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Assessment of Rheological Models for Run-out Distance Modeling of Sensitive Clay Slides, Focusing on Voellmy Rheology

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<table>
<tr><td rowspan="2">Thesis Title:
Assessment of Rheological Models for Run-out Distance Modeling of Sensitive Clay Slides, Focusing on Voellmy Rheology</td><td colspan="4">Date: June 23rd, 2014
Number of pages (with appendices): 130</td></tr>
<tr><td>Master Thesis</td><td>X</td><td>Project Work</td><td></td></tr>
<tr><td colspan="5">Name: ASHENAFI LULSEGED YIFRU</td></tr>
<tr><td colspan="5">Professor in charge/supervisor: ASST. PROFESSOR ARNFINN EMDAL</td></tr>
<tr><td colspan="5">Other external professional contacts/supervisors: VIKAS THAKUR AND SAMSON DEGAGO, SVV</td></tr>
</table>

Abstract

Sensitive clay landslides especially that of quick clay are the major natural hazards in Canada and Scandinavian countries. Fair estimation of post-failure movement (retrogression and run-out distances) is very important in taking remedial measures like hazard mapping and mitigation strategies to protect loss of human lives and properties as well as damage of infrastructures. To do these estimations, some empirical approaches have been used so far. However most fell short to give close prediction of the run-out distances. This situation gives rise to implement some of the existing mass flow numerical modeling tools to simulate post-failure movements of sensitive clays. Some preliminary studies were conducted to evaluate the extent to which the available flow (rheological) models are able to simulate run-out of sensitive clay slides.

This study continued the search and found the Voellmy rheological model implemented in RAMMS::Debris Flow and DAN3D. The model is tested by back calculating a small scale run-out laboratory model test and the 2012 Byneset, Norway, quick clay landslide cases. Preliminary attempt to numerically simulate quickness test of sensitive clays was also made.

Even though the same rheological model is implemented in RAMMS and DAN3D, some differences in the analysis results were observed. This rheological model was able to simulate the run-out distances of the given cases. However, its two governing friction parameters are found more sensitive to the flow conditions than the usual strength parameters of sensitive clays.

Some recommendations and future works are also given depending on the simulation results.

Keywords:

1. Remolded shear strength
2. Run-out distance
3. Voellmy rheology
4. Sensitive clays
5. Landslide

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Assessment of Rheological Models for Run-out Distance Modeling of Sensitive Clay Slides, Focusing on Voellmy Rheology

Sensitive clay slides in Canada and Scandinavian countries have been a source of destructions to properties and infrastructures as well as risk to human lives. To take remedial measures like hazard mapping and mitigation strategies for these natural hazards, approximate prediction of post-failure movement (retrogression and run-out) is found vital. Currently, simplified empirical tools are being used for prediction. However, most of them do not consider the mechanism associated with the post-failure movements of sensitive clay debris. This give rise to the need of using numerical tools and it becomes of an interest to this study.

Some studies have been conducted to assess the degree to which existing mass flow models (like DAN3D, BING and MassMov2D) might be used for sensitive clay slides and this study continues the assessment.

The expected tasks of this study in assessing, choosing and evaluating numerical tools along with their respective rheologies, study of the behavior of sensitive clay slide flows and some other related studies are given as follows.

Task Description:

- Conduct literature review on slides, sensitive clay flows and applications of the available rheological models.
- Study the different numerical tools and rheology models currently used for other mass flows (rock & snow avalanches, debris and mud flows).
- Adopt these tools and models for this study to simulate sensitive clay flows.
- Conduct a study on Voellmy rheology about its mechanisms governing the run-out of sliding mass.
- Back calculate and conduct a parametric study on the input parameters of Plastic and Voellmy rheologies based on small scale laboratory tests while assessing scaling effect.
- Back calculate the Byneset flow slide using Voellmy rheology and study its parameters.
- Evaluate the Voellmy rheological model implemented in RAMMS and DAN3D over its application, validity and significance in terms of run-out modeling of real sensitive clay slide event.

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Preface

This thesis is submitted in partial fulfillment of the requirement for Masters Degree (MSc) in Geotechnics and Geohazards at the Geotechnical Division of Civil and Transport Engineering Department, Norwegian University of Science and Technology (NTNU). It was carried out in the spring semester of 2014.

The idea for this thesis was raised by Prof. Vikas Thakur which focuses on assessment of numerical models to simulate post-failure movements of sensitive clay slides and is of a great interest of the Norwegian Public Roads Administration (NPRA).

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I would like to thank all my family members and friends for their support and encouragements throughout my study. I love you all and I am so happy to have each and every one of you in my life. My special thanks goes to Bezaye Tesfaye for proofreading the thesis and my long time friend Abebe Endale for being a good friend for almost a decade and specially for being very supportive during these two years of my stay in Norway.

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Ashenafi Lulseged Yifru

Contents

List of Figures

List of Tables

List of Symbols

Roman Letters

A	Area
B	Width
C	Cohesion
c	Yield strength value
c_u	Undrained shear strength
c_{ui}	Undrained shear strength at peak state
c_{ur}	Remolded shear strength (Residual undrained shear strength)
D	Diameter
D_f	Diameter of flow
E_D	Remolding energy/Disintegration energy
E_{kf}	Kinetic & Friction energy
E_P	Potential energy
F	Net driving force
f	Friction coefficient of Voellmy rheology in DAN3D
g	Gravitational attraction (9.81m/s^2)
G	Secant modulus
H	Height
h	Height
H_0	Initial height
H_f	height of flow
I_L	Liquidity index
I_P	Plasticity index
K_s	The inverse value of Gauckler-Manning coefficient (*1/n*)
L_0	Initial Length
L_F	Normalized run-out distance for small scale run-out model test
L_F	run-out distance measured from the toe of slope
L_{FL}	Flow length
L_R	Retrogression distance measured from the toe of slope
m	Mass
Mu	Friction coefficient of Voellmy rheology in RAMMS

N	Normal stress
N_s	Stability number
P	Tangential internal pressure resultant
p	Wetted perimeter
Q	Quickness [$1 - (H_f / H_0)$]
R	Vertical curvature radius of the path
R	Hydraulic radius (A/p)
r_u	Pore pressure ratio, (u/σ)
S	Basal resistance of Voellmy rheology in RAMMS
S	Softening modulus.
S_f	The slop of the failure line in NTH (σ'_3 vs τ) - plot
S_t	Sensitivity (c_u/c_{ur})
T	The basal resisting force in DAN3D
U	Velocity
u	Pore-pressure
V	Volume
v	Velocity
W_0	Initial width
Xi	Turbulence factor of Voellmy rheology in RAMMS

Greek Letters

α	The average run-out slope angle
γ	Unit weight
γ_r	Shear strain
μ	Friction coefficient of Voellmy rheology in RAMMS
μ_B	Bingham viscosity
ξ	Turbulence factor in Voellmy rheology
ρ	Density
σ	Total normal stress
σ'	Effective normal stress
τ	shear stress
τ	Shear stress

τ_y	Bingham yield stress
φ	Internal friction angle in degrees
Φ	Bulk friction angle
φ'	Effective dynamic friction angle

Abbreviations

1D	one dimensional
2D	two dimensional
3D	three dimensional
DAN	Dynamic Analysis (Software name)
DAN3D	Dynamic Analysis 3D (Software name)
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ENO	Essentially Non-Oscillatory
F	Flow slide
FL	Flake slide
LC	Large cylinder
NTH-plot	σ'_3 Vs τ - plot
RAMMS	Rapid Mass Movements (Software name)
RR	Retrogressive slide
RT	Rotational slide
SC	Small cylinder
SPH	Smooth particle hydrodynamics

1. Introduction

1.1. Background

Most landslides are catastrophic natural events that put human lives and properties at risk. Rock and snow avalanches, rock slides and rock falls, debris & earth flows and quick clay slides are few kinds of these natural events. Out of these, sensitive clay slide, snow avalanches and rock falls are the most frequent events that happen in Norway. Flow slide in highly sensitive clays, also known as quick clay slide, is a typical geo-hazard that its retrogression and run-out of debris pose a serious risk to human lives and infrastructure (Thakur et al., 2014b).

Delineation of possible impact areas as well as flow velocities and energies is an essential precondition for efficient action towards risk reduction, e.g. definition of hazard zones, dimensioning of technical structures etc. (McDougall and Hungr, 2004). To do such measures, one has to predict more or less precisely the extent of the landslide run-out distance. Several numerical models have been developed to simulate these landslides and help predict their flow extent. Numerical modeling of post-failure motion is one method for estimating the extent of a potential rapid landslide and providing parameters, such as velocity and flow depth, for the design of protective measures (McDougall and Hungr, 2005). This study will assess the applicability and validity of some numerical mass flow models to model post-failure movements of sensitive clay slides.

1.2. Objective of the Study

Knowing and predicting the extent of sensitive clay landslides before they happen will help in taking early measures to avoid damage of infrastructure and properties as well as help avoiding loss of human lives. This can only be fulfilled by correct estimation of run-out of the expected slide according to its soil properties. To do this, one need the right tool (numerical model) that is able to simulate the run-out of sensitive clays by using their strength properties for the basal resistance and approximately predict their run-out distance, flow depth and velocity.

The main objectives of this thesis are:

- To understand the mechanism governing the run-out of sliding debris using a rheology model known as the Voellmy model.
- To study the scaling effect induced by the laboratory based input parameter in the back calculation of field cases.
- To back calculate and conduct a parametric study on the input parameters of the Voellmy rheology by modeling the element tests, such as the quickness test and the small scale run-out laboratory test, proposed by Thakur and Degago (2012) and Thakur and Nigussie (2014) respectively.
- To back calculate the Byneset flow slide
- A critical appraisal over the application, validity and significance of Voellmy rheological model implemented in RAMMS and DAN3D in terms of run-out modeling of real flow slide events in quick clays.

1.3. Approach

A numerical approach has been adopted in this study to back calculate the flow behavior of remolded sensitive clay soils. In doing so, two small scale model tests and one real sensitive clay landslide, the 2012 Byneset flow slide have been considered. The two laboratory scale tests are; the quickness test proposed by Thakur and Degago (2012) and a small scale run-out laboratory model test by Thakur and Nigussie (2014).

Back calculation of each case was conducted in detail using two numerical tools namely, RAMMS::Debris Flow V1.6 and DAN3D Beta version 2. The Voellmy rheological model in RAMMS::Debris flow and the plastic and Voellmy rheological models in DAN3D are used. In addition to the back calculation analyses, parameter sensitivity studies on each model are also conducted.

1.4. Scope of the Study

Post failure movement in term of run-out observed for the 2012 Byneset flow slide case is back calculated by using RAMMS & DAN3D with the Voellmy rheological model. Two types of digital terrain models (DTMs) with 2m and 10m grid resolutions of the area were used for the study. Detailed parametric study of the model was conducted using the 2m grid resolution DTM.

Preliminary numerical modeling of quickness test using different scales of the original size were conducted by using the plastic rheology in DAN3D and the Voellmy rheology of RAMMS. Four different scales including the original size of the test were used to analyze the scaling effect during modeling of similar small scale laboratory tests.

For numerical modeling of the small scale run-out laboratory test, only the Voellmy rheology of RAMMS was used because different attempts were found unsuccessful while trying to model it in DAN3D.

1.5. Limitations

The following are some of the limitations faced during this study:

- RAMMS and DAN3D are the widely adopted tools to simulate snow avalanches and debris flow. However, these tools are yet to be fully verified if they are applicable for the modeling of flow slides in sensitive clays. In fact, as of now, there is no commercial tool available for modeling the run-out of sensitive clay debris.
- Unavailability of real sensitive clay slide data (pre-slide and post-slide digital terrain models, DTMs). In addition to this many of the sensitive clay slides happened near and inside water bodies. This makes it difficult to use them in the run-out numerical models even if the data are available. Because of this, only one real case landslide event is used.

- One of the numerical tool used (RAMMS) uses only one rheological model which is the Voellmy flow model.
- Only few material flow simulating softwares are developed well. Most of them are in their preliminary development stages and they are cumbersome to use.
- Attempts to incorporate GIS based debris flow models were unsuccessful due to their operating system requirement and yet they are in their preliminary stage of development. In addition to this, they are not in a user friendly version that the user needs to put give instructions using strings of commands (e.g. r.avaflow by (Mergili et al., 2012)).

1.6. Structure of the Thesis

Structure of the next chapters will be discussed hereafter.

Chapter 2: discusses literature reviews about sensitive clay soils, empirical and numerical run-out models and some relevant studies on run-out back calculations using numerical models.

Chapter 3: briefly discusses the numerical tools and models used in this study.

Chapter 4: presents the analyses, results and discussions of numerical simulation of two laboratory tests namely; quickness test and small scale run-out model test.

Chapter 5: presents the analyses, results and discussions of the real sensitive clay landslide case of Byneset. Back calculations and parametric studies are included.

Chapter 6: presents the summary and conclusion drawn out of the study.

Chapter 7: presents recommendation and possible future works in this area of study.

Appendices: presents data preparation and additional information about the simulation process.

2. Literature Review

2.1. Introduction

Landslides are an erosion processes of solid-liquid mixtures of (spatially and temporally) variable composition engaged in gravity-driven motion with free upper surfaces and potentially erodible basal surfaces (McKinnon, 2010). Sensitive clay slides in Scandinavia and Canada have been a source of destructions to properties, infrastructures as well as causes to losses of life.

Studies have been conducted to understand post-failure flow behaviors of sensitive clays in relation to their material parameters. Retrogression and run-out distances of a given landslide are the two important geomorphological measures required to represent post-failure movement and extent of hazard. Mitchel and Markell (1974) has also given an empirical relationship between stability number and retrogression distance based on 41 landslides happened in Canada. In addition, Thakur et al. (2014a) and L'Heureux (2012) compared retrogression behavior of 33 Norwegian sensitive clay slides with those happened in Canada with respect to their stability numbers, liquidity index and remolded shear strength. Locat and Demers (1988) has given the positive relationship between plastic viscosity, yield stress, remolded shear strength and liquidity index which are obtained from rheological behaviors of sensitive clays and can be used to assess the post-failure behaviors.

Beside these empirical relations to run-out distance of landslides, attempts have been made to model these post-failure movements using available numerical models which are mainly developed for other mass flows. These preliminary studies include those conducted by Thakur et al. (2014b) and Issler et al. (2012). They have tried to analyze weather these models which are developed for other mass flows work for sensitive clay slides or not.

This study continues these works and evaluates some of those mass flow numerical models for their application in simulating and back calculating Norwegian sensitive clays.

2.2. Sensitive Clays

2.2.1. Quick Clay and its Characteristics

Quick clay is a type of sensitive clay soil with a great potential of retrogressive failure and longer sliding run-out distance. In Norway, the classification of clay material as quick clay is based upon the sensitivity[†] of the material and/or a threshold value of the remolded shear strength. Remolded shear strength values, c_{ur} < 0.5kPa and/or sensitivity, S_t > 30 are considered as an identification for quick clays (NGF, 1974).

Quick clays are formed by leaching process of marine clay deposits of the glaciation era by percolating fresh ground water. During the deglaciation process, which is an unloading process, the marine clay deposits rose up above sea level along with the land. At this time, the salt ions washed out from the marine clay deposits leaving them in a metastable nature which is a sensitive structure composed of flocculated clay minerals. When these clays are remolded for instance during a slide, they turn more or less to a liquid soil mass that may flow rather freely long distances even in very gentle slopes of the terrain (Grande). This characteristic of quick clay, which is to liquefy when subjected to loading, is one of the major governing characters of post-failure behavior.

2.2.2. Sensitive Clay Slides

In nature the Canadian sensitive clays exhibit higher strength than the Scandinavian sensitive clays. As a result sensitive clay landslides in Canada tend to be dramatic when taking place in

[†] Sensitivity is the ratio between the undrained shear strength, c_u and the remolded shear strength, c_{ur} of a soil.

slope heights of 50 - 100 meters whereas in Scandinavia, the softer and weaker sensitive clays result in landslides within slopes of 10 - 30 meters high (Grande).

Sensitive clay slides usually triggered by a small initial slides that could even take place in a gentle slopes which made them to be underestimated. As it is described by in (Bjerrum, 1955, Mitchel and Markell, 1974) sensitive marine deposits of eastern Canada and Scandinavia, landslides are destructive events triggered by a possible small failure which result in an extensive retrogressive process.

These small initial slides that could trigger huge retrogressive landslide can be created by erosion of toe of a slop, increased ground water level that lowers the friction between soil particles and/or human activities which can be altering the natural slop of a terrain or increasing pore pressure due to construction activities like pile driving.

Retrogressive sensitive clay landslides are usually accompanied by run-out of debris. The term run-out refers to the depositional part of a landslide or debris-flow event, providing information on the areas potentially covered by the transported solid material (Scheidl et al., 2013a). However, quick clay slides in Norway usually occur along streams, rivers or in near shore areas and the debris are quickly eroded which makes it difficult to record the event and retrieve the required information. The retrogression process is usually a sequence of rotational slip failures which only stops when a stable slop with a higher undrained shear strength than the shear stress created. Schematic presentation of both retrogressive distance and run-out distance are presented in Figure 2.1. It is also shown that how the extents of the slide endanger the infrastructures.

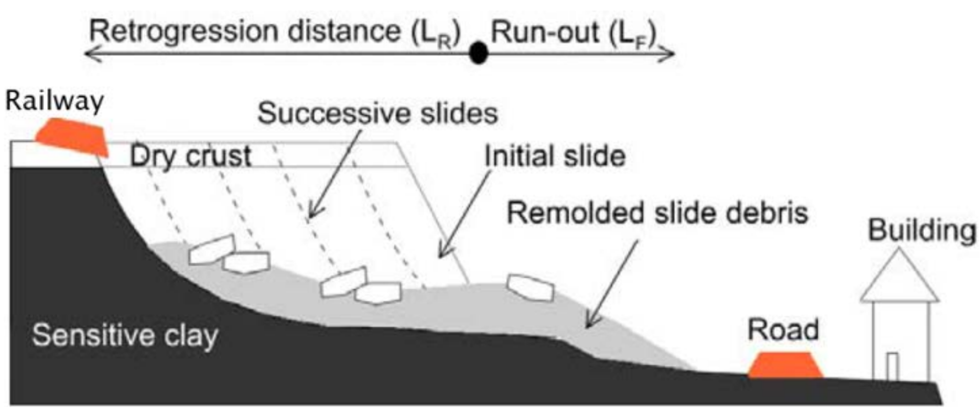


Figure 2.1: Retrogression and run-out distances of sensitive clay slide. Each measured from the toe of the slop (Thakur and Degago, 2014).

Table 2.1 is taken directly from Thakur et al. (2014a) and summarizes sensitive clay landslides reported in Norway. It presents recorded and estimated retrogression and run-out distances, index properties and shear strength values for 33 Norwegian landslides.

Table 2.1: Summary of sensitive clay slides reported in Norway[a] (Thakur et al., 2014a)

Year	Landslide (Ref.[b])	Type	L_R [m]	L_F [m]	V [10^5xm^3]	c_{ur} [kPa]	St [–]	I_L [–]	I_P [%]
1940	Asrumvannet[1]	F	?	?	?	0.1	200	3.1	13
1626	Bakklandet[2]	FL	70	50	?	0.1	30	2	6
1988	Balsfjord[3,22]	F	400	?	8	1	30	3	6
1974	Båstad[4]	F	230	700	15	0.53	35	1.8	8
1953	Bekkelaget[5]	FL/F	145	20	1	0.11	150	2.4	11
1953[c]	Borgen[6]	RR	165	?	1.6	0.7	100	1.2	20
1928	Brå[7-9]	FL	197	300	5	0.24	75	2	?
2012	Byneset[10,20]	FL	400	870	3.5	0.12	120	3.9	4.8
1955	Drammen[5]	RT	45	?	0.04	2.5	4	1.1	11
1625	Duedalen[8,9,11,21]	FL	410	?	5	0.07	209	?	?
1996	Finneidfjord[12]	RR	150	850	10	0.4	60	?	?
1980	Fredrikstad[13,14,15]	RR	45	22	1	<0.5	20	1	20
1959	Furre[16]	FL/F	300	90	30	0.1	115	2.1	11
1974	Gullaug[17]	FL/F	150	?	1.25	2	7.5	?	?
1967	Hekseberg[18]	FL	700	300	2	0.25	100	2.4	4
2009	Kattmarka[19]	RR	300	350	41703	0.24	63	2.9	8
1994	Kåbbel[20]	F	100	10	1	<0.5	>50	>1.2	20
1944	Lade[8,9,13.21]	FL	40	62	0.05	2.12	6.6	1	?
2002	Leistad[22,15]	F	250	25	?	0.15	110	1.5	6
1989	Lersbakken[15,22]	F	65	75	0.75	?	38-62	?	?
1954	Lodalen[23]	FL	40	10	0.1	17	3	0.8	17
2010	Lyngen[20]	F	153	411	3-Feb	0.14	51.4	2.1	
2000	Nedre Kåbbel[20]	F	120	10	1.8	<0.5	>50	>1.2	20
1978	Rissa[24]	RR&F	1200	50-60	0.25	100	2	5	?
1995	Røesgrenda[25]	RR	100	50	0.02	0.1	186	>1.2	<10
1974	Sem[15,26]	FL	100	20	0.68	1.4	8 - 14	?	?
1965	Selnes[27]	F	230	>400	1.4	0.35	100	2.3	7
1962	Skjelstadmarka[28]	F	600	2800	20	0.83	80	1.1	10
1816	Tiller[8,10,22.23]	FL	55	0.1	90	2.7	4	?	?
2012	Torsnes[23]	RR	25	0.063	<0.5	22	?	?	?
1953[c]	Ullensaker[29,30]	RR	195	1500	2	0.35	42	1.9	6.7
1893	Verdal[6,10,11,21]	FL	2000	5000	650	0.2	300	2.2	5
1959	Vibstad[31]	F	250	250	10	5	8	0.2	17

[a]*L_R = Retrogression distance measured from the toe of slope, L_F = run-out distance measured from the toe of slope; V = slide volume; c_{ur} = remolded shear strength along slip surface; S_t = sensitivity, I_P = plasticity index, I_L = liquidity index; F= flow slide, FL= flake slide RR= retrogressive slide, RT= rotational slide*

[b]*References: [1]Mayerhof (1957), [2]Egeland and Flateland (1986), [3]Rygg and Oset (1996), [4]Gregersen and Løken (1979), [5]Eide and Bjerrum (1955), [6]Trak and Lacasse (1996), [7]Holmsen (1929),[8]Reite et al. (1999), [9](Trondheim Municipality Reports (1981)), [10]Thakur et al. (2012a), [11]Furseth (2006),[12]Longva et al. (2003),[13]Holmsen and Holmsen (1946),[14]Karlsrud (1983), [15]Thakur et al. (2012a), [16]Hutchinson (1961), [17]Karlsrud (1979), [18]Drury (1968), [19]Nordal et al. (2009), [20](NVE Report (2012)), [21]Natterøy (2011), [22](NPRA Reports (1994)), [23]Sevaldson (1956), [24]Gregersen (1981), [25]Larsen (2002), [26](NGI Report (1974)), [27]Kenney (1967), [28]Janbu (2005), [29]Bjerrum (1955), [30]Jørstad (1968), [31]Hutchinson (1965)*

[c]*These two names represent the same landslide*

2.2.3. Empirical Relations for Retrogressive and Run-out Distances

Some empirical relations in retrogression and mobility of Norwegian clays are presented by Karlsrud et al. (1985), L'Heureux (2012), Thakur et al. (2014a). Quick clay landslides generally occur in Norway if the ravines are higher than 10 meters or if the natural slope of the terrain is steeper than 1:15. This criterion is used as one of the many criteria during the delimitation of a nationwide quick-clay mapping program of Norway.

According to Mitchel and Markell (1974) the retrogression can occur if the stability number, defined as $N_s = \gamma H / c_u$, is greater than 6 where H is the depth of potential failure and c_u is the undrained shear strength. An empirical relationship also found between N_s and retrogression distance (L_R). It is also given in the same paper that in general, large retrogressive failures occur in eastern Canada for I_L larger than 1.2 and/or c_{ur} < 1.0kPa. whereas in Norway, I_L > 1.1 and sensitivity greater than 30 can easily cause large landslides. The remolded shear strength notion is also given by Thakur and Degago (2012) and Thakur et al. (2014b) as for the Norwegian sensitive clays with c_{ur} > 1.0kpa, flow slide is less likely to happen after an initial slope failure.

L'Heureux (2012) showed the relation between stability number and retrogression distance as it is shown in Figure 2.2. The retrogression distance is found to increase with increase in stability number except two events that might be due to other geotechnical characteristics of the sensitive clay at those area.

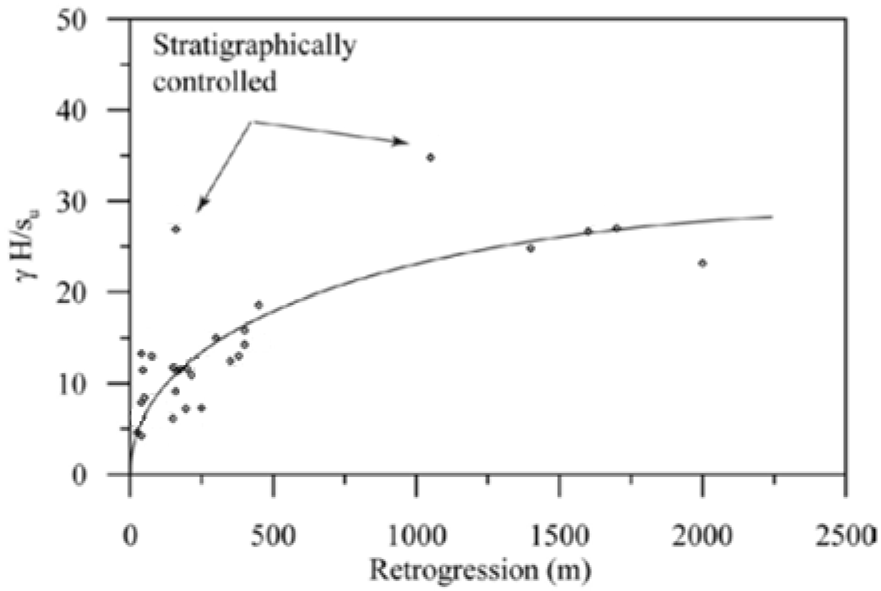


Figure 2.2: Stability number versus retrogression distance for Norwegian sensitive clay slides (Adopted from (L'Heureux, 2012))

While comparing sensitivity with liquidity index of Norwegian clays, large landslide with retrogression distance, L_R > 100 meters occur for S_t > 30 and I_L > 1.10. At the same time considerable retrogression observed when remolded shear strength, $c_{ur} \leq$ 0.5kPa as shown by Figure 2.3. In addition to these material properties, topography plays a great role in the retrogression and run-out distance of these sensitive soil slides. Well defined channels like valleys or river courses with steep longitudinal gradient or relatively wide and deep rivers or lakes contribute greatly for the retrogression and run-out distances.

In another study by Thakur and Degago (2014), the relationship between retrogression distance and remolded shear strength is given for some selected Canadian and Norwegian sensitive clay landslides. Figure 2.4 shows that the extent of flow slide decrease with increasing remolded shear strength of both types of sensitive clay soils. Almost all of the retrogression distances, L_R > 100m are observed for soils with c_{ur} < 1.0kPa.

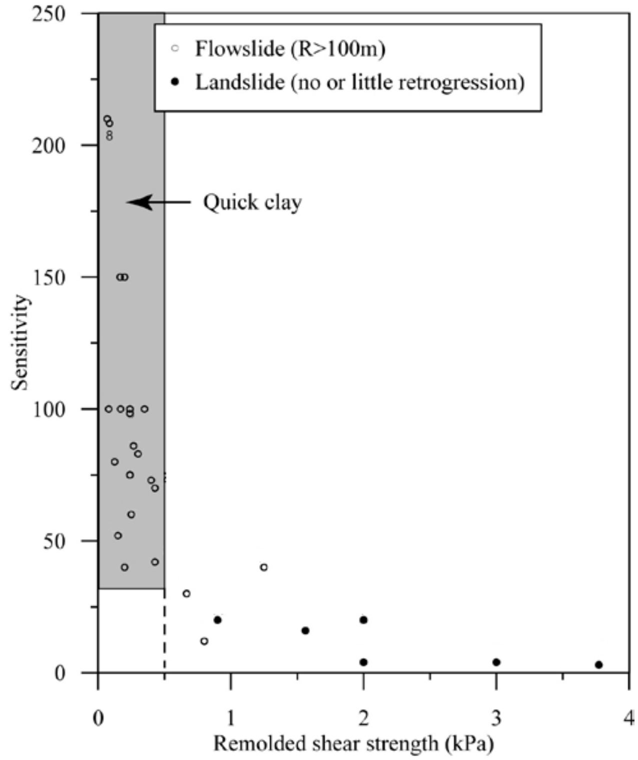


Figure 2.3: Remolded shear strength versus sensitivity for Norwegian clay slides (Adopted from (L'Heureux, 2012))

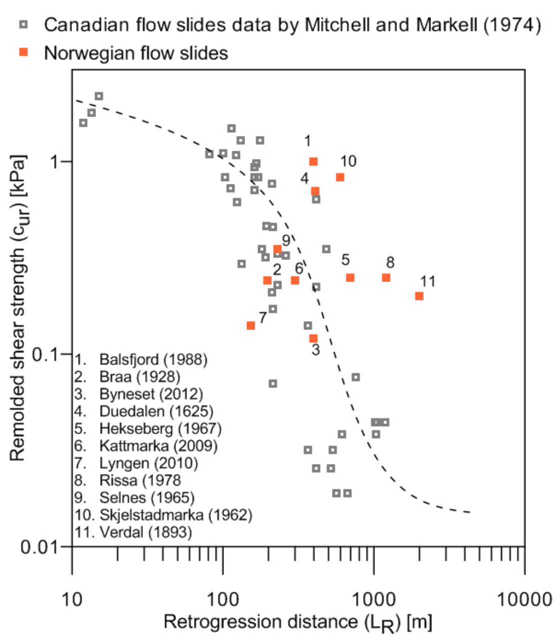


Figure 2.4: Retrogression distance as a function of remolded shear strength (Thakur and Degago, 2014)

2.3. Disintegration Energy of Sensitive clays

Sensitive clay landslides involve different energy transformation from the potential energy they originally have that has a direct significance on their final run-out distances. According to Thakur and Degago (2013), the potential energy is a function of slope geometry and soil density and the change in potential energy (ΔE_P) is transformed to remolding energy (E_D) which in other word called disintegration energy and kinetic & friction energy (E_{kf}) responsible for the slide movement. Equation (2.1) gives this energy relationship.

$$\Delta E_P = \Delta E_D + \Delta E_{kf} \tag{2.1}$$

In regard to law of conservation of energy, which states that energy can neither be created nor destroyed, the higher the requirement of disintegration energy by a slide, the lower the kinetic energy and the movement capacity of the slide. For a given potential energy of a slide topography, it is obvious that run-out distance would be longer if the disintegration energy required by the soil is low and vice versa.

Therefore proper estimation of disintegration energy of sensitive clays found vital in assessment and prediction of landslides. Thakur and Degago (2013) proposed an analytical solution to evaluate E_D per unit volume of sensitive clays based on an integrated study of their strength and stiffness properties in intact and remolded states, Equation (2.2). This disintegration energy is represented by the area under τ-γ curve given in Figure 2.5.

$$D_E = c_{ur}\gamma_r - \frac{c_{ur}^2}{2G} + \frac{1}{2}[(S_t - 1)c_{ur}]^2\left(\frac{1}{G} + \frac{1}{S}\right) \tag{2.2}$$

where c_{ui} and c_{ur} are the undrained shear strengths related to peak and residual states respectively, τ is shear stress, γ_r is shear strain, G is the secant modulus and S is the softening modulus.

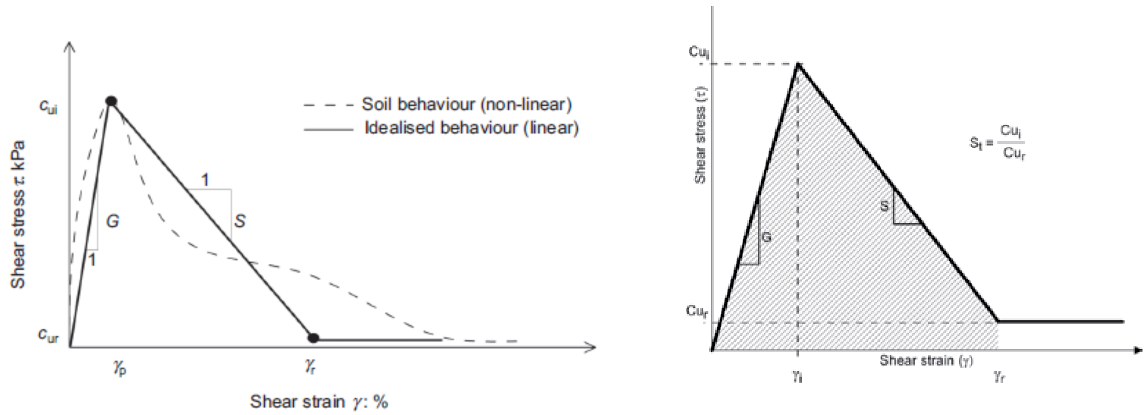


Figure 2.5: Stress-strain behavior of sensitive clays representing remolding energy under the shaded area (Thakur and Degago, 2013, Thakur et al., 2012b)

Thakur and Degago (2013) made linear approximation to the non-linear soil behavior to simplify the analytical solution as shown in Figure 2.5. A more detailed explanation about remolding or disintegration energy is presented by Thakur et al. (2012b).

The run-out modeling tools used in this study do not consider disintegration energy and the whole potential energy of a sliding height is converted to kinetic energy where it is used for the flow process. Therefore, the results obtained from these simulations might give longer run-out distances than they could have given if the concept of disintegration energy was incorporated in the models.

2.4. Numerical Tools for Flow Analyses

In Section 2.2.3 few empirical relations which help to estimate and predict retrogression and run-out of landslides were presented. Most empirical models like relation between retrogression distance and stability number, retrogression distance and remolded shear strength, liquidity index and sensitivity (L'Heureux, 2012, Thakur and Degago, 2014)give us correlations for quick estimation of retrogressions and run-out distances if good knowledge about the soil parameters of the slide prone area is available. However, these relations cannot and will not give us the exact prediction of retrogressions and run-outs. This is because these simplified empirical approaches are mainly attributed to poor understanding of the mechanism associated with the post failure movements of sensitive clay debris (Thakur et al., 2014b). Therefore the need for run-out prediction using numerical models which use flow rheologies is becoming important.

Numerical modeling to simulate run-out distance of debris flows is being studied by many researchers. Run-out distance of rock and snow avalanches are also into focus and are modeled as flow slides using computational fluid dynamics theory. Attempt to simulate sensitive clay flows using one of these numerical models, DAN3D, has been made by Thakur et al. (2014b) and promising results are obtained. The results will be discussed in detail in Section 2.5.

Selected rheological models and numerical tools are discussed next.

2.4.1. Rheological Models

Rheology is the study of the flow of matter, primarily in the liquid state, but also as 'soft solids' or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force (Schowalter, 1978).

