 2nd of June 2016, at Mjåland in Norway is the best example of this type of flow. The release volume for this debris flow is only a few tens of cubic meters, but its run out is 750m (Rese, 2017). The result of the simulation of Mjåland debris flow is shown is shown in ‘figure 7’ with respect to time. As it can be seen from the figure, the release volume of the flow is negligible as compared to the total volume of the solution.

According to the result of the simulation, the maximum flow is about 15000m^3, which is about 163 times the release volume. According to the local report about 400m^3 deposit was recorded on the road before disposal. This study focuses on numerical modelling of this particular debris flow and it will be explained in detail later chapters.

2.5.3. Debris flow mitigation measures

2.5.3.1. Strategy of protection

Integrated risk management is a tool to prevent and avoid natural hazards which includes a combination of land use planning, technical and bioengineering measures to guarantee an optimal cost-benefit ratio (Hübl & Fiebiger, 2005). The important concept of risk management is the design of mitigation measures which minimize the existing risk to an accepted level of residual risk. According to (Zollinger, 1985), there are two types of mitigation measures: active and passive measures.

Active measures deals with the hazard, while passive measures focus on the potential damage (Huebl & Steinwendtner, 2000). The strategy of protection describes the best combination of protection measures (figure 8). Defining the objectives of mitigation is a vital part of risk management process followed by laying out the protection concept, which states the methods selected in order to achieve those objectives. In the next step appropriate measures are selected to meet the tasks derived from the protection concept and this plan of measures is called the “safety system” (Kettl, 1984, 1998).

Figure 8. Figure: Strategy of Protection (Huebel et al., 2004)

The safety techniques include measures that guarantee the effective performance of debris flow mitigation. The final step within the planning process includes the detailed structural design of the mitigation measures and the development of a work plan of all projected works (Jakob & Hunger, 2005).

2.5.3.2. Mitigation measures

2.5.3.2.1. Active mitigation measures

Active debris-flow mitigation measures (table1) reduce the magnitude and frequency of debris flow by changing the initiation, transport, or deposition of debris flows. It can be achieved by either by changing the probability of occurrence of debris flow (deposition management) or by changing the debris flow itself (event management).

Table 1. Active debris flow mitigation measures **(Hübl & Fiebiger, 2005)**

Objective	Task	Measure
Disposition Management		
Decrease runoff	Decrease peak discharge	• Forestry measures • Watershed management • Diversion of runoff to other catchments
Decrease erosion	Decrease surficial erosion due to overland flow	• Forestry measures and soil bioengineering • Watershed management • Drainage
	Increase slope stability	• Forestry measures and soil bioengineering • Terrain alteration (grading, scaling) • Drainage control • Stabilization of the toe slope
	Decrease vertical and lateral erosion in the channel bed	• Channel enlargement • Channel-bed stabilization • Transverse structure (sill, ramp, check dam) • Longitudinal construction • Groyne • Soil bioengineering
	Decrease water discharge at high erodible channel reach	• Diversion of runoff to other catchments • Bypass

Even management		
Discharge control	Decrease peak discharge to prevent damage	• Water storage • Channel enlargement • Enlargement of the cross section at the channel crossings (e.g. bridges)
Debris control	Transformation process	• Debris flow breaker
	Deposition debris under controlled conditions	• Permanent debris deposition • Temporary debris deposition
	Debris flow deflection to adjacent areas	• Deflection to area of low consequence
	Organic debris filtration	• Organic debris rake

Some of the active debris flow mitigation measures are described below.

Debris-flow breaker

Debris flow breakers are mainly designed to reduce debris flow energy (Kettl, 1984). It slows the front of debris flow and force the debris to settle and furthermore down-stream reaches of the stream channel and settlement channels area exposed to considerably lower dynamic impact.

Figure 9. Schematic view of a debris flow breaker for energy dissipation **(Rudolf-Miklau, Hübl, & Suda, 2014)**

The dissipation of debris flow energy can either be reached by retarding the flow process or transforming the displacement process. The function of debris breaker is reached in combination with a retention basin (figure 9). The debris flow is allowed to enter to the basin where it interacts with the breakers and part of the debris is deposited in the basin (Rudolf-Miklau et al., 2014).

Deflection

Deflection structures are used to shift debris flow toward areas of low consequences. This requires the existence of areas with low economic value in which debris flows are allowed to deposit. These structures include dikes, groynes, and deflection walls.

Open-Type Sabo Dams

Open-type sabo dams (figure 10) incorporating steel pipes or iron bars have been used as debris flow control for structures for more than three decades. The opening is mainly designed to trap large boulders from the front part of the flow. Results from Various experiments showed that the most effective opening size for holding debris flow is 1.5 times, or less, the maximum grain size that is likely concentrated in the front part of the flow (Mizuyama, 2008).

Figure 10. Open steel pipe in sabo dam (http://www.ktr.mlit.go.jp/fujikawa/english/project/)

Debris flow barrier or wire net

A wire net (figure 11) can be used to trap debris flow. The advantage of wire net over the other is that it doesn't require people to work inside a torrent bed. Once the debris flow is over, the debris will be removed and the wire net will be replaced incase if damaged. Even though there is doubts concerning their durability, they have been used successfully in Switzerland and Japan(Mizuyama, 2008).

Figure 11. Wire net trapping debris (Mizuyama, 2008)

2.6. Run-out modelling of debris flows

2.6.1. Empirical Approach

Dynamic run-out models are used to simulate the effect of change in release volume and friction coefficients for different scenarios including those that have no historical evidences. It is common to use outputs of a model in which single values of intensities like depth in meters, velocities in m/s. However, these models depend on rheological parameters, which cannot be measured directly. As a result, these models are often subjected to uncertainties. Although there is no universal model for calculating run-out of debris flow, several models give a reasonable systematic approach to assess debris flows (Quan, 2012).

The most practical run-out prediction has essentially been carried out by empirical methods, which use correlations among data collected over years (Rickenmann, 1999). Empirical models are typically based on limiting criteria or on statistical relations and they are quiet effective in situations where understanding of material properties is limited and the flow path is controlled by changes in terrain (Fannin & Bowman, 2008).

Some of the most common empirical approaches in debris flow modelling are:

- Volume loss rate method
- Channel geometry
- Angle of reach method

- Geometrical method

It is easy to apply empirical methods, but they have their own shortcomings. Primarily they are limited to conditions similar to those where development is based. Secondly, they include neither the rheology of the debris flow nor the mechanics of the flow. There might also be certain uncertainties in predicting the debris flow parameters; for-instance, debris flow volume might either overestimated or underestimated (Rickenmann, 2005). Because of all these reasons, extreme caution should be taken while adopting empirical methods and also adequate field observation should be carried out to precisely determine the empirical relationships , (CHEN & LEE, 2004).

2.6.2. Physical Modelling

Physically-based mathematical models are able to use GIS tools because of this it is extremely popular especially in shallow landslides(Carrara, Crosta, & Frattini, 2008; Montgomery & Dietrich, 1994). A number of these models depends on a hydrological model along with a simplified, one dimensional slope stability analysis. Physical modelling involves studying debris flow using controlled field and laboratory investigation. The use of flumes to simulate a debris flow event and careful analysis of the flow with high speed photography or videography by placing sensors at different locations of the flow (Reid et al., 2011). Another example of a physical model is the one used by Norwegian National Road Administration to investigate the effect of deflection structures to channel debris flows under a bridge (figure 12). It was first developed Hiller and Jenssen (Hiller & Jenssen, 2009; Laache, 2016).

Figure 12 The debris flow model in 2009 when it was used to investigate the effect of channeling debris flows under a bridge by using deflection structures (Hiller & Jenssen, 2009)

The model was further advanced in 2012 by (Fiskum, 2012), when it was used to test the effectiveness of check dams, slit dams and baffles. In addition, he added a table which allowed him to investigate the run out distance (figure 13).

Figure 13. The runout table of the debris flow model after it was repainted. The table is 360 cm long and the grid is 20 x 20 cm (Laache, 2016).

2.6.3. Numerical Modelling

Now days, numerical simulation models are used as an alternative model; these models allow for determination of the flow parameters and the deformation along the flow path as well as the deposition (O'Brien, Julien, & Fullerton, 1993). Numerical approach is more substantial than empirical approach, but it has its own limitations. Debris flow characteristics depend on the dynamic interaction between the solid and fluid phases. Dynamical models are difficult to apply and require a calibration of rheologic or friction parameters which needs back calculation of the past events (Scheidl, Rickenmann, & McArdell, 2013).

Dynamic modelling is categorized in to lumped mass models and models based on continuum mechanics. A lumped mass model is a simpler dynamical method often represented by mass-point model, which is applied to determine the kinematic parameters of a single phase bulk mixture (CHEN & LEE, 2004). This one-dimensional model is based on two assumptions: discharge from upstream is constant and deposition starts at the place where the channel maintains nearly uniform slope (Scheidl et al., 2013). Although this method is simple to apply, it is unable to account for internal deformation and unable to simulate the movement of the flow front.

The most commonly used numerical method is based on the continuum mechanics. Continuum fluid mechanics model uses the conservation laws such as conservation of energy, conservation of mass and conservation of momentum that describe debris properties. This method utilizes rheological model to describe the material property of debris. In addition, it is used to model debris flow over irregular terrain (Quan, 2012). Important debris flow characteristics such as the velocity, acceleration and run-out distance can be predicted by using equations with carefully selected rheological model (Chen & Lee, 2000). According to (R. M. Iverson, 2005), these type of models can be computed by integrating the internal stresses in either vertical or bed-normal directions using shallow water assumption to obtain a form of the Saint-Venant or Navier-Stokes equations.

In shallow water assumption, either 1D or 2D solutions for unsteady flow can be obtained using momentum equation by evaluating the dynamic equilibrium for a single column (discretized unit) isolated from the flowing mass (equation 2.3, 2.4 & 2.5)(Quan, 2012).

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \tag{2.3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\,\frac{\partial u}{\partial y} = -g\left(-S_x + k\frac{\partial h}{\partial x} + S_f\,q_x\right) \tag{2.4}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + u\frac{\partial v}{\partial y} = -g\left(-S_y + k\frac{\partial h}{\partial y} + S_f\,q_y\right) \tag{2.5}$$

Where,

- ✓ ‘h’ is the flow thickness;
- ✓ (u, v) are the x and y components of the depth average velocities (m/s).
- ✓ Equation 2.4 & 2.5 are the momentum equations expressed in terms of acceleration (m/s^2)
- ✓ ‘g’ is the acceleration due to gravity.
- ✓ S_x = tanαx, the bed slope gradient in x direction
- ✓ S_y = tanαy, the bed slope gradient in y direction
- ✓ q_x and q_y are coefficients (Eq. 2.6 & 2.7)

The first term on the left side of the equation represents the local acceleration and expresses the time rate change at fixed position. The second and third terms on the left side of the equation represents the convective acceleration, i.e. the time rate of change due to change in position in the spatial field. The spatial derivative in the second term to the right is the time rate of change due to pressure differences with in the flow. S_f is the flow resistance gradient and it accounts for momentum dissipation within the flow due to frictional stress with the bed (Beguería, Asch, J, Malet, & Gröndahl, 2009).

$$q_x = \frac{-u}{\sqrt{u^2 + v^2}} \tag{2.6}$$

$$q_y = \frac{-v}{\sqrt{u^2 + v^2}} \tag{2.7}$$

The negative sign of both u & v indicates that S_f opposes the direction of the velocity.

Numerical method has the ability of computing the movement of the flow over irregular topographic terrains with good precision. They are also used to investigate runout frequencies and magnitude of landslides specially in the absence of data of former events (Quan, 2012).

Run-out models might be distinguished from one another based on different criteria. Based on the solution dimension, they are classified as either 1D or 2D. One dimensional models analyze the movement of the flow by taking the topography as a cross-section of a single pre-defined width while two dimensional models undergo the analysis considering the topography both in plan and cross section.

Another base for classification of models is the solution reference frame in which they are classified as Eulerian or Lagrangian. A Eulerian reference frame is fixed in space analogous to a viewer standing still as a landslide passes. This types of models usually requires the solution of a more complex equations. On the other hand, the Lagrangian reference frame moves with the local velocity which is analogous to an observer riding on the top of a flow. Unlike the Eulerian method this method simplifies the governing equation in which the material velocity and acceleration are expressed by equation 2.8 and 2.9 respectively(Quan, 2012).

$$\mathrm{V(X,t)} = \frac{\mathrm{D}\zeta(\mathrm{X,t})}{\mathrm{Dt}} \qquad 2.8$$

$$\mathrm{A(X,t)} = \frac{\mathrm{DV(X,t)}}{\mathrm{Dt}} = \frac{\mathrm{D}^2\zeta(\mathrm{X,t})}{\mathrm{Dt}} \qquad 2.9$$

Where, V velocity, A is the acceleration, X is the referential position, ζ is the motion that can be seen as a transport of points from the reference configuration to the current configuration during specific time interval [0, t]. The displacement of a particle located at a certain point ‘X’ can be expressed as equation 2.10.

$$U(X,t) = \zeta(X,t) - X \qquad 2.10$$

The Eularian reference is commonly applied because it is difficult to explicitly locate the position of X at t = 0 and identify the exact trajectory. In this reference the attention is given to a certain region in space and the material motion is observed within this region as time proceeds. The spatial velocity and acceleration can be represented by equation 2.11 and 2.12.

$$V = V(X,t) \qquad 2.11$$

$$a = a(X,t) \qquad 2.12$$

The displacement can be expressed as Equation 2.13

$$U(x,t) = X - \zeta^{-1}\ (x,t) \qquad 2.13$$

Rheology

The rheology of the flow is can be defined as the resistance forces in the debris flow that primarily occur between the flow and the bed path. Based on basal rheology, the dynamic models can be identified as frictional (coulomb) in which the resistance is based on the relation of the effective bed and normal stress at the base and the pore fluid pressure (Hunger & McDougall, 2009). In frictional-turbulent (Voellmy) rheology, the resistance features a velocity-squared resistance term called turbulent coefficient, ξ (table-2)(Quan, 2012).

Table 2 : Most common flow resistance terms used in dynamic run-out models(Quan, 2012)

Rheology	Flow resistance term, Sf
Frictional (Coulomb)	$\mathrm{Sf} = \tan \varphi'$ $\tan \varphi' = (1 - ru) \tan \varphi$ ▪ Sf is the unit base resistance ▪ r_u is the pore pressure ratio ▪ φ is the dynamic basal friction angle
Voellmy	$Sf = (tan\varphi' + \frac{u^2}{\xi h})$ ▪ Sf is the unit base resistance ▪ tanφ' = μ is the apparent friction coefficient ▪ u is the flow velocity ▪ ξ is the turbulent coefficient in m/s^2
Bingham	$Sf = \frac{1}{\rho g h}(\frac{3}{2}\tau c + \frac{3\eta}{h}u)$ ▪ Sf is the unit base resistance ▪ τc is a constant yield strength due to cohesion ▪ ρ is the density of the flow ▪ η is the viscosity parameter
Quadratic	$Sf = \frac{\tau c}{\rho g h} + \frac{K\eta}{8\rho g h^2}u + \frac{n^2 u^2}{u^{\frac{4}{3}}}$ ▪ Sf is the unit base resistance ▪ τc is the resisting shear stress ▪ u is the depth averaged velocity ▪ η is the viscosity of the fluid ▪ k is the resistance parameter, k=24 for laminar flow in smooth, wide rectangular channels, but increases with roughness and irregular cross sections ▪ n is the manning coefficient value that includes the turbulent and dispersive components of flow

Some of the currently available numerical models are RAMMS, DAN-3D and FLO-2D.

RAMMS

RAMMS (RApid Mass Movements Simulation) is a numerical simulation model to analysis the motion of geophysical mass movements (snow avalanche, debris flows, rock falls) from initiation to run-out in three dimensional terrain (Bartelt et al., 2013). It was first developed to model snow avalanche by WSL Institute for snow and Avalanche research SLF in Switzerland, but later it expands to include debris flow as well. It is used with a user friendly visualization tool that helps users to easily access, display, and analyze simulation results (Bartelt et al., 2013).

RAMMS uses the Voellmy-Salm fluid flow continuum model (Salm, 1993), which is based on the Voellmy friction model and it includes both the turbulent coefficient and the apparent friction (table-2)

DAN-3D

DAN-3D (Dynamic Analysis of landslide in three dimensions) is continuum dynamic model developed for the run-out analysis of extremely rapid, flow-like landslides, such as debris and avalanches. It is a 3D extension of the existing 2D model DAN, which uses a semi-empirical approach based on the concept of equivalent fluid in which the heterogeneous and complex landslide material is modelled as a hypothetical material governed by simple rheological relationships(Hunger, 1995; Quan, 2012). DAN-3D was developed by Scott McDougall as a part of his PhD thesis at the University of British Columbia in Toronto (McDougall, 2006).

This model allows for frictional resistance (frictional model) to act on the base of a flow which has internal friction.

The DAN-3D model is based on a Lagrangian formulation that discretizes the flow in a number of particles representing bed normal column of flow. It requires interpolation based on smoothed particle hydrodynamics to determine the value of each field parameters (McDougall, 2006; Quan, 2012). The user-defined simulation time is the stopping criteria for DAN-3D (Schraml, Thomschitz, McArdell, Graf, & Kaitna, 2015).

FLO-2D

FLO-2D is a Eulerian two-dimensional finite difference model that is able to route non-Newtonian flows in a complex topography based on a volume conservation model (Quan, 2012). It was developed at Colorado State University(USA) by O'Brien et al.in 1983 to analyze a water flood and mudflow, which has been broadly used in hazard assessment (Bertoldi, D'Agostino, & McArdell, 2012).

The boundary condition in FLO-2D is the inflow conditions are described as flow discharge versus time and values of Cv for each point in the hydrograph in upstream grid and the out flow condition is described in downstream grid elements(Quan, 2012).

3. Describing the case study

Describing of the case studies is a crucial part in back analysis of existing debris flow. However, getting precise data of an event is the main problem of debris flow modelling. There are always certain uncertainties in considering variables like peak discharge, flow velocities, volume of the flow, hydrograph shape or friction parametrization which might result significant error in modelling. This study focus on a Norwegian debris flow and give detail description of its back analysis.

For this study, a debris flow with entrainment was selected and back analyzed based on the investigations carried out by Silje Wilk Rese of Multiconsult (Rese, 2017). This report was the base of this study. Besides, Norwegian geological map was referred to get a better understanding of the geological structure of the area. Because of the flow's unknown total volume, the block release area method was used for simulation in RAMMS.

Figure 14. Overview map showing the location of the Mijåland debris flow

3.1. Fv.45 Hunnedalsveien, Mjåland

Mjåland is located approximately 7 km north of Byrkjedal in Rogaland County (figure 14&15). The mountainside is partly covered with moraine in which boulders, pebbles, sand and mud might be deposited in the form of a long ridge along the front or sides of glacier. This type of deposits are often affected by landslide and debris flow is common in such area.

