NTNU – Trondheim
Norwegian University of
Science and Technology

Numerical modelling of run-out of sensitive clay slide debris

Daniel Gebremedhin Nigussie

Geotechnics and Geohazards
Submission date: June 2013
Supervisor: Arnfinn Emdal, BAT
Co-supervisor: Vikas Thakur, Statens vegvesen

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

Norwegian University of Science

and Technology

Master Thesis – June 2013

<table>
<tr><td colspan="1" rowspan="2">Report Title:
<i>Numerical modelling of run-out of sensitive clay slide debris</i></td><td colspan="4">Date: 10 June 2013
Number of pages (incl. appendices): 102</td></tr>
<tr><td>Master Thesis</td><td>x</td><td>Project Work</td><td></td></tr>
<tr><td colspan="5">Name: Daniel Gebremedhin Nigussie</td></tr>
<tr><td colspan="5">Professor in charge/supervisor: Ass.Professor Arnfinn Emdal</td></tr>
<tr><td colspan="5">Other external professional contacts/supervisors: Dr.Vikas Thakur</td></tr>
</table>

Abstract:

Flow slides in sensitive clay deposits are common phenomena in Scandinavia and Canada. These flow slides have caused catastrophes to infrastructure and human life. The post-failure movements of such flow slides usually are characterized by their retrogression distances and or by the run-out distance of the slide debris. There are empirical and numerical methods used to assess the retrogression distance of slide debris. On contrary, convincing and accurate modeling techniques for run-out of sensitive clay slide debris, which is a very complex and challenging process, is yet to be developed Keeping this in view, this work presents a preliminary study to understand the run-out process in sensitive clay slide debris. An available numerical tool called DAN3D has been used to simulate the run-out process of three large flow slides occurred in Norway. In addition, back-calculation of a laboratory scale model test has been performed. A standardized calibration and adjustments on the models based on back analysis of real cases has to be done to use such models on sensitive clay debris analysis extensively. The Study shows that a very simple plastic model in DAN3D is able to estimate the run-out distance and the process.

Keywords:

1. Run out distance
2. Rheology
3. Remoulded shear strength
4. Viscosity

Norwegian University of Science and Technology *Master Thesis – June 2013*

Master Thesis

Spring 2013

For

Daniel Gebremedhin Nigussie

Numerical modelling of run-out of sensitive clay slide debris

Background

Landslides have been and are hazards that cause a drastic loss to human life and infrastructure. The risk increases in urban and more populated areas. The ability and efficiency to predict the intensity of landslides will greatly reduce the risk.

There are various reasons that could cause landslides. Some of the causes can be: geological, morphological or human causes. Among the types of landslides, clay slides (particularly highly sensitive clay slides) are the major interest in this thesis work. Highly sensitive clays, also known as quick clays, are found in Norway, Sweden and some part of Canada. Post-failure movements of the debris involved in sensitive clay slides have a potential to destroy human life and infrastructure. The ability to predict the extent and intensity of sensitive clay slide before it happens enhances to protect settlement and infrastructures from damage.

Post-failure movements in sensitive clay slides are characterized by two main parts, retrogression distance and run-out distance. A sensitive clay slide might be retrogressive, flow or may contain both parts. The study of the retrogressive behavior has been given much emphasis. This is due to the fact that, in sub aerial landslides retrogression is more of a problem than the flowability. The run-out of sensitive clay slides is usually along a channelized river or stream and the study of the flow behavior was less important so far. However, some of the sub-aerial slides have affected larger areas and the study of the flowability is important in this regard.

Back analysis, which is an analysis of an already occurred event, of the run out distance of the flow type slides has been discussed in detail. Empirical and numerical study has been made to characterize the run-out of sensitive clay slides.

This master thesis is a part of the national program called Natural Hazards- Infrastructure for floods and slides (NIFS).

Task Description

Empirical studies have been done on the run-out of landslides. Among the empirically developed relationship, an extensive data has been analysed by Coromias(1996) .This relationship has been applied to 12 landslide cases.

Numerical study has been made using a quasi-3D code, DAN3D (Dynamic Analysis of Landslides in Three Dimensions).The numerical study was conducted on three real cases; the Byneset landslide (2012), the Finneidfjord landslide (1996) and the Lyngen landslide (2010). In addition, a model laboratory landslide test has been modelled and back analysed using the numerical model. The numerical study comprises building a model, parameterizing and analyzing the simulation results.

The following are some of the expected results from this study:

- Literature review regarding sensitive clay slides in Norway
- A critical review of various numerical tools available to model run-out distances
- Application of DAN3D for sensitive clays
- Back calculation of three major sensitive clay slides in Norway
- Back calculation of the small scale model tests to study the significance of remolded shear strength in run-out of slide debris
- Suggestion for the further improvement of DAN3D

Ass. Professor Arnfinn Emdal
NTNU

Dr.Vikas Thakur
Norwegian Public Roads Administration

Contents

Preface and Acknowledgment

This master thesis was written at Geotechnical Division of the Norwegian University of Science and Technology (NTNU). Literature review and results from numerical simulations are included in this thesis work.

I would like to express my sincere gratitude to my supervisors Dr.Vikas Thakur and Ass.Professor Arnfinn Emdal for their immense assistance. I would like to thank Professor Oldrich Hungr (University of British Columbia) for providing DAN3D software, Dr.José Mauricio Cepeda (NGI) for providing surfer input files, Haragewoin Haile (NTNU) and Kenneth Sundli (NTNU). Last, but not least my special thanks to my family and friends who have been encouraging me throughout my studies.