The rheological models for debris flow and snow & rock avalanches uses the concept of fluid flows and adopt them for modeling the soil masses. It has been apparent that landslides with longer run-outs are related with a very low remolded shear strength (viscosity) of the soil after failure. It has also been pointed out that viscosity of a soil mass governs its slide dynamics. Hence, flow behavior can be quite complex and various types of flow behavior can exist depending on the soil type, pore-water salinity, mineralogy, and water content (Locat and Demers, 1988).

Figure 2.6 gives a schematic representation of the major flow types in a shear strain versus shear stress plot where the slop of each line corresponds to viscosity of the fluid. Curve 1 is representing Newtonian fluid which has a constant viscosity under varying shear stresses. Thickening (shear-thickening) liquids shown by curve 2 are those for which the viscosity increases with shear rate. Fluidizing (pseudoplastic) liquids shown by curve 3 have an opposite behavior, as the viscosity decreases with increasing shear rate resulting in shear-thinning behavior. Plastic or "Casson" fluids given by curve 4 are fluidizing bodies characterized by a yield stress (or yield point) and slowly decreasing viscosity at higher shear rates. The Bingham fluid is also characterized by a yield stress point but it has a constant viscosity afterwards.

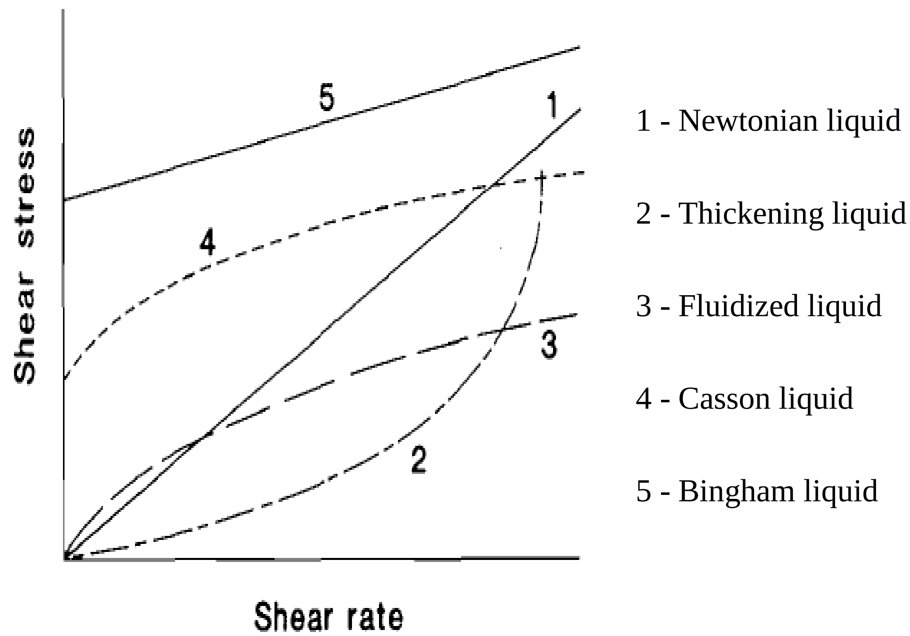


Figure 2.6: Relationship between shear stress and shear strain for different fluid types (Locat and Demers, 1988).

For most observed that sensitive clay cases, it appears that once the soil has reached its yield stress, the viscosity can be considered constant. most sensitive clays behave either as a Bingham or a Casson fluid, the latter behavior being related to less sensitive clays of higher pore-water salinities. (Locat and Demers, 1988).

Hungr (1995) similarly described that some landslides, such as debris flows, are saturated and have distributed velocity profiles resembling the flow of fluids. Some, like rockslide avalanches, contain stronger materials with limited internal deformation and move on thin mobile basal layers having shear strain concentrations.

Figure 2.7 shows a proposed semi-empirical approach towards dynamic modeling of a moving mass, which may in reality be heterogeneous and complex, replaced by an equivalent fluid whose bulk properties will approximate the behavior of the prototype.

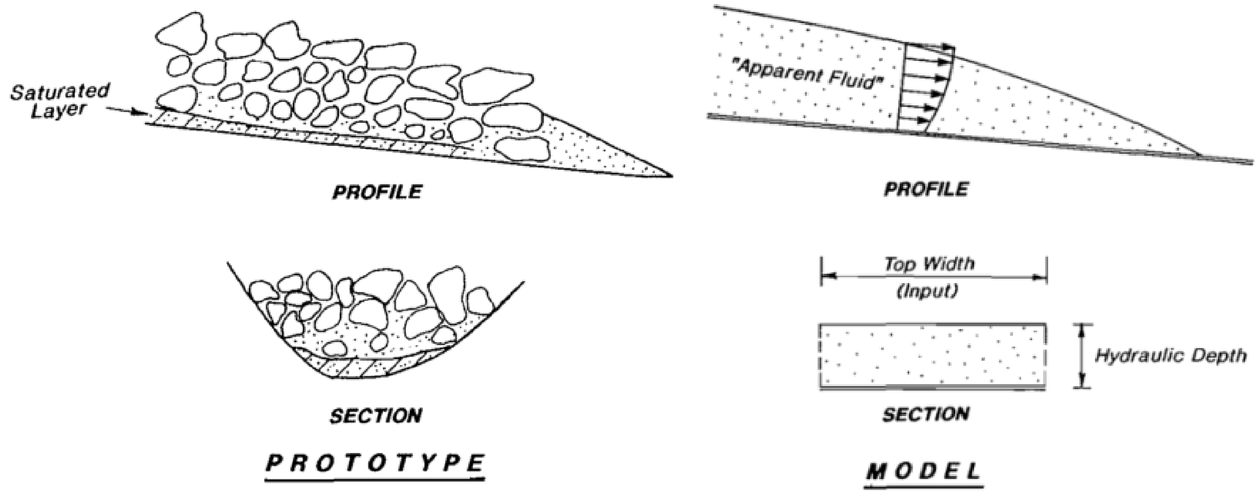


Figure 2.7: Schematic diagram showing concept of modeling a flow slide in which a homogeneous "apparent fluid" replaces the slide mass (Hungr, 1995).

The main basis DAN (Hungr, 1995) and subsequently DAN3D (McDougall and Hungr, 2004) built on is the above semi-empirical mass moving approach. The basal flow resistance term *T* is dependent on the choice of rheology of a material and it is a function of the known parameters of the flow like shear strength, friction angle, viscosity and so on.

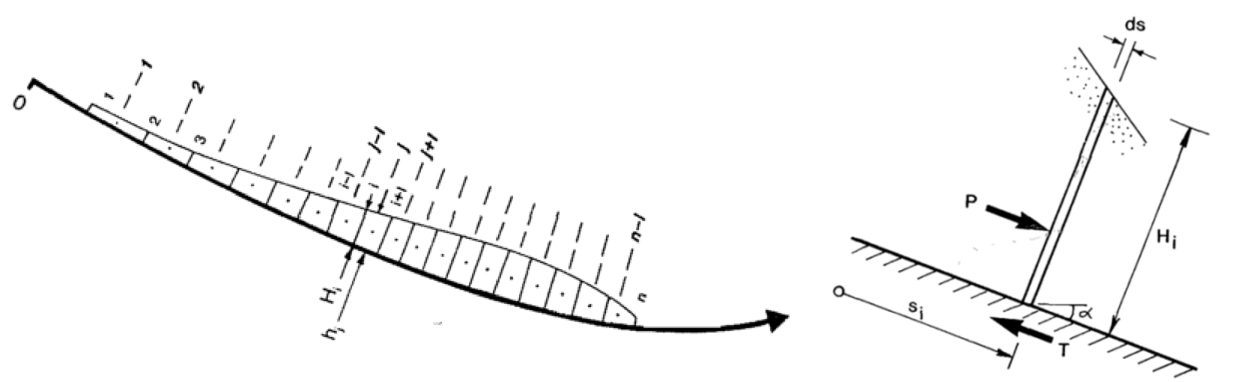


Figure 2.8: The Lagrangian mesh in curvilinear coordinate (left) and forces acting on a boundary block (right) (Hungr O., 1995)

The basal resistance is a time step explicit solution. Approximate initial condition of the sliding mass block assembly set up in terms of the curvilinear coordinate as shown on Figure 2.8 (left). Figure 2.8 (right) shows a single boundary block taken and its height and width are designated as H_i and B_i respectively. A mesh less Lagrangian solution method called smooth particle hydrodynamics (SPH) is also presented in Figure 2.9. The total volume of the slide mass is divided into number of elements, known as “smooth particles”. Each particle has a finite volume which may only increase with entertainment (McDougall and Hungr, 2004).

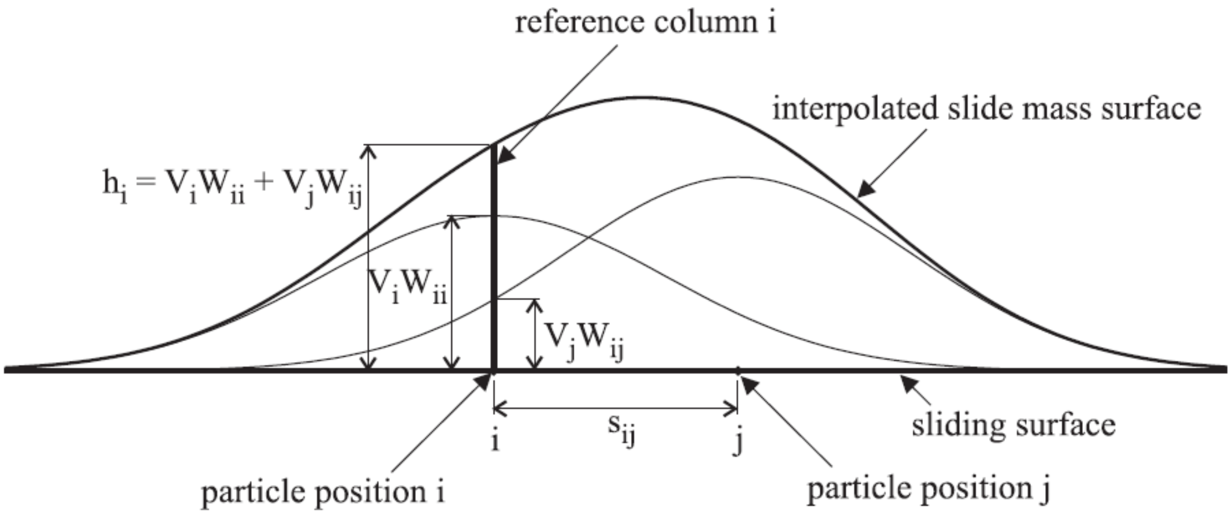


Figure 2.9: Schematic representation of smooth particle hydrodynamics solution method (McDougall and Hungr, 2004)

The net driving force, *F*, given by Equation (2.3) is acting on each boundary block (Figure 2.8) and consists of the tangential internal component of weight, *T* and *P* which are the basal resisting force and the tangential internal pressure resultant.

$$F = \gamma H_i B_i ds\ sin\alpha + P - T \tag{2.3}$$

Hungr (1995) presented seven basal resistance functions representing different rheological models and provided that $A_i = ds\ B_i$. These are plastic, friction, Newtonian laminar, Turbulent, Bingham, Coulomb viscous flows and Voellmy liquid. Out of these seven, five of which are used in DAN3D are given as follows.

I. *Plastic flow:* this flow is controlled by a constant shear strength, such as the steady state undrained strength, *c*, of liquefied material:

$$T = cA_i \tag{2.4a}$$

Thakur et al. (2014b) described this rheology as it is related with a pseudo-static motion of liquefied debris and the base shear resistance, τ, is assumed to be equivalent to a constant yield strength value, c.

$$\tau = -c \tag{2.4b}$$

II. *Friction flow:* this flow occurs when T is a function only of the effective normal stress, σ', on the base of the flow. This stress depends on flow depth, unit weight, γ, and pore pressure, u:

$$T = A_i \gamma H_i \left(cos\,\alpha + \frac{a_c}{g}\right)(1 - r_u)\,tan\,\emptyset \tag{2.5a}$$

where $a_c = v_i/R$ is the central acceleration depending on vertical curvature radius of the path, R, and r_u is the pore-pressure coefficient or ratio given by $r_u = u/\sigma$, where σ is total stress and u is pore-pressure. Similarly, the shear stress in this flow model can simply be given as:

$$\tau = -(\sigma - u)\tan\emptyset \tag{2.5b}$$

where bulk friction angle, $\emptyset = \arctan[\tan\emptyset'(1 - r_u)]$ and $\emptyset'$ is effective dynamic friction angle.

III. *Bingham flow:* the resisting force is a function of flow depth, velocity, constant yield strength (τ) and Bingham viscosity (μ). The mean flow velocity is derived from an assumption of a linear increase of shear stress with depth.

$$v_i = \frac{H_i}{6\mu}\left(\frac{2T}{A_i} - 3\tau + \frac{\tau^3 A_i^2}{T^2}\right) \tag{2.6a}$$

Thakur et al. (2014b) described this rheology as a combiner of plastic and viscous behavior and Bingham fluid behaves as a rigid material below a threshold yield strength, but as a viscous material above. The basal shear resistance, τ, is given as:

$$\tau^3 + 3\left(\frac{\tau_y}{2} + \frac{\mu_B}{2}v\right)\tau^2 - \frac{\tau_y}{2} = 0 \tag{2.6b}$$

where τ_y is the Bingham yield stress, μ_B is Bingham viscosity and v is the average depth velocity.

IV. *Voellmy fluid:* this model is introduced by Voellmy (1955) for snow avalanches. This model contains a friction term and a turbulent term and the basal resistance is given as:

$$T = A_i \left[\gamma H_i \left(cos\,\alpha + \frac{a_c}{g}\right) tan\,\varphi + \gamma \frac{v_i^2}{\xi}\right] \tag{2.7a}$$

Voellmy introduced the second term to summarize all velocity-dependent factors of flow resistance. The basal shear resistance is simply given as:

$$\tau = -\left(\sigma f \; + \frac{\gamma v^2}{\xi}\right) \tag{2.7b}$$

where ξ, the turbulence term, has dimension of acceleration and analogous to the square of the Chezy equation. f is the friction coefficient analogous to $\tan\varphi$.

V. *Newtonian laminar flow:* this flow occurs where *T* is a linear function of velocity with a dynamic viscosity μ.

$$T = \frac{3A_i v_i \mu}{H_i} \tag{2.8}$$

2.4.2. Numerical Tools

A summary of mass flow numerical tools together with rheological models they support were compiled by Luna (2012) and given in Table 2.2. It shows the available numerical tools for debris flow and rock avalanche analysis and back calculation. The classification is based on solution dimension (1D or 2D), solution reference frame (Eulerian or Lagrangian) and basal rheology.

Table 2.2: Summary of numerical models for run-out analysis of debris flow (Adopted from (Luna, 2012)).

Model	Rheology	Solution approach	Reference frame	Variation of Rheology	Entrainment rate
MADFLOW	Frictional, Voellmy and Bingham	Continuum Integrated	Lagrangian with mesh	no	Defined
TOCHING	Frictional (elastoplastic model)	Continuum Differential	Differential (adaptive mesh)	yes	Process based
RAMMS	Voellmy	Continuum Integrated	Eularian	yes	Process based and defined
DAN3D	Frictional, Voellmy, Bingham, Newtonian, Plastic	Continuum Integrated	Lagrangian meshless	yes	Defined
FLATMODEL	Frictional and Voellmy	Continuum Integrated	Eulerian	no	Process based
SCIDDICA s3-hex	Energy based	Cellular Automata	Eulerian	no	Process based
3dDMM	Frictional, Voellmy	Continuum Integrated	Eulerian	yes	Defined
PASTOR model	Frictional, Voellmy, Bingham	Continuum Integrated	Lagrangian meshless	yes	Defined
MassMov2D	Voellmy, Bingham	Continuum Integrated	Eulerian	yes	Defined
RASH3D	Frictional, Voellmy, Quadratic	Continuum Integrated	Eulerian	no	No Entrainment rate is used
FLO-2D	Quadratic	Continuum Integrated	Eulerian	no	No Entrainment rate is used
TITAN2D	Frictional	Continuum Integrated	Lagrangian meshless	no	No Entrainment rate is used
PFC	Inter-particle and particle wall interaction	Solution of motion of particles by a distinct element method	Distinct element method	no	No Entrainment rate is used
VolcFlow	Frictional and Voellmy	Continuum Integrated	Eulerian	no	No Entrainment rate is used
r.avaflow (Mergili et al., 2012)	Savage-Hutter Model	conservation of mass and momentum	?	no	?

2.5. DAN3D Applications

Hungr (1995) developed a continuum model called DAN (Dynamic ANalysis) based on a Lagrangian solution of the equations of motion. It simulates the characteristics of rapid landslides like debris flows, avalanches and liquefaction failures. It also allows the selection of a variety of material rheologies, which can vary along the slide path or within the slide mass.

The run-out analysis result will be compared with the run-out parameters: maximum distance reached, flow velocity, thickness and distribution of deposits and behavior in bends and obstacles in the flow path (Hungr, 1995). It is also noted by Thakur et al. (2014b) that accurate prediction of flow slide behavior, including retrogression distance, run-out length and flow velocity, are essential for hazard risk assessment.

This model is mainly developed for modeling snow and rock avalanches (Hungr, 2010). This numerical tool can serve as a versatile tool for modeling post-failure motion with a typical procedure of calibrating the model by back calculation of known cases and to predict the behavior of new events (Hungr, 1995). Therefore these rheological models for run-out distance modeling of sensitive clay debris has been studied by Thakur et al. (2014b). This preliminary study related to run-out modeling of sensitive clay debris under different rheological set-ups was conducted using a flow computation modeling software called DAN3D.

Four out of five basal rheological models in DAN3D, i.e. the plastic rheology, the Bingham rheology, the Friction rheology and the Voellmy rheology have been studied with a real quick clay slides happened in Norway. The fifth rheology is the Newtonian rheology which is a type of rheology mainly works for fluids that do not exhibit viscosity change with strain rate or relative velocity of flow, for example water. Therefore, it is not applicable for debris flows which are usually considered as non-Newtonian flows.

The Byneset quick clay slide is back calculated using different sets of input parameters according to the rheology selected. Suitability of each rheology for quick clay slides along with the input parameters is assessed. The set of input parameters like remolded shear strength c_{ur}, friction angle φ, viscosity μ, and soil unit weight γ, are easily obtainable from laboratory tests whereas friction coefficient f, and turbulence coefficient ξ, are usually obtained from back calculation of the landslides.

This quick clay slide happened on 1st of January, 2012, flows through a dry water canal (January 1st, 2012) having a very gentle slope of 3° for a distance of 870m. According to the results from the simulations and back calculations, Plastic rheology that requires only unit weight and shear strength of the flowing material (γ = 18kN/m3 and c_{ur} = 0.1kPa) as input parameters gave a fairly equivalent run-out distance with the actual observation at the field which is 870m.

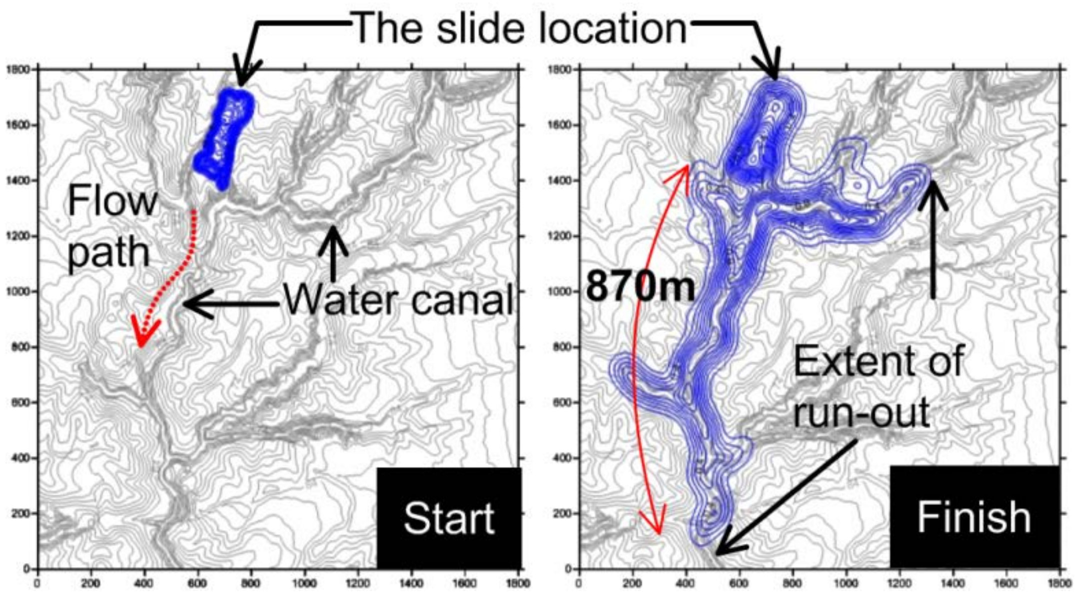


Figure 2.10: Back calculation of the Byneset landslide using plastic rheology in DAN3D. c_{ur} = 0.1kPa (Thakur et al., 2014b).

The flow contour given in Figure 2.10 represents the back calculated run-out distance using plastic rheology and the corresponding result shown in red circle in Figure 2.11. The effect of c_{ur} on the run-out distance is given in Figure 2.11 and found logarithmically decreased with increase of c_{ur}. This result showed that sensitive clays having c_{ur} > 1.0kPa are less likely prone to flow type slides.

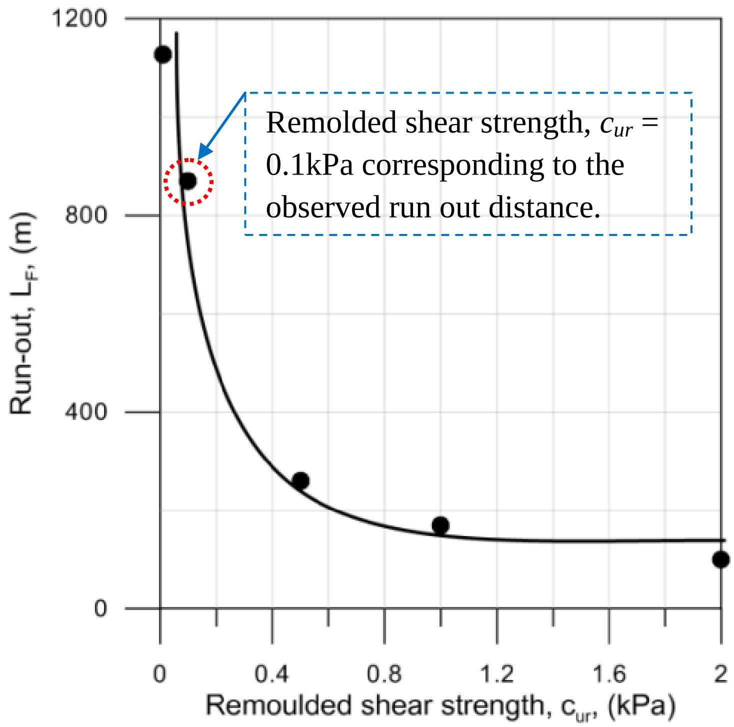


Figure 2.11: Run-out distance as a function of remolded shear strength of sensitive clays using the plastic rheology (Thakur et al., 2014b)

The two parameter Voellmy rheology gave a result that shows influence of f than that of ξ in the prediction of the run-out of sensitive clay debris flow although the best back calculated run-out distance was one third of the field run-out distance observed. On the other hand, the Bingham rheology gave unsatisfactory result with a run-out distance back calculation. The results obtained were ranging 4m - 10m although the writers tried to use different values of viscosity.

The result obtained from friction rheology back calculation rather agrees with plastic rheology despite the different input parameter it uses. Here φ is varied keeping pore-pressure ratio constant ($r_u = 0.9$). $\phi = 5°$ gave run-out distance close to what is observed in the field (red circled in Figure 2.12) and the writers compared this value with $f \approx 0.1$ as f is analogous to $\tan(\phi)$.

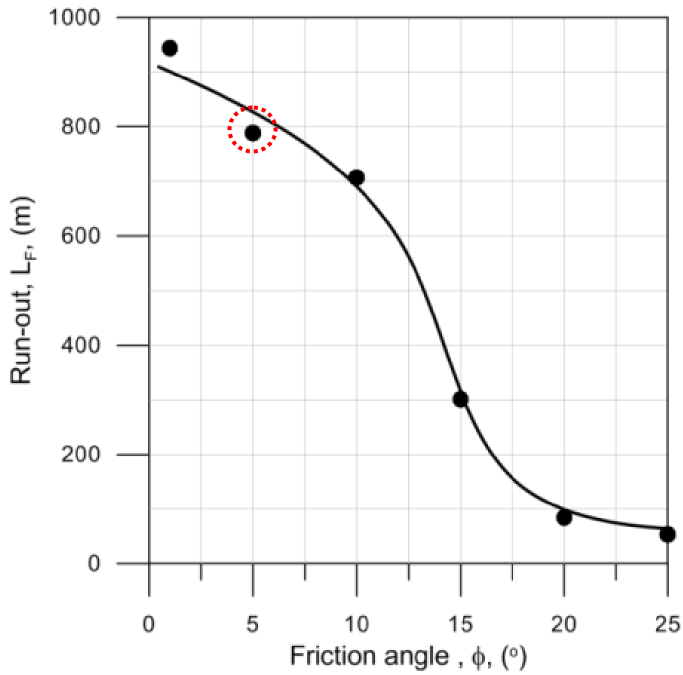


Figure 2.12: Run-out distance as a function of friction angle for constant r_u = 0.9 using friction rheology (Thakur et al., 2014b).

This paper finally describes the promising beginning of modeling sensitive clay debris flow using these rheological models. The plastic and friction rheologies, that need few input parameters which can easily be found from tests, seem to predict the run-out distance of this very case.

In another study Hungr and Evans (1996) has tried to simulate 23 rock avalanches using the numerical model called DAN which is a predecessor DAN3D. The writers used the Friction, Voellmy and Bingham rheologies to back calculate these events. The intension was to develop an analytical method of predicting rock avalanche run-out that has a better precision in resulting output distance and velocity. The three rheologies used and 23 of the rock avalanches analyzed and assessment made according to total horizontal run-out distance and length of the main deposit which are mainly found from the case history records.

When the influence of the rheologies studied by comparing the calculated and actual run-out distance of the main deposit, the Frictional rheology gave somehow erratic result where as the Voellmy rheology performed quite well except for few notable exceptions, see Figure 2.13 (left and middle). Figure 2.13 (right) shows the Bingham rheological model consistently overestimating the debris run-out length. The writers also mentioned that this rheology predicted depositions close to the source area which do not happen in reality in most cases.

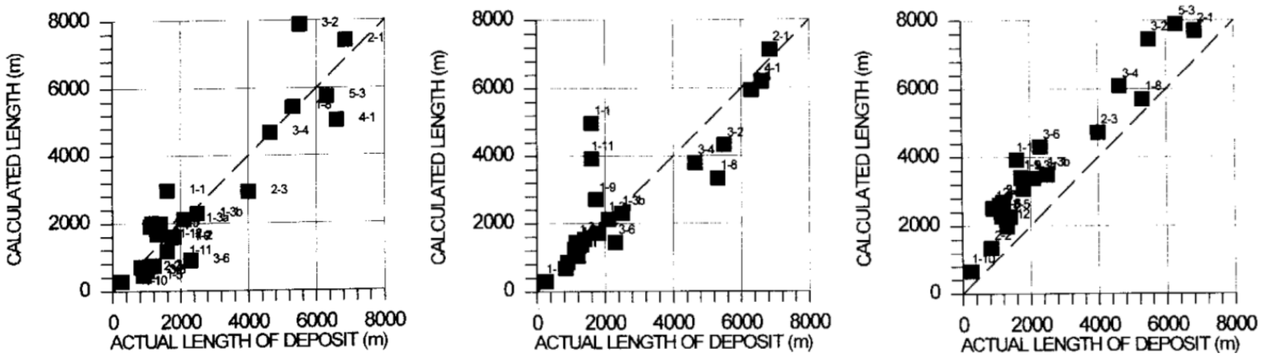


Figure 2.13: Deposition length prediction from friction model (left), Voellmy model (middle) and Bingham model (right) (Hungr and Evans, 1996)

After this back calculation the writers used the Voellmy rheological model with pre-determined material properties of friction coefficient, f = 0.1 (bulk friction angle, ϕ = 5.7°) and turbulence coefficient, ξ = 500m/s^2 and compared with actual run-out distances of the 23 avalanches (Figure 2.14). Actual run-out distance of 70% of the 23 landslide cases are found to be predicted within about 10% tolerance as shown by the following figure.

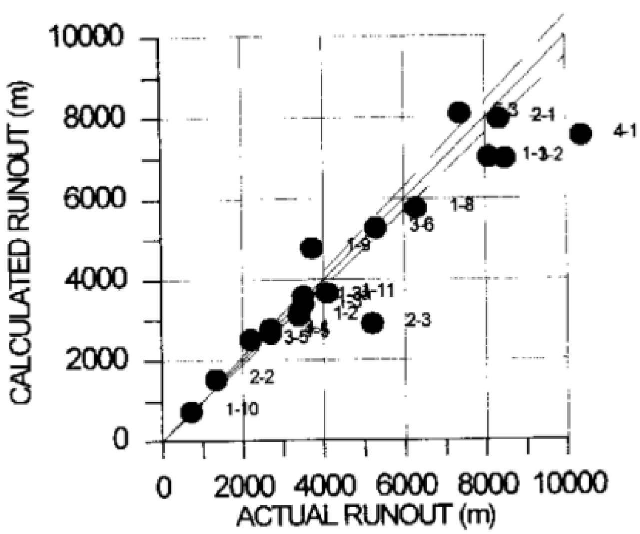


Figure 2.14: Run-out distance prediction using Voellmy model in DAN : f = 0.1 & ξ = 500 m/s^2 (Hungr and Evans, 1996)

From the above result, one can see that the Voellmy rheology of DAN gives the most consistent results in terms of debris spreading, distribution and velocity data of the rock avalanches.

2.6. RAMMS Applications

RAMMS (RApid Mass Movements) has been used to simulate and back calculate many debris flows. It uses the Voellmy rheology which has friction and turbulent terms as described in Section 2.4.1. Some of the studies conducted using this numerical tool are presented hereafter.

RAMMS has been used to simulate a potential natural hazard for a village of Lokavec in Slovenia by Askarinejad et al. (2013). They have tried to simulate 100000 m^3 of landslide which could possibly happen in the future with different kinds of scenarios to predict the run-out distances, flow heights, impact pressures and potential effects on downstream area. These different scenarios include release volume, internal friction and viscosity of the sliding mass.

The study resulted in showing low viscosity mudflow with small volume (5000 m^3) only endangering some part of the downstream area where as larger volume mudflows (like 15000 m^3 and 50000 m^3) were found catastrophic for the downstream area in terms of impact pressure as well as deposition height. The writers also mentioned that the choice of material properties (internal friction and viscosity) have played a significant role in predicting run-out distance and impact pressure.

Scheidl et al. (2013b) have studied 2D run-out predictions for debris-flow using empirically based simulation model (TopRunDF) and dynamic numerical simulation model (RAMMS). The RAMMS version this study used was RAMMS-avalanche with Voellmy fluid rheology.

For RAMMS-avalanche, the two governing parameters, μ and ξ, representing the friction and viscosity of material are altered to give the best fit of the Arundakopfbach (Italy) debris flow event as shown in Figure 2.15.

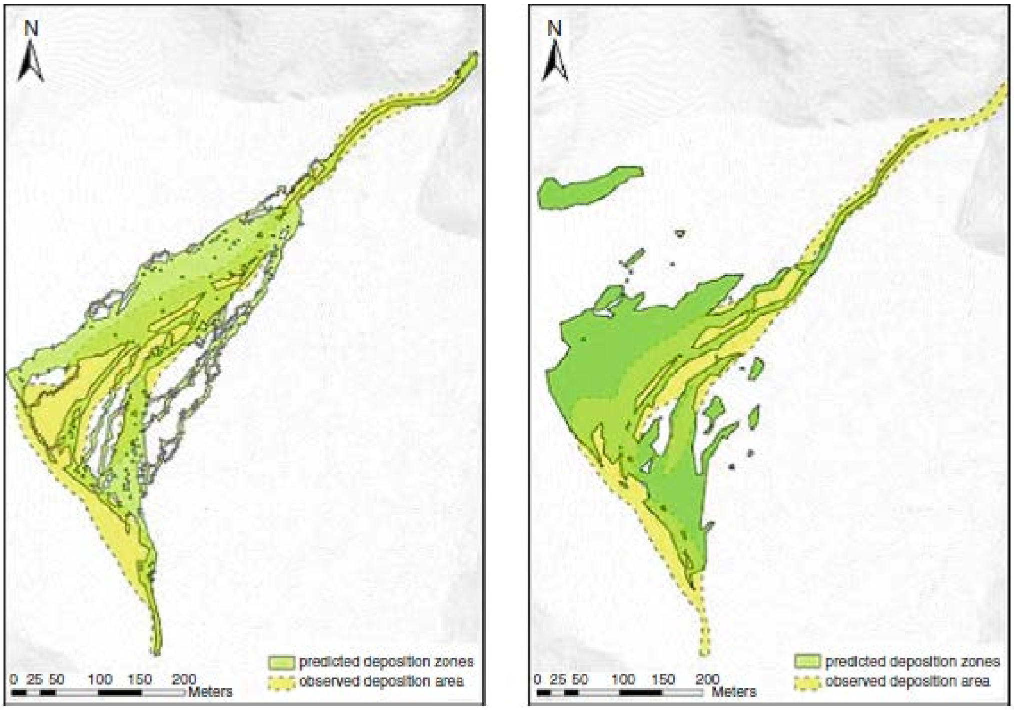


Figure 2.15: Best fit simulation results of the Arundakopfbach (IT) event by TopRunDF (left) and RAMMS (right) (Scheidl et al., 2013b)

These are few of the many rock avalanche and debris flow analyses conducted using the Voellmy rheological model in RAMMS. The two parameter model representing a Voellmy fluid was applied successfully to different gravitational mass movements.

3. Numerical Tools and Rheological Models Used

3.1. Introduction

In this study the Numerical tools used are RAMMS::Debris Flow and DAN3D. These tools have rheological models as described in Section 2.4.2 in which RAMMS uses only the Voellmy rheology and DAN3D uses five rheologies that comprises of: Newtonian, Plastic, Frictional, Bingham and Voellmy.

3.2. Voellmy Rheological Model in RAMMS

3.2.1. Background

RAMMS (RApid Mass Movements Simulation) is a numerical model for mass movements or run-out simulations. It is developed by WSL Institute for Snow and Avalanche Research SLF. The version used here is specifically made for debris flow and this paper investigates the extent to which this model simulates run-out of sensitive clay landslides, specially of Norwegian quick clays.

3.2.2. The Voellmy Rheological Model

Voellmy (1955) proposed this two-parameter rheological model to compute snow avalanches by referring open channel hydraulics and neglecting the viscous term. This rheology combines frictional and turbulent models such that increasing velocity results in increased drag. He assumed the avalanche as an endless-fluid accelerating quickly down an inclined long channel from rest to a steady, terminal velocity with constant flow height (Chen and Lee, 2003). The basal rheological resistance is a result of dynamic drag and given by Equation (3.1a).

$$\tau = \left(\mu\sigma \ + \frac{\gamma U^2}{\xi}\right) \tag{3.1a}$$

Where μ is the friction coefficient, σ is the normal stress, U is the moving velocity parallel to the base, ξ is the turbulence factor that constitutes the density and drag coefficients. The second term as a whole, which is the inertial term, reflects the dynamic energy of the avalanche.