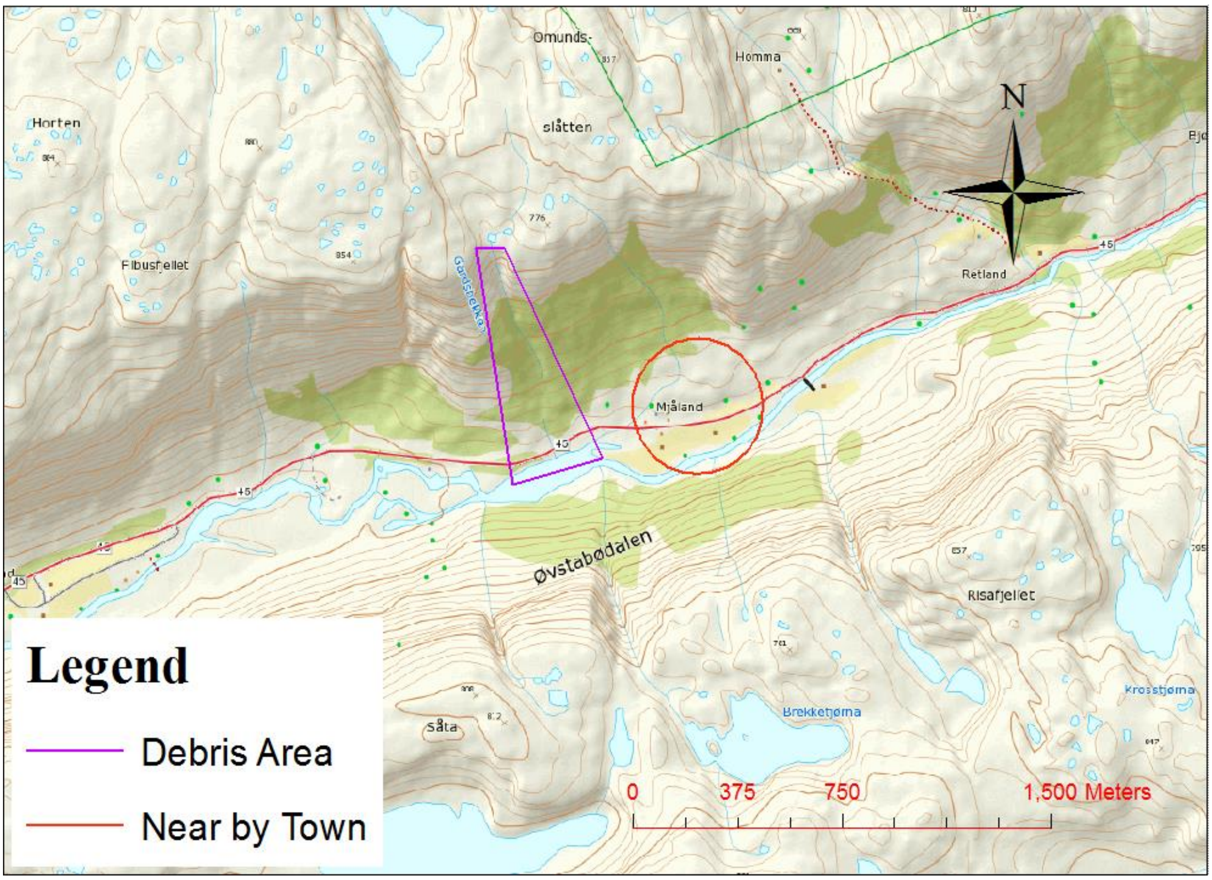


Figure 15. Area of debris flow.

The earth flow was occurred on the second of June 2016 which resulted in temporary shutdown of highway number 45 (Fv.45 Hunnedalsveien) of this particular area. Besides, there were damage on power line caused by the flow. It has gone in south facing hill that is 430 meters high. From bottom to top, starting from the road the mountain rises about 20^0 for the first 100 meters followed by $20\text{-}30^0$ rise in between before it reaches $30\text{-}40^0$ for the upper most part (Rese, 2017). There is a small pond located on the on the top of the mountain (figure 16). The area is covered with vegetation, which might have negative effect on the flow volume.

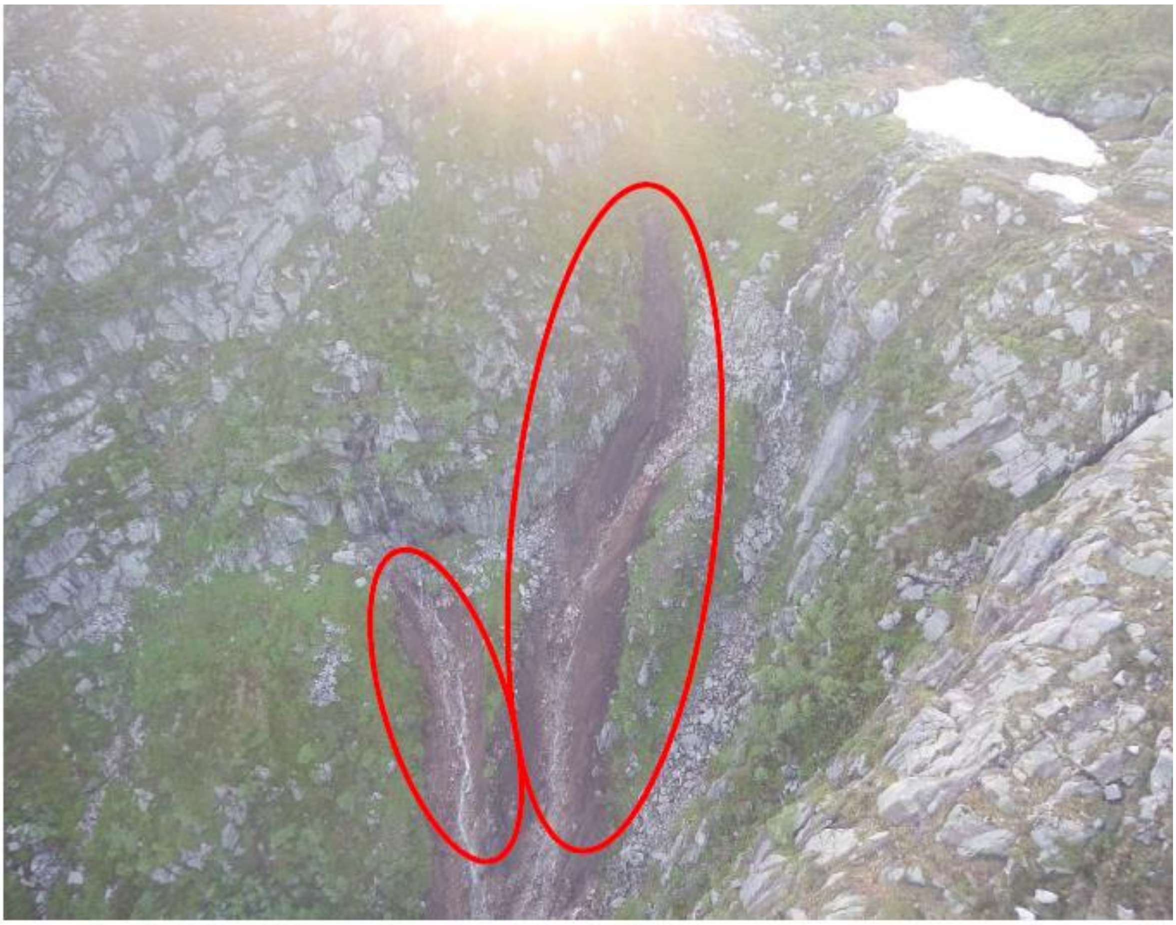


Foto 3 Tjern på toppen av fjellsiden. Løsneområdet vises til venstre i bildet

Figure 16. The starting area of the debris flow (Rese, 2017)

The debris flow was started around the top of the mountain roughly at 40^0 inclination. The run-out of debris flow depends on several factors, such as the elevation of the source area, the slope of the area and the soil thickness and composition. In case of Mjåland debris flow the first two cases were the main contributors to the relatively long run-out distance.

As it can be clearly identified from the comparison of the two conditions: before and after the event (figure 17), there was shallow surface slide of soft soil at the top whose volume covers only a portion of the total volume, but its volume increased as it moves down because of entrainment.

Entrainment in debris flow is incorporation of solid and fluid boundary material that mainly comes from the scouring of channel bed that doesn't significantly change the composition of the flow (R. M. Iverson, 2005).

Figure 17: Starting areas (a) and before (b) of the debris flow.(Rese, 2017)

Heavy Precipitation is one of the most common triggering factor of landslide. The Mjjåland debris flow has triggered following extreme precipitation that occurred around the area. The slope of the area is very steep (> 40^0 at the top), and also the mass has high water content therefore it reasonable to assume that the speed of the flow is high (Rese, 2017).

4. Methodology

This chapter deals with the methods and tools used to achieve the goal of the thesis. The numerical method, RAMMS in particular is used to back calculate the debris flow. This calculation is carried out by varying input parameters until modelled run-out distance is believed to be a sufficient representation of the field run-out distance. It is difficult to directly measure some of the flow characteristics such as velocity, volume, release area, but they can be indirectly predicted from observing the effect of the flow.

In this study a Norwegian debris flow with entrainment will modelled and the back analysis will be done accordingly. Back analysis is carried out to verify the applicability and flexibility of the model and to evaluate how well they reproduce the debris (Frekhaug, 2015). Before developing debris model, through field investigation of the study area is necessary to collect some of the input parameters. In addition, geological maps and past erosion history of the area are also important.

During calibrating a model that has input parameters which are continuous variables and have a wide range of possibilities , the principles of equality should be considered (H.Y. Hussin et al., 2012). This rule states the availability of different paths or ways that lead to the same result. Therefore, it is possible to have the same output despite of using different combination of input parameters. Equifinality is avoided in this study to arrive on one calibrated input parameters, which simplifies the sensitivity test of the input parameters.

During calibration, input parameters are determined based on a literature review and subsequent modelling. These include Voellmy friction coefficient μ, turbulent coefficient ξ, and the RAMMS entrainment coefficient, k.

This particular debris flow occurred recently hence there is no literature review associated with the study, which makes it even more challenging. After a series of trial simulations, the input parameters are calibrated and the result used in throughout the rest of the study of the study. Throughout this study the friction parameters were kept constant except for the case where the influence of their variation on the study was considered. On the other hand, the value of the release volume was allowed to vary until the desired run out distance is acquired.

The effect of uncertainties related to the initial volume, in terms of recreating the model with precise flow characteristics was assessed from the simulation results.

4.1. Building the numerical model

The digital elevation model (DEM), which defines the topography of the study area is the critical input parameter for the model. RAMMS require the digital elevation model (DEM) in ASCII format. In this study, the DEM obtained from one of Norwegian data source (hoydedata@kartverket.no) have converted to the ASCII files using ArcGIS application software.

4.1.1. RAMMS

RAMMs (Rapid Mass Movements) is a dynamic numerical modeling software package developed by the Swiss Federal Institute for Snow Avalanche Research (WSL/SLF) originally to model snow avalanche (B¨uhler, Christen, Kowalski, & Bartelt, 2011; Casteller et al., 2008; Christen et al., 2010; Fischer, Kowalski, & Pudasaini, 2012). However, by including certain tools it has further applied to other landslides: lahars, rock avalanches and debris flow (Quan, 2012; Schneider et al., 2010). The 2-D model is used to predict the velocities, flow heights, and impact pressures in a two and three-dimensional environment.

RAMMS uses the Voellmy-Salm fluid flow continuum model which describes the debris flow as a hydraulic-based depth average continuum model. It uses three dimensions: x and y which are on the plane of the direction of the mass movement and the elevation which is perpendicular to the flow direction given by z(x, y)(H.Y. Hussin et al., 2012). The debris flow is characterized by unsteady and non-uniform motion. Moreover, it is characterized by two parameters: height H (x, y, t) and the mean velocity U(x, y.t). One of the important steps in physical modelling is defining the release area as a polygon which also require determining the initial height, H of the flow.

The Voellmy-Salm model uses the following mass balance equation:

$$\partial_t H + \partial_x(HU_x) + \partial_y(HU_y) = Q(x, y, t) \qquad 1$$

Where U_x and U_y are the velocities in the x and y directions respectively, and Q(x, y, t) is the mass production source term and when $Q > 0$, it is called the entrainment rate while $Q < 0$, it is called deposition rate(Christen et al., 2010). The depth averaged momentum balance equations in the x and y directions are respectively given by:

$$\partial_t(HUx) + \partial_x\left(c_x\, HU_x^2 + g_z\, k_{\frac{a}{p}}\frac{H^2}{2}\right) + \partial_y\left(HU_X U_y\right) = S_{gx} - S_{fx} \qquad 2$$

And

$$\partial_t\left(HU_y\right) + \partial_y\left(c_y\, HU_y^2 + g_z\, k_{\frac{a}{p}}\frac{H^2}{2}\right) + \partial_x\left(HU_X U_y\right) = S_{gy} - S_{fy} \qquad 3$$

Where c_x and c_y are profile shape factors that are determined by the DEM and $k_{a/p}$ (1 for hydrostatic flow) is the earth pressure coefficient. Equation 2 and 3 include the gravitational accelerations in x and y directions that are respectively given by:

$$S_{gx} = g_x H \qquad 4$$

$$Sg_y = g_y H \qquad 5$$

The right Equation (2) and (3) contain the driving frictions in the x and y directions and are respectively given by:

$$Sf_x = nUx\,[\mu g_z H + g\,|\,U\,|^2] \qquad 6$$

Where, nUx and and nUy are velocity directional unit vectors in x and y directions, respectively. The total friction in Voellmy-Salm model is divided in to a velocity independent dry-Coulomb friction coefficient μ and a velocity dependent turbulent friction ξ.

4.1.1.1. Entrainment in RAMMS

Over years several dynamic run-out models have been developed that introduce entrainment modelling. These models generally use ‘processed based entrainment rates’ (Crosta, Imposimato, & Roddeman, 2009; H. Y. Hussin et al., 2012) where the volume of the entrained material is calculated by prescribed algorithms considering the material properties or use ‘defined entrainment rates‘(Chen & Lee, 2000; H. Y. Hussin et al., 2012) where the amount of entrainment is specified by the user. For this study, RAMMS run out model was used for the back analysis of one debris flow with high entrainment. One advantage of this model is its capability of modelling entrainment along the flow path. This is done by using a rate controlled entrainment method (figure 18),which regulates the mass being entrained in to the debris flow and regulate the time delay to accelerate this mass to the debris flow velocity (H.Y. Hussin et al., 2012). The entrainment method is mainly based on previous studies conducted by (H. Y.

Hussin et al., 2012; Sovilla, Burlando, & Bartelt, 2006).The entrainment rate Q (x, y, t) is given by:

$$Q(x,y,t) = \begin{cases} 0 \quad for \quad [h_s(x,y,0) - \int_0^t Q(x,y,\tau)d\tau] = 0 \\ \frac{\rho i^s}{\rho} KiU \; for \; [h_s(x,y,0) - \int_0^t Q(x,y,\tau)d\tau] > 0 \end{cases}$$

Where ρ (Kgm^{-3}) is the density of the initiated incoming debris flow, τ is the shear stress, and h_s (x, y, 0) (m) is the initial height of the entrainment layer at position (x, y) and time t=0 s. The total height of the entrainment layer in RAMMS can be divided in to three separate layers:

i (1,2,3) so that $h_s = \Sigma h_i$ and the density of each layer is given by ρi^s.

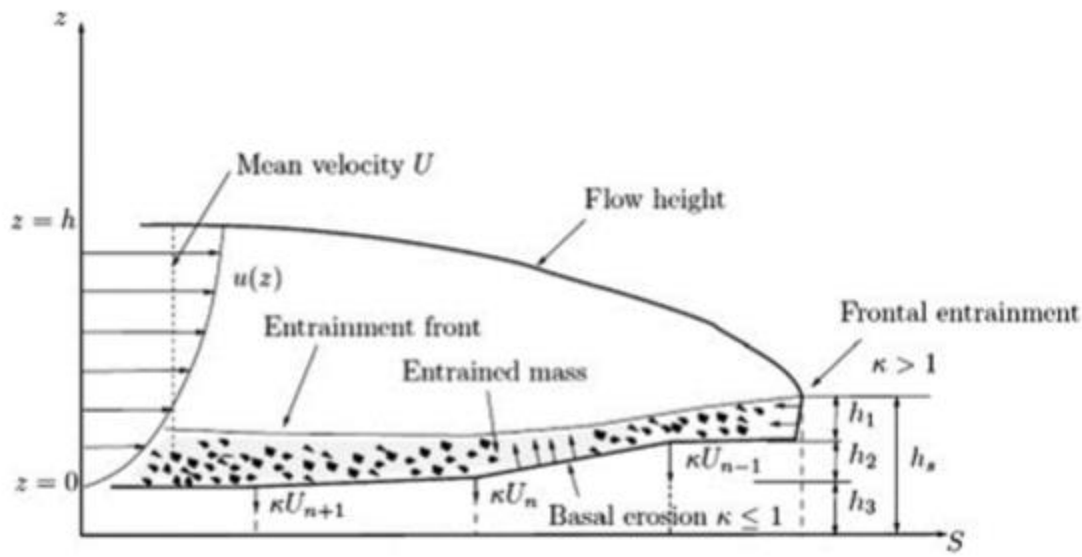


Figure 18: A schematic interpretation of the RAMMS entrainment model(H. Y. Hussin et al., 2012).

K_i is the dimensionless entrainment coefficient for each layer. In case a single entrainment coefficient is chosen, *Ki* can be simply defined as *K* (H. Y. Hussin et al., 2012). In this study the same entrainment coefficient is applied for both selected layers, except for the case in which the sensitivity of k itself is considered.

4.1.1.2. Stopping Mechanism in RAMMS

Stopping in RAMMS is based on the momentum (mv). For every dump step (calculation step), it summed up the moment of all grid cells, and compare it with the maximum momentum sum. If this percentage is less than a user defined threshold value, RAMMS aborts the simulation and debris flow is regarded as over(Bartelt et al., 2013). The recommended threshold value is between one and ten percent (1%-10%). For this thesis 5% threshold value was used.

4.2. Back- analysis of Fv.45 Hunnedalsveien, Mjåland event

Back analysis is primarily carried out to test the applicability and flexibility of the physical models to see how well they reproduce debris flow (Frekhaug, 2015). In this particular study, back analysis is carried out by focusing on entrainment using RAMMS. Besides, rheological parameters are calibrated and their sensitivity are examined by varying one of the parameters and keeping the other parameters constant.