The dimensionless value of μ is the ratio of the force required to slide on the interface to the force perpendicular to it. It is a measure of the resistance to motion caused by molecular adhesion of one face to the other over the areas of true contact. This parameter is dependent not only on the load (pressure or perpendicular force) but also on the contacting materials and the state of the interface (lubricated, dry, wet, contaminated, etc)(Chen and Lee, 2003).

In application of the semi-empirical techniques of the Voellmy rheology to rock avalanches, McLellan and Kaiser (1984) found that the travelling geometry is one of the major considerations in the choice of μ. The upper and lower bound limits of μ are given by the fahrboeschung (the inclination of the line joining the top of the pre-failed block and the distal tip of the debris) and the slope of the shallowest segment, respectively.

Chen and Lee (2003) suggested that the best prediction may be achieved by assuming that μ = tan α, where α is the average run-out slop or slop of streaming ramp which separates the rupture surface and accumulation area. In one of the cases studied here, the Byneset landslide case, the slop of flow topography can be in average 3° which makes the friction coefficient estimation to be μ = tan (3°) = 0.052.

When fluid pressures exist, it is the effective normal stress that controls the contact conditions between the two surfaces. The existence of pore-pressure in debris will result in a reduction of the basal friction (Chen and Lee, 2003). So the effective dynamic friction coefficient may be expressed as $\mu' = (1 - r_u)\,\mu$ by introducing the pore-pressure ratio r_u (McLellan and Kaiser, 1984). Alternatively, the friction coefficient, μ, is equivalent to tan (Φ) where Φ is the bulk friction angle (Hungr and Evans, 1996). The bulk friction angle, Φ, is related with the dynamic friction angle φ' using a pore pressure ratio, r_u as given in the friction rheology, $\tan \Phi = (1 - r_u) \tan \varphi'$.

3.2.3. Implementation of the Voellmy Model in RAMMS::Debris Flow V1.6

In this version of RAMMS, an ENO (Essentially Non-Oscillatory) scheme is used to numerically solve the governing differential equations in a general quadrilateral grid unlike the previous versions which were in strictly orthogonal grids that may cause some numerical instabilities. The new scheme improves numerical stability with the cost of longer computation time or slower computation speed (Bartlet et al., 2014).

This new version also made to include cohesion of the flowing material by modifying the previous basal resistance equation given in Equation (3.1b) in to Equation (3.2). It is obvious that when $C = 0$ in Equation (3.2), it becomes Equation (3.1b) which is the original formulation by Voellmy (1955).

$$S = \mu[\rho H g cos(\phi)] + \frac{\rho g U^2}{\xi} \tag{3.1b}$$

$$S = \mu N + (1-\mu)C - (1-\mu)C\, exp\left(-\frac{N}{C}\right) + \frac{\rho g U^2}{\xi} \tag{3.2}$$

where S is the frictional (basal) resistance, μ is a dry-coulomb type friction coefficient that scales up with normal stress, ξ is a velocity-squared drag or viscous-turbulent friction coefficient, ρ is density of the flowing material, g is the gravitational attraction, ϕ is the slope angle, H is the flow height, U is the flow velocity, $\rho H g cos(\phi) = N$ is the normal stress on the running surface C is the cohesion of the flowing material.

To evaluate the effect of cohesion in this model, μ has been set to be zero and gives the following Equation (3.3). This is when the basal resistance gets total contribution from the cohesion term otherwise the contribution decreases by a factor of (1- μ).

$$S = C - C\, exp\left(-\frac{N}{C}\right) + \frac{\rho g U^2}{\xi} \tag{3.3}$$

Equation (3.2) has been established using chute experiments with the flowing snow and real scale experiments with debris flows in Illgraben (VS) (Platzer et al., 2007). The manual recommends 0 - 2000Pa cohesion for debris flow simulation. This range of cohesion includes range of values of sensitive clays which are likely to flow type slides. These sensitive clays that are described as 'likely to flow' have a remolded shear strength (cohesion) value less than 1000Pa.

The friction coefficients are the main factors responsible for the flow behavior as μ dominates when the flow is close to stopping and ξ dominates when the flow is running quickly (Bartlet et al., 2013). Unlike snow avalanche, debris flow exhibits variety of flow composition which greatly influences the choice of the friction parameters, ξ & μ.

This version of Voellmy model used in RAMMS::Debris Flow uses a single-phase model that does not allow distinguishing between solid and liquid phases. It rather simulate the mass flow as bulk flow with a single value for each parameter unless a user delineate areas within the flow domain and assign different values. The landslide simulation can be initiated using either a block release or hydrograph (flow discharge as a function of time).

3.2.4. RAMMS Simulation Procedure

The interface of this software is given in Figure 3.1. The available digital terrain model (DTM) and the ortho-photo of the area must be uploaded in the software using the 'Project Wizard' command. The software gives its own calculation domain by default and the user is expected to define the release area. It is also possible to assign user defined calculation domains as required. Detail procedures of delineating calculation domain and release areas of the cases are presented in their respective Sections.

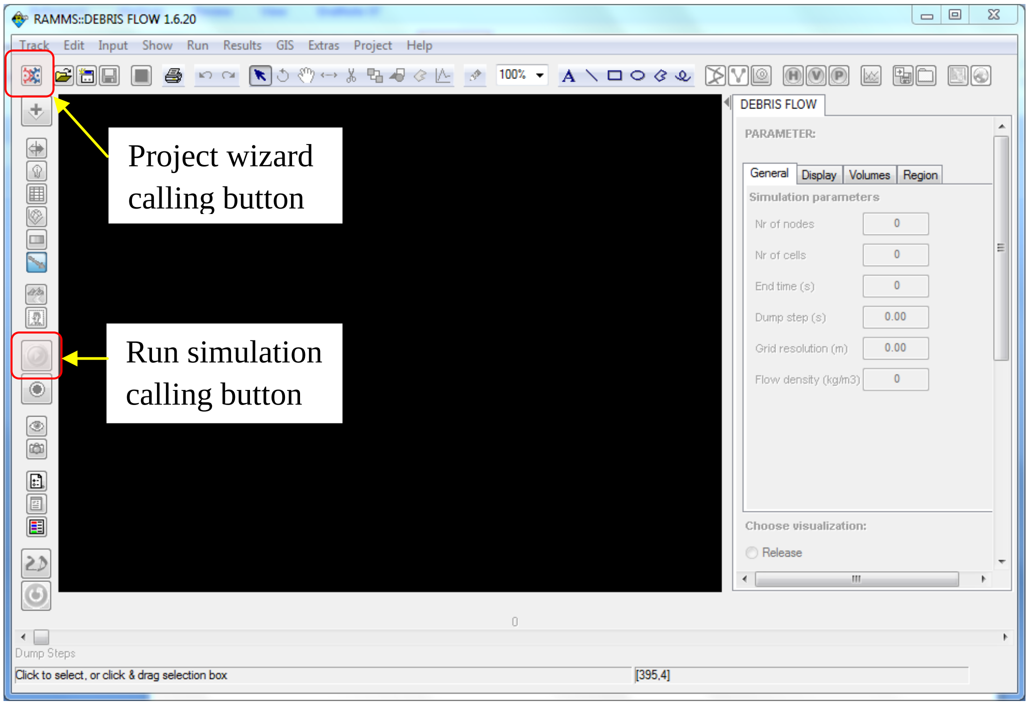
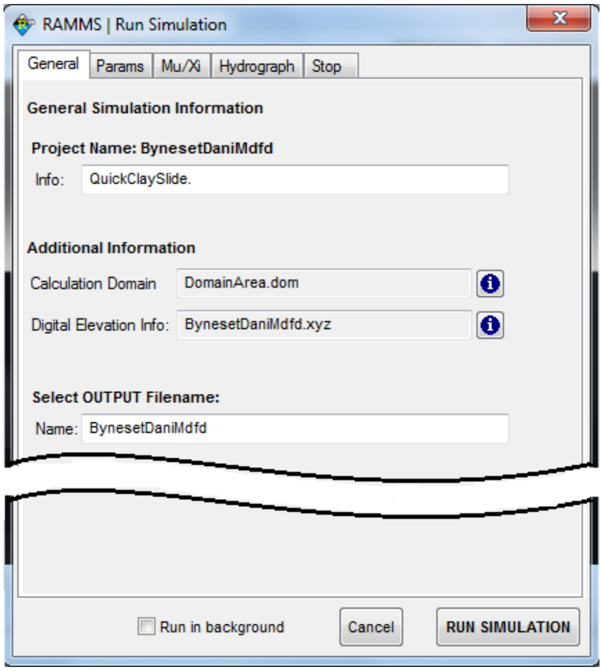
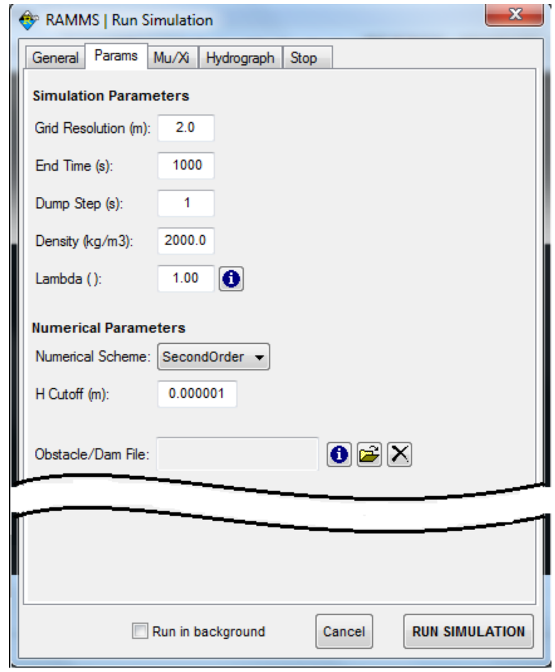


Figure 3.1: Screen print showing the interface of RAMMS::Debris Flow v1.6

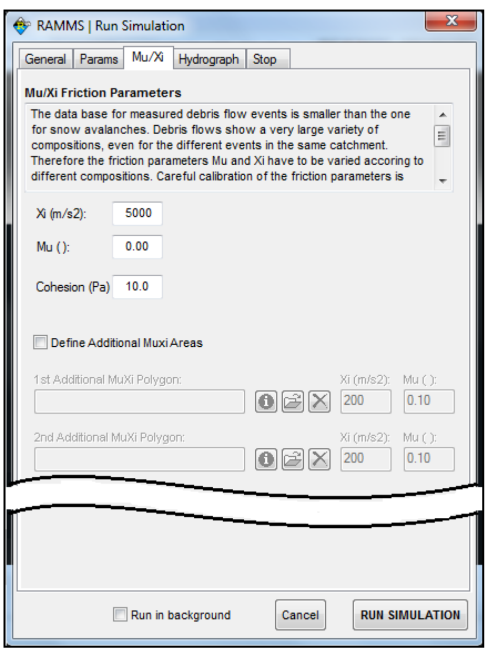
After setting the DTM data using 'project wizard' command, assigning the calculation domain and release are along with its height have to be done. Then the 'run simulation' command is called and a dialog box with General, Parameters, *Mu/Xi (μ/ξ)*, Hydrology and Stop tabs opens as shown on Figure 3.2(A). General tab, picture (A), contains general information about the project the user specified when creating the project using ‘Project Wizard’. Parameters tab, picture (B), contains simulation parameters most of which are left as default. Grid resolution is calculated from the input DTM data, End time is specified by user and in this study the default 1000 seconds used. Dump step is the time interval in seconds where the simulation is recorded, Density is an input parameter.



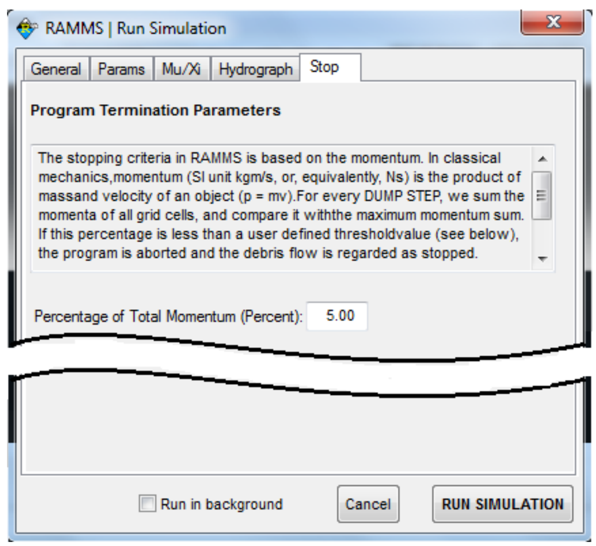
(A) General tab



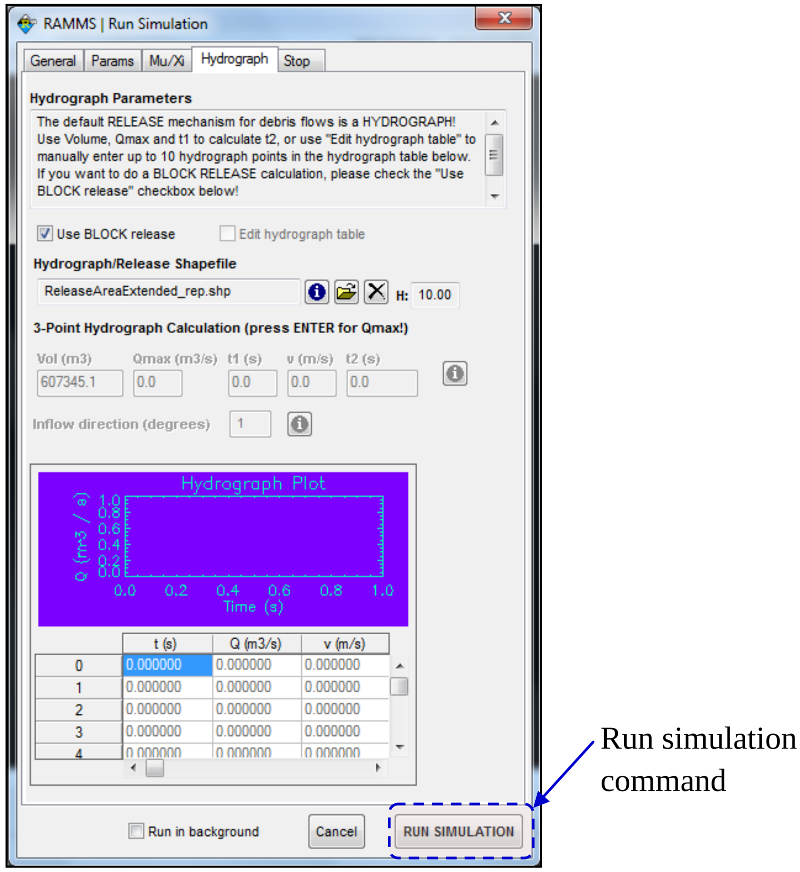
(B) Parameters tab



(C) *Mu* (μ), *Xi* (ξ) and *C* tab



(E) Stop tab



(D) Hydrology tab

Figure 3.2: Controlling and simulating parameter set up dialog box: RAMMS::Debris Flow.

Lambda is the active/passive earth pressure coefficient specified in RAMMS to modify the longitudinal pressure gradients driving the flow. Active refers to the dilatant flow regions and passive to compressive regions. However the default value, lambda = 1.0, disables this effect and it is recommended by the developers that use of other values will greatly affect the simulation result. For this study the default value was used. The numerical parameters are also left in their default values as it is recommended by the developers.

The μ/ξ friction parameters tab (C) is the main concern of this study and different combinations of ξ, μ and C have been used to simulate and back calculate the events. In the hydrology tab (D) hydrograph parameters namely block release and hydrograph table are given. Block release method is entirely used during this study. In the stop tab (E) the program termination parameter is given and it is discussed in the next Section. Finally running simulation ordered by clicking 'Run Simulation' button on this dialog box.

3.2.5. Simulation Stopping Mechanism

Stopping mechanism is based on momentum which is the product of mass and velocity. The software calculates the sum of the momentum for every dump step (calculation step) and compares it with the maximum sum of momentum as percentage. If this percentage is found to be lower than a specified threshold value given by the user, the simulation gets interrupted and the flow is regarded as stopped. As it is suggested by the manual, Bartlet et al. (2013), values between 1-10% are reasonable and in addition one should empirically determine the appropriate value for each test case. For this study, the default value (5%) has been used after comparing the results obtained by 1%, 2%, 3% and 5% as the lower values did not give significant difference on resulting flows except resulting in longer simulation time.

3.3. Plastic and Voellmy Rheological Models in DAN3D

3.3.1. Background

For this study, the Plastic and Voellmy rheological models implemented in DAN3D have been utilized to simulate the cases presented in Chapter 4 and Chapter 5. Detail descriptions of these rheologies are given in Section 2.4.1 and Section 3.2.2. Here only the procedures of simulation are presented.

3.3.2. DAN3D Simulation Procedure

The first dialog box (step 1) that shows up when opening and creating new file is the Control Parameters dialog box, Figure 3.3 (left). Here information about the project is entered and other parameters like erosion rate, maximum simulation time and time step is set.

The maximum simulation time and time step in seconds can be specified in the control parameter dialog box. The maximum simulation time (default is 1000 seconds) can be adjusted at the beginning, during or/and after finishing the simulation. Whereas the time step value, which is ranging typically between 0.05 and 0.1, can only be set at the beginning and higher values out of the specified range results in decreased precision in results (Hungr, 2010). Therefore the default values were used and were not changed throughout. This tool does not have stopping mechanism of a simulation before the specified maximum simulation time. Therefore the user must evaluate when to stop the simulation, or evaluate the actual run-out extent after the simulation ends.

This software requires two ASCII formatted digital terrain model, DTMs (*.GRD), grid files. One is representing the path topography file that defines the topography of the sliding surface whereas the second one is the source topography file which defines the vertical depth topography of the sliding mass at the initial time and position. These two files should have same grid size and spacing. Both DTM files advised to have (0,0) coordinate as minimum values of x- and y-coordinate to reduce the risk of precision loss due to the unnecessarily large numbers used in large geographical data (Hungr, 2010).

The ASCII *.grd grid files are assigned using the Grid File Assignment dialog box (step 2) shown in Figure 3.3 (right). In this case, no erosion map is used and erosion concept is not considered.

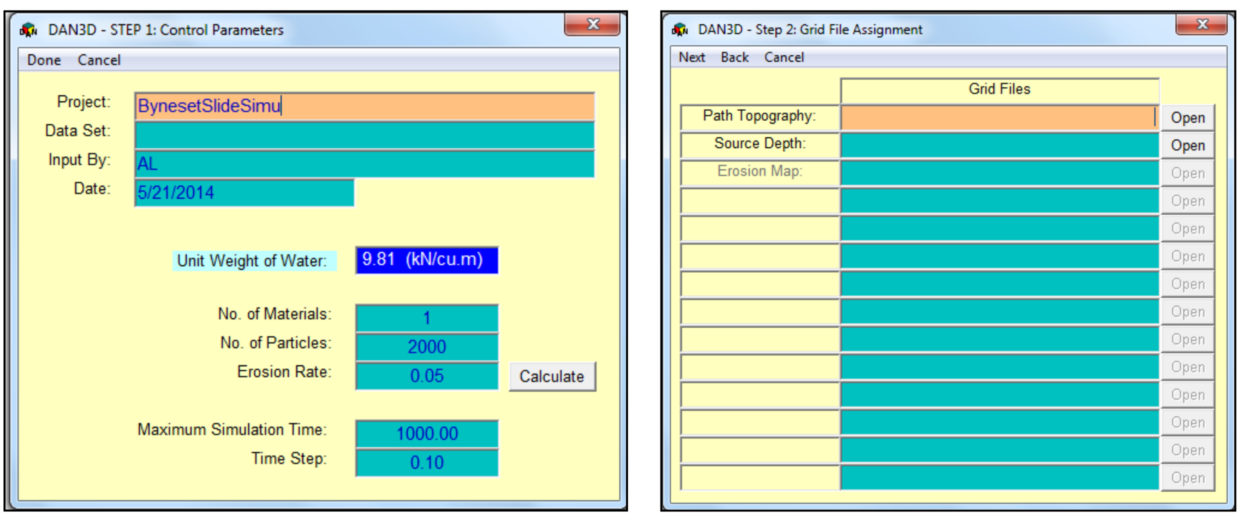


Figure 3.3: Control parameter (left) and grid file assignment (right) dialog boxes.

The next step (step 3) is to choose material type (rheological model) from the given five in the software which are; Friction, Plastic, Bingham, Newtonian and Voellmy rheological models. This study focuses on the Plastic and Voellmy rheological model. According to the material type (rheological model) the governing parameters are written in blue and those do not have any effect are written in white (Figure 3.4). The basal resistance (friction) parameters; friction coefficient, f and turbulence factor, ξ are varied for Voellmy rheology and shear strength value varied for plastic rheology to conduct the different back calculations and simulations.

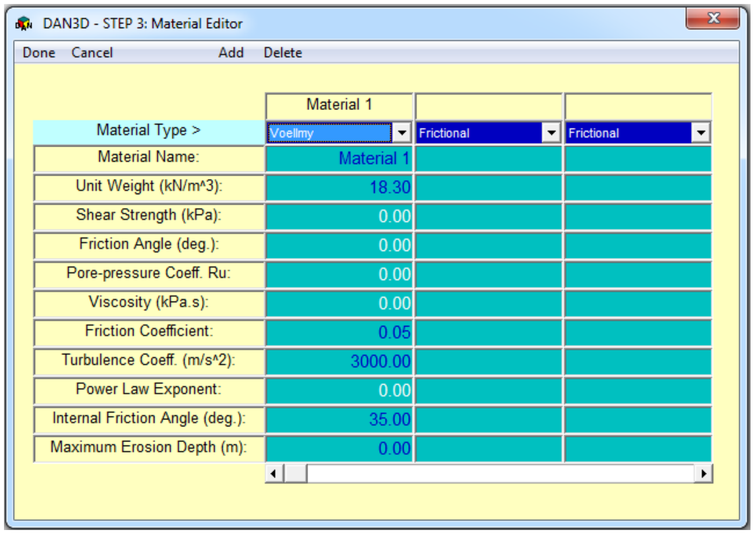


Figure 3.4: Material property dialog box showing rheology selection.

'Data output options' dialog box gives the opportunity to select which type of files the user wants to have as output. There is also 'parameters' tab where one can select location of the output files. Since this study concerned on the run-out distance back calculation, only nodal depth and nodal elevation grid files are selected as shown by Figure 3.5 (left).

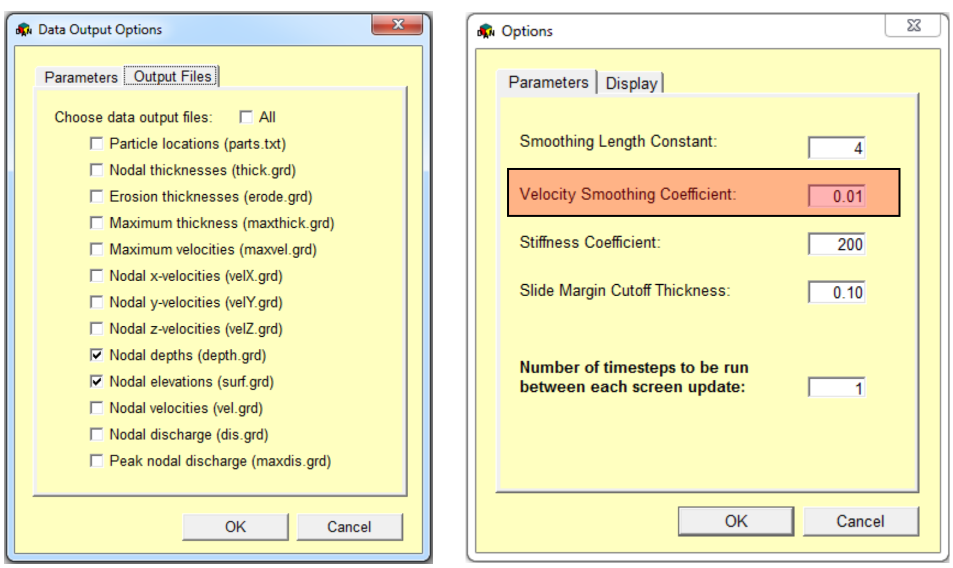


Figure 3.5: Data output options dialog box (left) and options dialog box (right)

In the options dialog box there is velocity smoothing coefficient (highlighted with red rectangle) which is an arbitrary coefficient used to determine how potent the velocity smoothing algorithm is (Hungr, 2010). The default value is found to be (0.00) in the software while 0.01 is written in the manual. Two sets of simulations were made using these values in order to evaluate its effect in the back calculation.

4. Laboratory Test Simulations

4.1. Introduction

Attempts to numerically simulate two laboratory test cases were made to evaluate the numerical tools used and to back calculate some important parameters from the models. These two laboratory tests are quickness test and small scale run-out model laboratory test. The quickness test is used to define the collapse behavior of remolded sensitive clays dictating about the flow potential of the soil with respect to its remolded shear strength (Thakur and Degago, 2012, Thakur and Degago, 2014). Whereas the small scale run-out model test aims to provide a basis for understanding the run-out distance of fully remolded sensitive clay debris (Thakur and Nigussie, 2014).

4.2. Preliminary Attempt to Numerically Simulate Quickness Test

4.2.1. Background about the Test

Quickness test is developed by Thakur and Degago (2012) which provides a quantitative description of remolded behavior of sensitive clays in terms of numerical value called quickness (Q). It can simply be defined as a test to explore flow potential of sensitive clay soils based on their remolded shear strength values.

Quickness is an adaptation of slump test of concrete for its consistency and workability. It is carried out by first placing a cylinder on a level surface and filling it with thoroughly remolded sensitive clay sample. Then the top end of the cylinder is leveled and the soil is released by lifting the cylinder slowly straight upward allowing it to flow by its own weight.

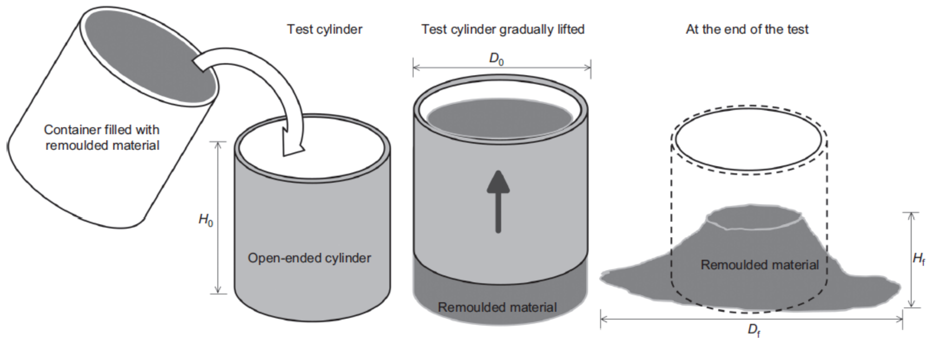


Figure 4.1: Quickness test procedure (Thakur and Degago, 2012)

Measurements for deformation height, H_f and spread diameter, D_f are taken as shown on Figure 4.1 and quickness of the material is calculated as Q = $(H_0-H_f)/H_0$. Quickness gives a percentage of the collapse level with respect to the original height of the material column, 100% representing complete collapse and 0.0% representing intact state with no deformation. This test is found to be significant and important as it amplifies small range of remolded shear strength of a material, 0.0kPa to 2.0kPa, to a scale from 0.0% to 100% which helps visualize the flow behavior of sensitive clay soils like as shown by Figure 4.2.

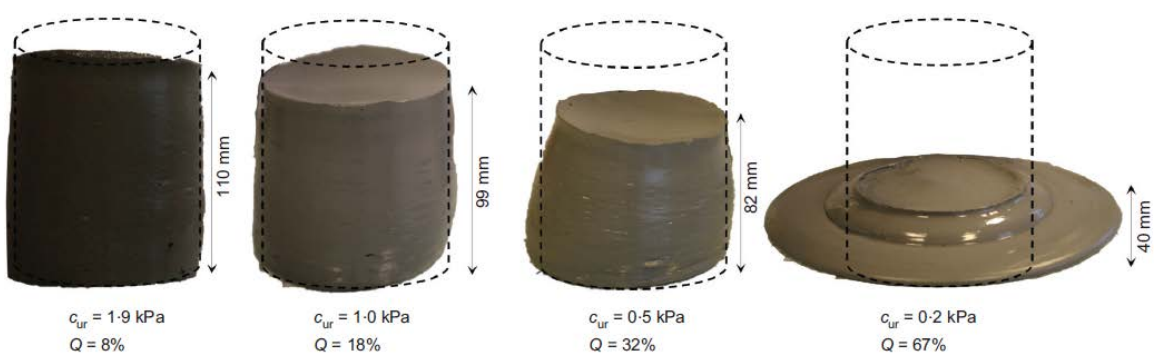


Figure 4.2: Slump and spread of remolded sensitive clays observed from quickness test conducted by the larger cylinder along with c_{ur} and Q values (Thakur and Degago, 2012).

The test was conducted with two different sized cylinders; Large cylinder (LC): D_0 = 100mm x H_0 = 120mm (ordinary proctor test mold) and small cylinder (SC): D_0 = 65mm x H_0 = 45mm, in which the volume of the larger cylinder is more than six times that of the smaller cylinder.

Figure 4.3 shows the result obtained comparing the two different sizes. Some of the scattered observations for very small c_{ur} values might be due to cylinder sizes. However, no matter how scattered the observations are, the quickness result shows that they all have potentials to flow. On the other hand, no significant result difference with respect to size were observed in flow potential evaluation of c_{ur} > 1.0kPa dictating that no flow potential is registered.

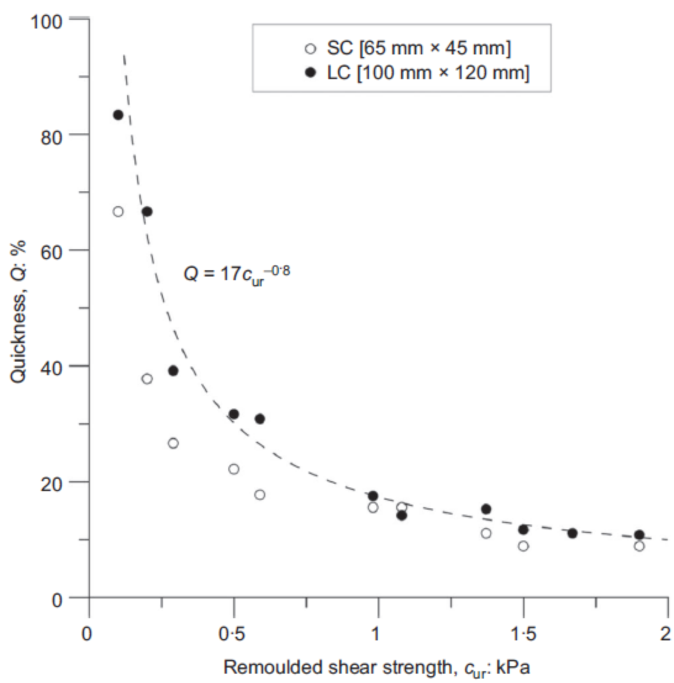


Figure 4.3: Quickness test results for various samples with small and large cylinders and different remolded shear strength values. (Thakur and Degago, 2012)

The large cylinder with size 100mm X 120mm is recommended and used for further studies for proposing some correlations as given in Table 4.1. The table shows the expected lower and upper bound values of quickness for a given remolded shear strength of sensitive clays.

Table 4.1: Lower and Upper bound of quickness values for various values of c_{ur} (Thakur and Degago, 2012)

Remolded shear strength, c_{ur} [kPa]	Quickness, Q [%]	
	Lower bound	Upper bound
< 0.1	> 60	> 80
0.5	20	32
1.0	15	17
1.5	9	12
2.0	9	11

As given in the study, out of the registered sensitive clay flow slides in Norway, none found to have a remolded shear strength ranging between 1.0kPa < c_{ur} < 2.0kPa. The study finally conclude that Q < 15% or c_{ur} > 1.0kPa seems to be threshold limit for flow potential where the extent of retrogression of a landslide is limited to the initial slide, Figure 4.4.

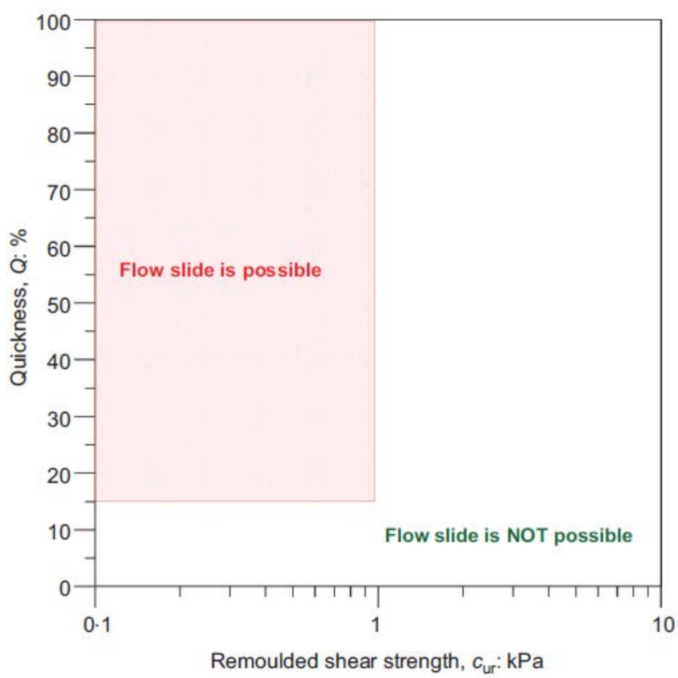


Figure 4.4: Proposed range of c_{ur} and Q to assess the potential for the occurrence of flow slides in sensitive clays after an initial slide (Thakur and Degago, 2012)

4.2.2. Objectives of Numerically Modeling the Quickness Test

It is described that the main aim of quickness test is to assess the flow potential of a given sensitive clay soil. It is not meant for determining run-out distances in which the two numerical models (RAMMS & DAN3D) meant for. These numerical models consider a given release mass as potentially flowing and use given parameters for resisting a flow according to the rheological formulation. Although these models cannot tell the flow potentials, by modeling quickness test some other aspects can be studied given that a material is potentially flowing.

Some aspects that are going to be studied are:

- Effect of size and scale in a given numerical model (Plastic rheology[†] in DAN3D)
- Effect of parameters used in the modified Voellmy rheology of RAMMS with respect to the flow behavior.

4.2.3. Modeling Aspects and Required Parameters

The two numerical modeling softwares, RAMMS and DAN3D, work with digital elevation models given as grid files. The minimum resolution of this grid for RAMMS, however, is 1m X 1m while that of DAN3D is found to be adjustable to the minimum possible which allow replication of the actual size of the quickness test cylinder (D_0 = 100mm X H_0 = 120mm). Therefore two different sizes in each modeling software were proposed and used. Their sizes and scales are given in Table 4.2 for DAN3D and Table 4.3 for RAMMS.