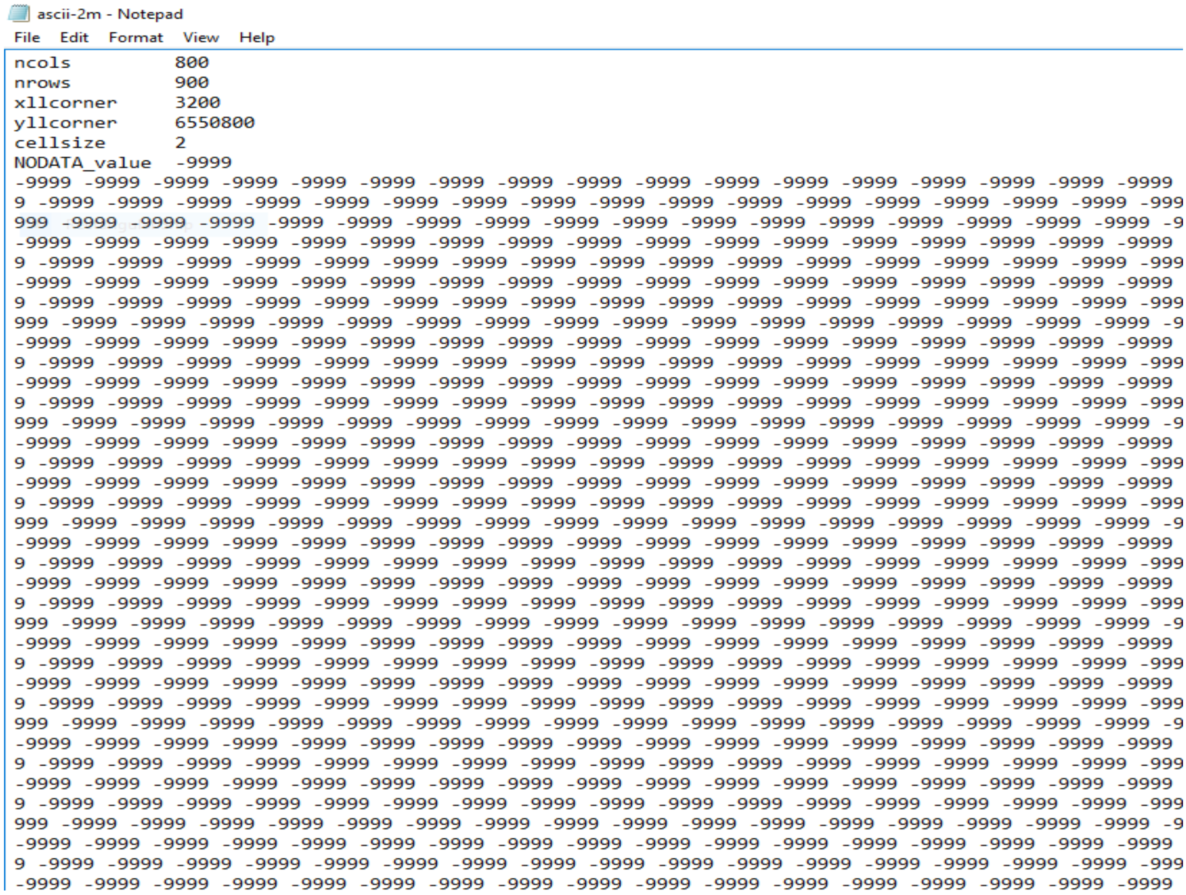
4.2.1. Application of Input Parameters

There are a number of critical data to be provided to successfully carry out simulation with RAMMS. Digital elevation model (DEM), defining the release area or hydrograph and release volume, and friction parameters (Christen et al., 2010). In addition, in modelling debris flow with entrainment the following input parameters area required: defining the entrainment area, defining depth of entrainment layer and coefficient of entrainment, k.

4.2.1.1. Topographic data – Digital Elevation Model (DEM)

Topographic data is the most important input parameter. The simulation result as well as its quality depends strongly on the resolution of the digital elevation model. The slope depends on the elevation differences with in the model which ultimately determine the direction of the flow.