† The plastic rheology is used because it uses shear strength of the material (τ) which can be easily related with the remolded shear strength (c_{ur}) of sensitive clays that was used in the actual test. This plastic rheology did also give a good result in back calculating the Byneset slide event by using c_{ur} value observed at the field. (Section 2.5)

Table 4.2: Sizes used in the actual quickness test and in the simulation model (DAN3D)

	Actual Size	Model size 1	Scaled up by	Model size 2	Scaled up by
D	100 mm	100 mm	1.0	1.0 m	10
H	120 mm	120 mm	1.0	1.2 m	10
V	941000 mm^3	941000 mm^3	1.0	9.42 m^3	$1x10^3$

The spread area prepared for the 100mm diameter model is 1.2m x 1.2m surface and for the 1m diameter model is 12m X 12m flat surface.

Table 4.3: Sizes used in the actual quickness test and in the simulation model (RAMMS)

	Actual Size	Model size 1	Scaled up by	Model size 2	Scaled up by
D	100 mm	100 m	$1x10^3$	10 m	$1x10^3$
H	120 mm	120 m	$1x10^3$	12 m	$1x10^3$
V	941000 mm^3	941000 m^3	$1x10^9$	942 m^3	$1x10^6$

The 100m diameter model is laid over 600m X 600m flat area and the 10m diameter model was laid on a flat area with size 150m X 150m which is enough to hold the flow extent when the mass is released. The extent of spread is directly related with the velocity of flow and the basal resistance. The flow velocity gained from the kinetic energy is converted from the potential energy the volume has at the beginning or before the release.

Potential energy of a model, in the other side, is directly related with the height of the model as given by Equation (4.1). Equation (4.1) & (4.2) give pressure as energy density (Nave, 2012). Since disintegration (remolding) energy cannot be considered in these numerical models and the original test is conducted using remolded sensitive soils, it is assumed that the whole potential energy is converted in to kinetic energy of the flow without considering remolding energy.

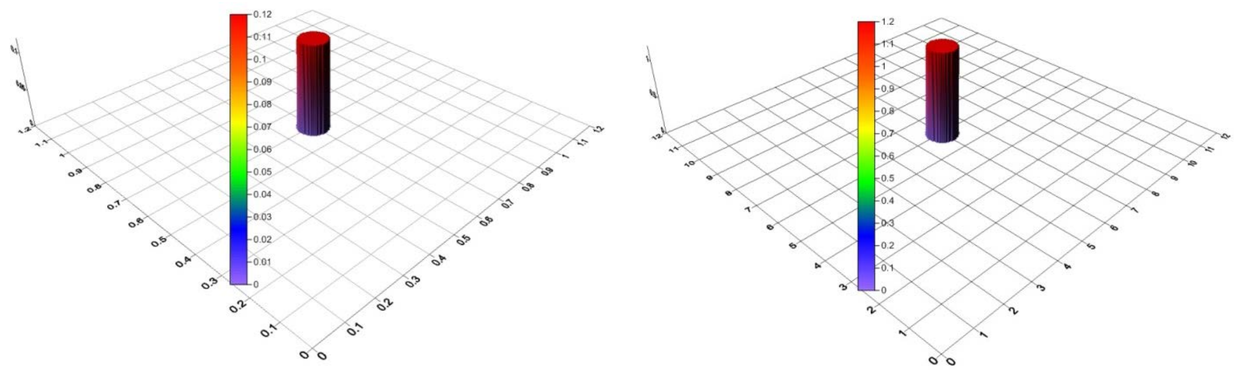
Fluid potential energy per volume:

$$\frac{Potential\ energy}{Volume} = \frac{mgh}{V} = \rho g h \tag{4.1}$$

Fluid kinetic energy per volume:

$$\frac{Kinetic\ energy}{Volume} = \frac{\frac{1}{2}mv^2}{V} = \frac{1}{2}\rho v^2 \tag{4.2}$$

Two grid files are required to define the problem setup in DAN3D. One is for defining the digital elevation model (DEM) of the source volume ready to flow and the second one is for defining the DEM of the surface where the mass will flow over. These two digital models are defined as shown in Figure 4.5 for both model size 1 & 2.



D = 100mm & H = 120mm model D = 1.0m & H = 1.2m model

Figure 4.5: Two models prepared to simulate quickness test in DAN3D

On the other hand, RAMMS requires only one DEM that represent a given surface where a material can flow over. The release volume is then defined on the surface by delineating a source area and assigning release height to it. The software doesn't have tools to draw special shapes like circles and the delineation was manually done. Figure 4.6 shows the two defined models along with their release volumes. As the diameter getting smaller (in the case of D = 10m), it is found difficult to get the intended circular shape since the smallest grid the software can consider is 1m X 1m.

The parameters used for simulating the test are taken from Byneset landslide data since this real case will be analyzed too. The remolded shear strength value is given as c_{ur} = 0.12kPa and c_{ur} = 0.1kPa is used for simplicity. Additional parameters required by the Voellmy rheological model in RAMMS that are not readily available for sensitive clay soils shall rather be studied in back calculations.

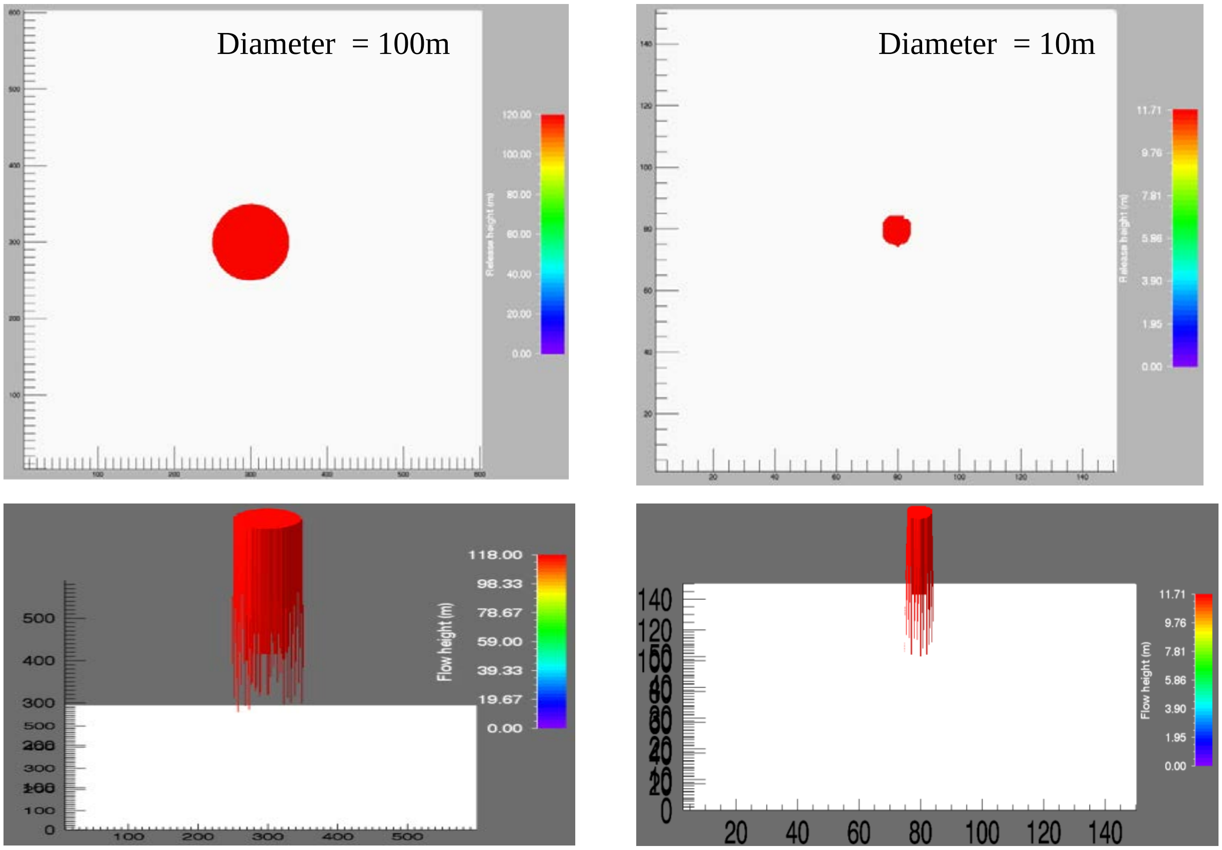


Figure 4.6: Models of 100m diameter (left) and 10m diameter (right) of the quickness test as defined in RAMMS.

4.2.4. Numerical Simulation Results

Simulation results from DAN3D and RAMMS::Debris Flow for model size 1 and model size 2 in the corresponding models are presented here. Figure 4.7 shows the actual laboratory test output with H_f being height of flow and D_f being diameter of flow.

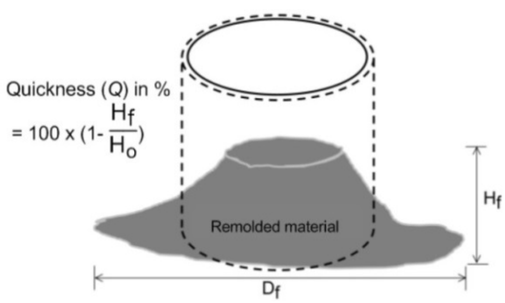
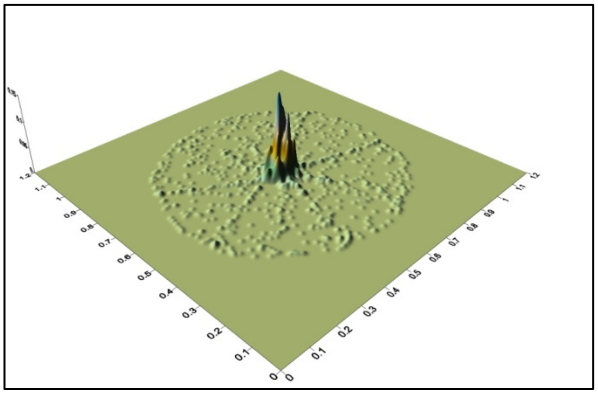


Figure 4.7: Quickness test with output measurements and quickness formula (Adopted from (Thakur and Degago, 2014))

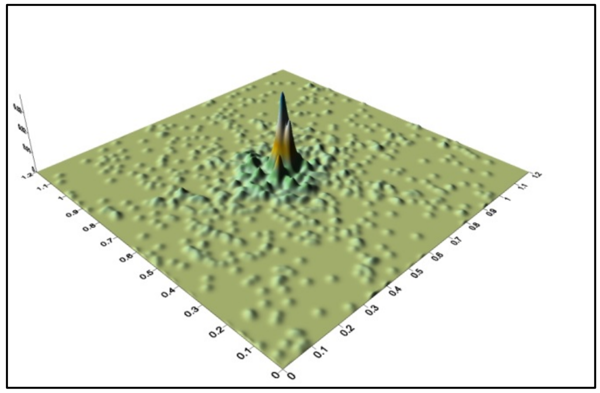
4.2.4.1. DAN3D Simulation Using Plastic rheology (0.1m X 0.12m)

In Figure 4.8 simulation result using *0.1m X 0.12m* (*100mm X 120mm*) model with c_{ur} = 0.1kPa is presented. The plastic model used in this case provides the basal resistance from the shear strength value of the soil, c_{ur}. As shown by the plots, the mass spread and covered the entire 1.2m X 1.2m flat area with a final maximum flow height of 0.0027m = 2.7mm which gives almost 99% quickness value. The mass flow on the entire area might be attributed to the neglected friction by the rheology and/or the simulation mechanism which drops the whole mass at once unlike the way the actual test conducted. The quickness value obtained, however, is expected for this c_{ur} = 0.1kPa value as it is given by the upper bound quickness value in the original study (Table 4.1 of Section 4.2.1).

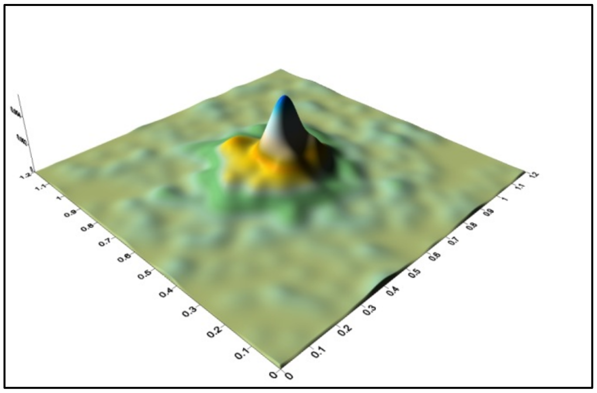
One can observe that the behavior of the flow in the first three steps is not smooth. The laboratory procedure is conducted with careful raising of the cylinder so that the mass will flow with its own weight. However the mechanism for modeling this situation is not possible and the volume is just dropped from its initial position at once. As a result this mechanism gave a turbulent initial steps with distributed masses.



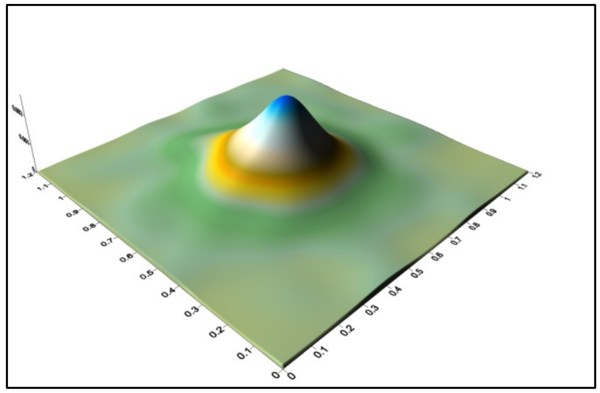
(A) t = 0.1 sec



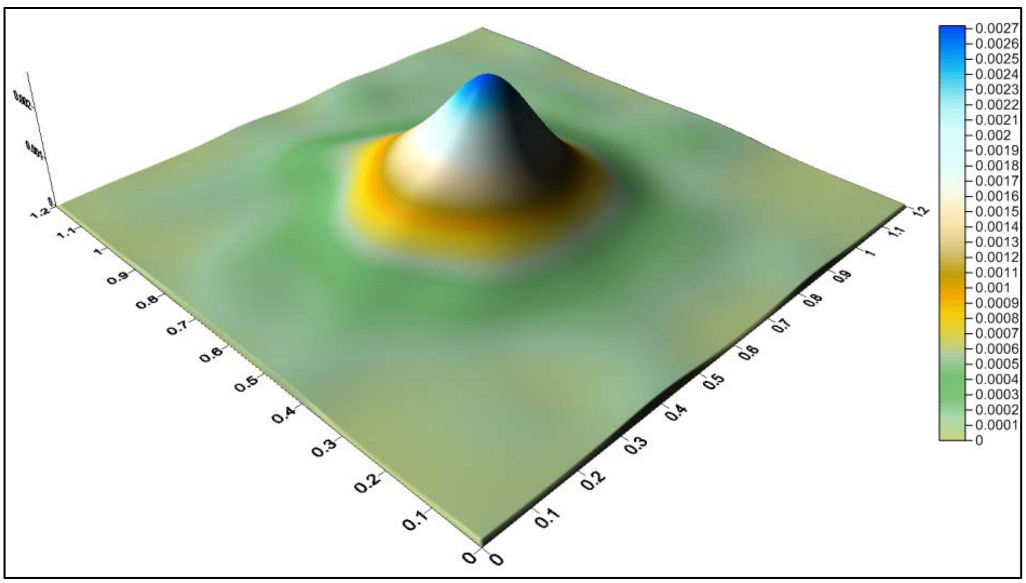
(B) t = 0.2 sec



(C) t = 0.3 sec



(D) t = 0.4 sec



(E) t = 0.5 sec (End of simulation, H_f = 0.0027m with 99% quickness)

Figure 4.8: All steps of simulation for c_{ur} = 0.1kPa with actual (0.1m X 0.12m) model size.

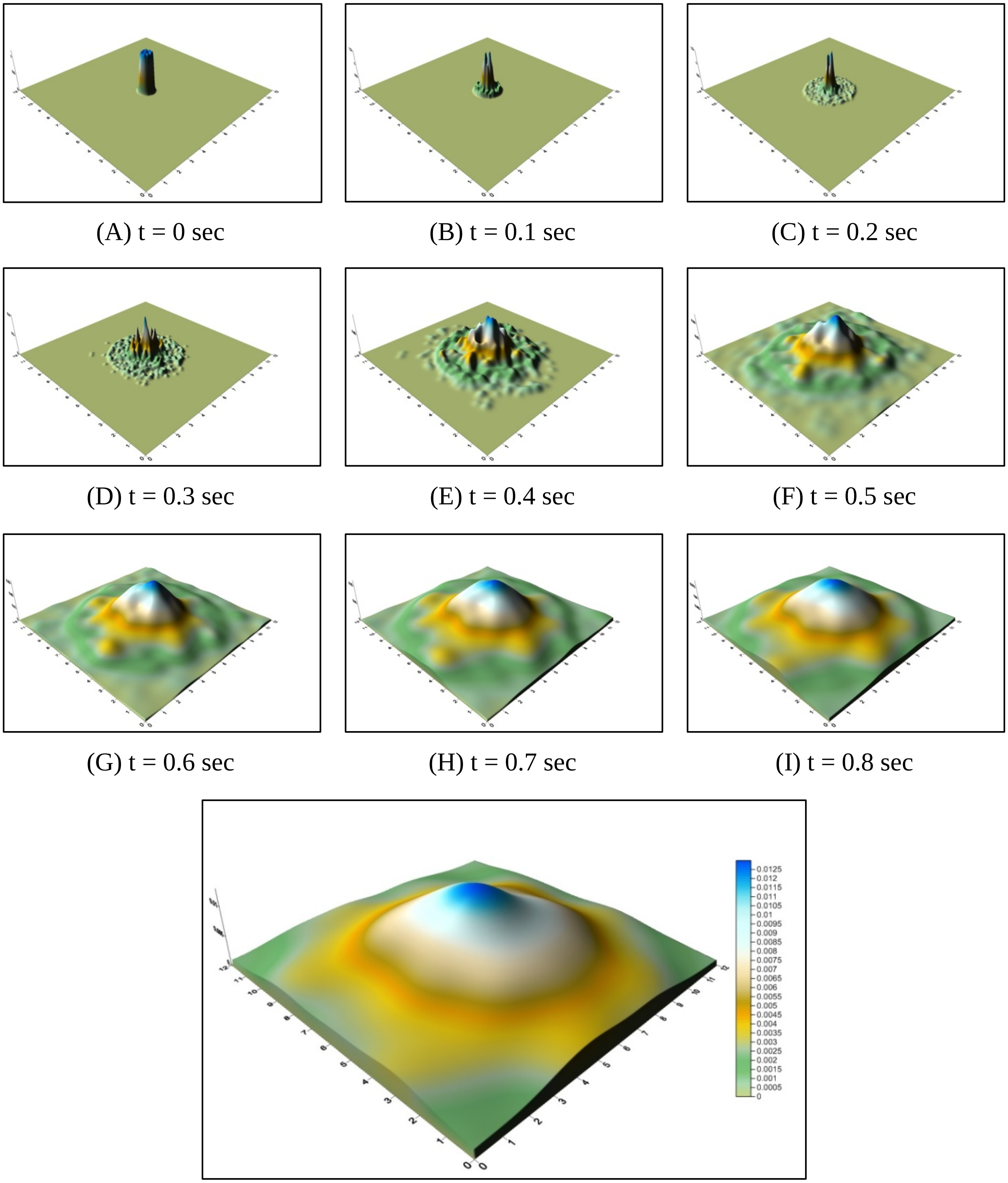
4.2.4.2. DAN3D Simulation Using Plastic Rheology (1.0m X 1.2m)

This numerical modeling tool is originally meant for landslides and debris flows which need large scale topographies and elevation models. To see the effect of using it for very small scale models like quickness test, an enlarged (scaled up) version of the test is simulated and examined.

Figure 4.9 shows the result from the model with 1m diameter and 1.2m height for c_{ur} = 0.1kPa. The first six steps from 0.0 second to 0.5 second show the sudden dropping of the material resulting in a wavy mass spreading on the surface similar to the previous case. It is yet found difficult to create a feature to slowly release the mass and the result shows some effect of the sudden drop of the material.

The final steps which covers around 1.0 second are observed as slow rearrangement and spreading of the mass to give its final height of flow of 0.0125m. This gives a quickness value around 99% and according to the c_{ur} value used, it is in the acceptable range.

The result also tells scaling up a model might increase the spread area accordingly but does not affect the quickness value. As stated in the previous case, the large spread might be because of the neglected friction and/or the flow starting mechanism which influenced the flow behavior. In addition to the starting mechanism, the modeling of a vertical wall creates a huge data gap since the maximum and minimum elevation values are given in consecutive grids (Appendix A). This might also affect the calculation procedure in the models.



(A) t = 0 sec (B) t = 0.1 sec (C) t = 0.2 sec

(D) t = 0.3 sec (E) t = 0.4 sec (F) t = 0.5 sec

(G) t = 0.6 sec (H) t = 0.7 sec (I) t = 0.8 sec

(I) t = 1.4 sec (End of simulation, H_f = 0.0125m with 99% quickness)

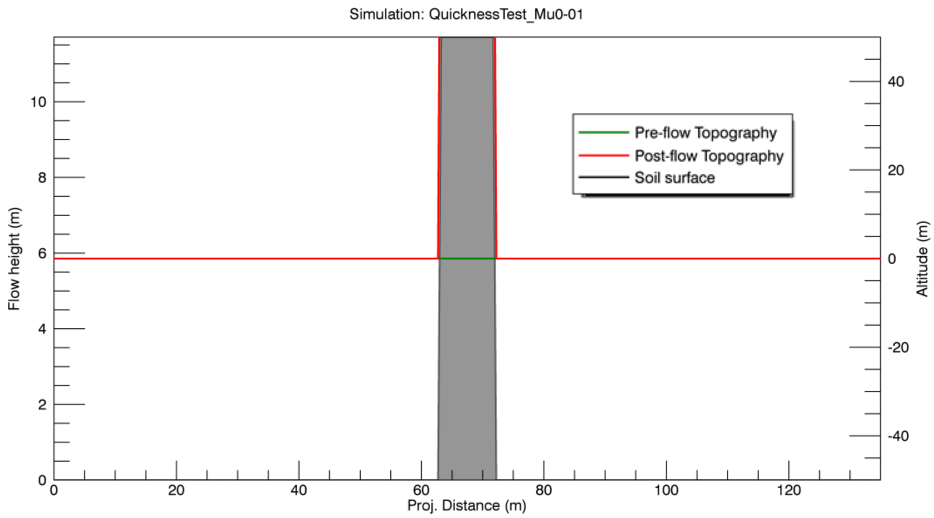
Figure 4.9: First few steps and end of simulation for c_{ur} = 0.1kPa with scaled up (1m X 1.2m) model size.

4.2.4.3. Parameter Selection in Modified Voellmy Model (RAMMS)

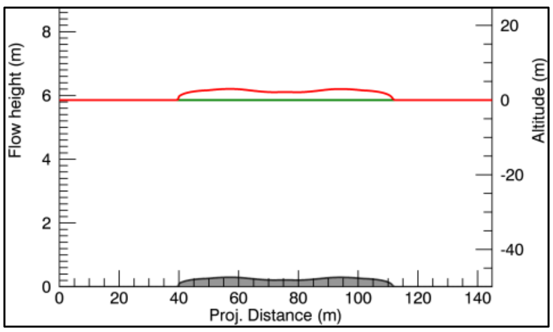
According to the results obtained by simulating in DAN3D with the actual and scaled model, the scaling effect is found to be very insignificant. Therefore simulations with two scaled up sizes of quickness test were run in RAMMS and results are presented as follows.

Unlike plastic rheology, the modified Voellmy rheology implemented in RAMMS::Debris Flow v1.6 takes three distinct resistance parameters which are cohesion (C), friction coefficient (μ) and turbulent factor (ξ). For this study of sensitive clays, cohesion is assumed to replace the remolded shear strength and set to be 100Pa. Then by using the 10m diameter model, different simulations were run by varying μ and ξ values and the results are presented in Figure 4.10.

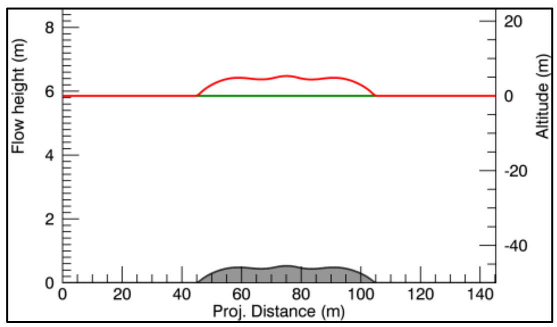
A result similar to the actual situation is observed when using ξ = 20m/s^2 and the friction coefficient is chosen to be μ = 0.01 as the average value of the two selected cases. Higher ξ values give flow behavior that looks like that of liquid flows and exhibit very wide spread diameters that are not observed during actual tests.



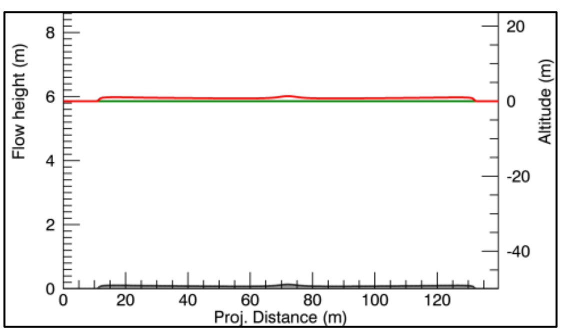
Initial condition with H = 12m



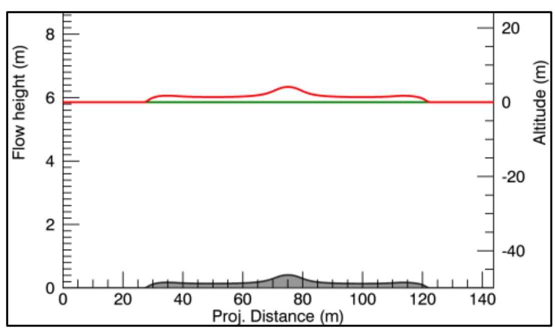
(A) ξ = 20, μ = 0.005



(B) ξ = 20, μ = 0.1



(C) ξ = 1000, μ = 0.005

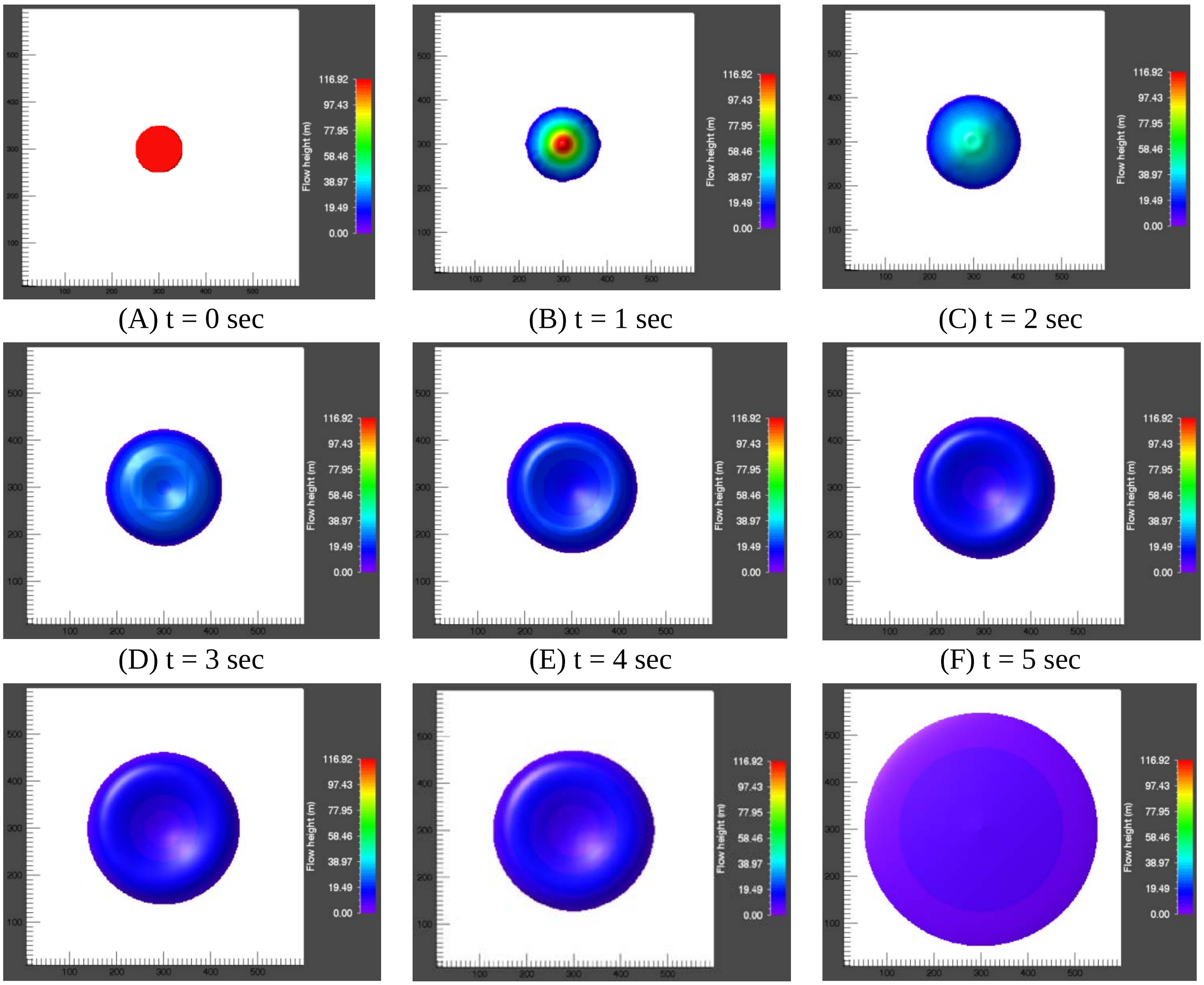


(D) ξ = 1000, μ = 0.1

Figure 4.10: Cross sectional view of different quickness test simulation results .

4.2.4.4. RAMMS [Modified Voellmy Rheology] Simulation (100m X 120m)

Using the above selected parameters of Voellmy rheology, further study conducted using the 100m diameter model to see the flow behavior. Figure 4.11 shows the first few and final steps of the simulation with parameters ξ = 20m/s^2, μ = 0.01 and C = 0.1kPa. In the first 4 seconds the whole mass dropped and created a depression in the middle due to the release energy. This shows the simulation mechanism drops the mass from its given height unlike the actual test procedure which contributes additional energy to the flow. The simulation took 35 seconds to spread in all direction and stop flowing.



(A) t = 0 sec

(B) t = 1 sec

(C) t = 2 sec

(D) t = 3 sec

(E) t = 4 sec

(F) t = 5 sec

(G) t = 6 sec

(H) t = 7 sec

(I) t = 35 sec

Figure 4.11: Simulation steps for ξ = 20m/s^2, μ = 0.01 and C = 0.1kPa with D = 100m and H = 120m model.

When the flow stopped, the measured flow height was 7.0m and this gives quickness value of 94% which is an expected value for $C = c_{ur}$ = 0.1kPa.

This simulation replicates the flow behavior with respect to circular horizontal spreading of the mass over the surface like the actual observed test result given in Figure 4.12. This feature makes RAMMS better than DAN3D in giving a realistic flow behavior.

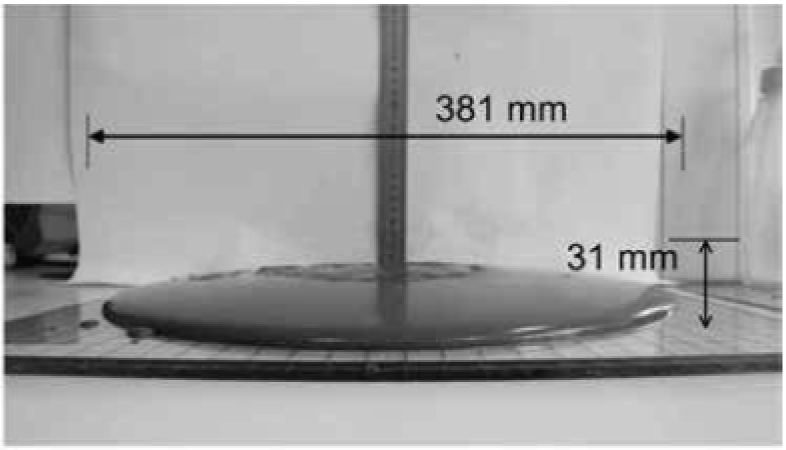
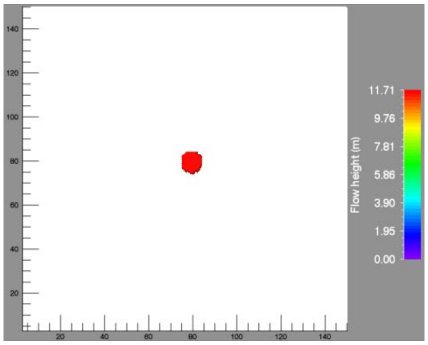


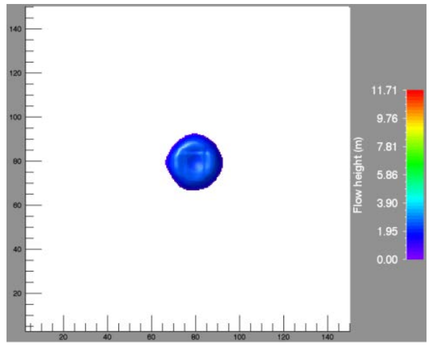
Figure 4.12: Spread diameter and flow height for c_{ur} = 0.2kPa (Adopted from (Thakur et al., 2013))

4.2.4.5. RAMMS [Modified Voellmy Rheology] Simulation (10m X 12m)

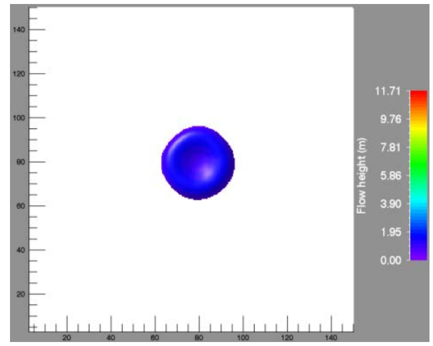
Although the scaling effect is found insignificant for this test, another scaled model with smaller diameter (10m) and height (12m) is simulated to confirm the insignificant scaling effect, see the behavior of the result and compare it with the larger one. In this case the flow was quick and completed in 10seconds (Figure 4.13). The additional dropping energy is witnessed here also with the depressions in the middle of the mass in the 1st and 2nd seconds. The mass then spread horizontally and stopped in the 10th second with flow height of 0.8m. This height of flow gives 93% quickness value which is exactly comparable with the 94% quickness value obtained with the 100m X 120m model. It is also noted that the flow behavior observed here is almost identical with the one with bigger model which assures again the scaling effect is not significant for this test.