After a series of trial simulation using DEM with different resolution, the 2m resolution was selected based on the quality of the result and because RAMMS needs the topographic data as an ESRI ASCII grid, the raster files are first converted to ASCII (figure 19) by using ArcGIS application software and then they are converted to the required format (ESRI ASCII grid) with in RAMMS. Another advantage of RAMMS is its ability to incorporate the Aerial and Orthographic map of the study area as tif file. Both are included first by converting in to the required format using ArcGIS application software which has conversion tool to carry out this particular objective.




```
ncols         800
nrows         900
xllcorner     3200
yllcorner     6550800
cellsize      2
NODATA_value  -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
9 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

Figure 19: ESRI ASCII grid

4.2.1.2. Release volume

The debris flow was inspected by Slije Wiik Rese of Multiconsult on 2nd of June, 2016. According to the report the release volume is very small, only few tens of cubic meters (figure 20) therefore most of the volume of debris is contributed by entrainment.

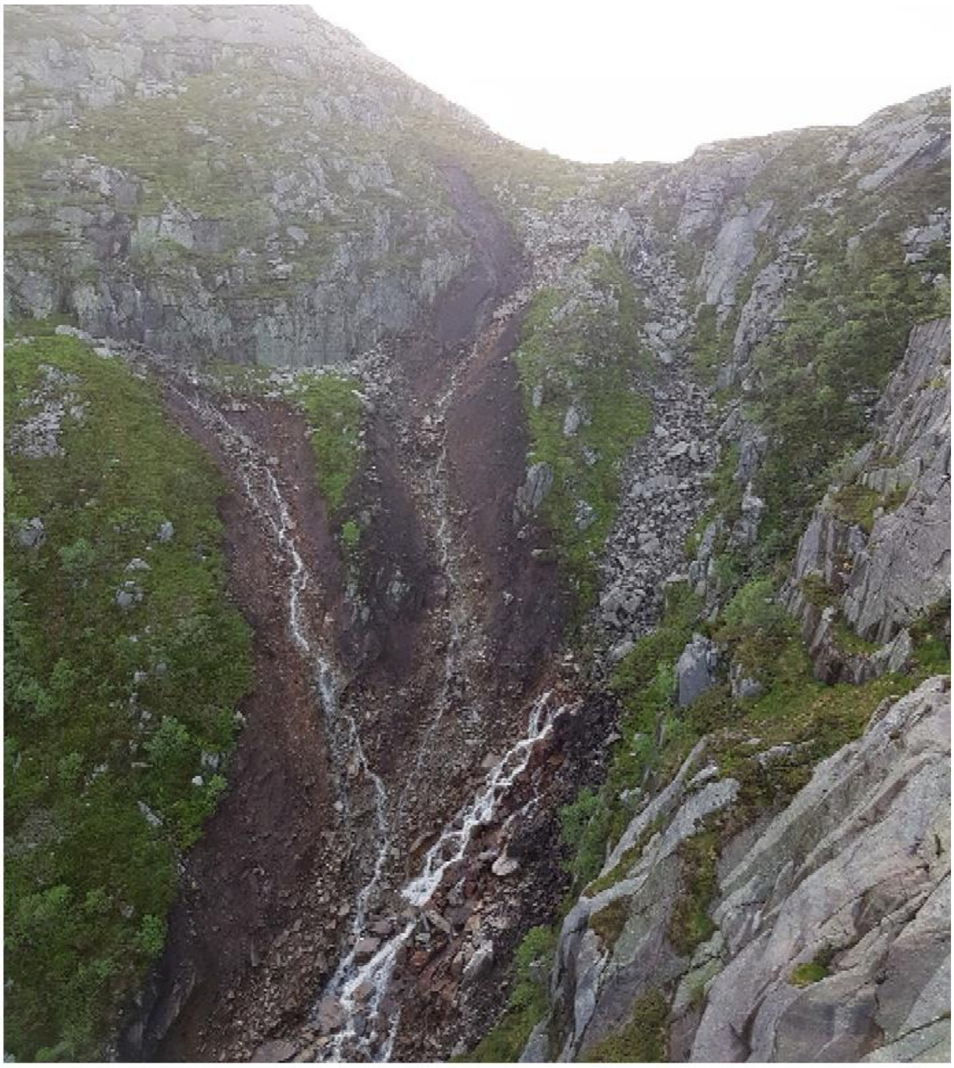


Foto 4 Løsneområdet for skredet

Figure 20: The start area of the debris flow

The flow is shallow at the starting point but gradually increases as it moves downward as it grabs more soil and rock fragments. Even though the Author hasn't independently conform both the volume of the flow and release height, a reasonable value was taken based on the report. The release area is carefully prepared in shape function using ArcGIS and imported in to RAMMS.

4.2.1.3. Friction Parameters

Friction parameters are another important input parameters in modelling of debris flow. The physical model of RAMMS debris flow uses the Voellmy-fluid friction law, which basically divides the frictional resistance into two parts: a dry-Coulomb type friction expressed in terms of coefficient μ and scales with the normal stress and a velocity-squared drag or viscous – turbulent friction represented by coefficient ξ (Christen et al., 2010).

The model was run a number of times in order to optimize each parameter. The range of values between 0.01 to 0.4 was considered for μ while values between 100 to 1000 m/s^2 was used for ξ by keeping the other parameters constant. The simulation result of the calibrated parameters is shown in figure 21 & 22.

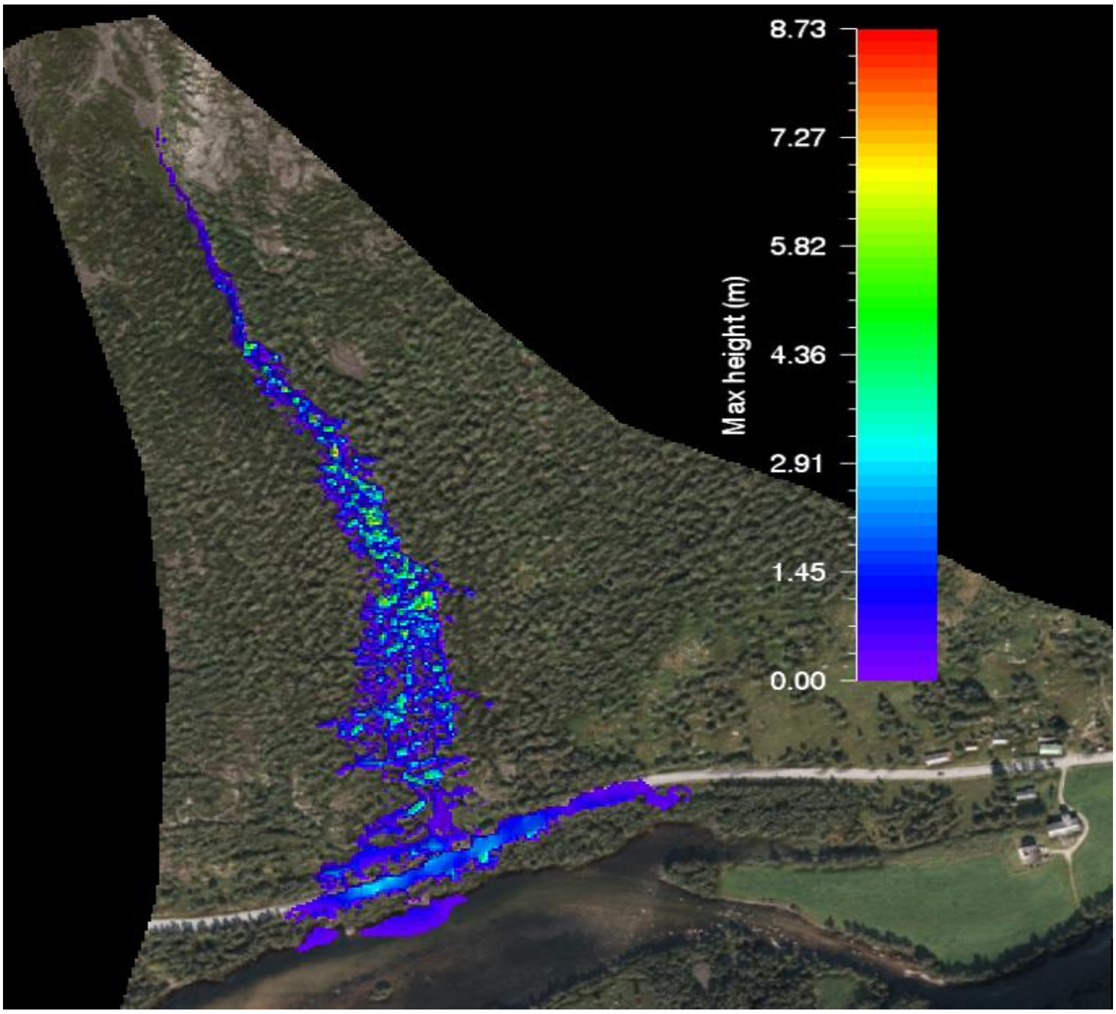


Figure 21. Simulation result for $\mu = 0.1$, $\xi = 500 m/s^2$ & $k = 10$.

5. Results

This chapter focus on discussing the results based on the applied methodology in the previous chapter. The back calculation for Fv.45 Hunnedalsveien, Mjåland is carried out using RAMMS and the results are presented in both the deposition and velocity distribution throughout the debris path. Besides, a number of simulations are carried out to calibrate the rheological parameters. Finally, sensitivity analysis for each parameters is carried out to see the reaction of the model with respect to each of them.

The simulation result is presented in figures.

5.1. Results of the back – calculation

5.1.1 Model Calibration

When the predicted ejected volume (92m^3) was applied, the flow stopped after 240m, which was only 32% of the actual run-out (750m) figure 22, which indicated that the release volume was not enough to cause the actual run-out. Therefore, it was quite clear that the majority of the mass for the flow was contributed by the entrainment. The maximum velocity observed during this flow was 6.56 m/s.

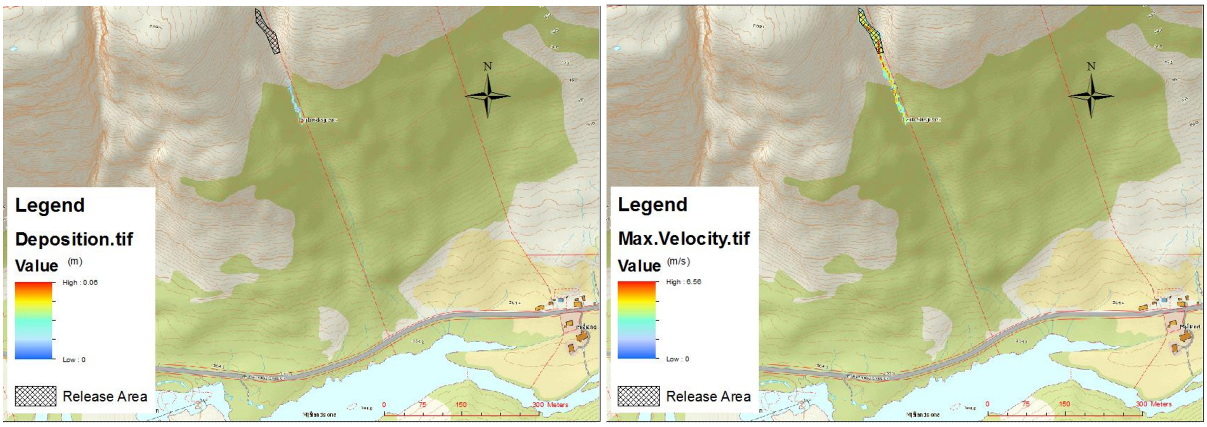


Figure 22. Velocity distribution of the back-analyzed Mjåland debris flow for ejected volume without entrainment.

One of the advantage of RAMMS is its ability of using entrainment during the run-out phase of the flow. However, it restricts the number of layers used in simulation to two, which may not represent the actual condition in the area. This is especially true in long channelized and un-channelized flow with different area at various intervals.

One of the challenges during the selection of entrainment layers for this particular project was the inconsistency of flow characteristics; the upper part of the flow was channelized whereas the lower part was un-channelized (figure 23), which makes it difficult to accurately select the best representation of this layers.

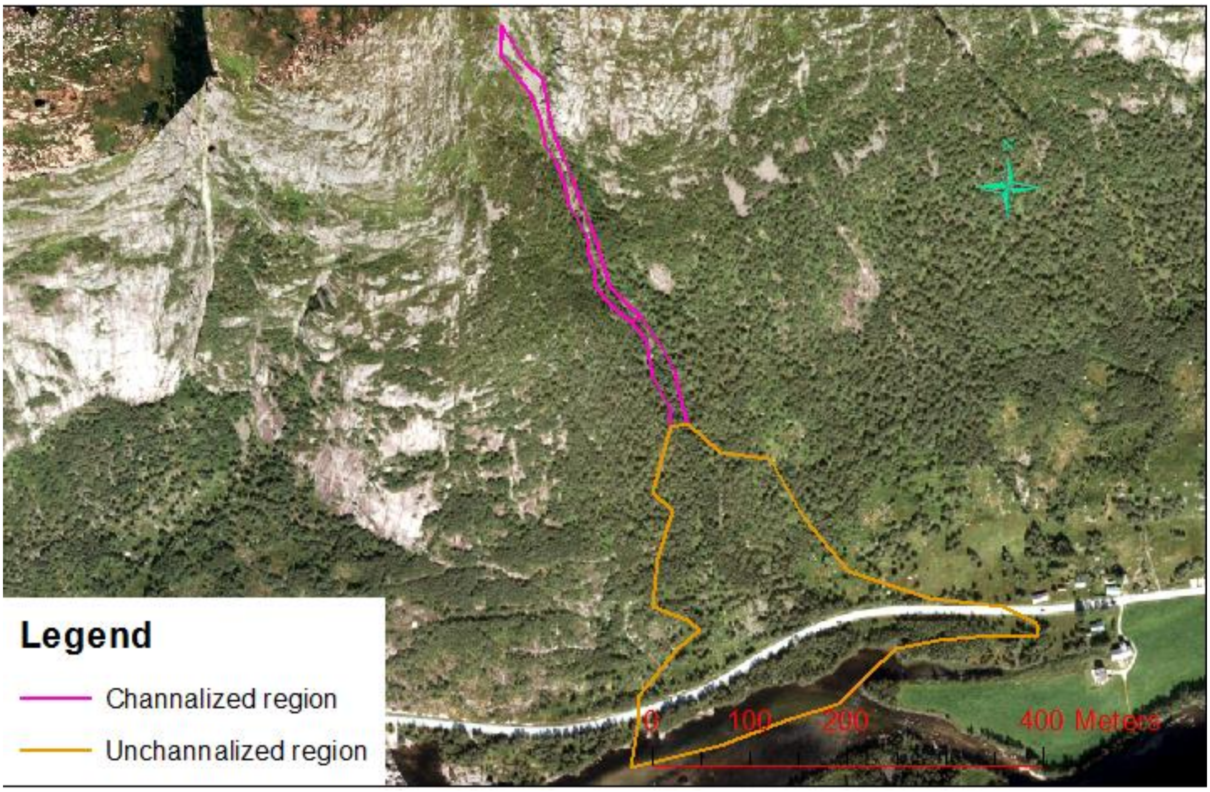


Figure 23. Characteristics of the flow

In order to predict the accurate location and area of the entrainment layers, it is necessary to carry out thorough field investigation. The field investigation was not carried out by the author due to time constraints, but the June 2, 2016 investigation carried out by Silje Wiik Rese (Multiconsult ASA) was used. Besides, the past erosion characteristics of the study area was carefully studied along with geological and orthographic map of the area.

Finally, two entrainment layers with different area are selected based on the channel characteristics (figure 24).

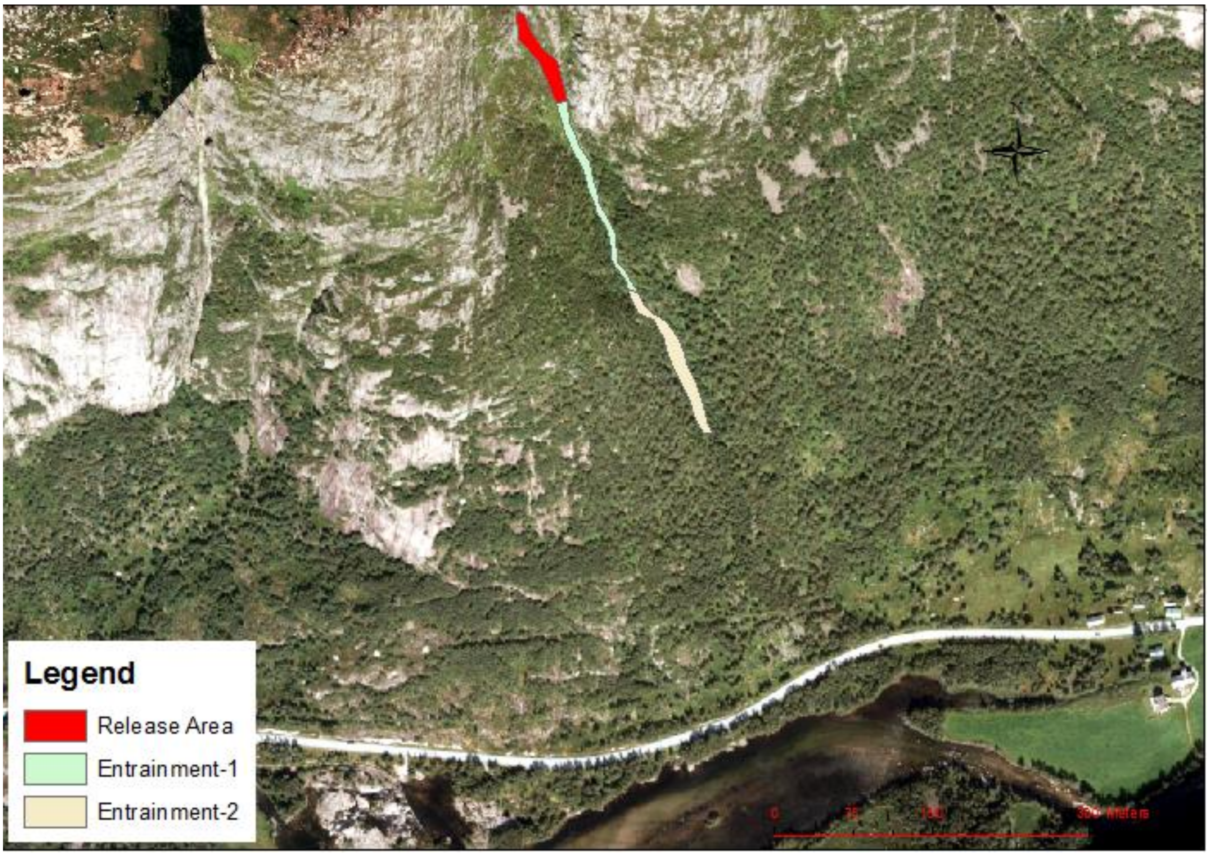


Figure 24. Orthphotograph of Mjåland with selected Entrainment layers.

Once the location and area of the entrainments selected, the next step is to determine its depth. A number of trial simulations has done using different combinations of thickness layers to get the most reliable one. During trial simulation, the total run-out and deposition at the road location were used as a standard criteria.

The procedures followed can be described as follow. Two entrainment layers (E_1 and E_2) are selected and used as in put parameter in RAMMS; then the simulation is carried out. Finally, the run-out distance from the simulation models are compared with the observed run-out distance in the field along with the maximum deposition at road level and the one which best represent both the actual run out distance and the deposition was selected.

The two entrainment layers (E1 & E2), which best produce both the run-out and deposition at road level are 3m & 5m respectively. An example run-out simulation results for two combinations of layers [(E_1 = 3, E_2 = 5) & (E_1 =2, E_2 =3)], with ξ = 500m/s^2, μ = 0.1 and K = 10 are also presented (figure 25 & 26)

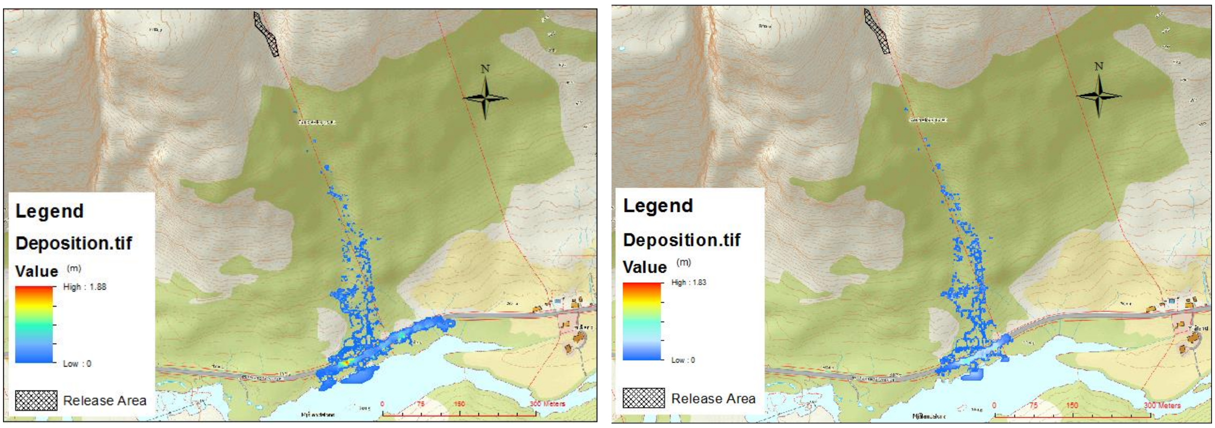


Figure 25. Deposition for (E1 = 3 & E2 = 5m) left and (E1 = 2 & E2 =3m) right.

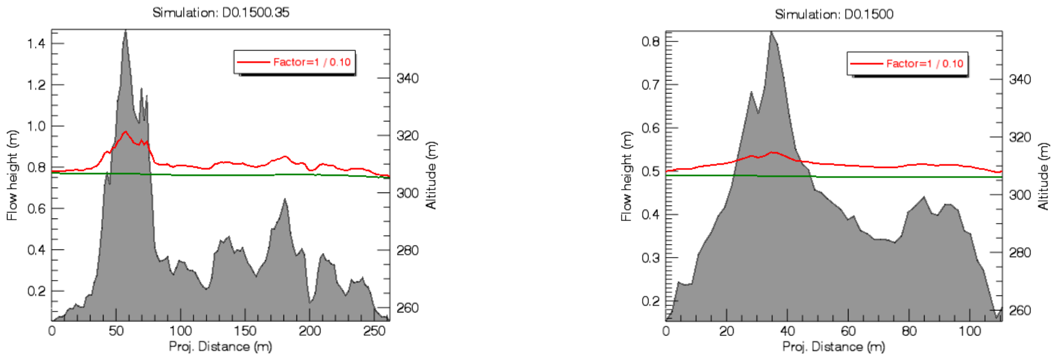


Figure 26. Deposition at the center line of the road (E1 = 3& E2 = 5m) left and (E1 = 2 & E2 =3m) right.

As can be seen in the figure 25 & 26, the run-out distance is almost identical for both conditions, but there is a clear difference in the amount of debris deposited at road level. The deposition in the first case is almost twice of the second case. This is mainly due to the increase in entrained materials with increase in the depth of the layers. In other word, the flow increases with increase in depth of entrainment. It is higher in the first case than the later (figure 27 & 28). The maximum flow is 14899m^3 and 10000m^3 for the first case and second case respectively.

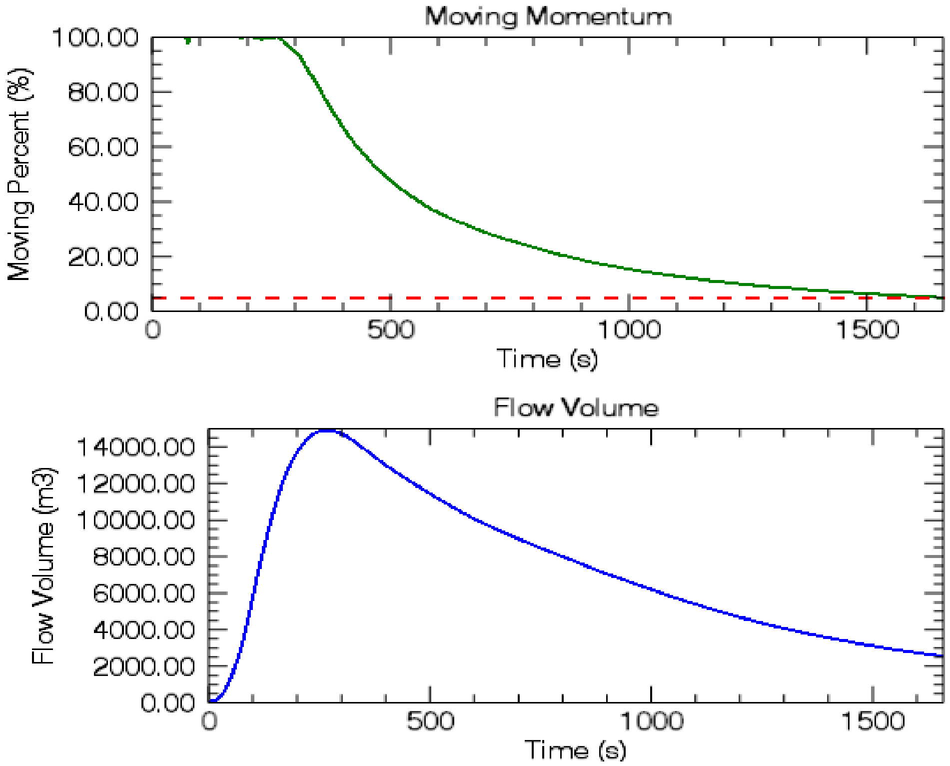


Figure 27. Moving momentum and flow volume for (E_1=3&E_2=5m)

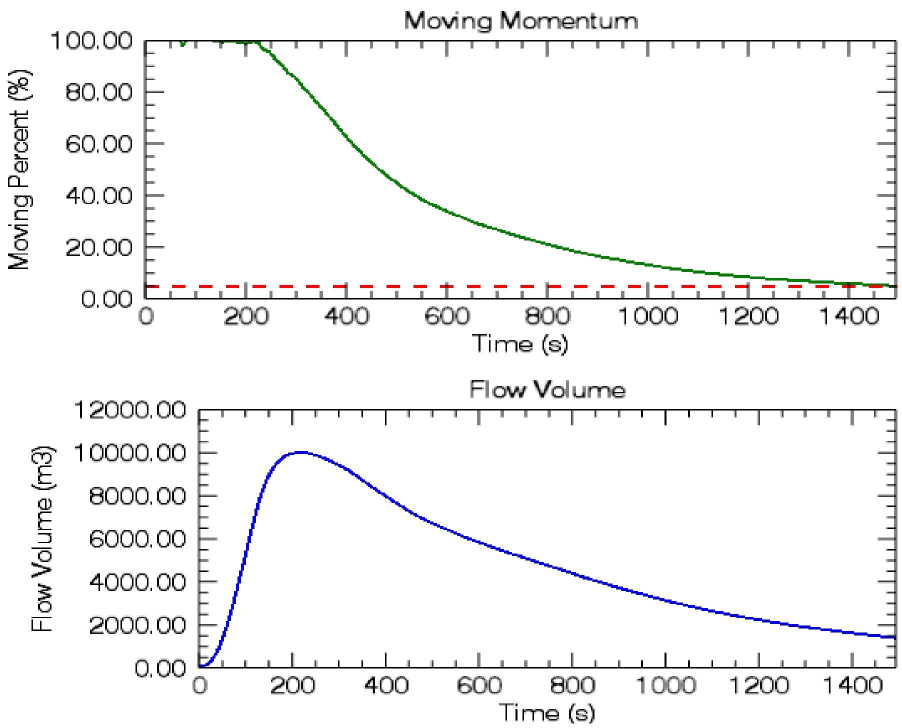


Figure 28 Moving momentum and flow volume for (E_1=2&E_2=3m)

The maximum amount of entrainment produced depends on several factors such as turbulence friction (ξ), coefficient of friction (μ) and entrainment coefficient (k). Therefore, to get the best simulation all these factors should be taken in to consideration. The simulation run out for both cases is 750m, whereas the maximum deposition is 1.45m and 0.82m for the first and second case respectively. The actual run-out and actual deposition are 750m and 2m respectively (Rese, 2017). The result indicated $E_1 = 3$ & $E_2 = 5$m are better combinations to represent the actual debris flow and used in the rest of simulation.

5.2. Sensitivity Analysis

Three input parameters were considered to study the sensitivity of the flow; the friction coefficient, μ, the turbulent friction, ξ and the RAMMS entrainment coefficient, K. Each input parameters was varied by certain percentage from its original calibrated value using systematic sampling technique keeping the other two constant. The calibrated values are K = 10, ξ = 500m/s^2 and μ = 0.1. The run out and the maximum deposition at road level are 750m and 1.45m respectively (figure 29 & 30).

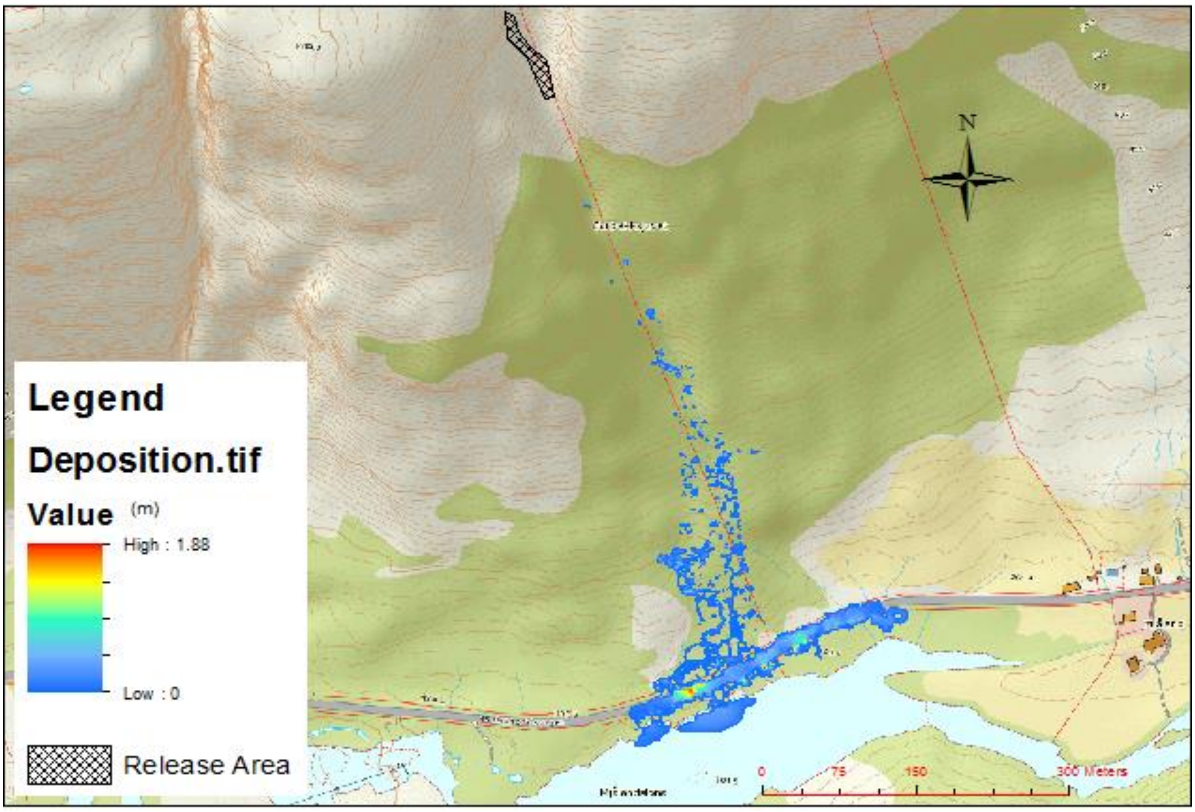


Figure 29: Deposition for the calibrated parameters.

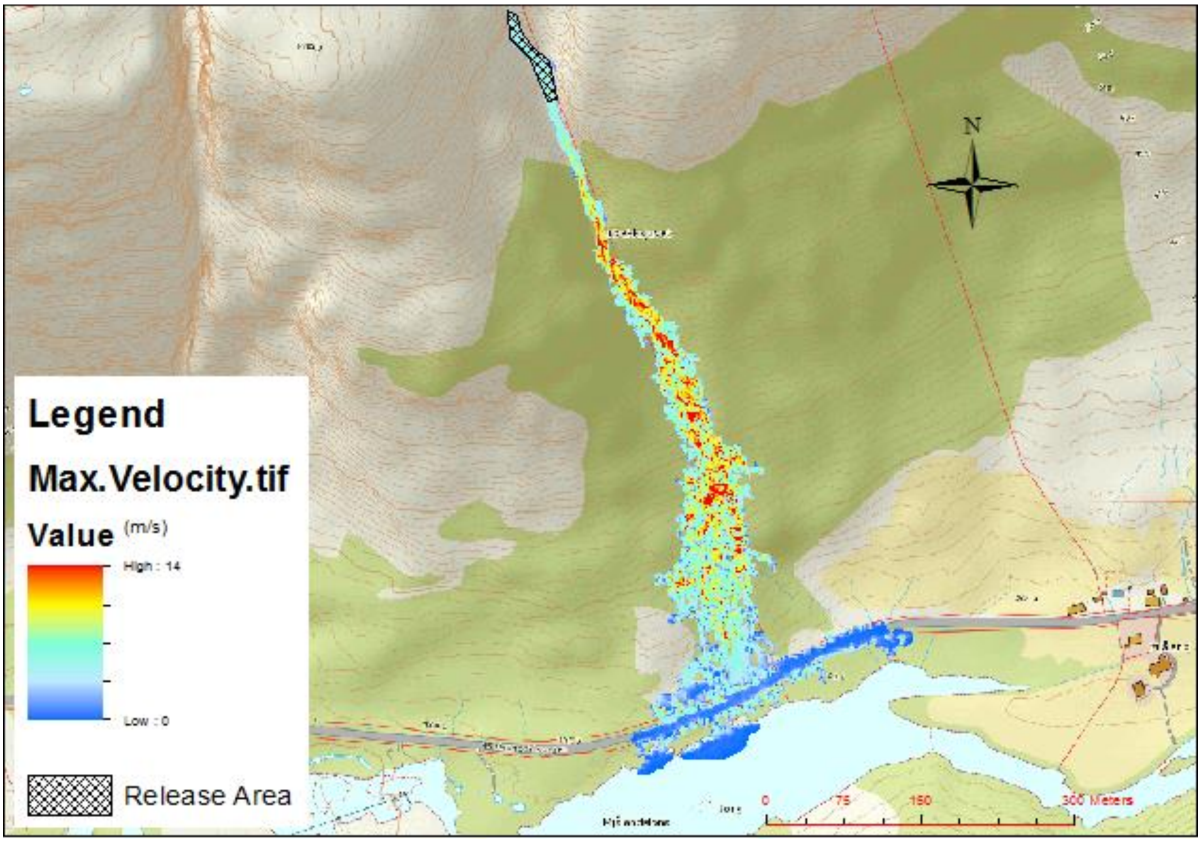


Figure 30. Maximum Velocity for the calibrated parameters.

5.2.1. Sensitivity Analysis of Entrainment Coefficient, k

As stated in section 5.1.1, the ejected volume is very small and hence the majority of the mass movement is contributed by entrainment. After a series of trial simulation using different combinations of thickness layers, the calibrated value of K is 10; to see the sensitivity of the flow with respect to k, the range of values between 1 to 10 are considered and the results with respect to run-out distance and deposition at road level are shown in figure 31. During measuring the width at road location, values in which the deposition is less than or equal to two are ignored because of the possibility that they might washed away by the flow and as a result they might not be seen in the actual debris flow. Therefore, to best simulate the actual flow these values are ignored.

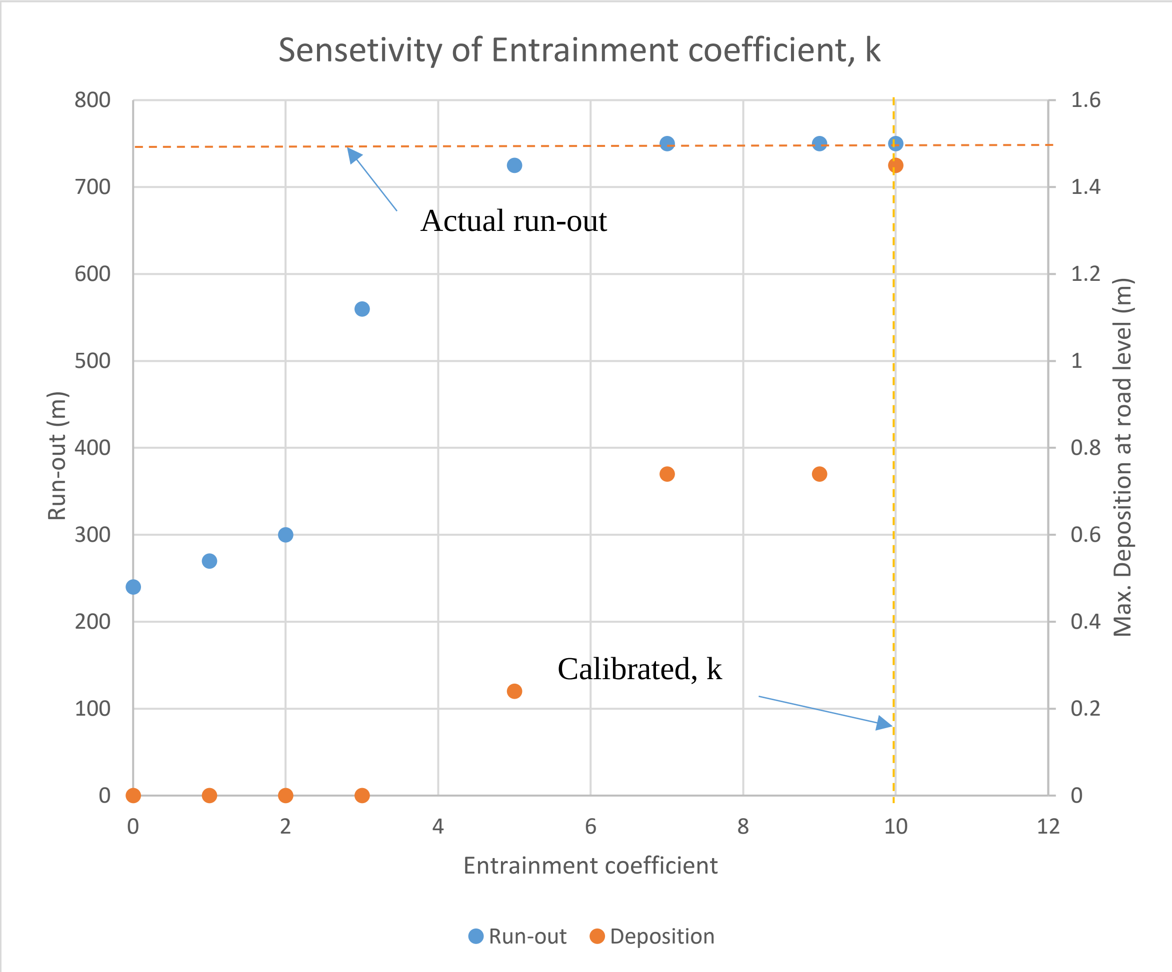


Figure 31. Sensetivity of Entrainment coefficient, K

As shown in the figure, the run-out is very small (240m) with the absence of entrainment (k =0), but it slowly increases until the coefficient of friction is equal to two (k=2), where the run out is 300m. The run-out dramatically changes from K= 2 to K = 3, where it increases by 87% followed by smooth increase between k = 3 and k = 6. For the selected depth of entrainment, the required run-out can be achieved by k values ranging from 6 to 10 m/s^2

Even though the run out is obtained by range of k values, the deposition produced at road location by each of them varies because they all have different flow. The deposition increases with increase k value. The minimum and maximum values are 0.24m and 1.45m respectively for k = 5 and k = 10 respectively. Both the intensity of maximum velocity and deposition are also increased with the k value (Appendix C). The average velocity of the flow is between 5 & 8 m/s^2.

5.2.2. Sensitivity Analysis of Friction coefficient, μ

According to (Bartelt et al., 2013) the value of μ for simulation in RAMMS normally ranges between 0.05 and 0.4 and values outside this range rarely provide useful simulation results. Approximate elevation difference of the study area is 725 – 300 = 425m and approximate slope of the area/stream/ = arc-sin (425/750) = 34.5º. The approximate friction coefficient is tan 34.5 = ~ 0.7, which is very high. The calibrated μ value is 0.1

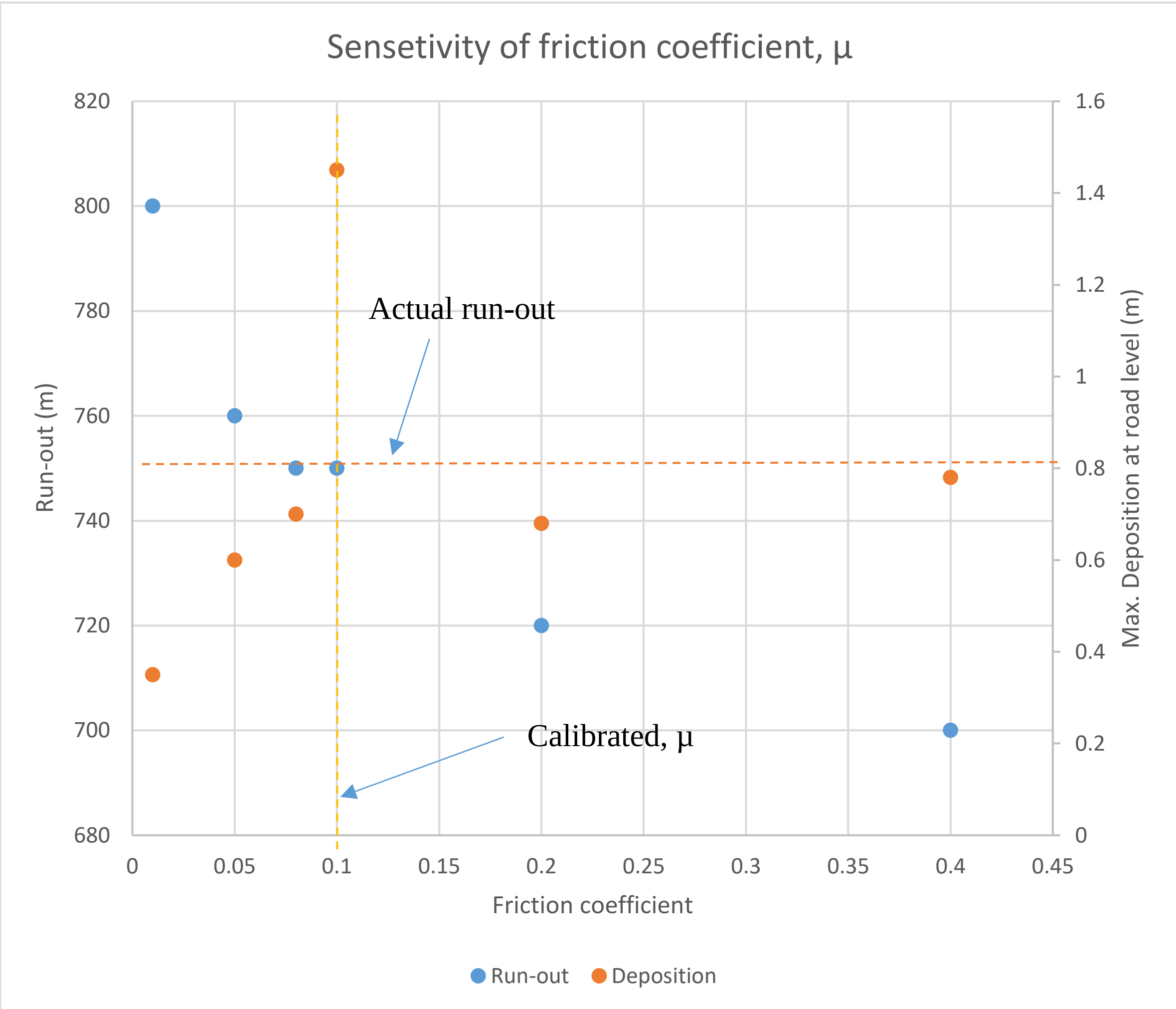
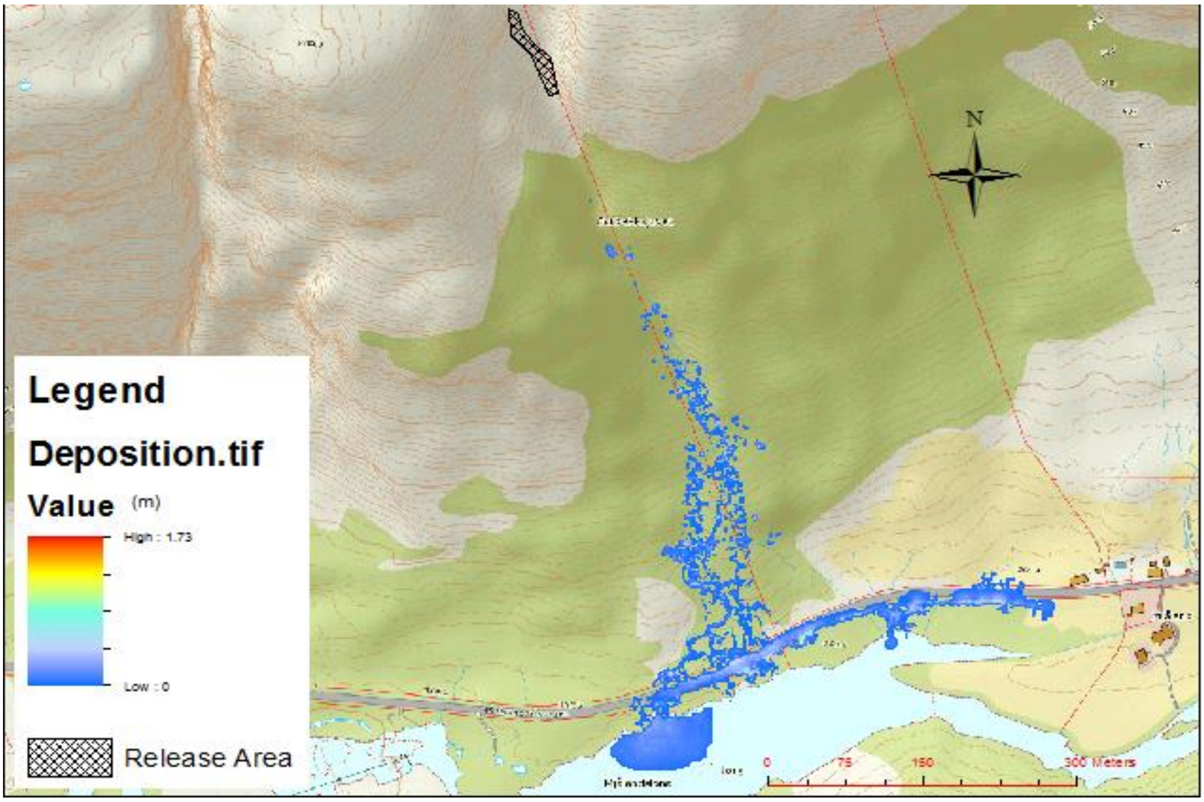


Figure 32: Sensitivity of friction coefficient, μ

The sensitivity of μ is analyzed by using values ranging from 0.01 to 0.4 and the result is presented in figure 32 with respect to run-out distance and deposition at road elevation. As shown in the figure, both the run out distance and deposition decrease with increase in friction coefficient. This is mainly because of the increase in resistance to motion associated with increase in coefficient of friction, μ.

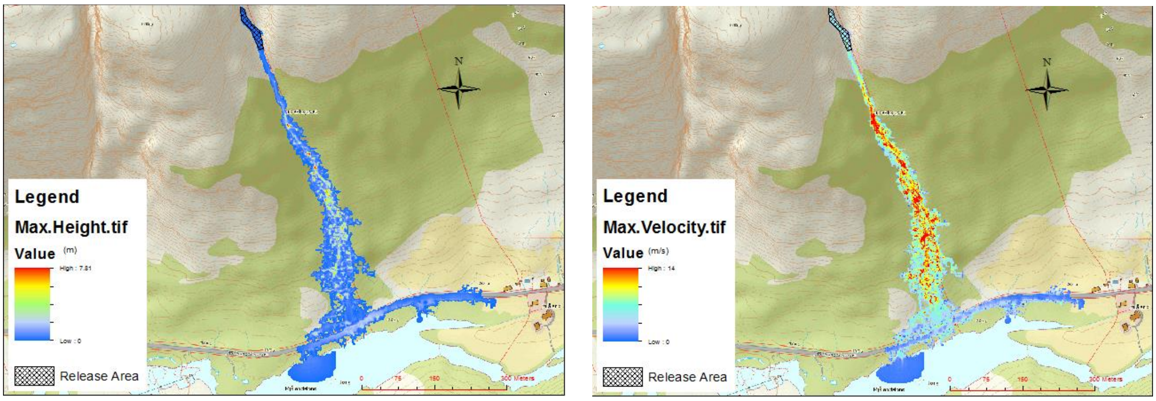
The minimum run-out is 700m which corresponds to μ= 0.4m and the maximum value is 800m which corresponds to μ = 0.01. Similarly, the deposition at road location ranges from 0.35 m (μ =0.01) to 1.45m (μ =0.1). It is also noted that the run out distance reacted slowly with respect to change in friction coefficient as compared to change in coefficient of entrainment.

The simulation result of each μ values are shown in Appendix A, where it is expressed in terms of deposition, maximum velocity and maximum height. The result for μ = 0.01 is shown in figure 33&34 as an example.



(a) Deposition at the end of simulation (5% moment)

Figure 33. Simulation result for μ = 0.01 (Deposition)



(b) Deposition (left) and Maximum Velocity (right) for $\mu = 0.01$, $\xi = 500m/s^2$ & K = 10

Figure 34: Simulation result for μ = 0.01(Velocity)

From figure 29, 30, 33 & 34, the intensity of the maximum velocity shown in red color in the figure is higher for $\mu = 0.01$ as compared to for $\mu = 0.1$. In other words, the average velocity of the flow for $\mu = 0.01$ is higher than $\mu = 0.1$. Similarly, the intensity of the maximum height shown in red color in the figure is higher for $\mu = 0.01$ as compared to for $\mu = 0.08$, which indicates that the average deposition is higher in the first case than the later.

5.2.3. Turbulent coefficient, ξ

The calibrated value for turbulent coefficient, ξ is $500m/s^2$. To analyze the sensitivity of the flow with respect to ξ, values ranging from 100 – 1000 m/s^2 are considered and the result is shown in figure 35 in terms of run out and the deposition at road level.

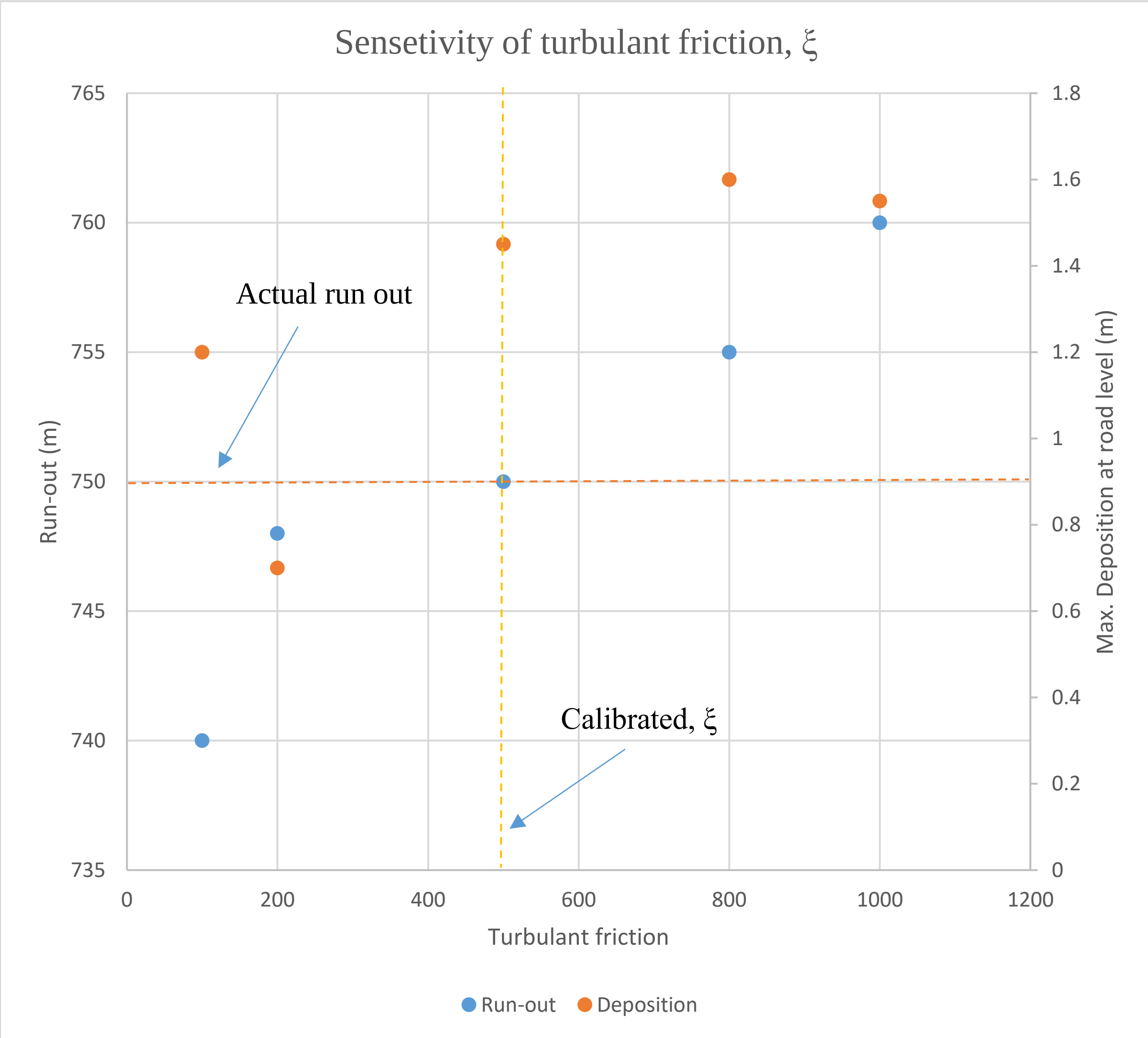
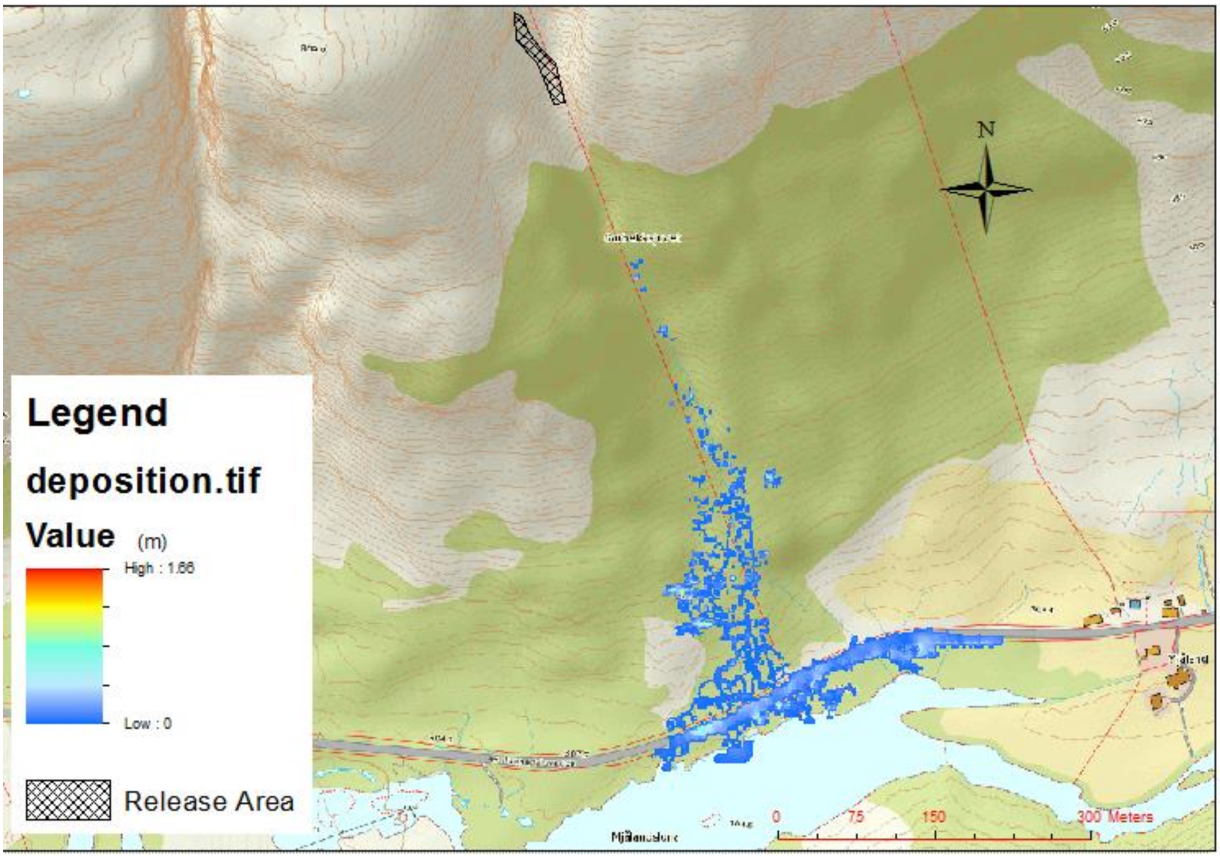


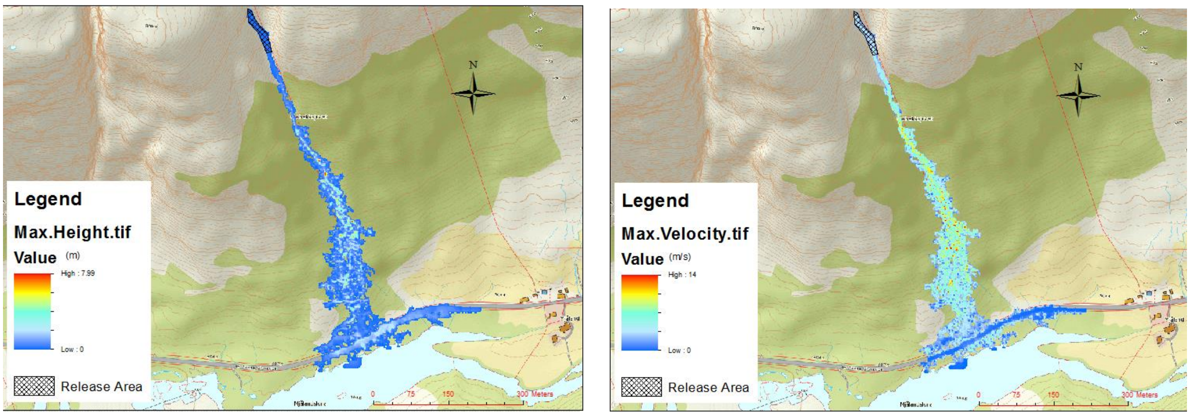
Figure 35: Sensitivity of turbulent friction

As can be seen in figure 35, the run-out distance almost increases uniformly from 740m for ξ = 100m/s^2 to 760m for ξ = 1000m /s^2. The rate of change of run-out distance is relatively small as compared to the rate of change of turbulent friction. For instance, for a 60% decrease of ξ from the calibrated value, the run out decreases only by 0.27% and for the same percent increase of ξ from the calibrated point, the run out increases only by 0.67%. On the other hand, the change of deposition at road level with respect to turbulent friction is variable unlike run-out. For instance, it is higher for ξ = 100m/s^2 and 500m/s^2 as compared to ξ = 200m/s^2.

The simulation result for each ξ values are shown in Appendix B, where it is expressed in terms of deposition, maximum velocity and maximum height. The result for $\xi = 200 m/s^2$ is shown in figure 36.



(a) Deposition for $\xi = 200 m/s^2$ (μ = 0.1, k=10)



(b) The maximum height (left) and maximum Velocity (right) for $\xi = 200 m/s^2$

Figure 36: Simulation results (a) Deposition & (b) Velocity for $\xi = 200 m/s^2$

From figure 30 & 36, the intensity of the maximum velocity shown in red color in the figure is higher for the calibrated value $\xi = 500 m/s^2$ as compared to for $\xi = 200 m/s^2$. In other words, the average velocity of the flow for $\xi = 500 m/s^2$ is higher than $\xi = 100 m/s^2$. In other case, the intensity of the maximum height shown in red color in the figure fades away for $\xi = 100 m/s^2$ as compared to for $\xi = 500 m/s^2$, which indicates that the average deposition is higher in the latter case. The maximum velocity is for $\xi = 500 m/s^2$ is between 9-14 m/s^2, while 7-11 m/s^2 for $\xi = 100 m/ s^2$.