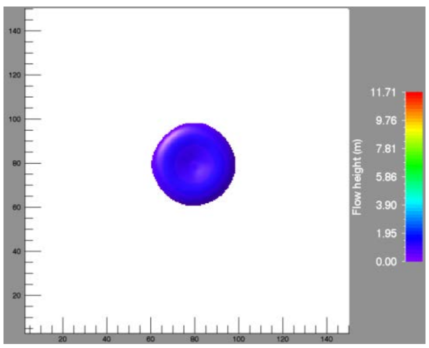
(A) t = 0 sec



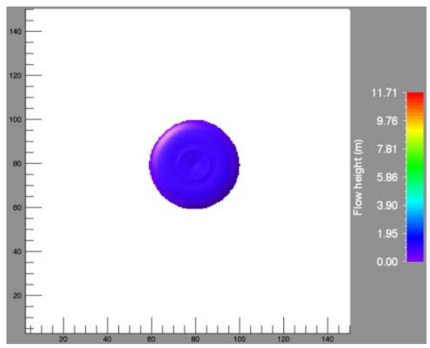
(B) t = 1 sec



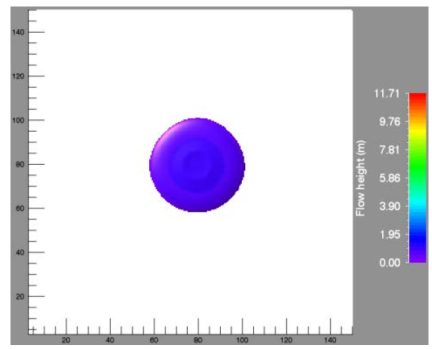
(C) t = 2 sec



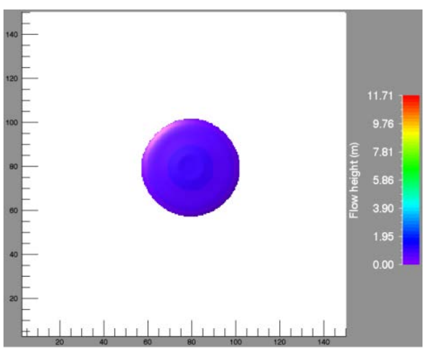
(D) t = 3 sec



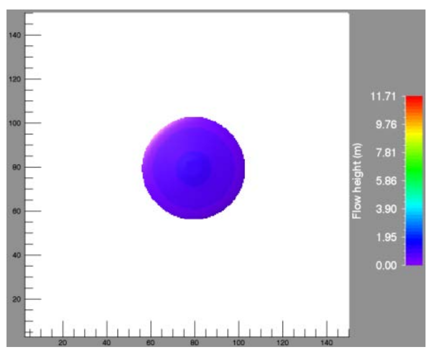
(E) t = 4 sec



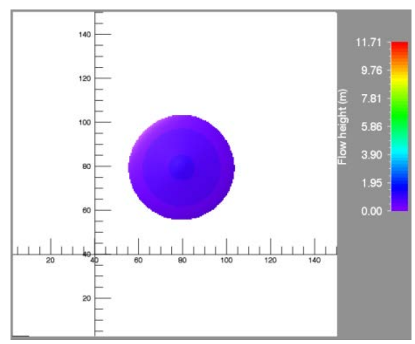
(F) t = 5 sec



(G) t = 6 sec



(H) t = 8 sec



(I) t = 10 sec

Figure 4.13: Simulation steps for ξ = 20m/s^2, μ = 0.01 and C = 0.1kPa with D = 10m and H = 12m model.

4.2.5. Discussions

By modeling quickness test using different scaled models in these two numerical models, it is shown that the models properly back calculate the quickness values and simulate the actual test for the flow-able sensitive clay soil with c_{ur} = 0.1kPa.

The simulation with actual size using plastic rheology in DAN3D sets a basis for the scaling effect assessment. Except the flow mechanism which drops the mass at the start of the simulation, the model back calculated the quickness value. The other scaled up model also gave the expected quickness value regardless of the scaling.

In modeling the quickness test using the Voellmy rheology in RAMMS using the two scaled up models, better visualization of the flow steps were obtained. The result found here actually give a very close behavior with the actual test. However, the selection of turbulence and friction parameters was just by back calculation from few tests. These two parameters are found difficult to assign to this specific flow behavior test and can vary from one flow condition to another.

But for the selected parameters, the two differently scaled models yield amazingly close quickness result that show the very insignificant effect of scaling in modeling using this tool. This result is used as a basis for modeling a scaled up 'small scale run-out laboratory test' using the Voellmy rheology as given in the next Section.

Some inabilities of the numerical models during modeling this quickness test are listed below.

- Immediate dropping of the mass when starting the simulation created additional driving force and unrealistic velocity of flow unlike what is observed in the actual test procedure.
- The modeling of a vertical wall using gridding creates data gap since values of top and bottom elevations are given in consecutive grids (Appendix A). This might affect the simulation calculation due to the information gap. The disturbance observed at the beginnings of the simulations in DAN3D might be attributed to this reason.

4.3. Run-out Model Test Simulation

4.3.1. Background

A number of laboratory tests have been conducted in order to understand the flow behavior and run-out distance of sensitive clay debris. Out of these, a simple laboratory model test introduced by Thakur and Nigussie (2014) is one of them. This laboratory procedure aimed at providing a basis for understanding run-out of fully remolded sensitive clay debris. During their study around 35 different sensitive clay samples were extracted from the Lersbekken, Byneset and Olsøy landslide locations of Norway and were tested.

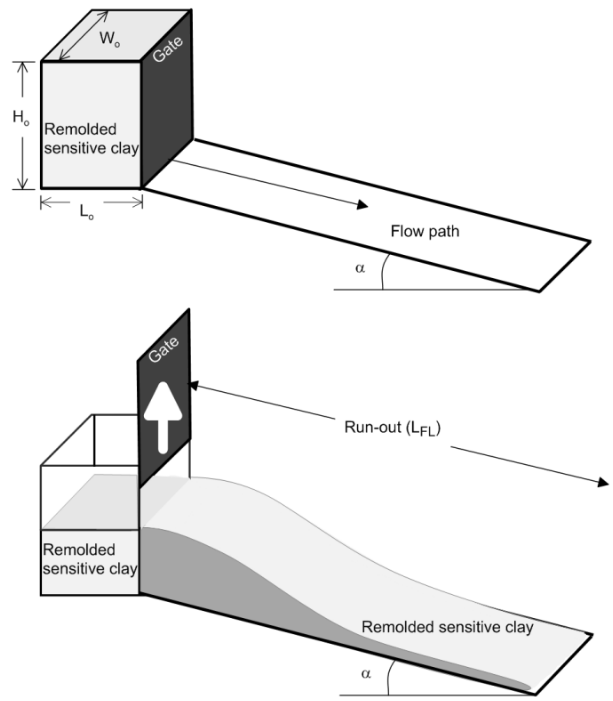


Figure 4.14: The run-out model test set-up (Thakur and Nigussie, 2014)

Figure 4.14 illustrates the test model set-up. The box has a size of $W_O = 100mm, H_O = 150mm\ and\ L_O = 200mm$ for its width, height and length respectively. The box is made open on top where the remolded material can be poured in and its front side is made to slide up imitating breach of a dam. The sloped surface for run-out distance measurement has L_{FL} = 1.0m long distance and a slope of 8.53° (0.15:1).

The test procedure is started by filling up the box and properly leveling off its top with thoroughly remolded sensitive clay sample. And then the front gate is pulled up slowly with a minimal disturbance to the sample. Then the run-out distance over the sloped surface is recorded against the remolded shear strength of the material.

Normalized run-out distance (L_F) in (%) is plotted against remolded shear strength for each sample. The normalized run-out distance is the percentage ratio of each sample's run-out distance with respect to that of sample with c_{ur} = 0.1kPa. This is because the aim of the test was not to predict the run-out distance length rather to visualize the run-out of sensitive clays with respect to their different remolded shear strength values. Another reason mentioned by Thakur and Nigussie (2014) is that c_{ur} = 0.1kPa is the smallest value that can be measured in laboratory using falling cone test.

The result obtained from this laboratory procedure was summarized as sensitive clays with c_{ur} < 0.3kPa can be considered as susceptible to large run-out distances while witnessing drastic decrease in run-out distance with increase remolded shear strength from 0.1kPa to 0.3kPa. In addition to this, clays with c_{ur} > 1.0kPa exhibit from very small to no run-out distances and Figure 4.15 illustrates the result found from this laboratory tests.

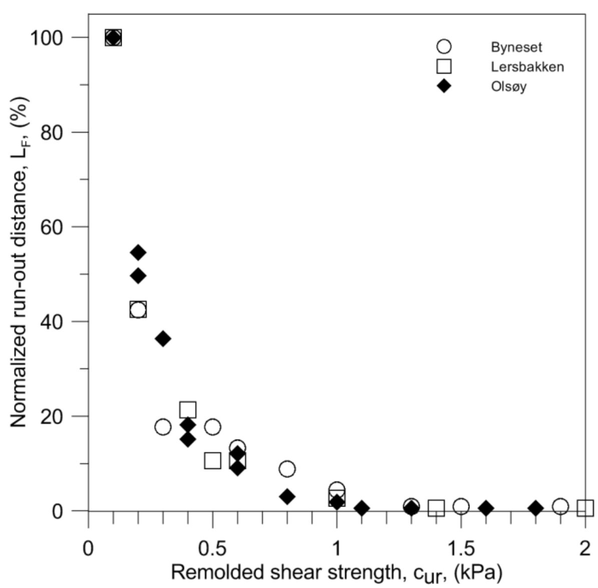


Figure 4.15: Plot showing L_F versus c_{ur} for soil samples from three different landslide locations. (Thakur and Nigussie, 2014)

Sensitive clays with c_{ur} > 0.3kPa behave like semisolid material that flow like a monolithic mass which has significant friction at contact plane resulting in a great role in the flow process. For sensitive clays with relatively low c_{ur}, the expected friction resistance have little influence on the flow as the inter-particle friction between the sliding material will be sufficiently low like water (Thakur and Nigussie, 2014). This concept will be considered during the study of different c_{ur} values during this model simulation.

4.3.2. Simulation Procedures of Run-out Model Test

Back calculation of this run-out model test is conducted using modified Voellmy model in RAMMS::Debris Flow.

Because of the limitation of minimum resolution requirement that can be considered in RAMMS which is 1m X 1m, the model size is scaled up by $1\text{x}10^2$ and as a result its volume is scaled up by $1\text{x}10^6$ as shown in Table 4.4. The scaling effect has been discussed in the simulation of quickness test and found to be very insignificant for the flow behavior. It is obvious that the run-out distance will get longer due to the additional kinetic energy converted from additional potential energy due to scaling. This numerical model converts the whole potential energy in to kinetic energy and does not consider other energy forms like remolding energy. It is also found unnecessary to consider remolding energy for this case as the original laboratory test is conducted by using remolded sensitive clay samples.

Table 4.4: Dimensions of the actual laboratory test and the simulation model.

	Actual Size	Model size	Scaled up by
L_0	200 mm	20 m	$1\text{x}10^2$
H_0	150 mm	15 m	$1\text{x}10^2$
W_0	100 mm	10 m	$1\text{x}10^2$
V0	3000000 mm^3	3000 m^3	$1\text{x}10^6$
L_{FL}	1000mm	100 m	$1\text{x}10^2$

According to the model size given in the above table, a hypothetical digital elevation model as shown by Figure 4.16 is prepared. The path topography, calculation domain area and the release areas are defined. The green rectangular line is the calculation domain area whereas the red square represents the release area with elevation height of 15m. See Appendix B for this grid data preparation method.

The procedures to run this simulation is described in Section 3.2.4. Back calculations and parametric studies are conducted with this model by varying the governing parameters (cohesion (C), friction coefficient (μ) and turbulence factors (ξ)) of Voellmy rheological model.

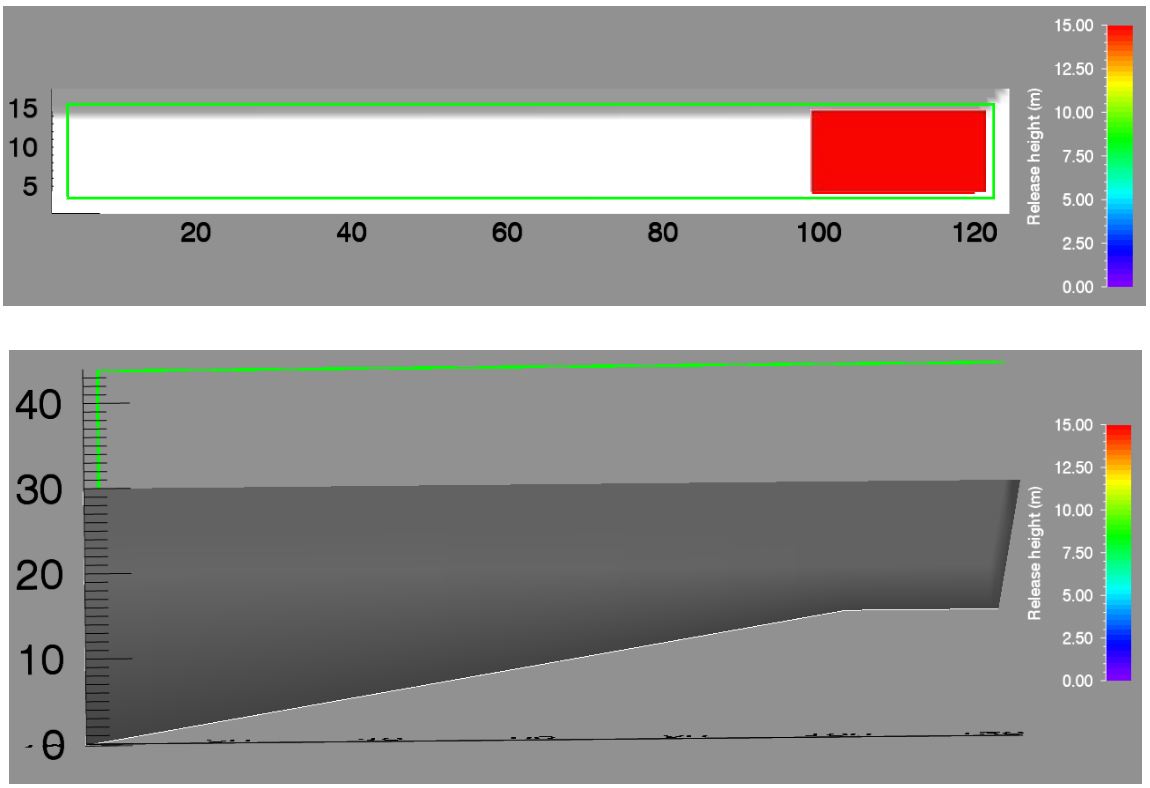


Figure 4.16: Plan (top) and elevation (bottom) views of the modeled digital elevation model.

4.3.3. Laboratory Model Test Simulation Results

4.3.3.1. Selection of Parameters

The first study conducted using this model is to evaluate the run-out response of each governing parameter in the Voellmy rheological model. Turbulence factor, ξ varying from (5 - 10000)m/s^2 were used to simulate the model along with zero friction coefficient, μ = 0.0, and the minimum cohesion value, C = 100Pa. The result plotted in Figure 4.17 shows that ξ > 1000m/s^2 gives longer run-out distances beyond the model flow size, L_{FL} = 100m. Therefore, only values $\xi \leq$ 1000m/s^2 are used for the rest of the study.

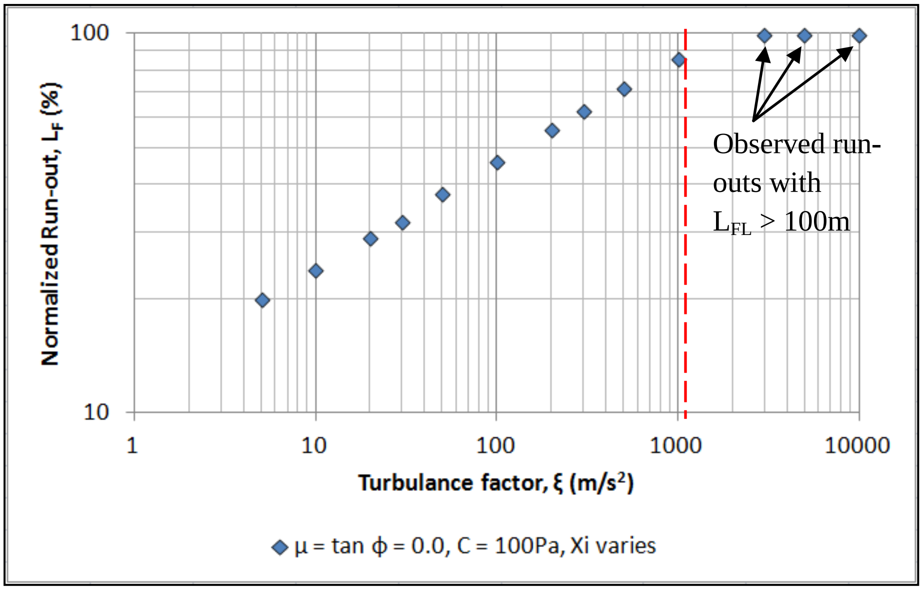


Figure 4.17: Normalized run-out distance as a function of turbulence factor for μ = 0 & C = 100 Pa

Cohesion values are chosen to vary between 0.1kPa and 1.0kPa as this range can easily show the entire behavior from flow-able to less flow-able types of sensitive clays. On the other hand, values of the friction coefficient, μ, are chosen to vary between 0.0 and 0.2 which correspond to friction angles between 0.0 and 11.3°. For this laboratory test, friction angle can easily be back calculated as the slop of the flow surface line. Therefore the choice of μ was centering around the slope value 8.53° (μ = tan 8.53° = 0.052).

4.3.3.2. Combined Effect of Turbulence Factor and Friction Coefficient

According to the above selection of parameters, further simulations were run. The maximum run-out distance observed when ξ = 1000m/s^2 and μ = 0.0 is found to be 86m over the 100m path (Figure 4.18). This value was then used to normalize the rest of observed run-out distances. Note that for a better visualization of these profile pictures, the vertical scale is exaggerated almost 10 times higher than the horizontal.

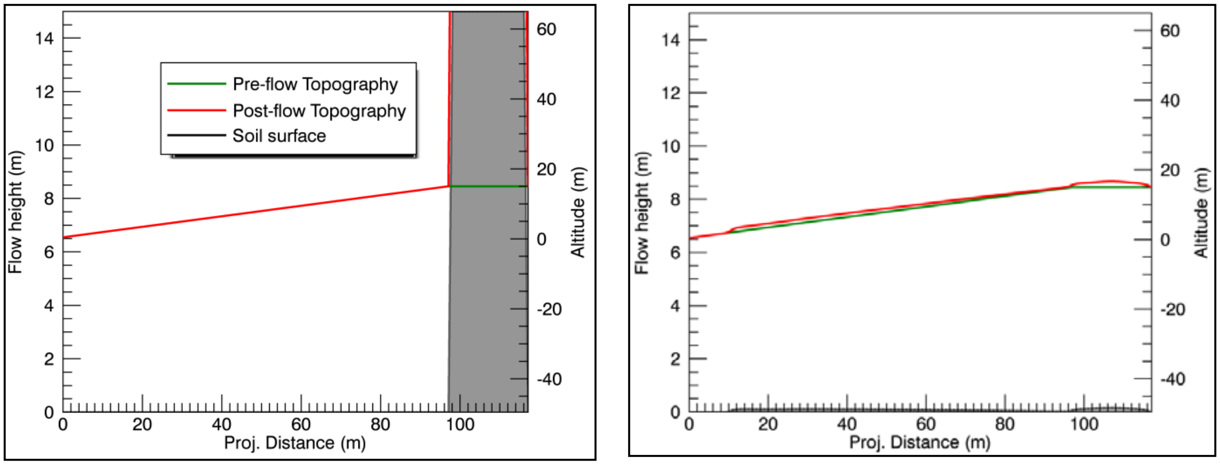


*Figure 4.18: Initial condition of the test (left) and run-out result of the laboratory test simulation (right) with ξ = 1000 m/s^2, μ = 0.0 and C = 100Pa.*As the cohesion value used is C = 0.1kPa that is a value for a very sensitive clay soil, the result is expected to show the maximum run-out distance. Good combinations of the basal resistance parameters for such soil behavior is observed when $0.0 < \mu < 0.1$ combined with ξ = 1000m/s^2. Values of ξ can also be lowered up to 800 m/s^2 as observed on the trend of the plot.

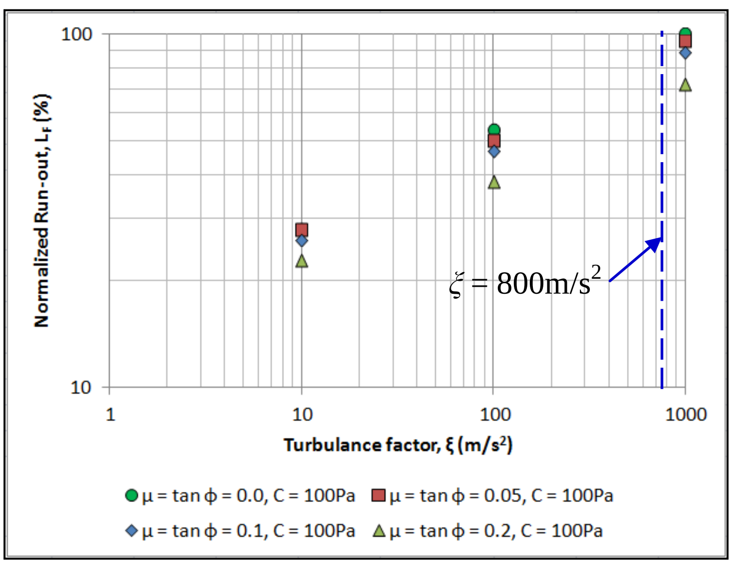


Figure 4.19: Normalized run-out as a function of ξ and μ for C = 100Pa.

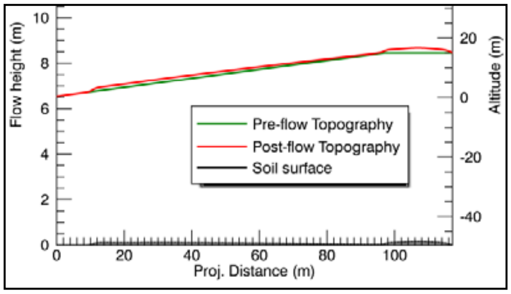
Figure 4.17 and Figure 4.19 also show that using very small value of ξ (10 m/s^2 - 300 m/s^2) will greatly reduce the run-out distance regardless of the low cohesion value used. Therefore, to study the effect of cohesion term on this run-out model test simulation, ξ = 1000 m/s^2 is selected.

4.3.3.3. Effect of Cohesion Parameter in the Modified Voellmy Model [RAMMS]

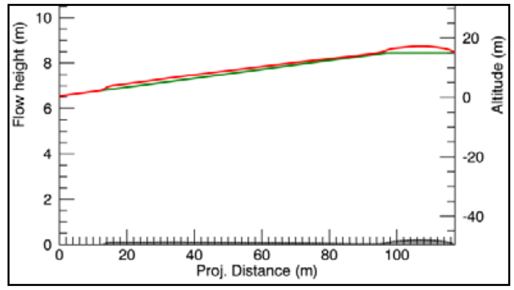
It is known that the remolded shear strength is one of the important soil consistency parameters of sensitive clay flows, liquidity index and viscosity being the others. In this study the cohesion term provided by the modified Voellmy rheological model in RAMMS::Debris Flow V1.6 will be studied in relation to remolded shear strength of sensitive clay slides.

Simulations were run based on the parameter selections in previous Section. Turbulence factor, ξ = 1000 m/s^2, was chosen and kept constant and friction factors of μ = 0.0 and μ = 0.15 are used as they represent friction angle of 0° (for easy flowing range 0.1kPa < c_{ur} < 0.3kPa) and 8.53° representing the slope of the flow path (for the semisolid sensitive clay types with c_{ur} > 0.3kPa).

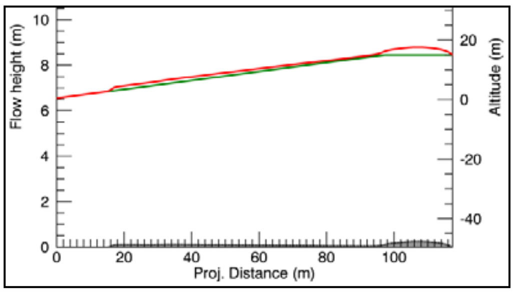
Figure 4.20 shows the different run-out distances observed for different values of cohesion and the respective flow behavior responses. While using higher cohesion values, a decrease in the flow run-out was observed. However, the dramatic decrease in flow run-out for an increase in remolded shear strength of sensitive clays, c_{ur} from 0.1kPa to 0.3kPa and further to 1.0kPa could not be observed. Therefore, the flow model can be said that it is insensitive to change in the cohesion parameter values. It is also observed by Equation 3.3 in Section 3.2.3 that for μ = 0.0 the last term $\left(\frac{\rho g U^2}{\xi}\right)$ completely controls the flow velocity thereby control the flow behavior and contribute to the basal resistance more than the cohesion term.



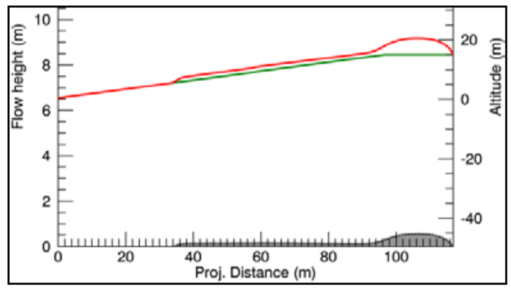
C = 100Pa, μ = 0.0, L_{FL} = 86m



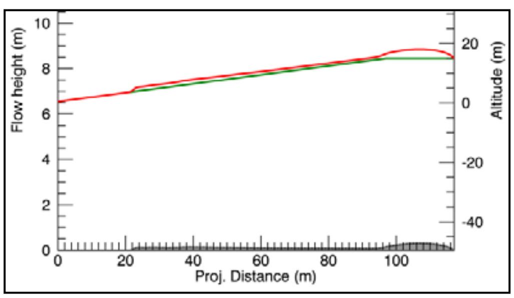
C = 200Pa, μ = 0.0, L_{FL} = 83m



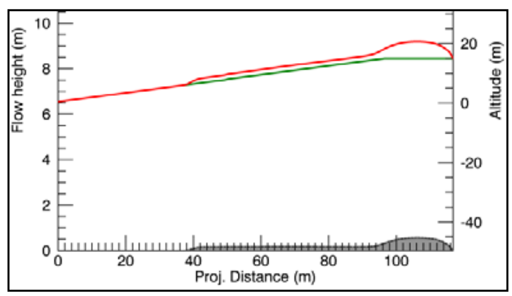
C = 300Pa, μ = 0.0, L_{FL} = 80m



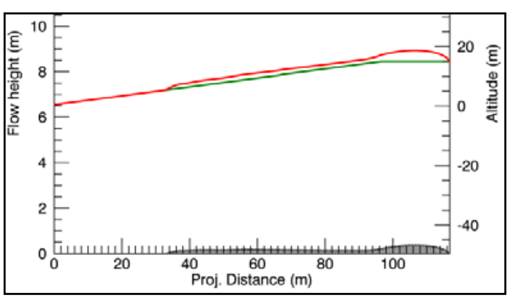
C = 300Pa, μ = 0.15, L_{FL} = 63m



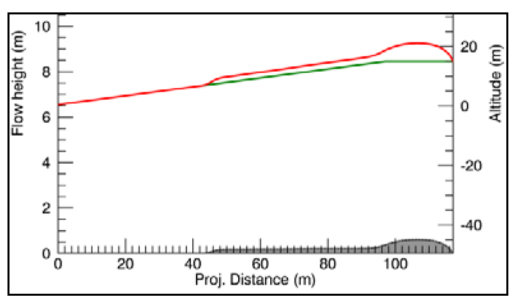
C = 500Pa, μ = 0.0, L_{FL} = 75m



C = 500Pa, μ = 0.15, L_{FL} = 59m



C = 1000Pa, μ = 0.0, L_{FL} = 63m



C = 1000Pa, μ = 0.15, L_{FL} = 53m

Figure 4.20: Run-out results for different values of μ and cohesion for (ξ = 1000m/s^2).

The resulting normalized run-out distance versus cohesion plot is presented in Figure 4.21. Since the actual laboratory model test showed no significant run-out distance for c_{ur} > 1.0kPa, this study will only focus on the range of sensitive clay soils with potential to flow (c_{ur} < 1.0kPa) as the numerical model meant for run-out analyses only.

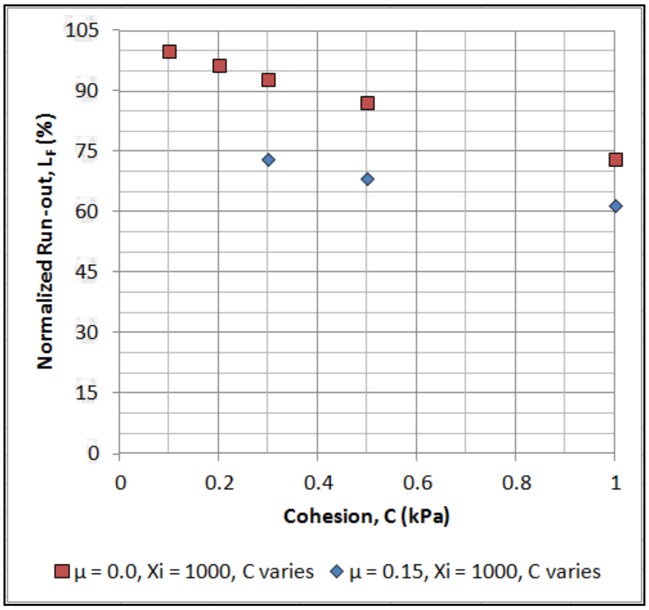


Figure 4.21: Normalized run-out distance, L_F versus cohesion, C and friction, μ.

At the beginning, the simulations were run with zero friction coefficient and constant ξ. The expected dramatic decrease in the normalized run-out for c_{ur} < 0.3kPa and further decrease for c_{ur} < 0.5kPa is not observed. It looks that the response of normalized run-out distance is linearly related with the increase in cohesion value which was not observed from the laboratory model test.

It is important to note that the recommended cohesion value by the manual Bartlet et al. (2014) to back calculate or simulate debris flow is 0.0kPa – 2.0kPa. This recommendation tells that a material with cohesion value 2.0kPa is considered as flow-able material unlike in sensitive clay soils. This could be one of the reasons for the difference in the observed simulation result and the actual laboratory model test result.

Correction was made for simulations with (c_{ur} > 0.3kPa) for materials considered semisolid in nature. The correction was providing friction resistance coefficient between the flow surface and the flowing material. Since a friction coefficient provided by a contact surface is a function of slope of the surface, μ = tan (8.53˚) = 0.15 is used.

The correction gives improved results by providing additional resistance to the flow. The flow length is reduced by (20 – 12)%, the larger being for c_{ur} = 0.3kPa and the smaller being for c_{ur} = 1kPa. However the result obtained is not as significant as the actual observed behavior of the laboratory result.

The situations explained above makes it clear that the cohesion term provided in the modified Voellmy rheology cannot replicate the behavior of the remolded shear strength of sensitive clay soils. This situation could be improved by providing different turbulence factors for the corresponding cohesion values although it is not easy to calculate and set turbulence factor as was done for friction coefficient.

4.3.3.4. Effect of Turbulence Factor

To see the effect of turbulence factor, additional simulations were conducted with ξ = 800 m/s^2, ξ = 500 m/s^2 and ξ = 100 m/s^2. The results are plotted in Figure 4.22. The first plot (left) shows the normalized run-out distance for each ξ value normalized by the corresponding maximum run-out value from each set. All the plots almost overlapped on one another showing that the flow behavior is almost similar whether the run-out distance is long or not. Moreover, it is seen that the resistance offered by the cohesion term is less significant than offered by ξ and μ.

Figure 4.22 (right) shows the actual flow distances observed from the simulations. As the turbulence factor has inverse relationship to the basal resistance, the smaller the turbulence factor, the higher the basal resistance and therefore the shorter the run-out distance. This is clearly observed in the plot for ξ = 100 m/s^2. However the effect of friction coefficient for c_{ur} > 0.3kPa reduced and became almost constant ranging between 8m - 10m, the bigger value corresponds to the higher cohesion value, c_{ur} = 1.0kPa. On the other hand the effect of cohesion term is found very small again.

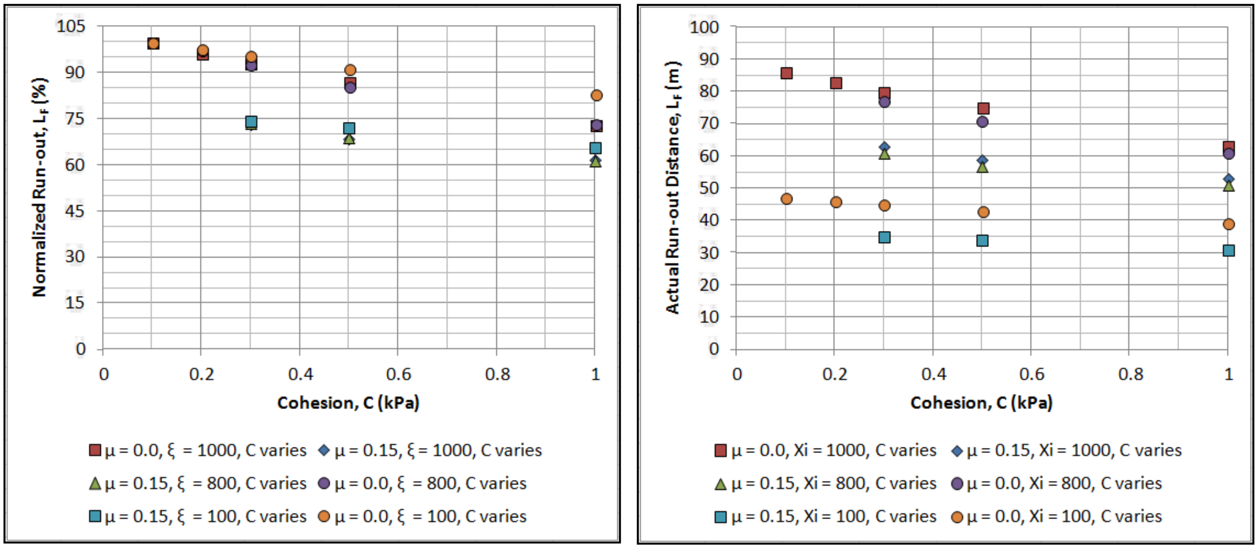


Figure 4.22: Normalized run-out distance versus cohesion (left) and actual run-out distance versus cohesion (right) for different values of μ and ξ.

Instead of normalizing each case with the corresponding longest run-out distance, all are normalized with the longest run-out distance of all the cases and plotted in Figure 4.23. The plot has similar trend with the right plot of Figure 4.22. Figure 4.23 shows possible combinations of the three governing parameters to back calculate the run-out distance behavior. From this plot one can see using different ξ value for different c_{ur} values might give the trend of the laboratory result (e.g. c_{ur} = 0.1 with ξ = 1000 m/s^2 & μ = 0.0, c_{ur} = 0.2kPa with ξ = 100m/s^2 & μ = 0.0, c_{ur} = 0.3kPa with ξ = 100m/s^2 & μ = 0.15, etc as shown by the dotted line in Figure 4.23) although it is cumbersome and does not seem practical.