As can be seen from the results, the velocity and height of the flow are high. This is due to their direct relation with volume of entrainment, which ultimately determines the volume of the flow.

5.3. Simulation result for (E_1 =1m, E_2 =2m)

The debris flow run-out is also modelled using low depth of entrainments 1m and 2m for layer one and layer two respectively. The calibrated friction parameters are $\mu = 0.7$ and $\xi = 200 m/s^2$. The result of simulation is shown in figure 37 and figure 38. As can be seen from the figure, the run-out can be obtained, but the deposition at road level is very small (0.53m). The reported observed deposition at road level is 2m.

The maximum velocity is 9.42m/s which is within the normal range for debris flow. The sensitivity of the model towards coefficient of entrainment (K), coefficient of friction (μ) and turbulence friction is tested too. The result indicated that the trend is similar to that of (E1= 3 & E =5). The model is highly sensitive to coefficient of friction, k. And it also depend on friction parameters.

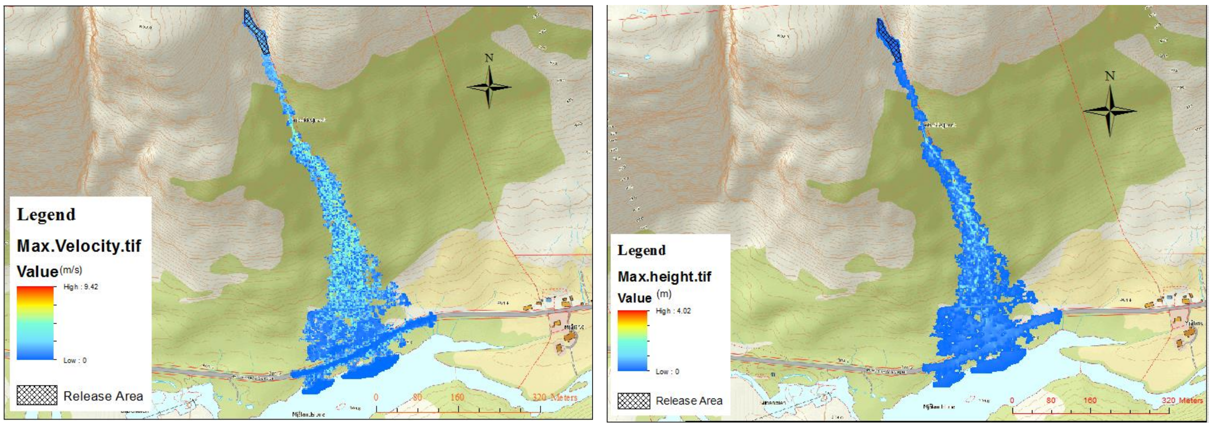


Figure 37. Velocity (left) and height of the flow (right)

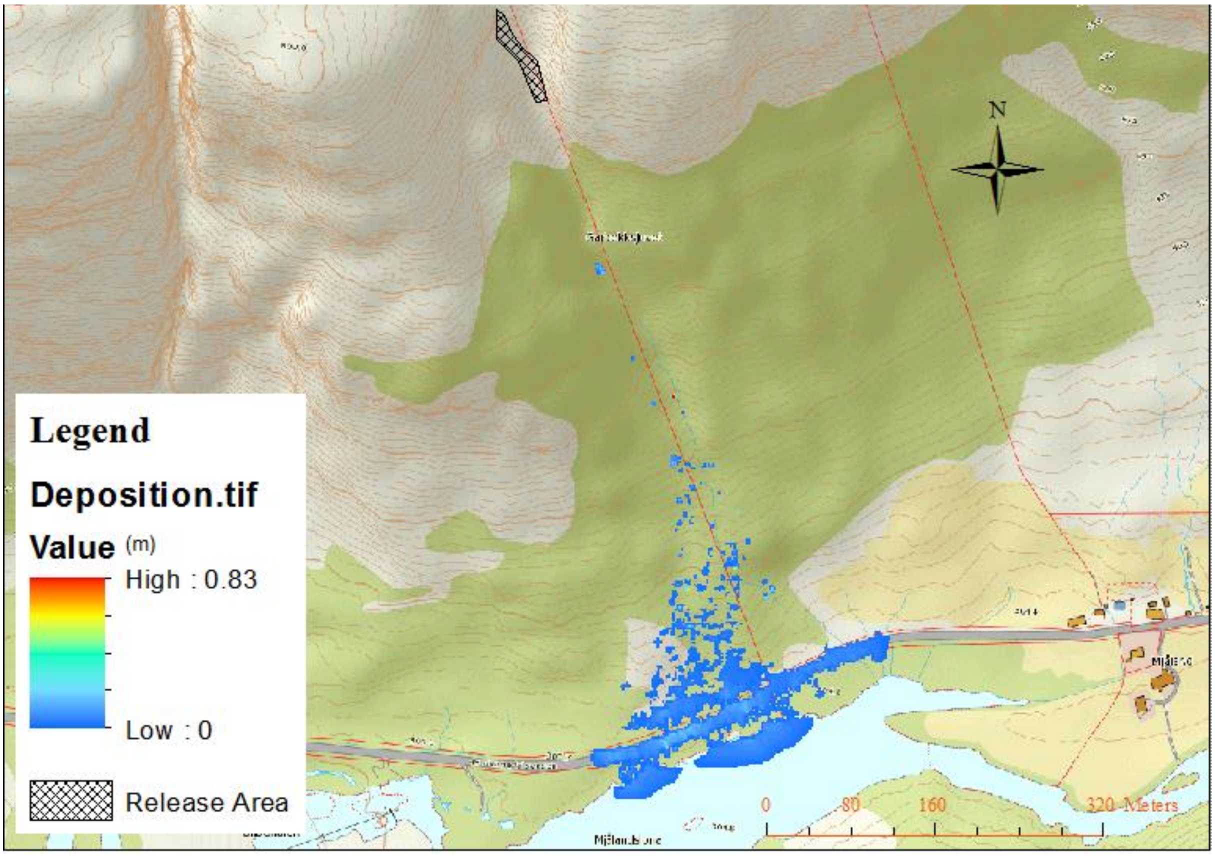


Figure 38. Deposition at road level

The result also showed that the calibrated friction coefficient, μ = 0.7 agrees with one of the results obtained by empirical prediction parameters.μ ~ = tan ϕ = tan 34.5 = 0.68, where ϕ is the slope of the area.

5.4. Discussion

The goal of this study was to back calculate debris flow with entrainment using numerical model. RAMMS is able to simulate Fv.45 Hunnedalsveien, Mjåland debris flow. The run-out distance, deposition, velocity and height of the flow were used as a basic criteria for the back analyze. Some of the results are discussed below.

5.4.1. Voellmy rheology model

RAMMS numerical model assumes the flow as a single–phase with a constant Voellmy rheology, which means it doesn't consider the interaction between the solid and liquid phase of the flow. This is one of the limitations of RAMMS.

5.4.2. Run-out distance

The ejected release volume is very small, but by including two entrainment layers with different depths the required run-out was obtained. The run-out distance is mainly depend on the volume of the entrained layers and the coefficient of entrainment, K. It is also influenced by rheological parameters (friction coefficient and turbulent coefficient). Its value increases with increase of k, this is because more particles are entrained and joined the mass movement.

5.4.3. Velocity of the flow

The slope of the area is relatively high (34.5^0) hence the velocity of the flow is expected to be high. Besides, it also depends on friction parameters. It decreases with increase in coefficient of fiction. The velocity of the flow in this particular study depends on the depth of entrainment.

At the start of the flow the velocity is very small, but it increase gradually as the flow proceeds grabbing more mass until the mid of transportation zone then it slowly decreases. The velocity obtained by this simulation is relatively higher than the normal range of debris flow, the possible reasons might be:

- High slope of the study area (34.5^0)
- Very small release area, which forced to use high depth of entrainment to model the run-out and it resulted in unusually high velocity around this areas. Therefore, the value of the release area should be verified by carrying out further measurement using advanced equipment.

5.4.4 Height of the flow

Like the velocity of the flow, the height of the flow showed wide variation over the course of the flow. The simulation result showed that there is a direct relationship between the velocity and the flow. In other words, the flow has high velocity and high height near the end of the second entrainment area (figure 24).

5.4.5. Sensitivity of rheological parameters.

The model is highly sensitive with respect to entrainment coefficient, k as compared to the other parameters, which indicates that the volume of the flow is mainly controlled by the entrainment.

It is also noted that the amount of entrained material depends on both friction coefficient and turbulent friction.

Therefore although there is no single empirical equation that relates entrainment coefficient with other the amount of entrained material

6. Summary and conclusion

6.1. Summary

The main objective of this thesis was back calculation of debris flow runout with its entrainment behavior using a numerical model. To attain this particular objective, one Norwegian debris flow namely Mjåland debris flow was selected and back analyzed using RAMMS.

During modelling, it was noted that the simulation result depends on the resolution of digital elevation model (DEM). Digital elevation models with higher resolution give better simulation result than those with lower resolution but it takes longer time to simulate. The simulation result is evaluated varying the input parameters: entrainment coefficient (K), friction coefficient (μ) and turbulent friction (ξ). These parameters are not mutually exclusive; in fact, they are interrelated. Therefore, it is required to use the appropriate combination of these parameters to get the best simulation.

The amount of entrained materials depends on four factors: area of the entrained material, entrainment coefficient, friction coefficient and turbulent coefficient. About 15000m^3 flow is needed to produce the required run-out distance(750m), which can be obtained for μ ranging from 0.05 to 0.2 and ξ ranging from 200m /s^2 to 1000m/s^2 . The volume of the flow drops for $\xi \geq$ 1000m/s^2 and $\xi <$ 100m/s^2. Similarly, the volume of the entrained material is lower for $\mu \geq 2$.

The sensitivity of the model with respect to entrainment coefficient, k is very high. For instance, for the calibrated friction parameters, changing the value of k from 9 to 10 shifts the volume of the flow from 13774m^3 to 14899m^3, which is about 8% increase in volume. On the other hand, the sensitivity of the flow with respect to μ and ξ is relatively low.

Generally, the simulation result indicated that very high and very low values of both friction coefficient (μ) and turbulent friction (ξ) have a negative effect on the volume of entrained material.

The depth of the entrainment layers selected are high. This is mainly associated with very small ejected volume and long run-out. The required run-out can be obtained either by changing the entrainment volume or changing the friction parameters. The sensitivity of the model towards friction parameters is very low and hence the only option left to increase the volume of the flow is by increasing the entrained volume. Moreover, this high depth of layers created high velocity and high height around the end of the entrained areas.

The run-out model give reasonable velocity and height for depth combination of (E_1 = 1.5m & E_2 =2m), but it fails to deliver the reported deposition at road level. In addition, the calibrated friction parameters agree with the values obtained by using the existing prediction tools.

6.2. Conclusion

Numerical models include entrainment either through the help of calibration or user defined erosion rates. RAMMS include entrainment using a rate controlled entrainment method, which regulates the mass being entrained in to the debris flow and regulate the time delay to accelerate this mass to the debris flow velocity.