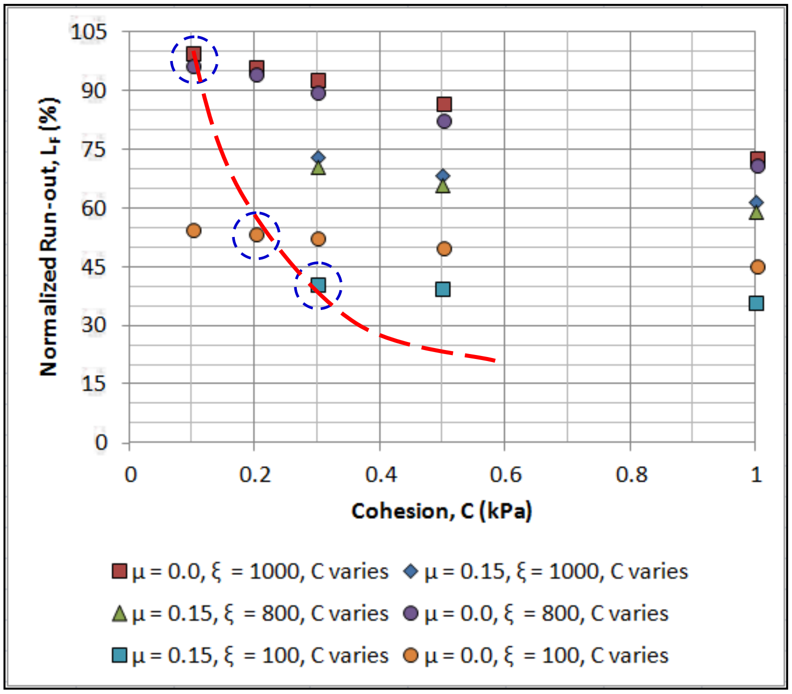


Figure 4.23: Normalized run-out distance as a function of C, μ and ξ.

4.3.4. Discussions

Out of the three governing parameters given in the modified Voellmy rheology, the friction coefficient is the easiest to determine and verify as it can be approximated by tangent of the slope angle of path topography.

The cohesion term is found to be less responsive to the dramatic run-out distance change offered by remolded shear strength of sensitive clays varying between 0.1kPa and 0.5kPa. This might be due to the fact that the two friction parameters (μ and ξ) are the main flow process controlling parameters of the model. They are terms responsible for providing resistance during and at the end of the flow. Another reason which could give rise to this inability of the Voellmy model is that lack of consideration of pore-pressure build-up inside sliding debris as it is formulated based on total stress approach.

The friction coefficient was considered to be tangent of the run-out path slop angle (tan 8.53° = 0.15) for this study. This value was applied for flows with semi-solid material behavior ($c_{ur} \geq$

0.3kPa). The result from μ = 0.15 showed its positive contribution for the reduction of run-out distance with increase in c_{ur}.

The observed results show that use of smaller values (e.g. ξ < 500m/s^2) reduces the flow velocity and make the flow stop at early stage of the flow. On the other hand, use of larger values (e.g. ξ > 500m/s^2) resulted in an increased flow velocity and the material flow behaves like liquid substance with longer run-out distances. Due to these characteristics, it is difficult to categorize ξ parameter as material property. It is rather a parameter for the flow behavior and flow condition.

Thakur et al. (2014b) presented a rough estimation which can be applied for ξ as ($\xi = K_s^2 R^{1/3}$) where K_s (= $1/n$) is the inverse value of Gauckler-Manning coefficient (term for the roughness of the flow surface) and R (=A/P) is the hydraulic radius which is a ratio between area of flow and wetted perimeter of the flow. This explains that this parameter depends more on the flow conditions than the flowing material.

5. Real Case Simulation of the Byneset Sensitive Clay Slide

5.1. Background

The Byneset sensitive clay slide happened few hours after the new year day of 2012. The place is located in Sør trøndelag 10 km west of Trondheim city. The scar area has an approximate width of 150 meters and retrogression distance of 350 meters from the toe of the first slide. This scar has an average height of 10 meters and the volume of the slide approximately becomes 3 - $3.5x10^5 m^3$. The whole volume of the scar area evacuated giving a run-out distance of around 870m. The debris flow followed a low discharge stream line with average slop of 3°. As it is explained by Thakur et al. (2014b), the run-out is not believed to be facilitated by the water in the stream because of the winter season and low discharge of the stream.

Figure 5.1: Photo showing scar of Byneset landslide with the run-out path.

The actual observed run-out distance of this slide is presented in Figure 5.1 and Figure 5.2, where the former shows a photo of the slide area while the latter showing the laser scan of the area after the slide. The main run-out covering around 870m is running up to point D as shown in Figure 5.2 while there are still few secondary run-out branches in directions of A, B and C.

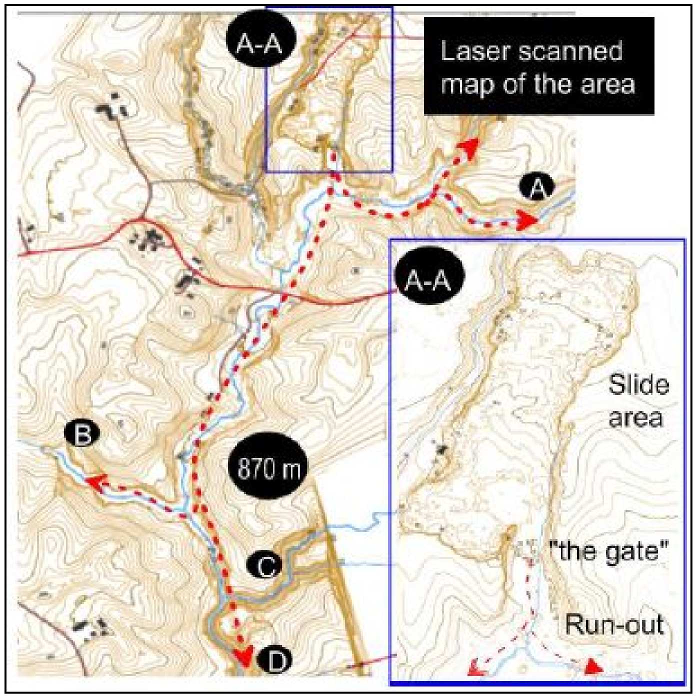


Figure 5.2: New topography of the area after the slide happened (Thakur and Nigussie, 2014)

From the detailed geotechnical investigations conducted soon after the slide by the authority (Statens vegvesen, SVV), some important parameters are found and presented in Table 5.1.

Table 5.1: Geotechnical parameters of the sensitive soil at Byneset. (Nigussie, 2013)

Parameters	Symbol	Unit	Value
Unit Weight	γ	kN/m3	18.3
Undrained shear strength	C_u	kPa	10 - 25
Remolded shear strength	C_{ur}	kPa	0.12
Maximum Sensitivity	S_t	-	400
Plasticity Index	I_p	%	5
Liquidity Index	I_L	-	3.8

5.2. Required Input Parameters

The Voellmy rheological model, as described in detail in Section 3.2.2, requires two parameters that are not related with sensitive clays. These parameters are the turbulence factor and friction coefficient. The new RAMMS::Debris flow incorporates cohesion term in its version 1.6 and in this study the remolded shear strength of sensitive clays is considered as its equivalent. However, the Voellmy rheological model implemented in DAN3D takes only the original friction parameters and does not take cohesion as an input.

Since this study is focusing to back calculate the event and evaluate the models with their parameters, different sets of parameters were used. Table 5.2 shows the range of parameters used for the analyses.

Table 5.2: Range of required input parameters for back calculating the Byneset landslide.

Parameter	Symbol	Unit	RAMMS::Debris Flow	DAN3D
Turbulence factor	*Xi* (ξ)	m/s^2	1 - 10000	100 - 10000
Friction coefficient	*Mu* (μ/*f*)	-	0 - 0.4	0.005 - 0.1
Cohesion	*C*	Pa	0 - 2000	-

Internal friction angle is required as an input parameter in DAN3D and 35° is given as default value which represents dry fragmented rock. This parameter is used to derive the tangential stress coefficients *kx* and *ky* using a formula developed by Savage and Hutter (1989). Sensitive clays are also found to have internal friction angle around 35° after conducting the following calculation.

Figure 5.3 shows isotropicaly consolidated undrained triaxial test result for a sample of sensitive clay soil in NTH-plot. The slop of the failure line, S_f, is found to be around 1.04 which is used to calculate the internal friction angle, φ, using Equation (5.1).

$$tan\,\varphi = \frac{S_f}{\sqrt{1+S_f}} \qquad (5.1)$$

$S_f = 1.04$ gives $\varphi \cong 35^0$ using Equation (5.1) and this value is used during all the analyses conducted in DAN3D.

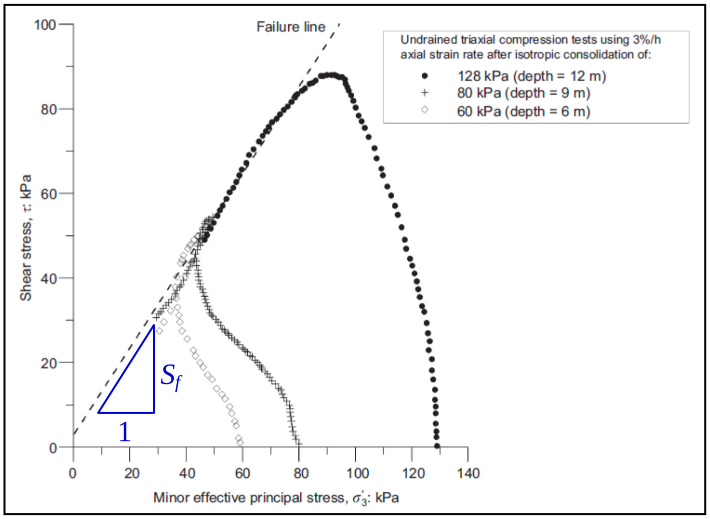


Figure 5.3: Determination of internal friction angle using result of consolidated undrained triaxial test on sensitive clay samples prepared for quickness test (Thakur and Degago, 2012)

5.3. Calculation Procedure in RAMMS::Debris Flow

This software requires input pre-landslide topography of the area in the form of Digital Terrain Model (DTM). This data is kindly provided by Gunne Håland & Vikas Thakur of Statens vegvesen (SVV), Trondheim. The resolution of the DTM was 10m and another 2m resolution data was found from previous study by Nigussie (2013). Ortho-photo and map consisting the corresponding TIFF-file can be included to visually enhance the run-out process.

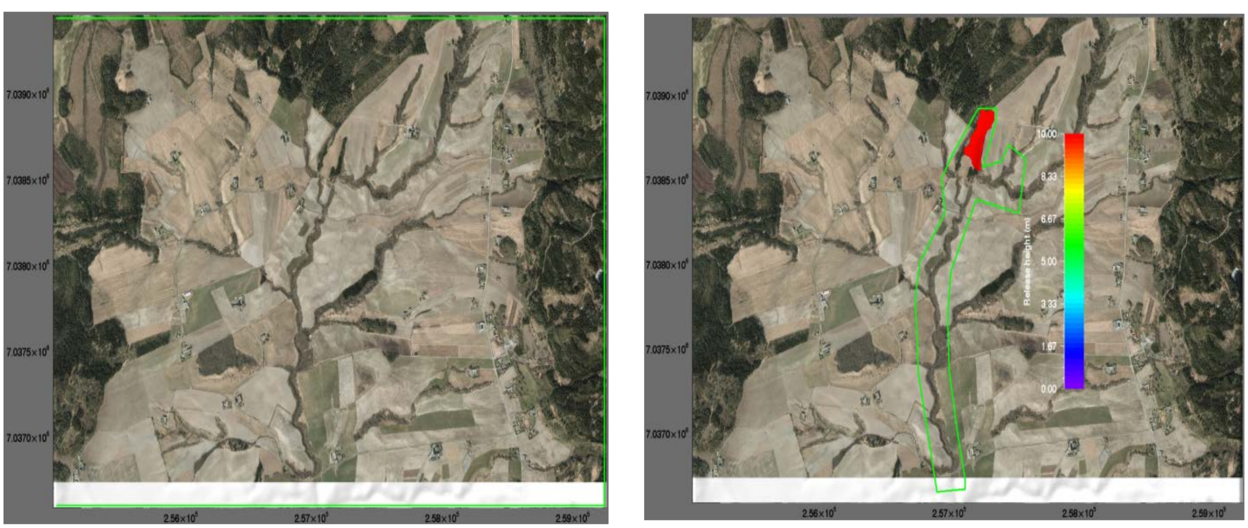


Figure 5.4: Setting up DTM and ortho-photo (left) and delineation of release and calculation domain areas (right)

Using the ‘Project Wizard’ command, the DTM and the ortho-photo are created as shown in Figure 5.4 (left). The software gives its own calculation domain by default which is the green square. But the user defined release areas and calculation domains should be delineated to get the required back calculation result, Figure 5.4 (right).

The rest of simulation procedures are described in Section 3.2.4.

5.4. Calculation Procedure in DAN3D

DAN3D requires two ASCII formatted digital terrain model, DTMs (*.GRD), files. One is representing the source topography of the area alone and the other is representing the original topography of the area without the source, Figure 5.5. This file is found from previous study conducted by Nigussie (2013) with DAN3D using other rheological models and kindly given by Daniel G. Nigussie.

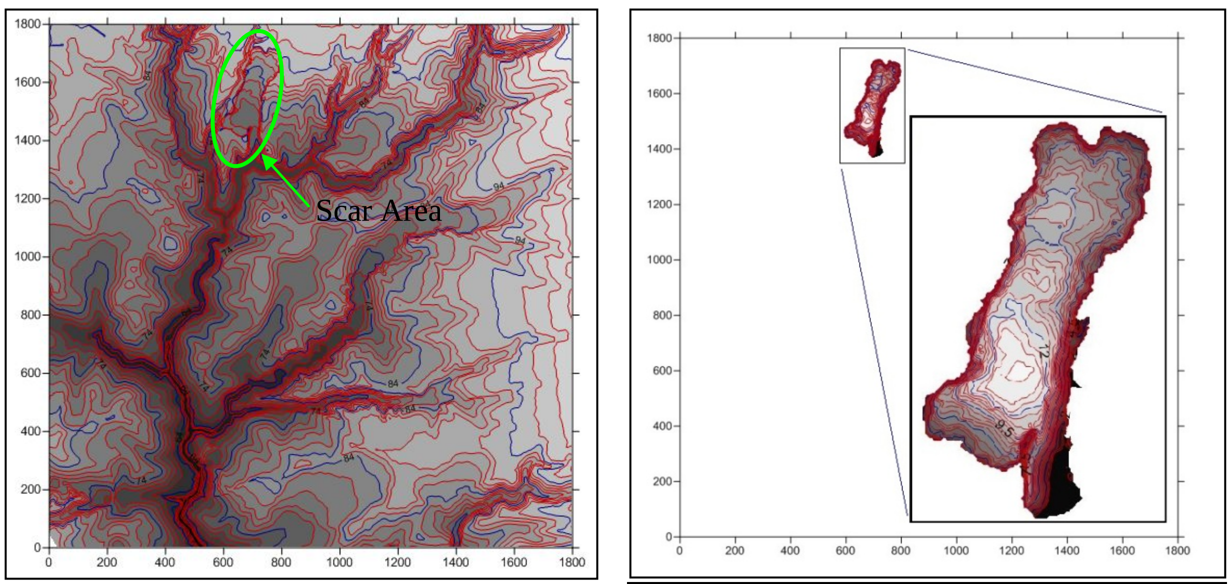


Figure 5.5: Input DTMs representing Byneset path topography without source (left) and source topography without the rest of the topography (right)

The rest of simulation procedures are described in Section 3.3.2.

5.5. Byneset Landslide Simulation Results

The actual Byneset landslide area, before and after the slide, is presented in Figure 5.6 to have a clear view of the event.

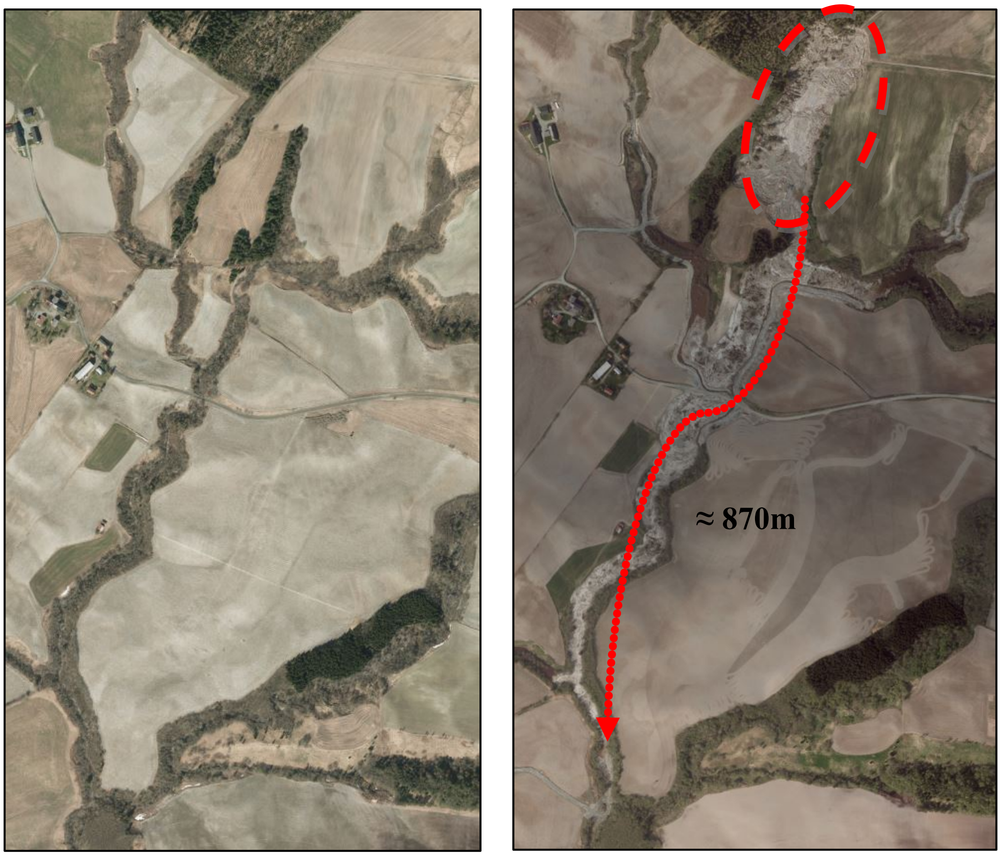


Figure 5.6: Pre-slide and post-slide photos of Byneset landslide

5.5.1. RAMMS Simulation Results: Significance of Data Resolution

The Byneset landslide was analyzed using two different data with 10m grid and 2m grid digital terrain models (DTMs). Both DTMs represent the slide topography prior to the slide. The RAMMS manual Bartlet et al. (2013) described that the simulation results can be affected by the resolution and accuracy of the topographic input data. Therefore the results found from these two input data are discussed and compared here.

When defining release volume in RAMMS, RAMMS places the volume over the given terrain. But in the Byneset case, the volume is cut out from the terrain and flowed. So defining the release volume as it is on top of the terrain will give additional potential energy to the whole mechanism which in turn give an extended run-out distance due to an additional kinetic energy. However the 2m grid DTM data is available in such a way that the release area is made to represent post-slide terrain which means the terrain model has depression at the release area (Figure 5.7 (left)). This situation helps to alleviate run-out overestimation problem due to additional potential energy and to guide the flowing mass in its natural flowing course.

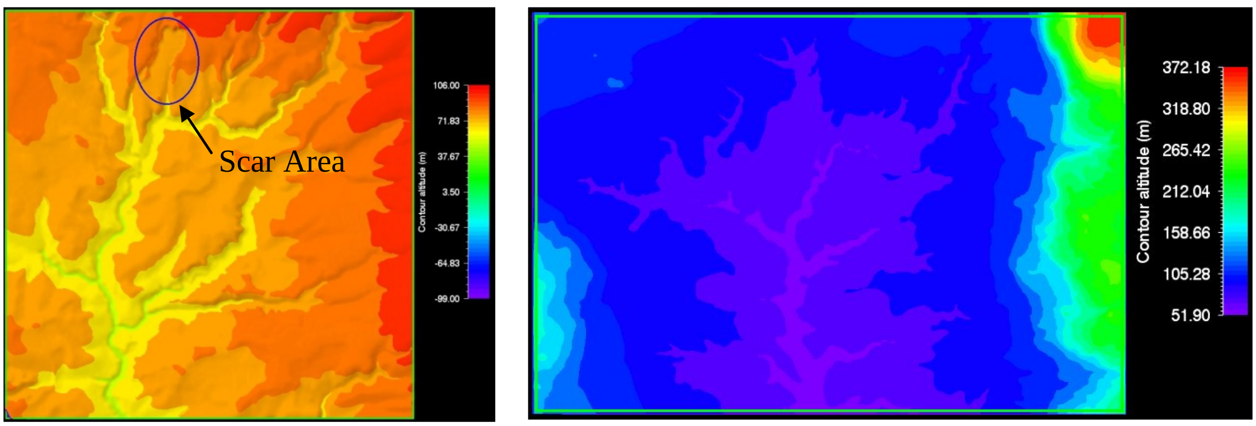


Figure 5.7: 2m grid DTM (left) and 10m grid DTM (right) of Byneset pre-slide data.

As clearly seen on the first image of Figure 5.7, the scar or release area is distinct whereas in the second image, fully pre-slide DTM is shown. One can also see the resolution difference between the two DTM data and that the 2m grid data distinctly shows the terrain and flow path.

To assert the simulation result dependency on resolution of the DTM data, run-out simulations using both DTMs were conducted with similar sets of the friction parameters. The resulting run-out distance as a function of grid resolution, turbulence factor, friction coefficient and cohesion is plotted in Figure 5.8.

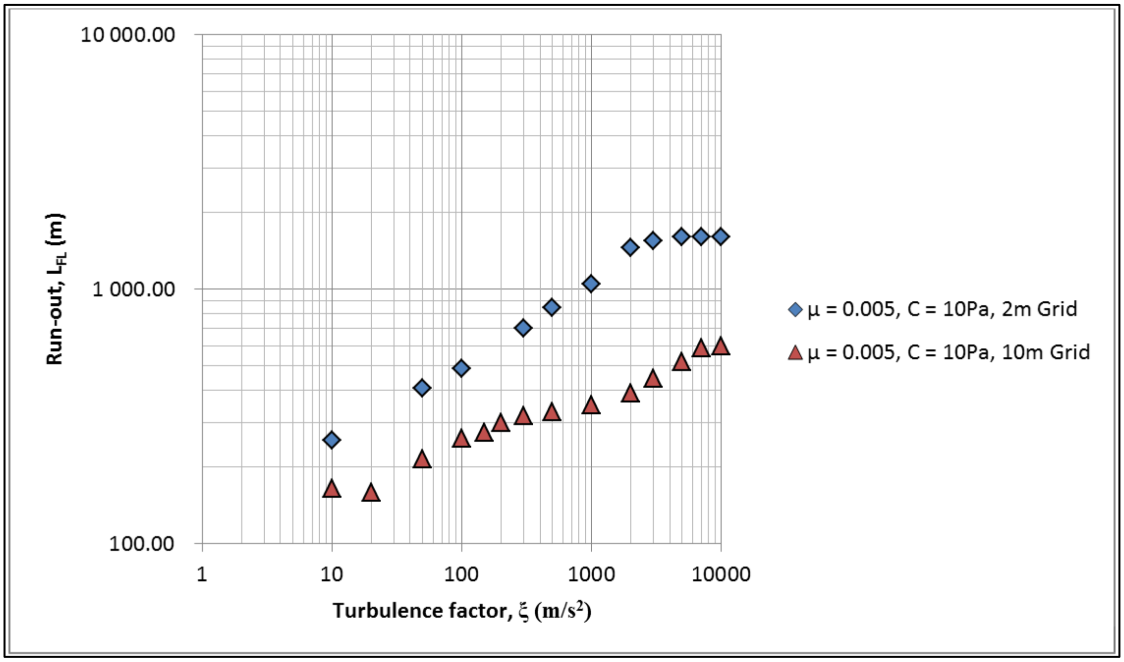


Figure 5.8: Run-out distance versus Turbulence factor for given μ and C values for 2m and 10m grid DTMs.

Unlike the expected potential energy problem described above, the 2m grid DTM data yield a longer run-out distance than the 10m grid DTM data. This is because part of the released material that goes in to the channelized flow in the case of the 10m grid data is less than in case of the 2m grid data. This is attributed to the fact that the release mass is placed over the pre-slide terrain which makes it flow in all directions without bound.

Efforts were made to control the spreading mass by delineating the calculation domain area very close to the boundary of the release area as shown in Figure 5.9. A better opening in the front side had to be given to allow the mass to flow out of the release area and enter into the path.

This delineation procedure is very arbitrary and can differ from person to person. This difference, of course, will have some effect in the simulation result of run-out distance estimation.

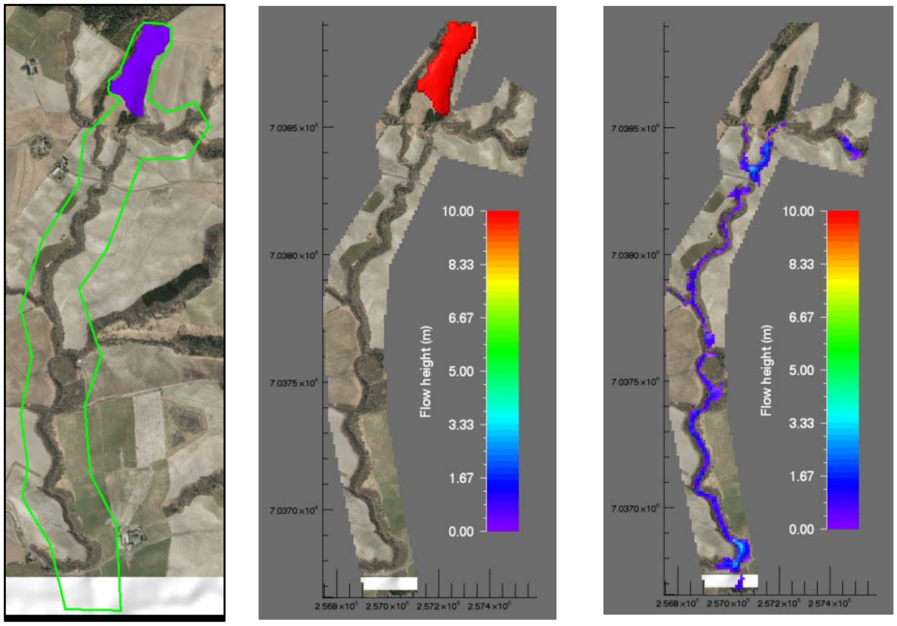


Figure 5.9: Delineation of calculation domain area (left), initial stage of slide (middle) and final stage of slide (right) with 10m grid data.

Although the calculation domain made very close to the release area and open at the front, the software gives warning to enlarge calculation domain area specifying some amount of outflow volume, Figure 5.10. This outflow volume is the portion of the release volume blocked by or passed across the calculation domain boundary. This problem is mainly a result of the definition of the release volume on top of the given terrain which allows it to flow in every direction.

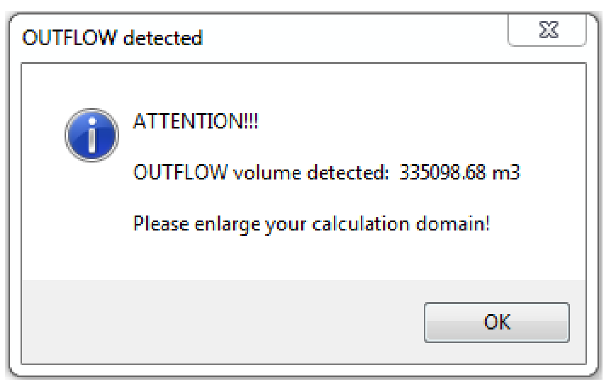


Figure 5.10: Warning message for detected outflow volume

Figure 5.11 shows the first few steps of the Byneset slide simulation after delineating the calculation domain and release areas as shown on Figure 5.9. These example pictures are from the analysis by setting values of the three parameters as $\mu = 0.01$, $\xi = 10000\text{m/s}^2$ and $C = 0.0\text{kPa}$.

This is to show how the flow behaves with the minimum basal resistance using the 10m grid data.

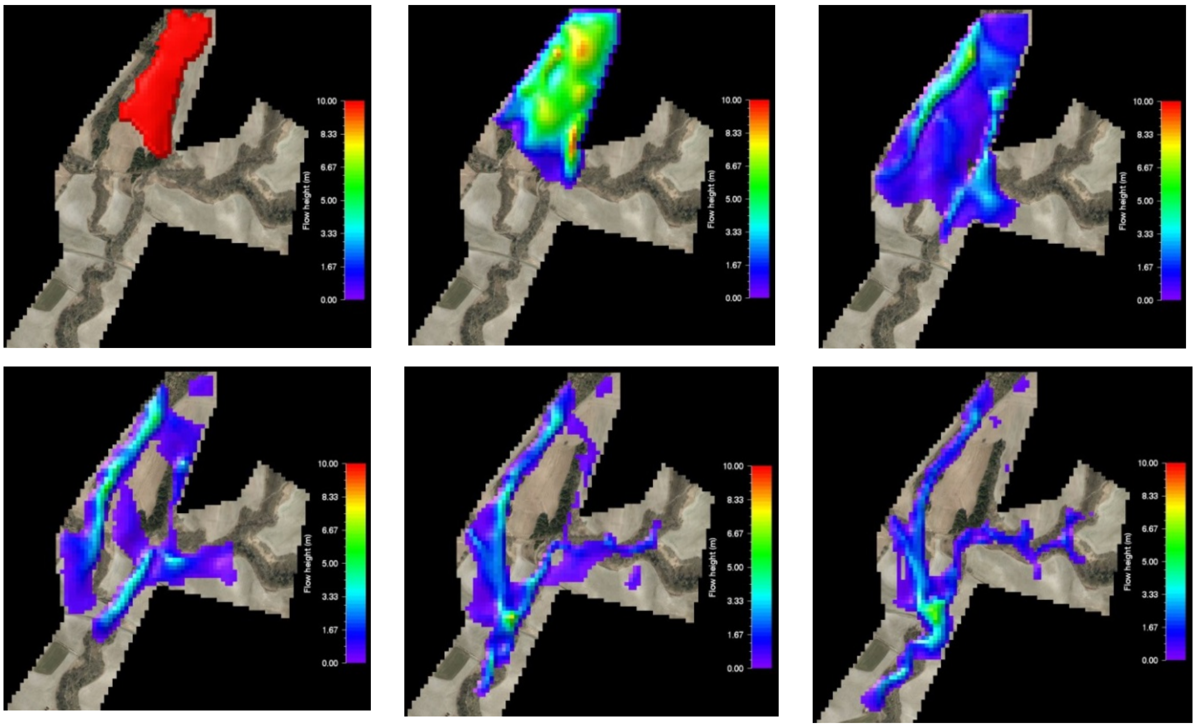


Figure 5.11: Initial few steps of the run-out simulation process of Byneset slide using 10m grid DTM

The flow started from the release area by spreading in all directions and proceeded down in to the flow path not through the actual observed way. It ran over the terrain and ended up in the channel as shown on the last picture in Figure 5.11. One can also observe the volume loss in the other three directions. Finally, running the rest of the studies with the 2m grid data found advantageous due to its resolutions, result precision and suitable confining release place for defining the release volume.

5.5.2. RAMMS Simulation Results Using 2m Grid Data

The detailed studies were conducted using the 2m grid DTM. The depression at the release area helped in defining the release volume in its right location and guided the mass to the gate of the flow which more or less imitated the actual flow situation. The calculation domain and release areas are defined and delineated as shown on Figure 5.12. An example run-out simulation result with ξ = 2000m/s^2, μ = 0.005 and C = 0.1kPa is also presented. This DTM data help the simulation process to look better and gives a better accuracy and precision in the result. The run-out follows the flow path the actual flow slide followed.