In general modelling debris flow with high entrainment is challenging as it requires thorough field investigation and laboratory tests. RAMMS is highly efficient in modelling debris with low entrainment. It is also possible to model debris with high entrainment using RAMMS numerical modelling. However, a thorough field investigations and laboratory tests are required to determine some of the input parameters like entrainment area, release area, release volume and density of the flow.

The volume of entrained material is governed by the compatibility of friction parameters. In other words, the volume of the flow required to model certain run out depends on both parameters.

For debris flow with very small release volume and long run-out, the flow volume is mainly controlled by the volume of entrainment. The depth of entrainment layers affects both the velocity and height of the flow. High depth creates unusually high velocity and high height, which are outside the normal range for debris flow.

6. 3. Limitation of the study

Some of the limitation of this study are:

- Scarcity of data: The mjåland debris flow occurred recently, hence there are limited number of data associated with the flow. For instance, the DEM hasn’t updated after the flow, which might help to predict the characteristics of the flow such as channel width, depth and etc.

- RAMMS uses only one rheological model, the Voellmy Salm model, which means it doesn’t consider the interaction between solid and liquid phase.
- The simulation result depends on the resolution of the DEM.
- Absence of empirical relations to predict entrainment.
- Absence of empirical technics that correlate entrainment with rheological parameters.
- The number of entrainment layers used in RAMMS are limited in to two, which makes it difficult to use in long channel of variable width at different location.
- Equifinality is not considered during this study due to time constraint.

7. Recommendations and future works.

7.1. Recommendations

Based on the back calculation of Mjåland debris flow, modelling debris flow with entrainment using RAMMS should be accompanied by thorough field investigation and laboratory tests because part of the input parameters in RAMMS are obtained from field investigation.

The quality of the model depends on the resolution of the digital elevation model (DEM) used as input in RAMMS. Therefore, one should try to use different DEM to get the more reliable one. Usually DEM with higher resolution give better result.

During modelling debris flow run-out with entrainment, selecting the entrainment area should be accompanied by GPS measurements.

For RAMMS developers

- RAMMS use only Voellmy Salm model, which doesn't consider the interaction between the components of debris. It would be very interesting to see future development to incorporate this behavior of debris flow in the model.
- The simulation of debris using DEM with high resolution takes very long time. Therefore, further modifications should be done to make it independent of the DEM.

7.2. Future Work

To overcome the limitations described under section 6.3, further studies should be done. Some of them might be:

- Exploring the relationship between entrainment and rheological parameters to find a simplified empirical formula that relates entrainment with rheological parameters.
- Exploring the relationship between resolution of DEM and simulation results in order to create a resolution independent application software or advance RAMMS.
- Exploring equifinality and studying the sensitivity of a model towards such characteristics.

Reference

Anda, E., & Blikra, L. (1998). Rock-avalanche hazard in Møre & Romsdal western Norway,. *Geothechnical Institute*.

B¨uhler, Y., Christen, M., Kowalski, J., & Bartelt, P. (2011). Sensitivity of snow avalanche simulations to digital elevation model quality and resolution. *Ann. Glaciol, 52*, pp. 72-80.

Bartelt, P., Buehler, Y., Christen, M., Deubelbeiss, Y., Graf, C., McArdell, B., . . . Schneider, M. (2013). RAMMS (rapid mass movements simulation). Switzerland.

Beguería, S., Asch, v., J, T. W., Malet, J.-P., & Gröndahl, S. (2009). A GIS-based numerical model for simulating the kinematics of mud and debris flows over complex terrain. *Natural Hazards & Earth System Sciences, 9*(6), 1897-1909.

Bertoldi, G., D'Agostino, V., & McArdell, B. (2012). An integrated method for debris flow hazard mapping using 2D runout models. *In Interpraevent 2012 Proceedings, 23–26 April 2012, (ed.) S.n. Grenoble, France*, pp. 435-446.

Breien, H. (2005). *On the dynamics of debris flows: case study Fjærland, Western Norwaya*

debris flow triggered by a natural dam breach. (Master), University of Oslo, Oslo.

Carrara, A., Crosta, G., & Frattini, P. (2008). Comparing models of debris-flow susceptibility in the alpine environment. *Geomorphology, 94,* pp.353-378.

Casteller, A., Christen, M., Villalba, R., Martinex, H., Stockli, V., Leiva, J. C., & Bartelt, P. (2008). Validating numerical simulations of snow avalanches using dendrochronology: the Cerro Ventana event in Northern Patagonia, Argentina. *Natural Hazards and Earth System Sciences, 8*, pp. 433-443.

CHEN, H., & LEE, C. (2004). Geohazards of slope mass movement and its prevention in Hong Kong. *Engineering Geology, 76*, 3-25.

Chen, H., & Lee, C. F. (2000). Numerical simulation of debris flows. *Canadian Geotechnical, 37(1),* 146-160.

Christen, M., Kowalski, J., & Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three diamentional terrain

Cold regions science and technology, 63(1), 14.

Crosta, G. B., Imposimato, S., & Roddeman, D. G. (2009). Numerical modelling of entrainment - deposition in rock and debris -avalanches. *Eng.Geol., 109*, P.135-145.

Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. *National Academy of Siences, 247* 36-75.

Fannin, J., & Bowman, E. T. (2008). Debris flows - Entrainment, Deposition and Travel

Distance. *Geotechnical News, 25(4),* pp. 3-6.

Fischer, J.-T., Kowalski, J., & Pudasaini, S. P. (2012). Topographic curvature effects in applied avalanche modeling. *Scintific Technology, 74*(75), pp. 21-30.

Fiskum, E. (2012). Flomskred: Testing av ulike sikringstiltak i modellforsøk.

Frekhaug, M. H. (2015). *An assessment of prediction tools to Norwegian debris flows.* (Master), NTNU, Trondheim, Norway.

Gauer, P., & Harbitz, C. B. (2014). *'Chapter 9. Skreddynamikk'. In Skred, skredfare og*

siktingstiltak-praktiske erfaringer og teoretiske prinsipper, (eds.). Oslo: Norges Geotekniske Institutt and Universitetsforlaget, pp.

189 – 200.

Glade, T. (2005). Linking debris-flow hazard assessments with geomorphology. *Geomorphology, 66(1)*, 25.
Håland, G. (2012). Lærebok

Drift og vedlikehold av veger. *Statens vegvesens rapporter*, 1-26.
Hiller, P., & Jenssen, L. (2009). Modellforsøk med flomskred mot bruer - virkning av bruåpning og ledevoller.
Hübl, J., & Fiebiger, G. (2005). debris-flow mitigation measures. *Springer*, 446-485.
Huebel, J., Ganahl, E., Gruber, H., Holub, M., Holzinger, G., Moser, M., & Pichler, A. (2004). Grundlagenerhebung für das Schutzkonzept Lattenbach (Catchrisk). Grundlagen fuer eine Murenprognose und darauf aufbauend die Entwicklung eines Warn- und Alarmsystems. *WLS Report 95, 1*.
Huebl, J., & Steinwendtner, H. (2000). Debris flow hazard assessement and risk mitigation *felsbau, Rock and Soil Engineering, 1*, 17-23.
Hunger, O. (1995). A model for the runout analysis of rapid flow slides, debris flows, and

avalanches. *Canadian Geotechnical Journal*, *32*(4), pp. 610-623.
Hunger, O., Evans, S., Bovis, M., & Hutchinson, J. (2001). A review of the classification of landslides of the flow type. *Environmental & Engineering Geoscience, 7*, pp. 221-238.
Hunger, O., & McDougall, S. (2009). Two numerical models for landslide dynamic analysis. *Computers & Geosciences, 35*(5), pp. 978-992.
Hussin, H. Y., Quan Luna, B., Van Western, C. J., Christen, M., Malet, J.-P., & Van Asch, T. W. J. (2012). Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Faucon catchment, Southern French Alps. *Natural Hazards and Earth System Sciences, 12*(10), pp. 3075-3090.
Hussin, H. Y., Quan Luna, B., Van Western, C. J., Christen, M., Malet, J.-P., Van Asch, T. W. J., & 3075-3090., p. (2012). Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Faucon catchment, Southern French Alps. . *Natural Hazards and Earth System Sciences, 12*(10), pp.3075-3090.
Iverson, M. (1997). Physics of Debris Flows. *Reviews of Geophysics 35*(August 1997), pp. 245-296.
Iverson, R. M. (2005). *Debris-flow mechanics. Debris-flow hazards and related phenomena.* : Springer.
Jaedicke, C., Lied, K., & Kronholm, K. (2009). Integrated database for rapid mass movements in Norway. *Nat. Hazards Earth Syst. Sci., 9*, 469-479.
Jakob, M., & Hunger, O. (2005). *Debris flow hazards and related Phenomena*. New York: Springer.
Johnson, A. M. (1984). *Debris flow, in slope Instability*. New York: John Willy.
Kettl, W. (1984). Vom Verbauungsziel zur Bautypenentwicklung: Wildbachverbauung im Umbruch. *Wildbach- und Lawinenverbau, 48*, 61-98.
Kettl, W. (1998). Vom Gefahrenpotential zum Verbauungssystem. *Wildbach- und Lawinenverbau, 62*.
Laache, E. (2016). *Model Testing of the Drainage Screen Type Debris Flow Breaker.* (Masters), NTNU, Trondheim, Norway.
McDougall, S. (2006). A new continuum dynamic model for the analysis of extremely rapid landslide motion across complex 3d terrain (Doctor of Philosophy), THE UNIVERSITY OF BRITISH COLUMBIA Toronto.
Mizuyama, T. (2008). Structural Countermeasures for Debris Flow Disasters *International Journal of Erosion Control Engineering, 1*(2), 38-43.
Montgomery, D. R., & Dietrich, W. E. (1994). . A physically based model for the topographic control on shallow landsliding. *Water Resources Research . 30*, pp.83-92.
Norem, H. S., & Sanderson, F. (2012). Flom-og sørpeskred. Project report” Klima og Transport” *SW report* (Vol. 73). Oslo.
O’Brien, J., Julien, P. Y., & Fullerton, W. T. (1993). Two-dimensional water flood and

mudflow simulation. *Journal of hydraulic engineering, 119(2)*, pp. 244-261.
Quan, L. B. (2012). *Dynamic numerical run-out modeling for quantitative landslide risk*

assessment. (Ph.D), The University of Twente, Enschede, Netherlands.
Reid, M. E., Iverson, R. M., Logan, M., Lahusen, R. G., Godt, J. W., & Griswold, J. P. (2011). *Entrainment of bed sediment by debris flows: Results from large-scale experiments. Debrisflow Hazards Mitigation, Mechanics, Prediction, and Assessment*.
Rese, S. W. (2017). Fv.45 Hunnedalsveien, Mjåland 'Assessement of the debris flow course': Multiconsult.
Rickenmann, D. (1999). Empirical Relationships for Debris Flows. *Natural hazards, 19(9),* pp 47-77.
Rickenmann, D. (2005). ‘Runout prediction methods’. In Debris-flow Hazards and Related

Phenomena, (eds.). *Springer*, pp. 305–324.
Rudolf-Miklau, F., Hübl, J., & Suda, J. (2014). *Standardized stress model for design of torrential barriers under impact by debris flow (according to Austrian Standard Regulation 24801)*. Paper presented at the INTERPRAEVENT 2014 in the Pacific Rim, , At Nara, JAPAN.
Salm, B. (1993). Flow, flow transition and runout distances of

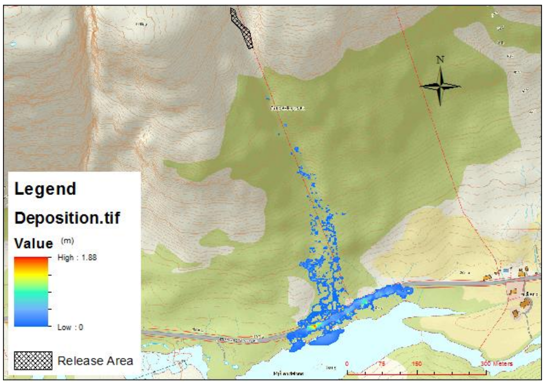
flowing avalanches *Annals of Glaciology, 18*, pp. 221-226.
Scheidl, C., Rickenmann, D., & McArdell, B. W. (2013). Runout Prediction of Debris Flows and Similar Mass

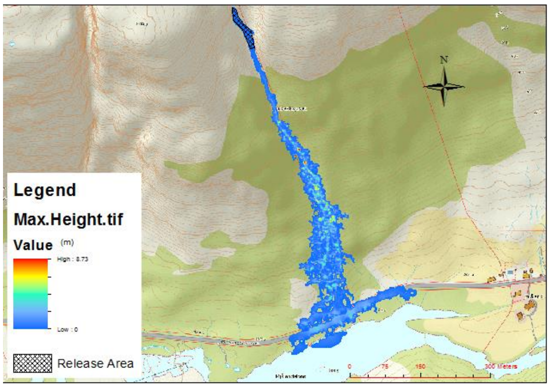
Movements. *Landslide Science and Practice, 3*, 221- 227.
Schneider, D., Bartelt, P., Caplan-Auerbach, J., Christen, M., Huggel, C., & McArdell, B. W. (2010). Insights into rock-ice avalanche dynamics by combined analysis of seismic recordings and a numerical avalanche model. *Geophysical Research, 115*(20).
Schraml, K., Thomschitz, B., McArdell, B. W., Graf, C., & Kaitna, R. (2015). Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models. *Natural Hazards and Earth System Sciences Discussion, 3*(2), pp. 1397-1425.
Sovilla, B., Burlando, P., & Bartelt, P. (2006). Field experiments and numerical modelling of mass entrainment in snow avalanches. *J.Geophys. Res., 111*(16).
Takahashi, T. (2014). *Debris flow: Mechanics, Prediction and Countermeasures* (2 ed.): CRC press.
Thakur, V., Nigussie, D., & Degago, S. A. (2014b). *A Preliminary study of rheological models for run-out distance modeling of sensitive clay debris.* . Paper presented at the 8th European Conference on Numerical Methods in Geotechnical Engineering., Delft, Netherland.
Van Wazer, J. R., Lyons, J. W., Kim, K. Y., & Colwell, R. E. (1963). *Viscosity and Flow Measurement -- A laboratory handbook of*

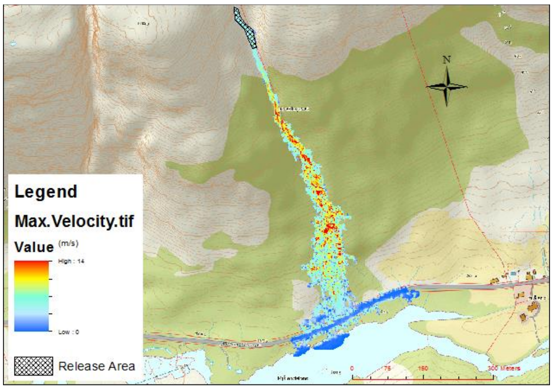
Rheology. : Interscience, Wiley.
Yifru, A. L. (2014). *Assessment of Rheological Models for Run-out Distance Modeling of Sensitive Clay Slides, Focusing on Voellmy Rheology.* (Masters Degree), Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
Zollinger, F. (1985). Debris detention basins in the European Alps. In: A. Takei (ed.), International Symposium on Erosion. *Debris Flow and Disaster Prevention*, 433-438.

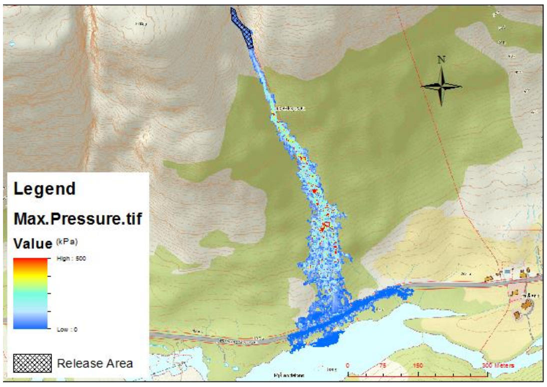
Appendix A: Simulation result for Sensitivity test of friction coefficient, μ

μ =0.1, ξ = 500 & K= 10 (Calibrated result)

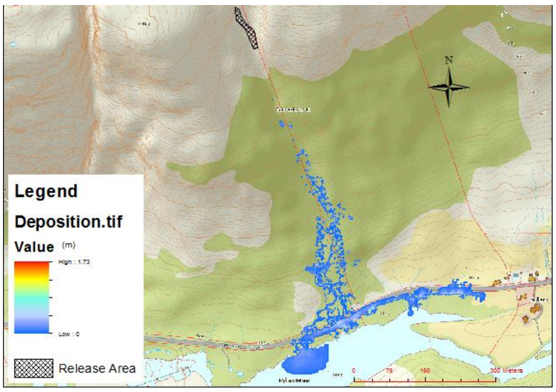


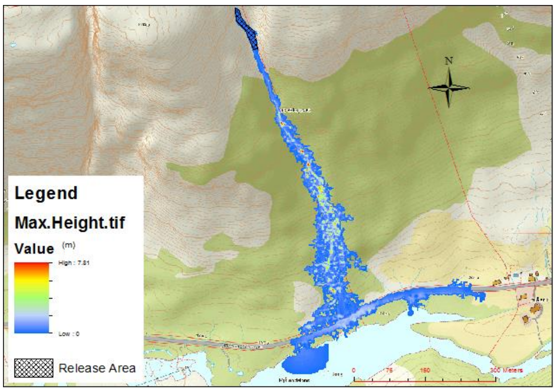


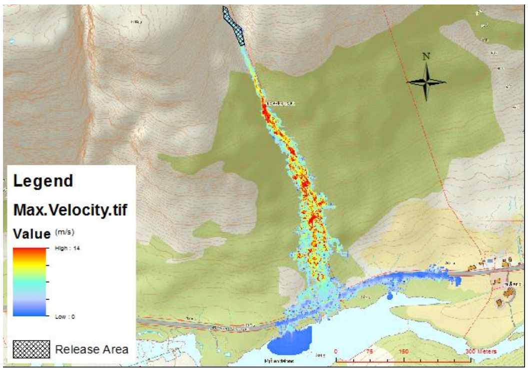




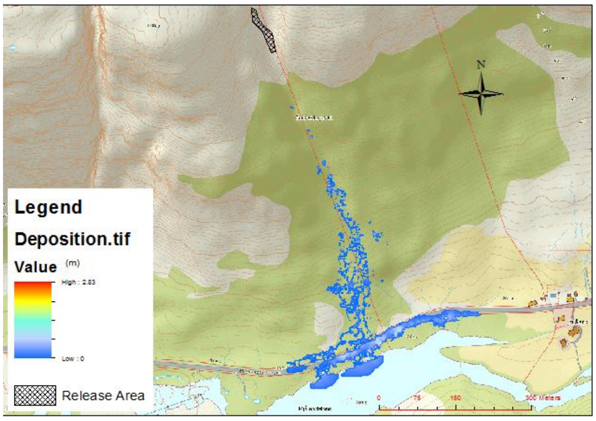
Simulation result for μ =0.01, ξ = 500 & K= 10, E1 = 3, E2 = 5

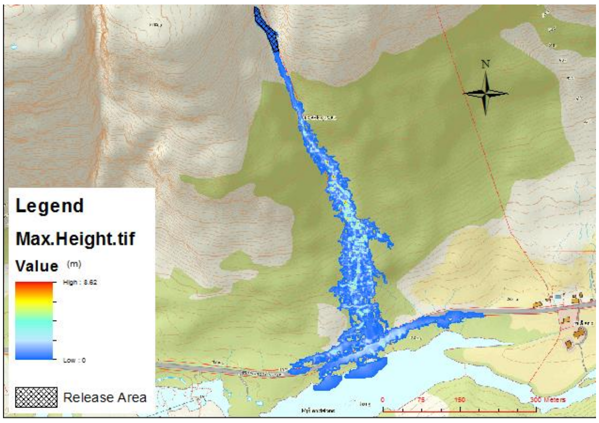


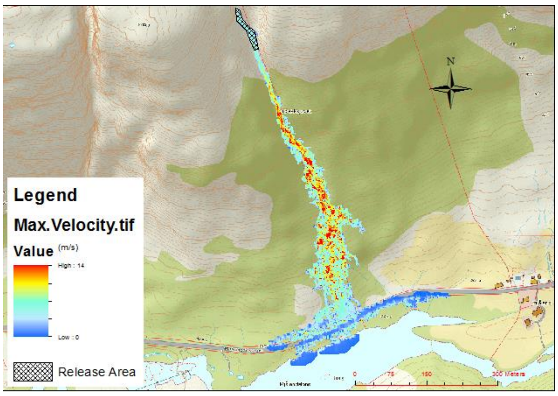




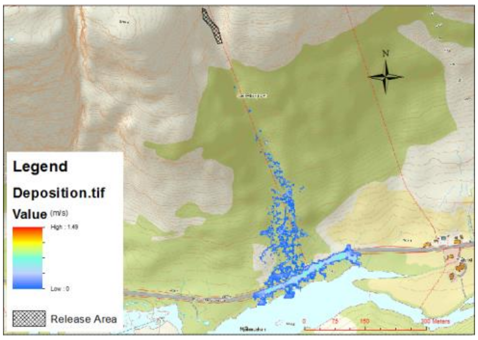
Simulation result for μ =0.05

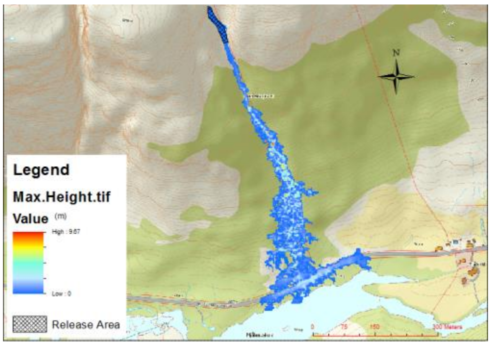


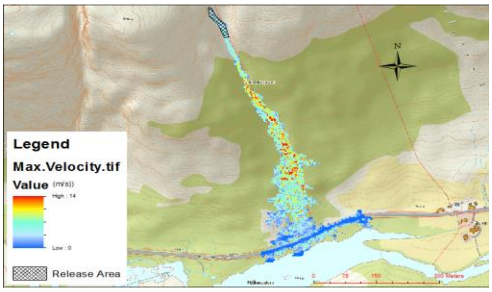




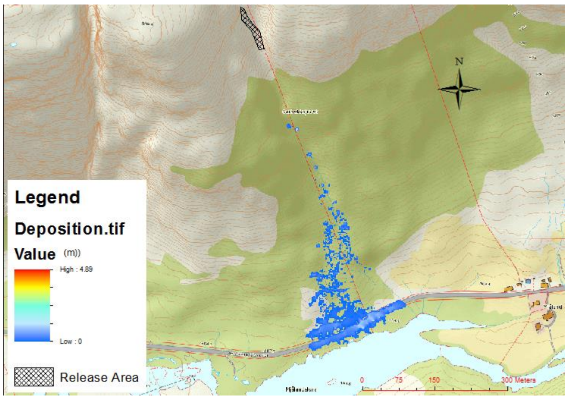
Simulation result for μ =0.2

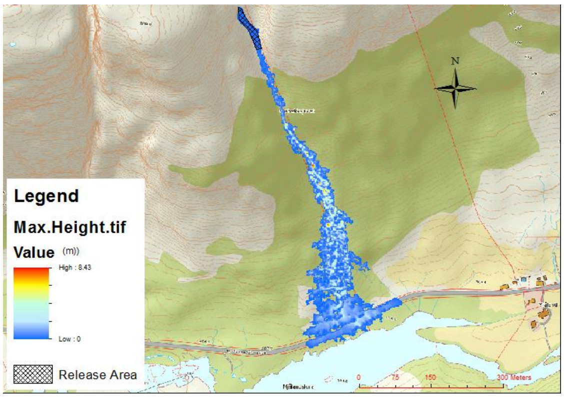


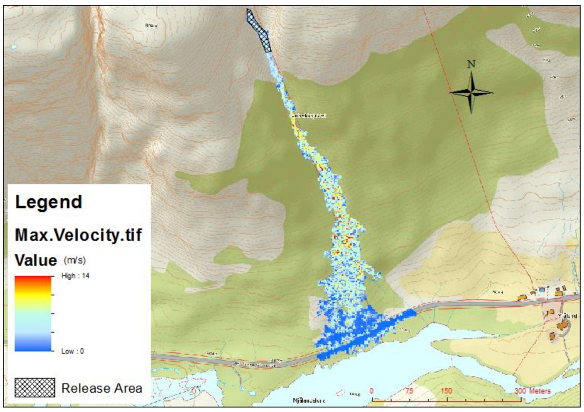




Simulation result for μ =0.4

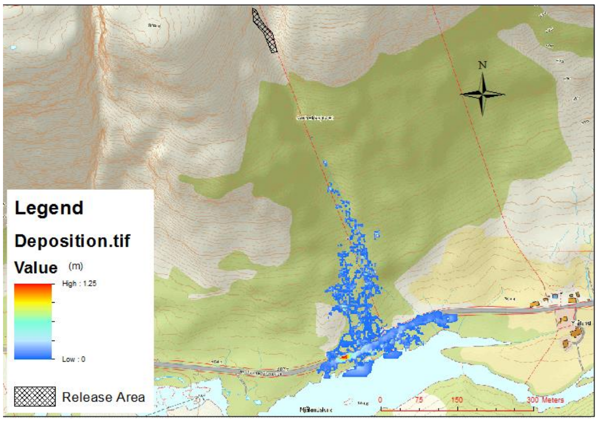


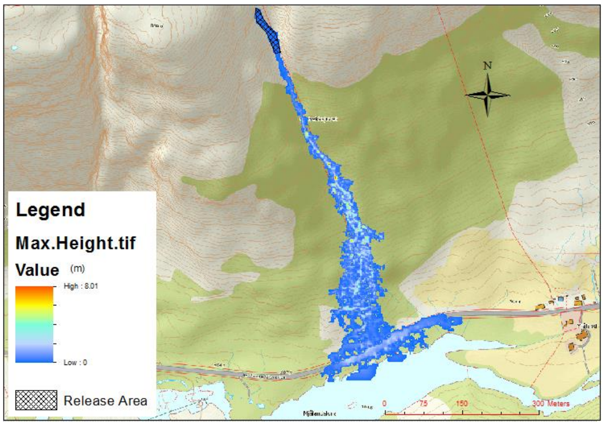


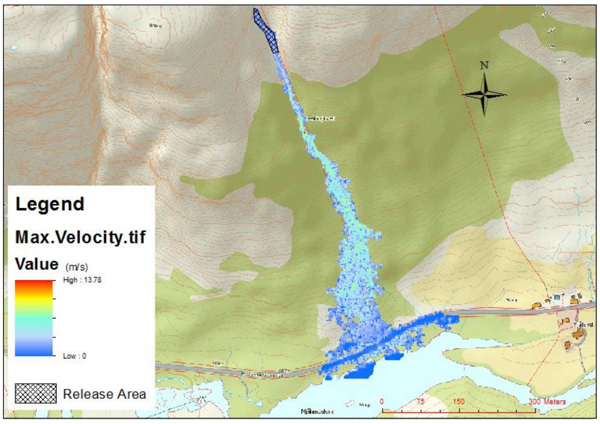


Appendix B: Simulation results for Sensitivity test of turbulent friction, ξ

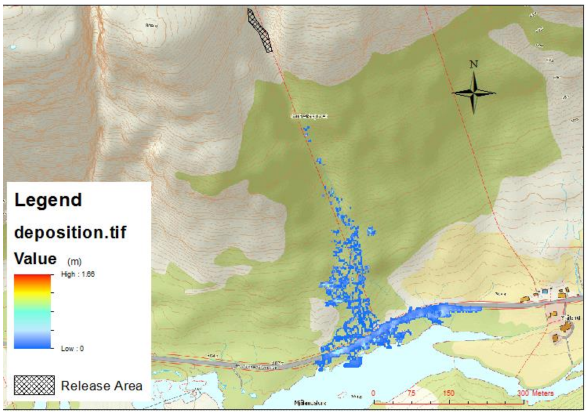
Simulation result for ξ = 100

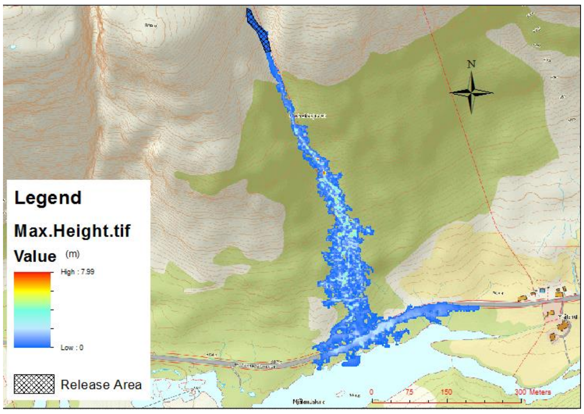


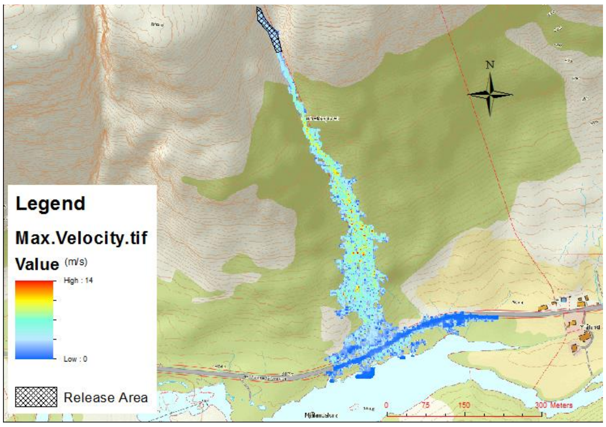




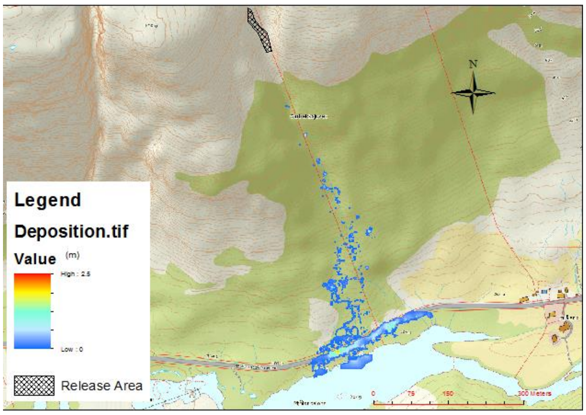
Simulation result for ξ = 200

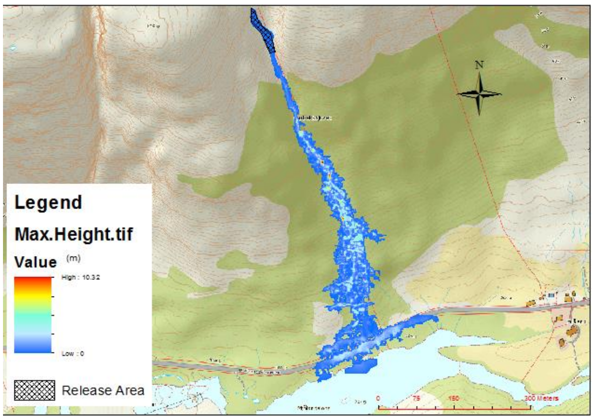


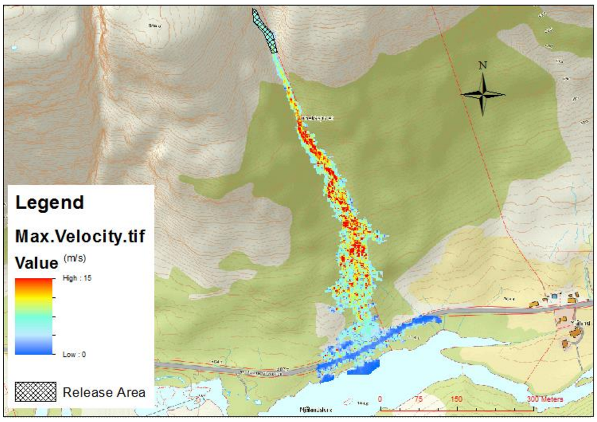




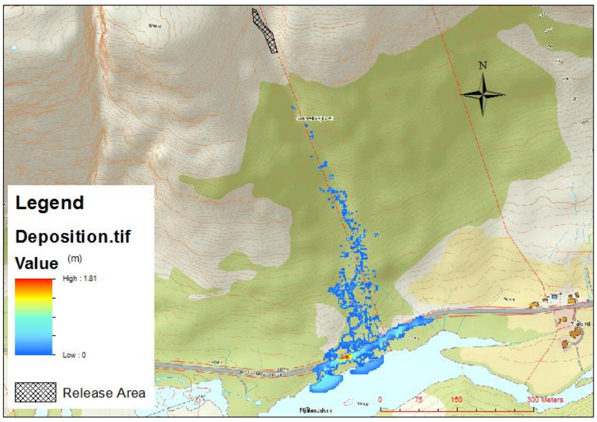
Simulation result for $\xi = 800$

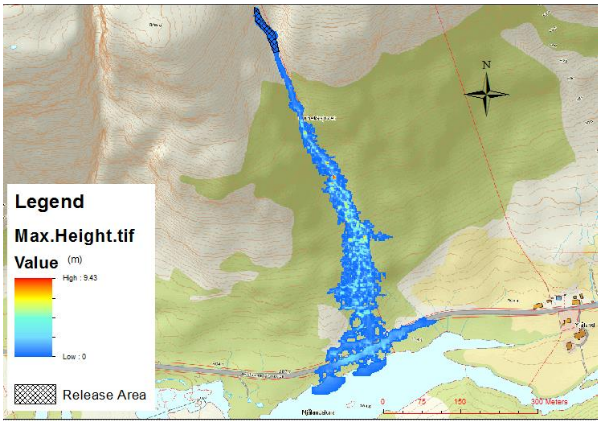


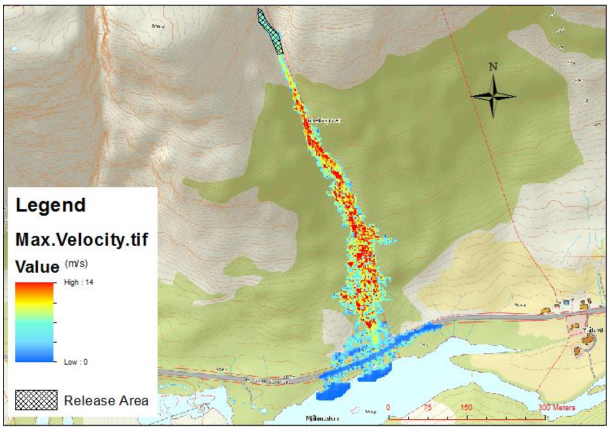




Simulation result for ξ = 1000

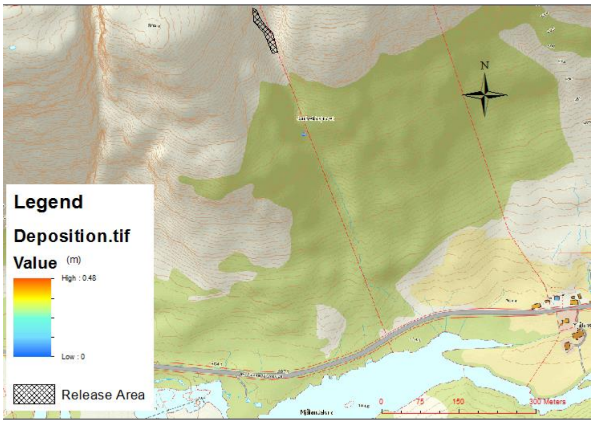


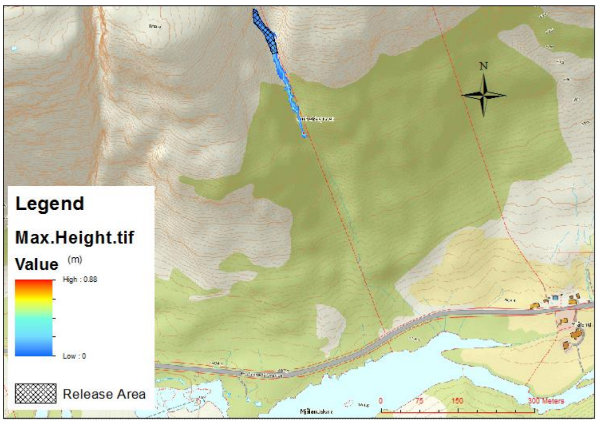




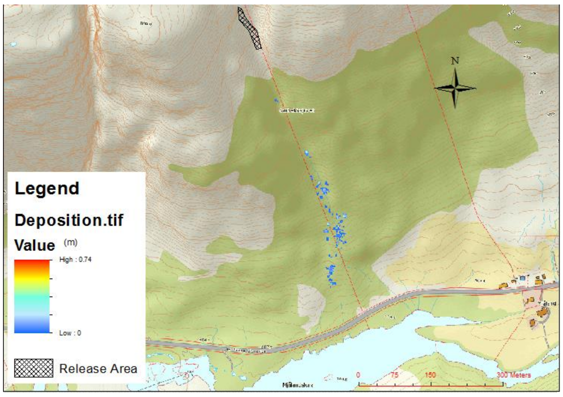
Appendix C: Simulation results for Sensitivity test of Entrainment coefficient, k

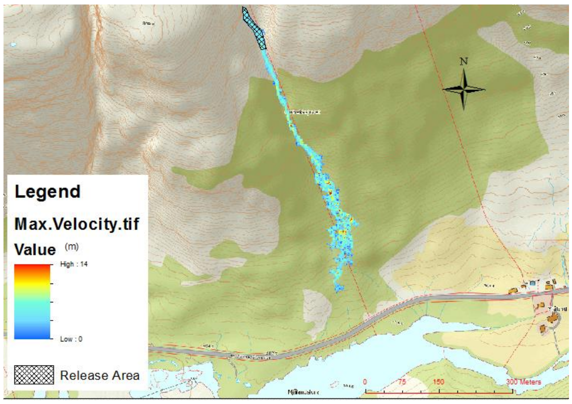
K =1



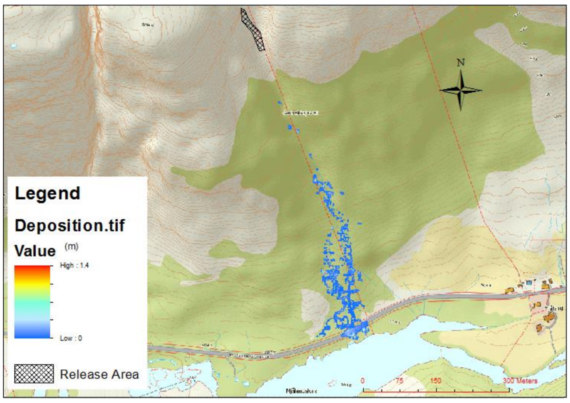


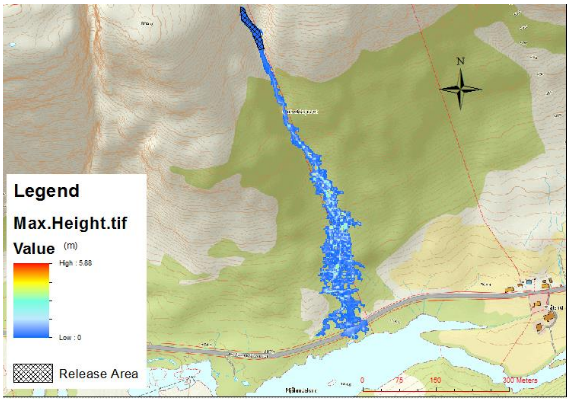
Simulation result for K=3





Simulation result for K =5





Simulation result for K =9