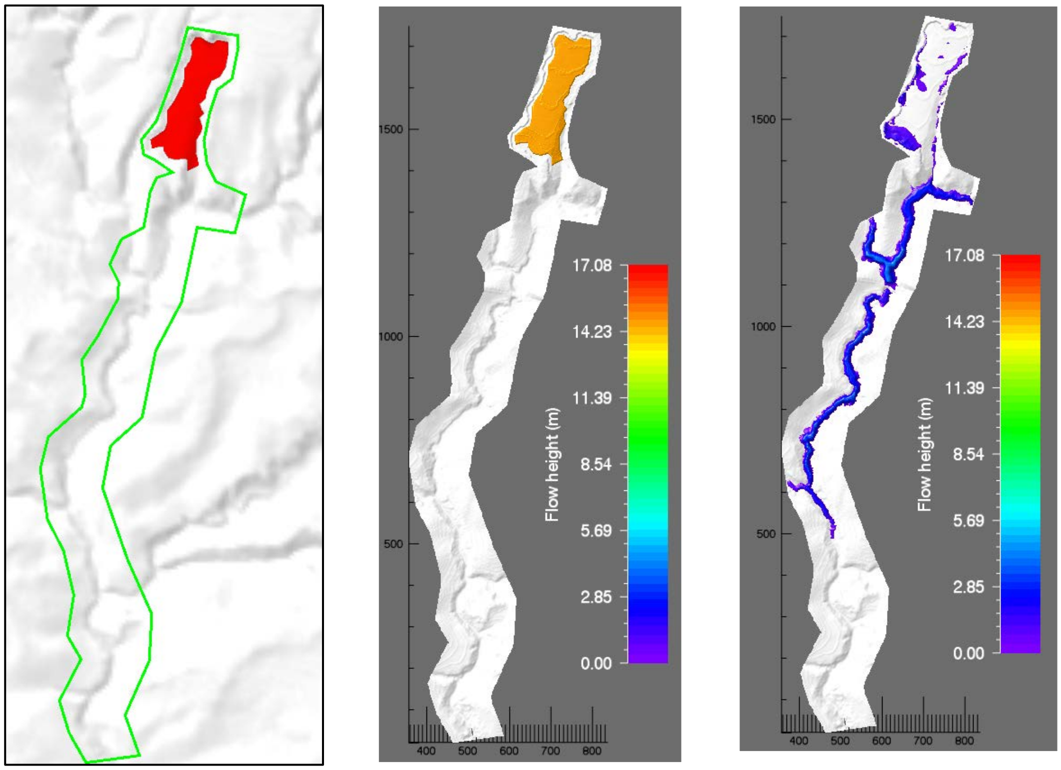
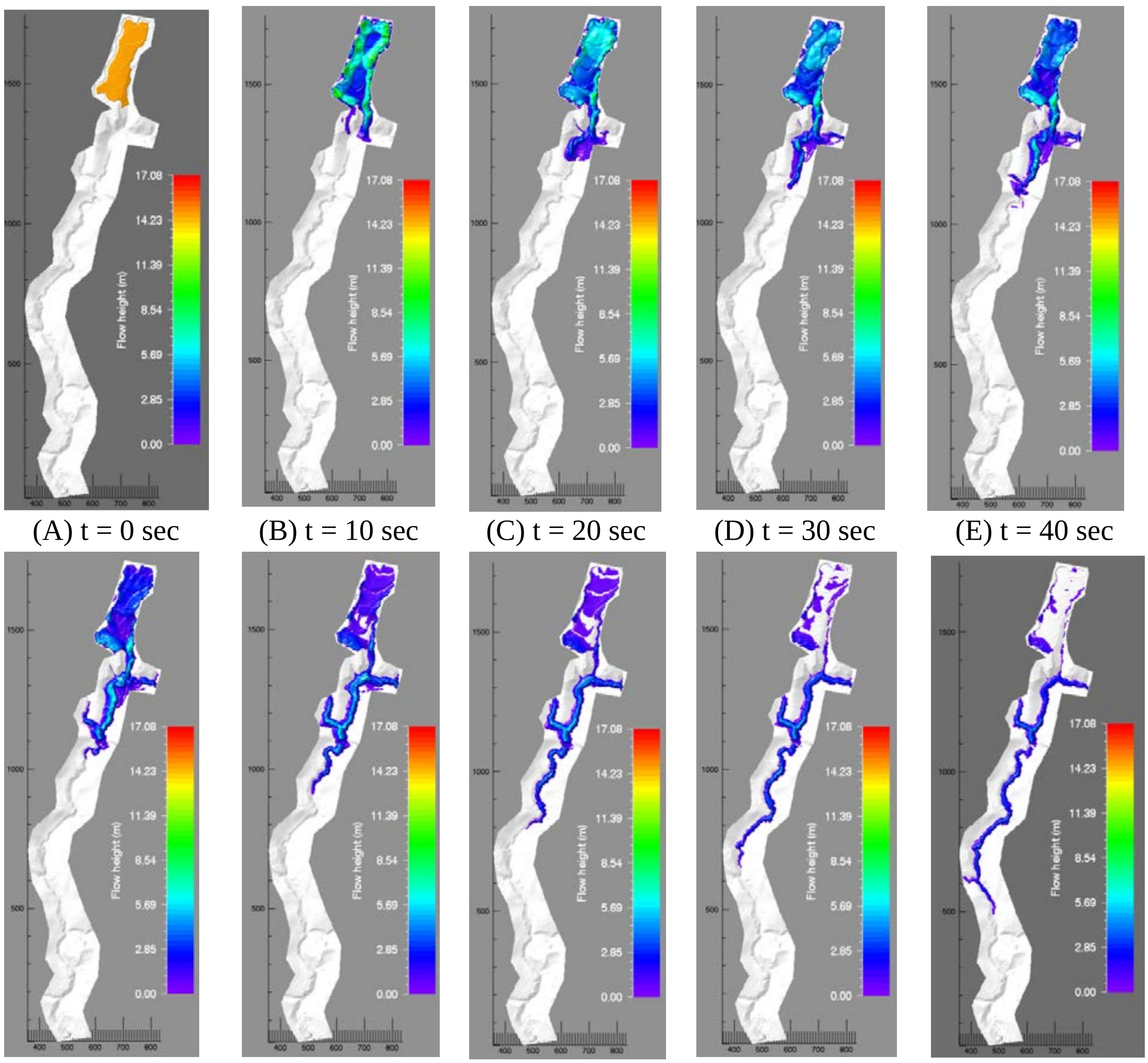


Figure 5.12: Domain and release areas (left), initial stage of slide (middle) and final stage of simulated run-out (right)

A more detailed step of the run-out simulation is presented in Figure 5.13 which gave similar run-out distance as the actual observed. Picture (A) and (J) represent the start and end of the simulation. The simulation steps dictate that the mass flow looks like flow of flood and the run-out continued until almost all of the release mass evacuated the release area.

Simulation of this case and also other cases lasted for a very short period relative to the actual flow duration. This short flow period resulted in a maximum average velocity around 30m/s which is 3 times higher than the actual observed maximum flow velocity. The simulation result also show that the maximum overall flow velocity is 150m/s in which it happened inside the release area while the mass turbulently moves into the channel. The actual observed maximum flow velocity within the release area and at the maximum run-out distance along the main channel barely reaches 10m/s (Issler et al., 2012). This might be caused by the Voellmy model formulation which is very much dependent on the velocity related parameter. As it is witnessed from the simulations, the mass flowed as liquid behaving like flood. This is because of high value of ξ which is mainly responsible to control velocity of flow. Note that the basal resistance and the turbulent factor are inversely related and the higher the turbulent factor the lower its contribution to the total basal resistance.



(A) t = 0 sec (B) t = 10 sec (C) t = 20 sec (D) t = 30 sec (E) t = 40 sec

(F) t = 60 sec (G) t = 100 sec (H) t = 140 sec (I) t = 200 sec (J) t = 288 sec

Figure 5.13: Simulation steps of the Byneset landslide for ξ = 2000m/s^2, μ = 0.005 and C = 0.1kPa

5.5.3. Parametric Study of the Voellmy Rheology in RAMMS

Out of the three parameters given in the modified Voellmy basal resistance equation, each has been studied individually and their effect and sensitivity in the run-out distance estimation has been presented.

Several simulations have been run while varying values of μ and ξ for a fixed C = 0.1kPa using the 2m grid DTM data. Run-out distances are measured along the flow path using profile line following the stream course, Figure 5.14 (left & middle). However the actual field run-out distance (≈ 870m) was measured as displacement from starting point of the slide to the end point of the run-out. A simulated run-out distance with similar end point as observed in the field will have longer value on the profile plot, Figure 5.14 (right). Therefore the actual run-out distance observed as 870m becames around 1000m in this profile plots. The profile plot also gives average flow depth. For most of the simulation results, average flow depth is found to vary between 1.5m and 3.0m.

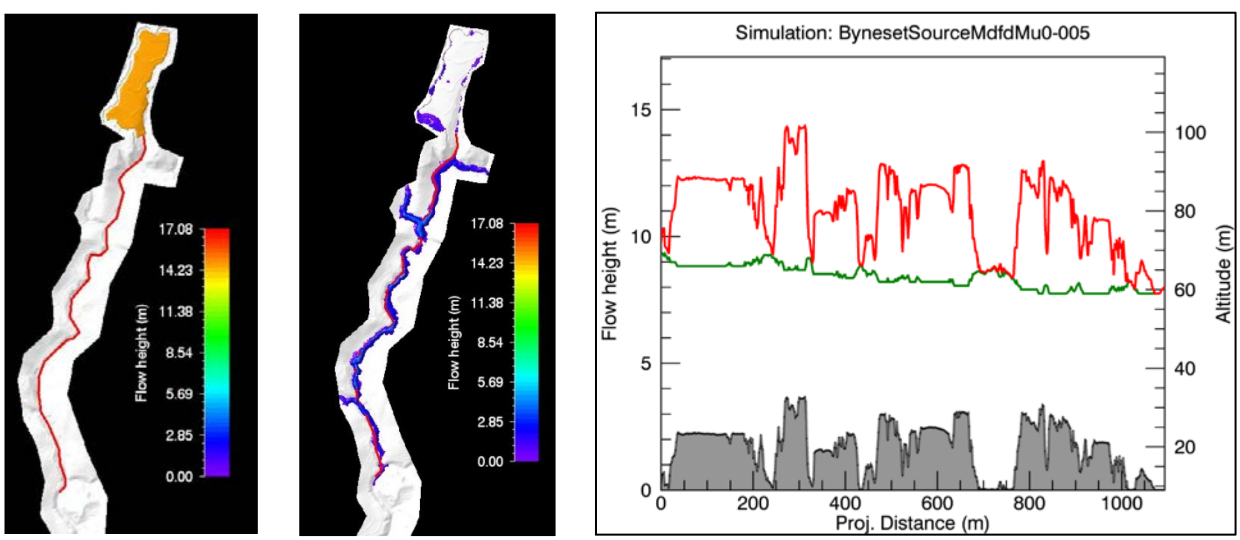


Figure 5.14: Profile line along flow path (left), profile line together with the run-out (middle) and section showing depth of flow and run-out distance along the profile (right)

5.5.3.1. *Sensitivity Analysis of Friction Coefficient, μ*

The friction factor, μ, represents the portion of basal resistance provided by the roughness of the terrain and the flowing material. The manual suggested to use tangent of the slop of the terrain on which the mass flows. Values of μ normally range between 0.05 and 0.4 and values of μ larger than 0.4 rarely provide useful simulation results (Bartlet et al., 2013). In the Byneset case, the slop of the flow path is approximately 3° which gives friction coefficient of tan(3°) = 0.052.

Friction coefficient values μ = 0.005, 0.01, 0.1 and 0.2 which can correspond to slop angle α = 0.29˚, 0.57˚, 5.71˚ and 11.31˚ respectively are used in the analyses. McDougall and Hungr (2005) calibrated the friction coefficient, μ, ranging between 0.01 and 0.2 together with turbulence coefficient, ξ, ranging between (100 – 600)m/s^2 for debris flow for use in Voellmy rheological model. Figure 5.15 shows that the run-out back calculation with μ = 0.01 gave a close run-out result (red dot line) whereas the calibrated turbulence coefficient (100 - 600)m/s^2 range completely gave shorter run-out distances than observed in the field (red dotted line). This might be attributed to the total stress approach of the model that give higher basal shear resistance by undermining the pore-pressure effect.

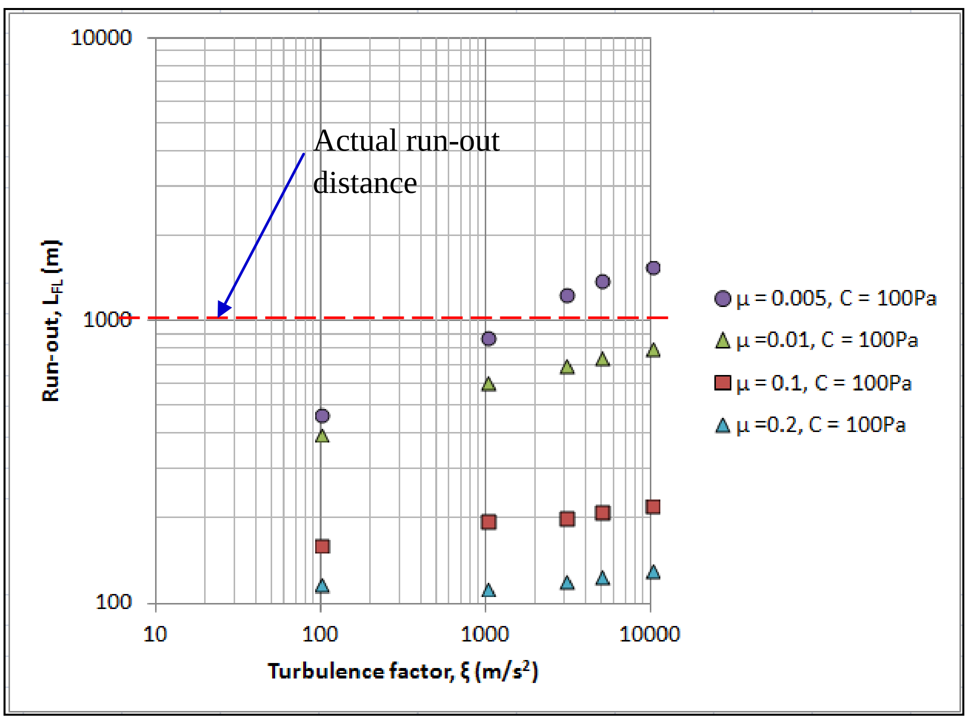


Figure 5.15: Run-out distance as a function of μ and ξ for C = 0.1kPa

The friction coefficient, μ = 0.01 gives a close run-out distance estimate of the actual observed with the help of a very large value of ξ = 10000m/s^2. However by using smaller friction coefficient value like μ = 0.005, it was possible to obtain the actual run-out distance in combination with ξ = 1000 m/s^2. For μ = 0.1 and μ = 0.2 the flow found to come to stop very early before reaching the actual observed distance. According to the results of μ = 0.01, it is found that applying μ = 0.052 which is a value related with the actual terrain slop (α = 3°) will not give the required run-out distance.

5.5.3.2. Sensitivity Analysis of Cohesion Parameter, C

To evaluate the effect of cohesion term, C = 0.1kPa and 0.2kPa are selected. These two values were selected because greater or smaller values will not back calculate the required run-out distance. These two cohesion values used with zero friction coefficient value to get their full contribution to the basal resistance. The observed result shows the decrease in run-out by increasing cur from 0.1kPa to 0.2kPa is ranging between 7% and 22% (Figure 5.16). Whereas when the friction value, μ = 0.01, introduced, the change for each case reduced to range between 2% and 15%. This might be due to reduction of cohesion contribution by a multiple of (1- μ).

In other words, keeping turbulent factor and velocity of flow constant, the maximum contribution of cohesion term to the basal resistance is when μ = 0.0 and it decreases by the factor of (1 - μ) for μ > 0.0. For example, increase in cohesion value by 100Pa adds 100Pa to the basal resistance capacity for μ = 0.0 and adds only 60Pa for μ = 0.4 which in both cases very small when compared to the contribution from the other two terms. This explains that the cohesion term defined in this basal resistance equation and the remolded shear strength value of sensitive clays might not be analogous.

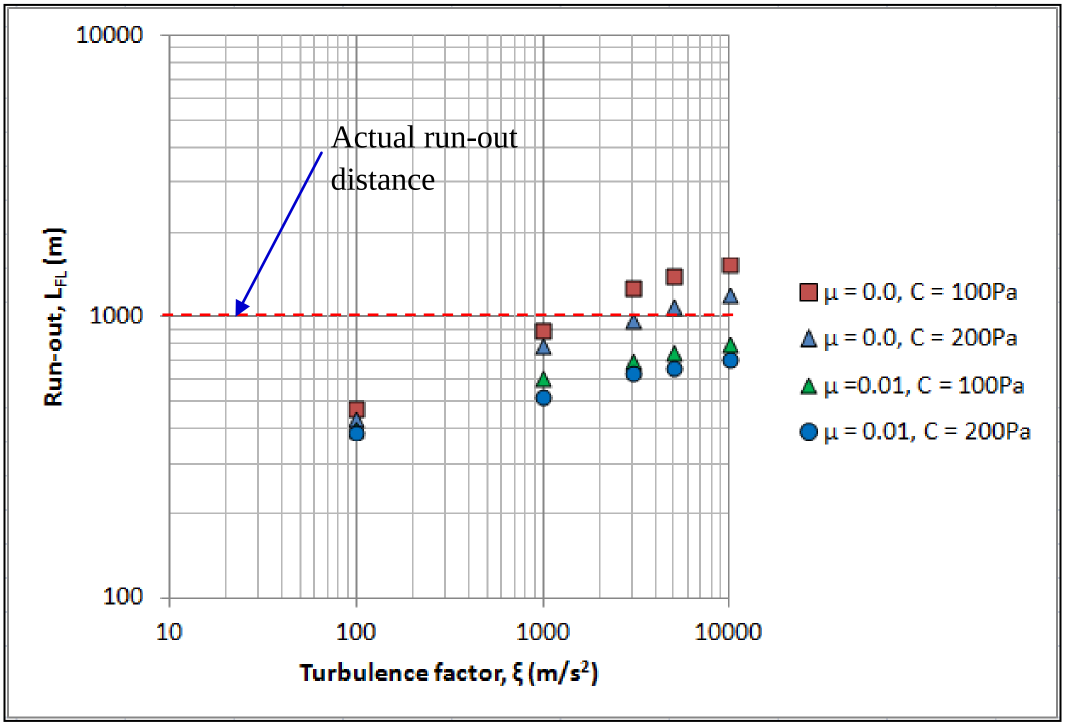


Figure 5.16: Run-out distance as a function of μ and ξ for two selected cohesion values.

5.5.3.3. Sensitivity Analysis of Turbulence Parameter, ξ

In Section 5.5.3.1 and Section 5.5.3.2, different values of turbulence factor were used. From those results we can see that wide range of values estimated the actual observed run-out distance. As it is seen from Figure 5.15 and Figure 5.16, values ranging between ξ = 1000 and ξ = 10000m/s^2 could give the required run-out distance when combined with different μ and C values.

Unlike μ and C, this friction parameter is difficult to relate it with the material behavior as it is there to describe the turbulent behavior of the flow (Bartlet et al., 2013). The manual also described that typically small values of ξ are reported for granular flows while relatively large ξ values are sometimes associated with muddy flows. This description agreed with the range of results obtained from this back calculation as the Byneset quick clay landslide can be categorized as muddy flow.

It can be said that the selection of ξ depends on the selected μ as the run-out distance is greatly affected by μ. For this specific case, ξ ranging between 3000m/s^2 and 5000m/s^2 can be used together with μ ranging between 0.0 and 0.01 and C = 100Pa. However putting μ = 0.0 which is providing frictionless surface for a real landslide case can be unrealistic. Figure 5.17 shows close back calculation of the actual landslide event.

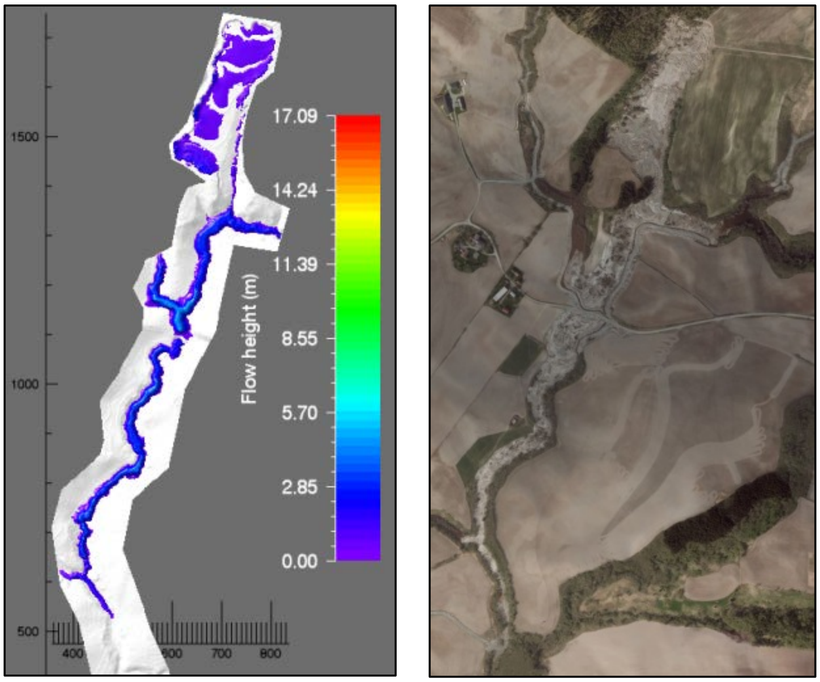


Figure 5.17: Back calculated and actual run-out distances: ξ = 3000m/s^2, μ = 0.005 and C = 0.1kPa

5.5.4. Simulation in DAN3D

The basal resistance of Voellmy rheology in DAN3D uses the original formulation and has only the two friction parameters, ξ and f, unlike in RAMMS::Debris flow which considers additional flow resistance contribution from cohesion of the material, C. Equation (5.2) gives the Voellmy basal resistance equation in DAN3D where f ($\equiv \mu$ of RAMMS) is friction coefficient, σ ($\equiv N$ of RAMMS) is stress normal to the bed and γ is unit weight of the flowing material.

$$\tau = \sigma f + \frac{\gamma v^2}{\xi} \tag{5.2}$$

As described in the simulation procedure in Section 5.4, two different default values (0.0 and 0.01) of 'velocity smoothing coefficient' are given by the software and the manual. This coefficient is used to determine how potent the velocity smoothing algorithm is (Hungr, 2010).

The parametric study used these two values and evaluated the corresponding run-out distances with respect to the two friction parameters. The run-out distance is measured using a straight line extending from toe of the scar to the tip of the flow as shown by Figure 5.18 as done in actual field measurement.

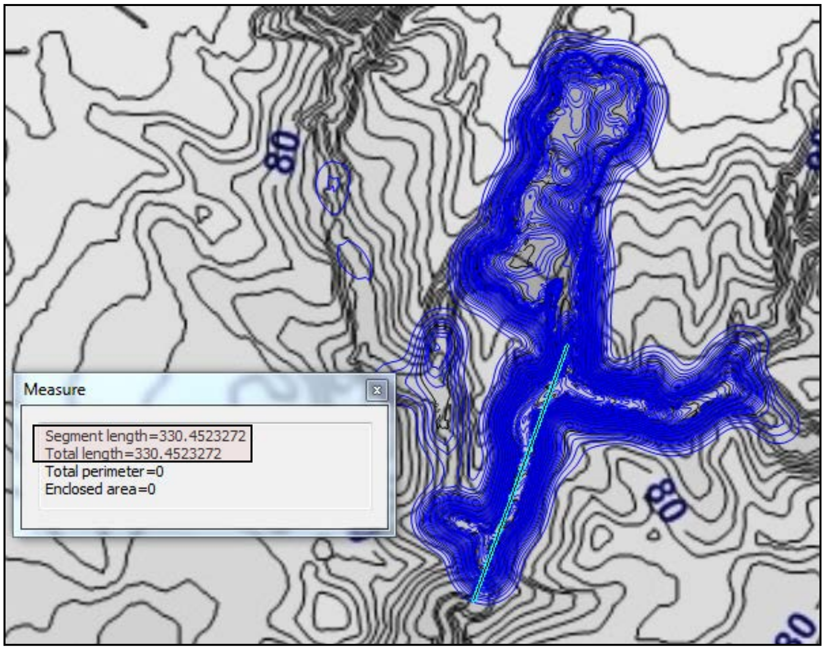


Figure 5.18: Run-out measurement method used for DAN3D simulation results

5.5.4.1. Sensitivity Analysis of *f* and ξ [velocity smoothing coefficient = 0.01]

The back calculation was conducted with different sets of *f* and ξ parameters. The plot in Figure 5.19 shows a very small response with respect to change in ξ. The inconsistent and less responsive run-out distances observed while varying ξ for a given value of *f* may have been resulted from instability of the software (beta version) and/or this velocity smoothing coefficient. On the other side, *f* = 0.005 and 0.01 gave relatively increased run-out distance for ξ = 10000m/s^2 which is not observed for the other *f* values. However consistent decrease in run-out distance to an increase in friction coefficient is observed although none of the run-out estimations could barely reach 600m.

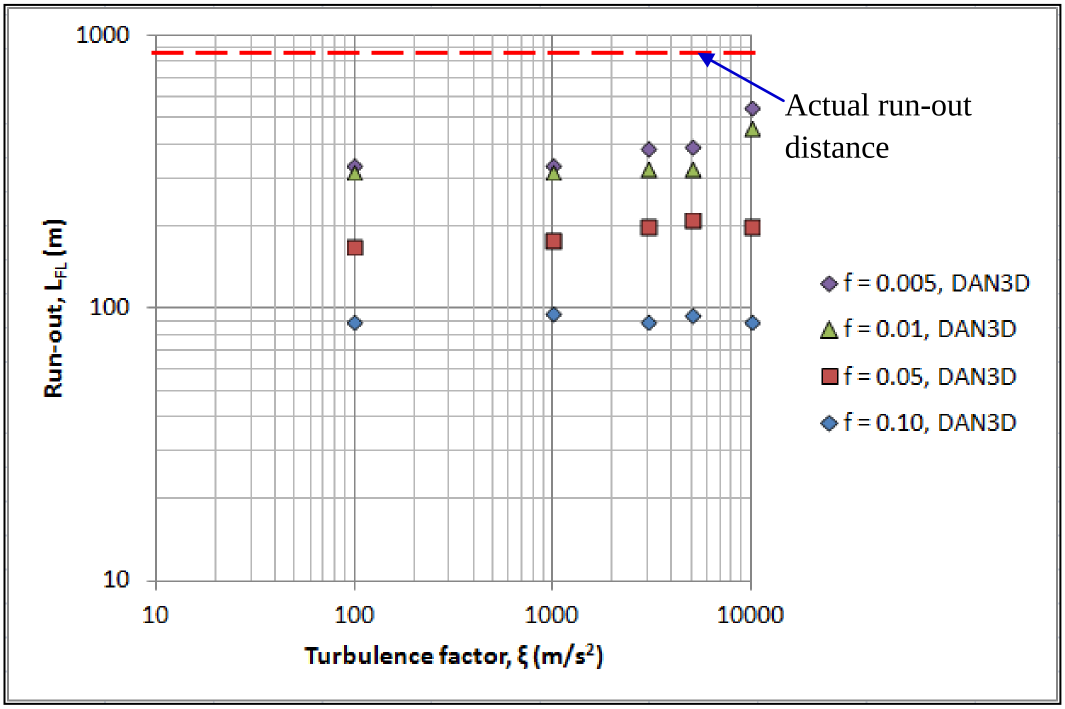


Figure 5.19: Run-out distance as a function of ξ and f for velocity smoothing coefficient value of 0.01.

Although it is for rock avalanches with steep topographies, Chen and Lee (2003) suggested that the best prediction for the friction coefficient may be achieved by assuming it as tan α, where α is the average run-out slop or slop of streaming ramp which separates the rupture surface and accumulation area. In the Byneset landslide case, the slop of flow topography is in average 3° which makes the friction coefficient estimation to be f = tan (3°) = 0.052.

However f = 0.05 gave a run-out ranging between 170m and 211m with varying ξ between 100m/s^2 and 10000m/s^2. This run-out distance is found very short when compared with the actual observed (870m shown with red dotted line). Improved run-out distances observed when f made five times smaller, f = 0.01 and further made even smaller to f = 0.005 although the improvement in the run-out distance is in the order of only 100m - 200m.

The steps presented in Figure 5.21 are simulated with ξ = 3000m/s^2 and f = 0.01. The output 'depth.grd' grid files from DAN3D are plotted using Surfer 11 software (Surfer 11.6.1159 Surfer Mapping System, Golden Software, Inc.).

This set of parameter gives a run-out distance, L_{FL} = 330m, which is attained around the 100th second (K). The flow progressed until the 100th second and after that it showed very small change until the 1000th second which is illustrated by the similarity of (K) and (L).

During the first 100 seconds, the maximum flow velocity was found to be high and dropped from 17m/s to 9m/s (Figure 5.20) which resulted in significant flow progress. Then it ended up around 6m/s average velocity for the rest of the flow course and this average velocity was only for accumulation of additional material over the existing run-out distance. The maximum flow velocity obtained here for most of the flow time except at the beginning is not far from the actual observed which is close to 10m/s.

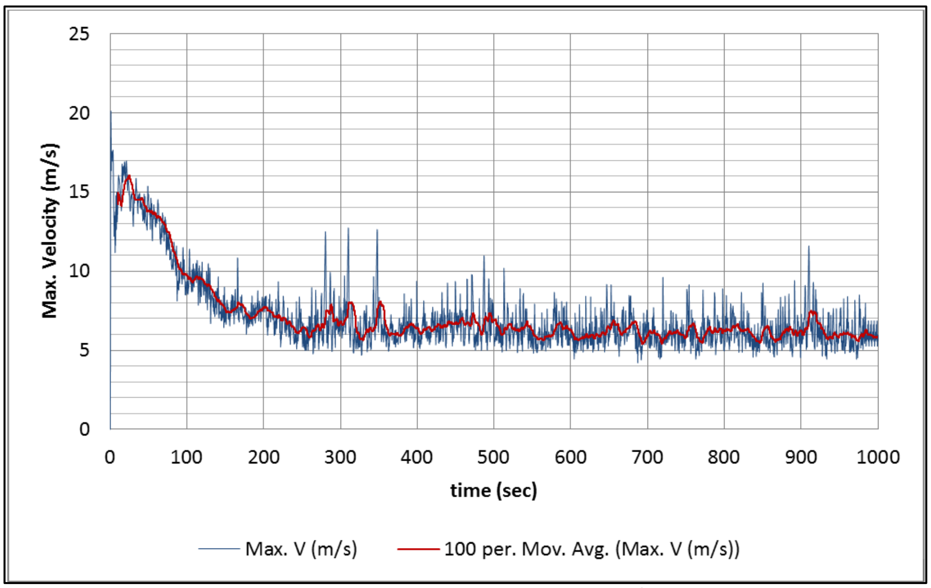
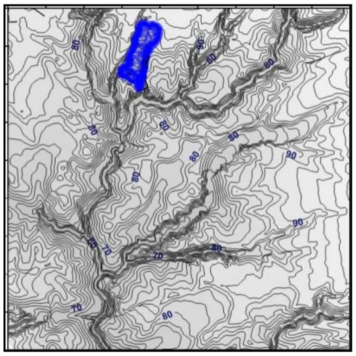
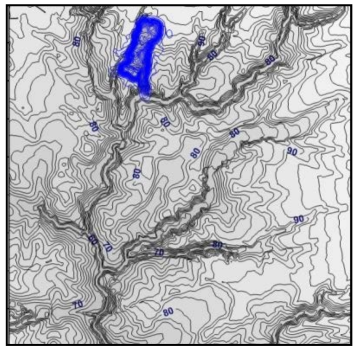


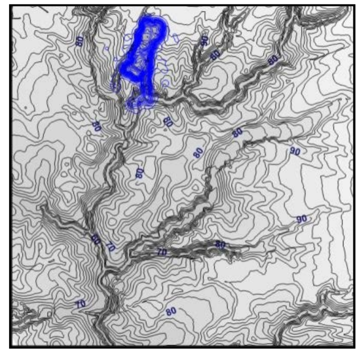
Figure 5.20: Maximum velocity versus time plot: ξ = 3000m/s^2 and f = 0.01



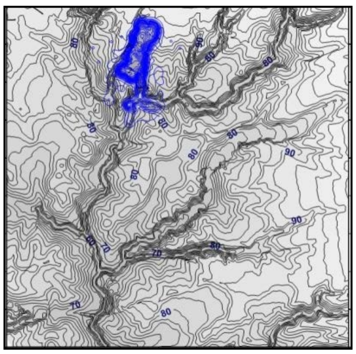
(A) t = 0 sec



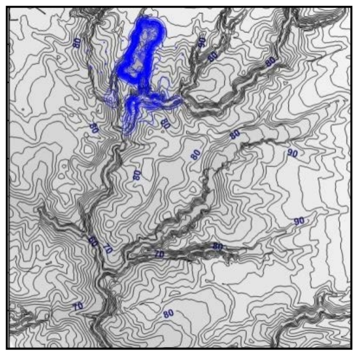
(B) t = 10 sec



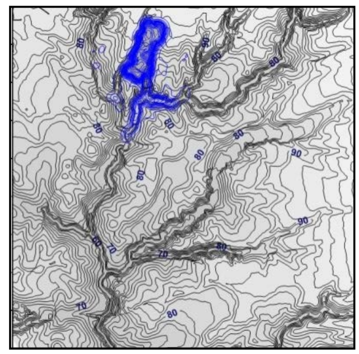
(C) t = 20 sec



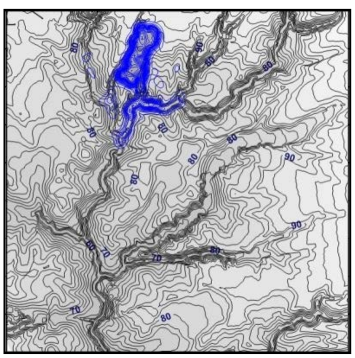
(D) t = 30 sec



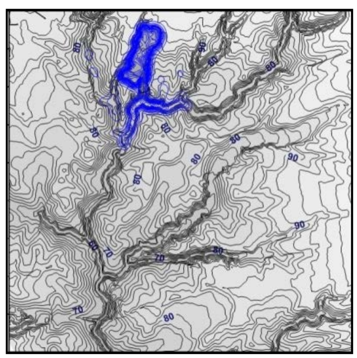
(E) t = 40 sec



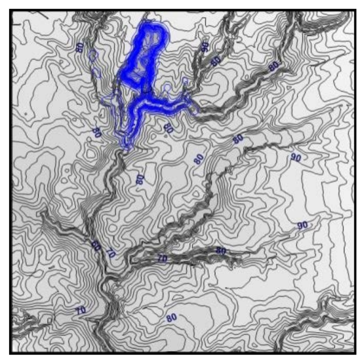
(F) t = 50 sec



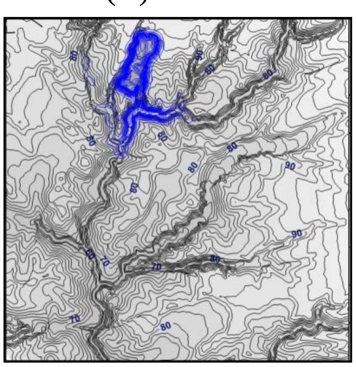
(G) t = 60 sec



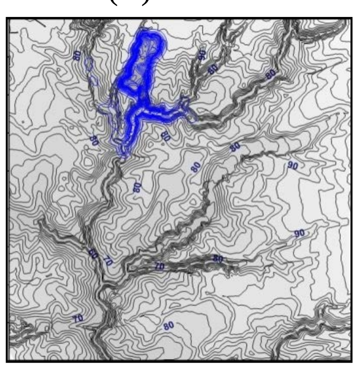
(H) t = 70 sec



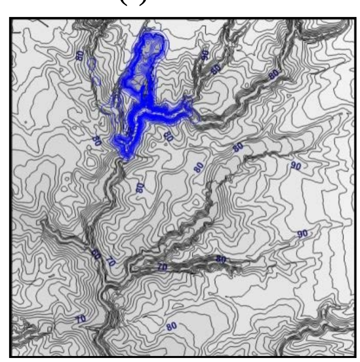
(I) t = 80 sec



(J) t = 90 sec



(K) t = 100 sec



(L) t = 1000 sec

Figure 5.21: Simulation steps of Byneset landslide in DAN3D: ξ = 3000m/s^2 & f = 0.01.

The average thickness dropped from 8.0m and stayed around 2.7m soon after the 15th second (Figure 5.22). The run-out process is almost stopped around the 100th second and rearrangement within the flow mass happened afterwards alongside other considerable run-out flows through the two left and right branched streams as shown in Figure 5.21.

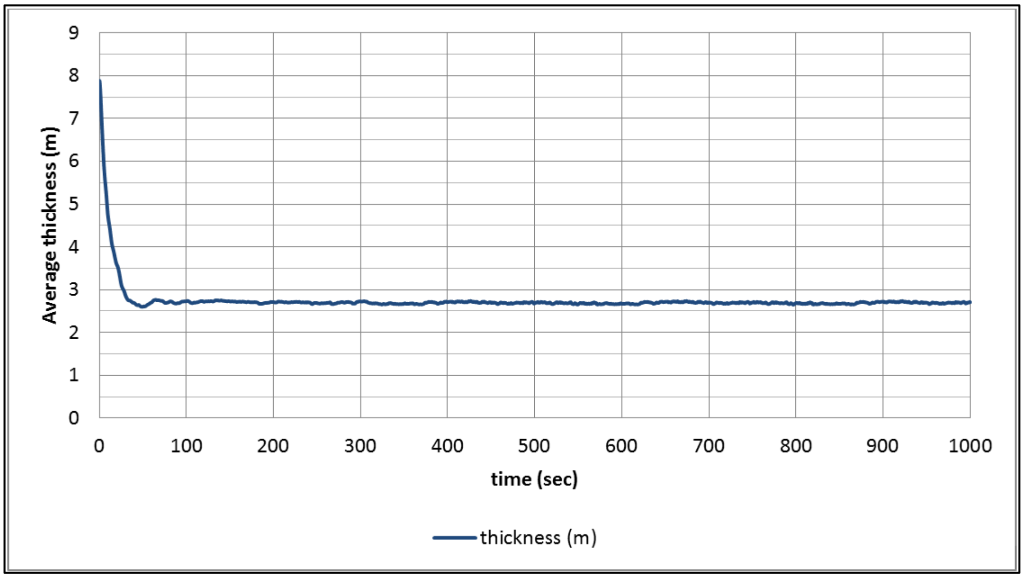


Figure 5.22: Average thickness versus time plot: ξ = 3000m/s² and f = 0.01

5.5.4.2. Sensitivity Analysis of f and ξ [velocity smoothing coefficient = 0.0]

The simulation results found here (velocity smoothing coefficient = 0.0) shows that the insignificant run-out response when varying ξ in the previous Section (velocity smoothing coefficient = 0.01) is mainly contributed from the selection of velocity smoothing coefficient. The results are plotted in Figure 5.23.

For smaller friction coefficient values (e.g. *f* = 0.01 & 0.005), effect of turbulence factor on the run-out distance is found to be significant than for higher values like *f* = 0.05 and 0.1. The active contribution of ξ to the basal resistance leads to some interesting longer run-out results that correspond to the actual observed.

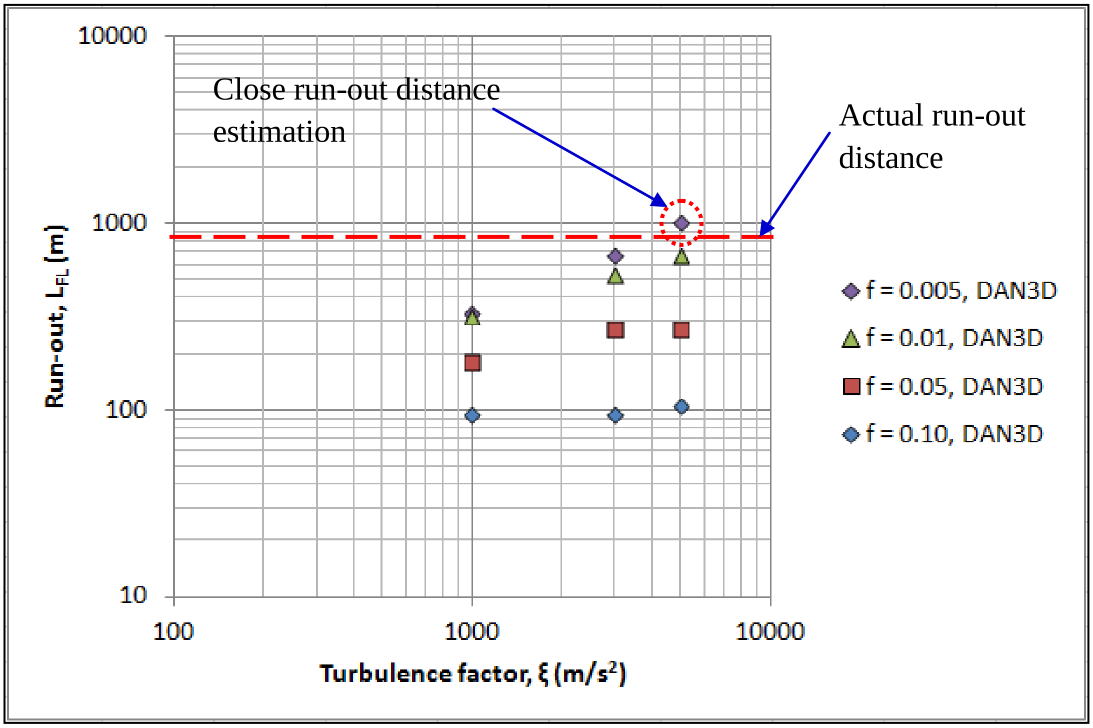
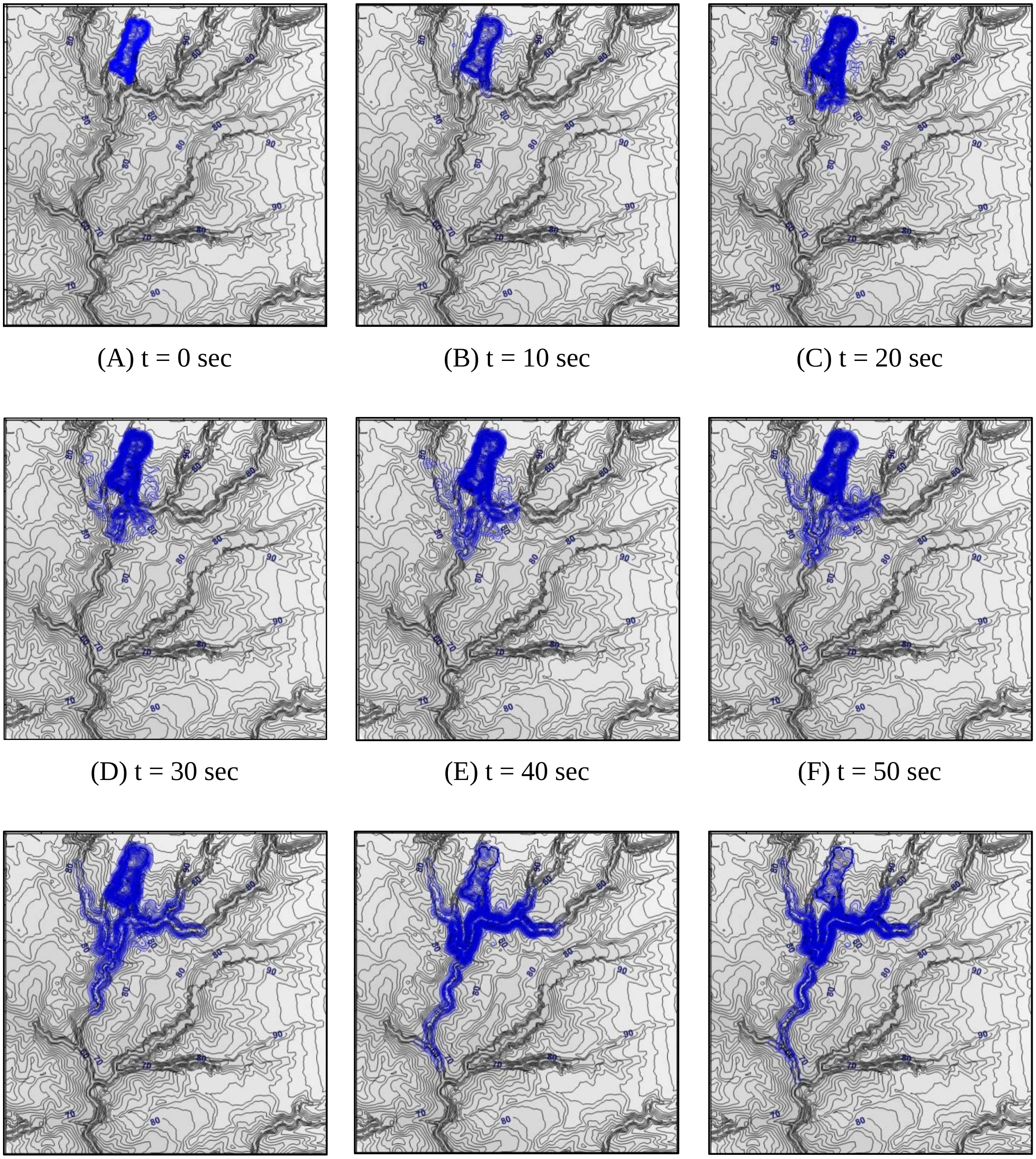


Figure 5.23: Run-out distance as a function of ξ and f for velocity smoothing coefficient value of 0.0.

Friction coefficient value, *f* = 0.005, and turbulence factor value, *ξ* = 5000m/s^2, gave an interesting back calculation of the Byneset landslide. The step by step process is presented in Figure 5.24. This back calculation has a run-out distance of 1000m through the main stream and a considerable run-out distances in the secondary branches to the left and right.

The run-out was progressed smoothly through the main path and in to the two branches within the first 100 seconds. As pictures (K) & (L) of Figure 5.24 show, additional mass accumulation in paths near the source and additional couple of hundred meters of run-out are observed in the remaining 900 seconds.



(A) t = 0 sec (B) t = 10 sec (C) t = 20 sec

(D) t = 30 sec (E) t = 40 sec (F) t = 50 sec

(J) t = 100 sec (K) t = 500 sec (L) t = 1000 sec

Figure 5.24: Simulation steps of Byneset landslide in DAN3D: ξ = 5000m/s^2 & f = 0.005.

The whole flow situation can be illustrated by using the maximum velocity versus time plot, Figure 5.25. It shows a higher velocity range (15 – 22)m/s for the first 100seconds which facilitated an extended run-out distance within short period. The remaining run-out was facilitated by the average maximum velocity (8m/s) using the rest 900 seconds. In addition to the assumed effect of the velocity smoothing coefficient, use of higher ξ and smaller f values gave a reduced basal resistance. Reduced basal resistance together with higher velocity of flow contributed to this long run-out distance which is close to the actual one.

It is also observed that the average maximum velocity of flow is found to be in line with the actual flow observed in the field (10m/s). The average flow depth which is 1.5m (Figure 5.26) is lower than the previous case. This is because of the longer run-out distance which has distributed the flowing mass in a larger area.

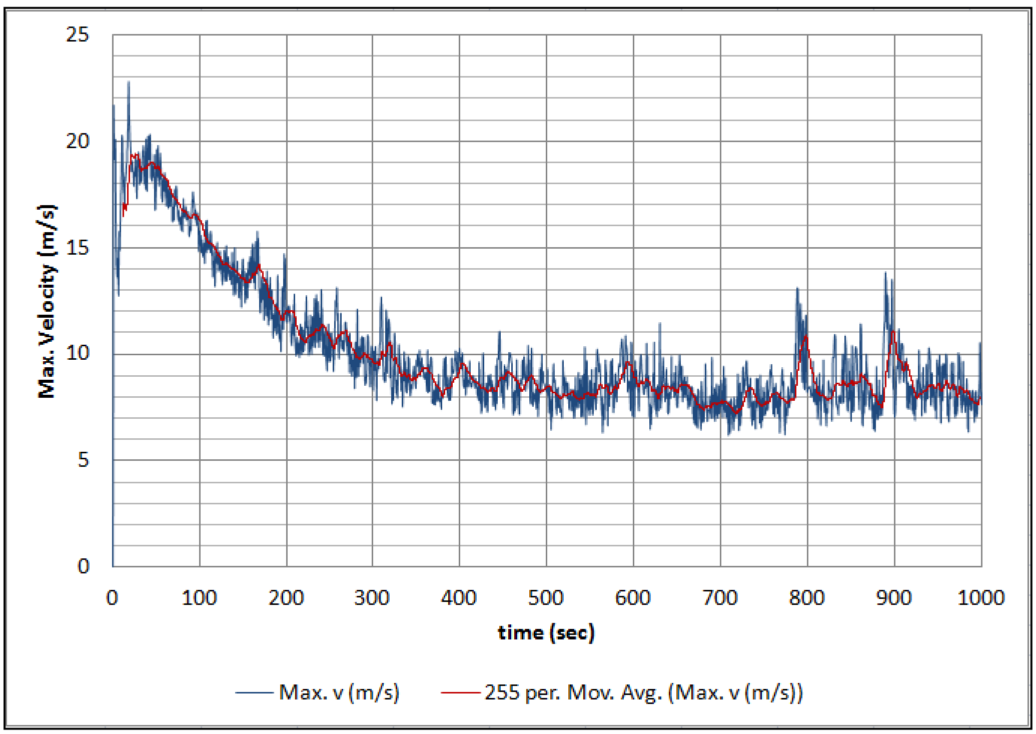


Figure 5.25: Maximum velocity versus time plot: ξ = 5000m/s^2 and f = 0.005

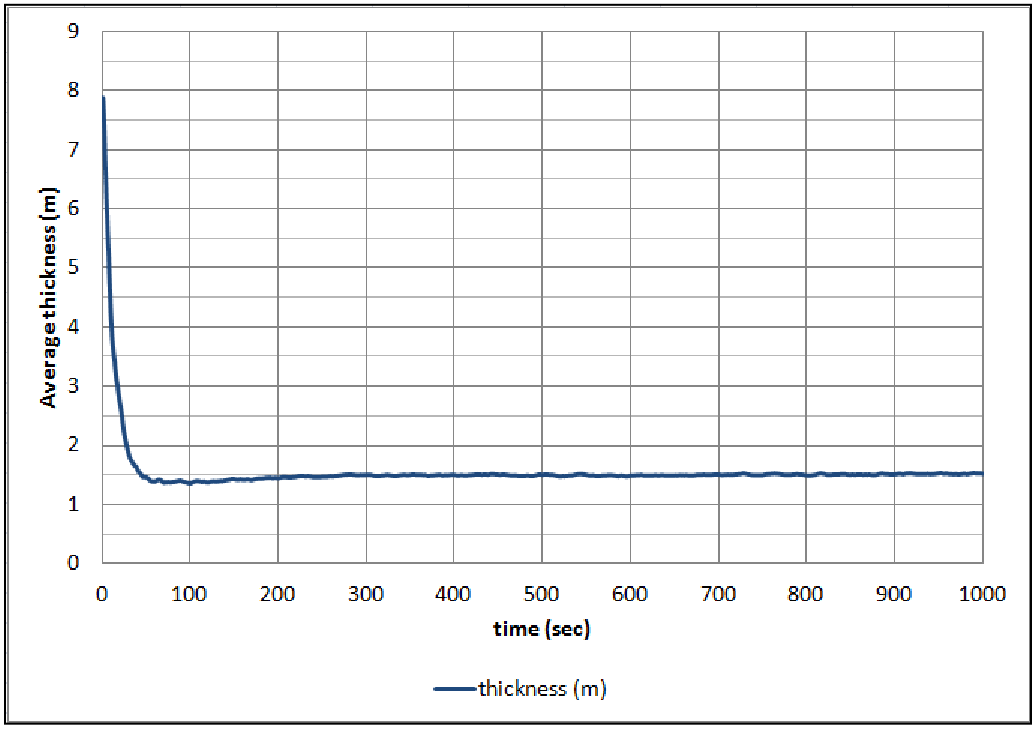


Figure 5.26: Average thickness versus time plot: ξ = 5000m/s^2 and f = 0.005.

5.6. Discussion on the Voellmy Rheology of RAMMS & DAN3D

Even though same data (2m resolution DTM) used in both RAMMS and DAN3D to evaluate Voellmy rheology, method of defining the release volume and some calculation mechanisms differ. It is also shown that the result is very dependent on the resolution of DTM other than the governing parameters.

The simulations in RAMMS are way faster than in DAN3D. This might be because of the fact that RAMMS is a commercial, well developed, software whereas this version of DAN3D is developed for research purpose and is a beta version. It only takes from few seconds to couple of minutes to simulate this case in RAMMS while it takes more than 5 hours to simulate it in DAN3D. It is also shown that how the results from this beta version of DAN3D might be affected due to some calculation parameters like 'velocity smoothing coefficient'.

When comparing the results, RAMMS gave higher flow velocity than DAN3D for same ξ and μ values. It is advised to note that formulation of the Voellmy rheology in the current RAMMS version and DAN3D are slightly different due to the cohesion term included in RAMMS. Average maximum velocities of (20 - 30)m/s were observed while using RAMMS and (7 - 20)m/s were obtained while using DAN3D. In DAN3D, the average velocity value dropped from the maximum value quickly and stayed around 8m/s for the rest of the simulation until a user specified time reached. During flow at this velocity, the run-out progress found very slow and didn't contribute much to the total run-out distances observed. Average flow height in RAMMS vary between 1.5m - 3m while in DAN3D it is observed to be in between 1.5m - 2.0m after it has dropped from its original 8m height.

The Voellmy model is based on a total stress approach which is unable to capture the excess pore-pressure effect of fine grained soils. Such fine grained saturated soils like sensitive clays generate excess pore-pressure in response to immediate loadings or sudden stress. The generation of excess pore-pressure will have significant influence in the internal resistance offered by the soil and the Voellmy model does not seem it considers this effect.

5.6.1. About the Cohesion Parameter, *C*

The cohesion parameter defined in the modified Voellmy model of RAMMS::Debris Flow V1.6 can barely represent the remolded shear strength of sensitive clays. This is shown by the results obtained in the simulations. A rough calculation that shows cohesion contribution to the basal resistance was made. Keeping ξ and velocity of flow constant, the maximum contribution of cohesion term to the basal resistance is found when $\mu = 0.0$ and it decreases by a factor of $(1 - \mu)$ for $\mu > 0.0$. For example, increase in cohesion value by 100Pa adds 100Pa to the basal resistance capacity when $\mu = 0.0$ and adds only 60Pa when $\mu = 0.4$ which in both cases, its contribution is found very small when compared with the contribution from the other two terms.

Trial simulation results show that even higher values of cohesion like C = 1000Pa and 2000Pa could not govern the flow run-out unless contributions of μ and ξ to the basal resistance made intentionally very low. Doing so, on the other hand, results in an unusually long run-out distances for such high cohesion values. This is why it is said that the model basal resistance is insensitive to change in cohesion value. However, for a failure happened with $c_{ur} > 1.0$kPa, no flow slide could occur afterwards and it is stated in Thakur and Degago (2012) that no flow slide has been registered in Norway on sensitive clays with 1.0kPa < c_{ur} < 2.0kPa.

5.6.2. About the Friction Coefficient, *μ/f*

This friction parameter, μ/f is found more sensitive in controlling the run-out distance of a given flow than C and ξ. It is learned that μ/f can be estimated as the tangent of the slop of the flow terrain. However the back calculated values in both RAMMS and DAN3D show that $\mu/f = 0.005$ - 0.01 gave a better estimation to the run-out distance of the Byneset landslide which has an approximate 3° flow path slop with $\mu/f = 0.052$. With $f = 0.052$ in DAN3D, it could be possible to obtain the actual run-out distance but only with the cost of a very high value of $\xi = 10000\text{m/s}^2$.

5.6.3. About the Turbulent Factor, *ξ*

The turbulence factor, ξ is referred as viscous-turbulent coefficient by RAMMS manual and describes turbulent behavior of the flow (Bartlet et al., 2014). It is difficult to relate it with the property of the flow material but it rather can be related with the flow condition and behavior. The concept of how to roughly estimate this parameter is described in Section 4.3.4. The rough estimation is given as $\xi = K_s^2 R^{1/3}$ which makes this parameter more of a descriptive parameter to the behavior and conditions of a flow.

From complexity of natural terrains and stream channels, use of the above approach to estimate ξ does not seem practical. However for flows in a simple defined channel, approximation is possible as the formula meant for open channel hydraulics.

Having said that, as it is suggested by the developers of RAMMS, calibration of the friction parameters specially ξ is required for any case. From the back calculation of Byneset slide in RAMMS and DAN3D, use of ξ ranging between 3000 m/s^2 - 5000 m/s^2 can be used as starting points for calibrating the Voellmy model for similar run-out cases like the Byneset sensitive clay slides.

6. Summary and Conclusion

6.1. Introduction

Voellmy rheological model is first designed for snow avalanche simulation and later adopted to debris flow in RAMMS and DAN3D. DAN3D uses the original Voellmy rheology basal resistance equation and on the other hand RAMMS::Debris flow V1.6 uses the modified Voellmy rheology basal resistance equation which has an additional term for cohesion of the flowing material.

6.2. Summary on Scaling effect during numerical modeling

Small scale laboratory tests have been used to study parameters governing flows of sensitive clay slides. In this study a very simple scaling effect assessment was conducted by simulating quickness test using different scales for a given remolded shear strength value of c_{ur} = 0.1kPa.

Both plastic model in DAN3D and Voellmy model in RAMMS back calculated the expected quickness value for c_{ur} = 0.1kPa regardless of four different model sizes used including the original size. The results from DAN3D exhibit flow disturbance at the beginning of the flows which might be attributed to the data gap in defining the vertical wall of the flowing mass source. Moreover results from both numerical tools showed that the flow mechanism at the beginning of the flow is rather fast and collapsed vigorously which is quite different from the actual test behavior observation.

Wide ranges of the friction parameters, μ and ξ, satisfied the result expected for c_{ur} = 0.1kPa when back calculating in RAMMS. However, what was observed interesting was the results obtained were not affected by the scaling, giving 94% and 93% for H = 100m and H = 10m model sizes respectively. This quality of the numerical models and tools made the study of another small scale laboratory test simulation possible with a scaled up model.

6.3. Summary on Small Scale Run-out Test Simulation

The second small scale laboratory test simulation was back calculation and parametric study of 'small scale run-out model test' using the modified Voellmy rheology in RAMMS. Summary of the Back calculation and parametric study results are given below.

In general, the rheology is found less responsive to the dramatic run-out distance decrease with increasing c_{ur} from 0.1kPa to 1.0kPa. This might be attributed to the fact that the flow, during and at the end, is majorly controlled by the friction parameters. Another reason which could give rise to this less responsiveness is that the lack of the model to incorporate the effect of pore pressure build-up inside sliding debris during the run-out.

Applying friction coefficient, μ according to the slope of the path contributed to the expected decrease of run-out distance with respect to increase in c_{ur} although the contribution found very small.

It is also shown that systematic combination of the cohesion, C and the two friction parameters, μ and ξ, could replicate the varying flow behaviors of sensitive clays with 0.1kPa < c_{ur} < 1.0kPa. ξ ranging from 100m/s^2 to 1000m/s^2 and μ = 0 and 0.15 were chosen to match the lab results. These varying values, especially that of ξ, to replicate the flow behavior shows that selection of these parameters is more dependent on the flow geometry and conditions than the property of the flowing material.

6.4. Summary on Byneset Slide Analyses

Efforts were made to back calculate the Byneset landslide using DAN3D and RAMMS with their respective version of the Voellmy model. The results obtained from these two tools may not only be affected by the different versions of Voellmy model they use but also by their different way of defining release volume and other mechanisms. Another effect on the outputs may also result from some differences in computational methods they might use. In addition, the result was also found dependant on the resolution of the digital terrain model (DTM) data. The total stress approach in the basal resistance formulation of Voellmy rheology produces higher basal shear resistance by considering the pore-pressure build up inside the sliding debris. However, in reality the excess pore-pressure in debris will result in a reduction of the basal friction.

The cohesion term, the modified Voellmy model incorporated (RAMMS), found insensitive for this real case simulation. This phenomenon was also seen while simulating the small scale run-out test. Therefore more focus was given to the friction parameters.

The friction coefficient is found mainly related with the slope of the flow path stretching from start to end. This approximation to $\mu(f)$ (tan 3° = 0.052) gave more resistance to the flow and make the flow stop earlier than what was actually observed while simulating in both DAN3D and RAMMS. However, $\mu(f)$ = 0.005 - 0.01 back calculated the run-out distance in combination with the appropriate range of turbulence factor.

Two ways to estimate friction coefficient are:

- $\mu = \tan(\Phi)$ where Φ is the bulk friction angle.
- $\mu = \tan(\alpha)$ where α is the slope angle of a line connecting the flow start to the end.

Wide range of values of ξ were able to simulate this case in both DAN3D and RAMMS, (while using c_{ur} = 0.1kPa in RAMMS). The range found to vary between $3000\text{m/s}^2 < \xi < 5000\text{m/s}^2$ which might be attributed to the gentle slope of the flow that requires more energy to drive the flow. These high values of ξ greatly decrease the resistance offered by the velocity term. This tells us ξ might also be depend on the slope of the terrain.

6.5. Conclusion

The attempt to model and analyze scaled up small scale laboratory tests using numerical models in DAN3D and RAMMS (plastic and Voellmy respectively) found less affected by the scaling.

This might be helpful for numerically modeling and analyzing other types of small scale tests of sensitive clay slides.

As the RAMMS manual dictated, calibration of the friction parameters is needed to simulate any given case. The results found from the back calculation of the small scale run-out laboratory test ($800 m/s^2 < \xi < 1000 m/s^2$) and the Byneset slide ($3000 m/s^2 < \xi < 5000 m/s^2$) show that one need to use different ξ values for different flow conditions even when using same type of soil. This asserts that ξ is not that much dependent on the flowing material rather it should be evaluated in reference to the flow condition, flow size and even slope of the path on which the flow takes place.

However it can be suggested as, ***for preliminary studies only***, for large scale sensitive clay slides with gentle slope like Byneset, ξ ranging between $3000 m/s^2$ - $5000 m/s^2$ can be used as starting values for calibrating the Voellmy model together with friction coefficient values ranging between μ = 0.005 - 0.01. Great care must be taken while using these values and selecting a representative one because these values are suggested relying on simulation results of only one case of sensitive clay slide.

7. Recommendations and Future Works

7.1. Recommendations

7.1.1. Recommendation to Users

After conducting back calculations and simulation of one real landslide case and two laboratory procedures using the Voellmy rheological model in RAMMS and DAN3D, it is found that the turbulence factor and friction coefficients must be calibrated for each sensitive clay landslide case situation. The writer recommends careful use of the model and its parameters for sensitive clay slides. As a reminder to users, the plastic model in DAN3D gave a better and close result to back calculate sensitive clay slides by using the remolded shear strength of the soil as described in Section 2.5

7.1.2. Recommendation to Developers

The writer recommends DAN3D developers to work on reducing the long simulation time it takes. Although it is a very powerful tool, long simulation time is disallowing users from exploring it more. In addition, some calculation parameters like 'velocity smoothing coefficient' are ambiguously given in the manual and the default setting which considerably affected the results obtained.

For RAMMS developers, the writer recommends to work on more on the cohesion term introduced in version 1.6. This is a good start but after this study, the cohesion term is found to lack potential to represent different soil types, specially remolded shear strength of Scandinavian sensitive clay soils.

Another recommendation is on the definition of release volume. Most of sensitive clay landslides happen in gentle slopes and detach from the original terrain to flow through their paths by gravity force and the available potential energy. However the current 'release volume' defining mechanism does not allow these phenomena and the writer recommends the developers to consider this situation in the future versions.

7.2. Future Work

As it is described in (Section 1.5 Limitations), many studies need to be done by fulfilling the limitations of this study. Possible future works are listed below:

- Exploring the available rheological models in DAN3D using more real case sensitive clay landslide cases, preferably subaerial, to back calculate the observed run-out distances.
- Additional studies on the Voellmy rheology of RAMMS using other landslide data and investigate its parameter sensitivity (e.g. sensitivity of ξ to different slopes of flow for a given type of material).
- Evaluating the other available numerical modeling tools as well as some of the GRASS GIS based numerical run-out models. Few of them can be found in (http://grasswiki.osgeo.org/wiki/Natural_Hazards).
- In a higher study level, developing rheological model specific for simulating run-out of sensitive clay slides.

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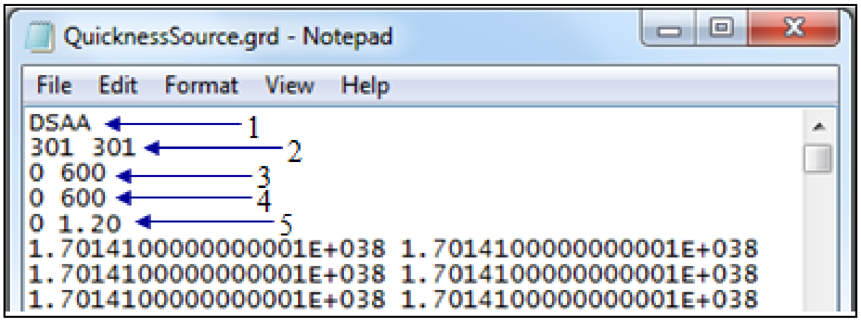
Appendices

Appendix A: Model Grid Preparation of Quickness Test Release Shape



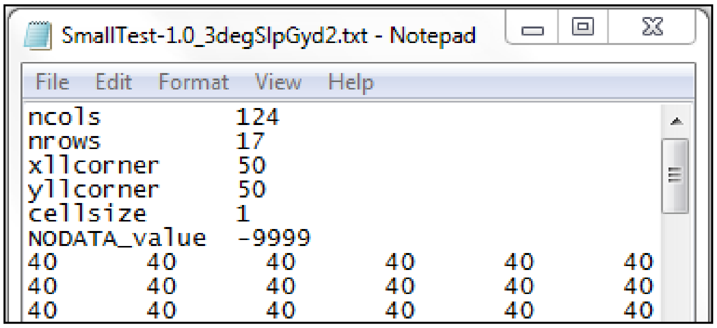
(1) DSAA identifies the file as an ASCII grid file
(2) Number of grid lines along x- and y-directions respectively (number of column & row lines)
(3) Minimum and maximum x-values of the grid respectively
(4) Minimum and maximum y-values of the grid respectively
(5) Minimum and maximum z-values of the grid
The cell size is 2 [=600/(301-1)]

###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###
###	###	###	###	###	###	###	###	###	###	###	0	0	0	0	0	0	0	###	###	###	###	###	###	###	###	###	###	###
###	###	###	###	###	###	###	###	0	0	0	0	1.2	1.2	1.2	1.2	1.2	0	0	0	0	###	###	###	###	###	###	###	###
###	###	###	###	###	###	0	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###	###	###	###	###
###	###	###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	0	###	###	###	###	###
###	###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###	###
###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###
###	###	###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###	###	###
###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###
###	###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###	###
###	###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###	###
###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###
###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###
###	###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###	###
###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###
###	###	###	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	###	###	###
###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###
###	###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###	###
###	###	###	###	###	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	###	###	###	###	###
###	###	###	###	###	###	0	0	0	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0	0	0	###	###	###	###	###	###
###	###	###	###	###	###	###	###	0	0	0	0	1.2	1.2	1.2	1.2	1.2	0	0	0	0	###	###	###	###	###	###	###	###
###	###	###	###	###	###	###	###	###	###	###	0	0	0	0	0	0	0	###	###	###	###	###	###	###	###	###	###	###
###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###

'###' is the number 1.70141E+38 which is a standard blanking number used by Surfer to differentiate from real zero values (Hungr, 2010).

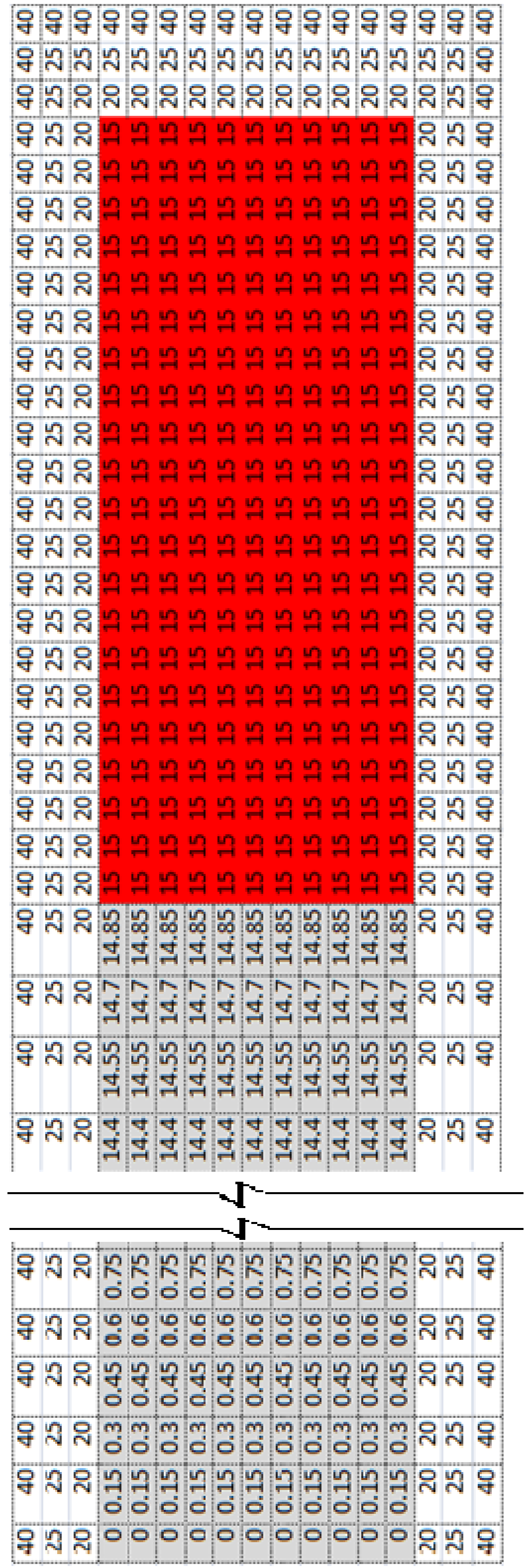
Appendix B: Model Grid Preparation for Small Scale Run-out Laboratory Test

Grid preparation for use in RAMMS
Size 10mX15mX20m with L = 100m and slop 8.53°

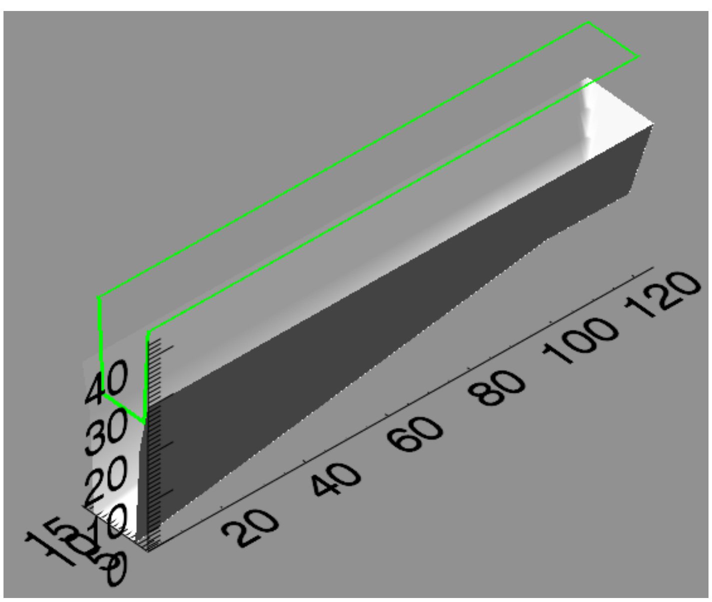


```
SmallTest-1.0_3degSlpGyd2.txt - Notepad
File  Edit  Format  View  Help
ncols         124
nrows         17
xllcorner     50
yllcorner     50
cellsize      1
NODATA_value  -9999
40      40      40      40      40      40
40      40      40      40      40      40
40      40      40      40      40      40
```

ncols = number of columns
nrows = number of rows
xllcorner = x-coordinate of the lower left corner of the grid
yllcorner = y-coordinate of the lower left corner of the grid
cellsize = resolution of the data



40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
40	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	40
40	25	20	20	20	20	20	20	20	20	20	20	20	20	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	15	15	15	15	15	15	15	15	15	15	15	20	25	40
40	25	20	14.85	14.85	14.85	14.85	14.85	14.85	14.85	14.85	14.85	14.85	14.85	20	25	40
40	25	20	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	20	25	40
40	25	20	14.55	14.55	14.55	14.55	14.55	14.55	14.55	14.55	14.55	14.55	14.55	20	25	40
40	25	20	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	20	25	40
40	25	20	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	20	25	40
40	25	20	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	20	25	40
40	25	20	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	20	25	40
40	25	20	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	20	25	40
40	25	20	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	20	25	40
40	25	20	0	0	0	0	0	0	0	0	0	0	0	20	25	40



Three-dimensional view of the model