List of Figures

List of Tables

1. Introduction

Landslides are downward and outward movements of a slope (it can be either gentle or steep).The sloping surface might be comprised of one or both of these materials: soil, rock or artificial fill. It is possible to differentiate landslides based on the material involved and mode of the slide movement.

There are various reasons that could cause landslides. Some of the causes can be: geological, morphological or human causes. Among the types of landslides, clay slides (particularly quick clay slides) are the major interest in this thesis work. Quick clays are soft sensitive marine clay deposits which are found in Norway, Sweden and Canada .Slides related with such clays have caused catastrophes to human life and infrastructure. Ever since the data is recorded, as much as 1000 people have died in Norway only .The ability to predict the extent and intensity of quick clay slide before it happens enhances to protect settlement and infrastructures from damage. A mapping of potential quick clay areas is underway in Norway.

Back analysis, which is an analysis of an already occurred event, of some of the well documented cases is the major part of this work. Hazard mapping for quick clay slides can be based on retrogressive potential, run out distance, volume of debris and velocity of the sliding mass.

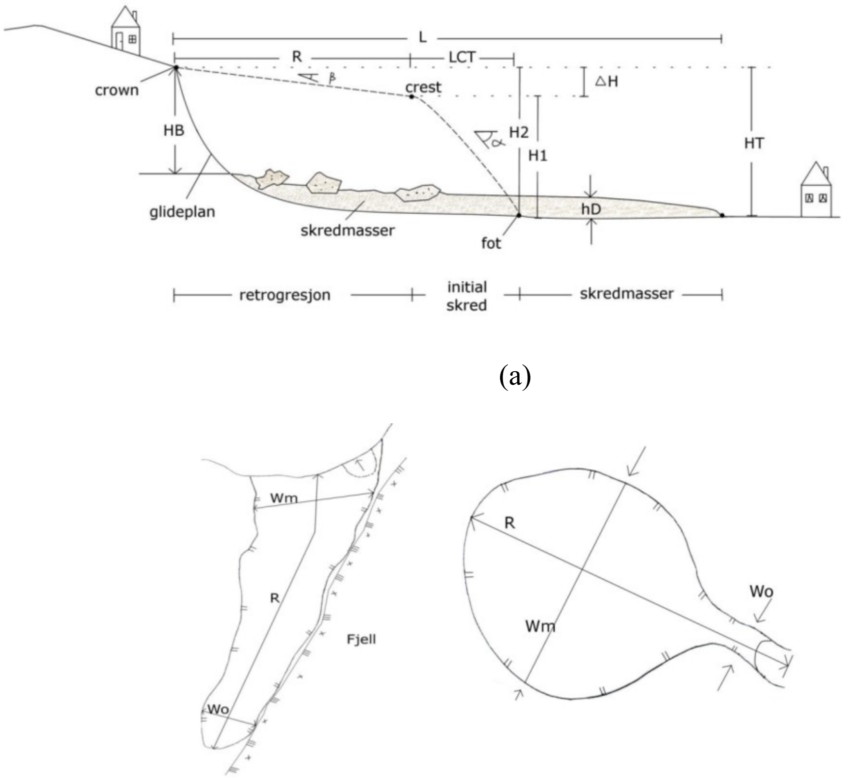
Numerical models that can fairly simulate quick clay slide movements have not yet been developed. Quick clay slides have a complex and peculiar behavior than other types of landslides for instance rock falls, snow avalanches or other debris flow. The existing numerical models are best suited for the before mentioned slide types. The analysis was done in a quasi-3D code called DAN3D.In addition, empirical relations has been studied together .The analysis results and theoretical backgrounds related with the post slide movements are discussed in the subsequent chapters.

2. Literature review

Landslide hazard related with sensitive clays are common in Scandinavia and Canada. Such clays liquefy when loaded above a certain threshold value and can trigger large slides. The Rissa slide in 1978 is the one which is well recorded, a small fill along the shore line has mobilized as much as 5 to 6 million m^3 of soil mass (Gregersen 1981).

2.1 Geometrical representation of landslide

The geometrical representation of landslides is important to characterize and study them in detail. A well-developed geometrical representation made by Natterøy (2011) as shown below.



(a)

(b) (c)

Figure 2-1 Geometrical representation of a landslide. (a) Cross section (b) and (c) top view .Glide plane also called rupture surface where the slide mass (skredmasser) moves along. h_D – deposit depth, H_T – total drop height, H_1 – initial drop height, H_2 – vertical extent of failed volume, ΔH – altitude difference along back slope, H_B – escarpment height, L – total run-out length, L_{CT} – length of fore slope, R – retrogression distance, W_0 – minimum width of the release gate, W_m – maximum width of the release area (Natterøy 2011)

2.2 Types of Landslides

According to US geological survey slides can be categorized into the following major classes:

- Slides: this is a general term that refers to mass movements. A weak zone separating from a more stable underlying material. Slides can be divided in two:
    - Rotational slide-In this type of slides, the rupture surface creates an upward concave shape (fig 2-2A).
    - Translational slide-A mass moving along a planar surface .This type of slide is the same as block slide but (fig 2-2C) except that block slides might be a single unit or coherent pieces.
- Falls-a sudden movement of masses such as rocks from steep slopes.
- Topples-forward rotation of masses on a pivotal point.
- Flows-under flow slides there are five categories
    - Debris flow-due to heavy rainfall or rapid snow melt, loose soil or rock might flow along a slope as shown in figure 1f.
    - Debris avalanche-are debris flow with very rapid mass movements.
    - Earth flow-a liquefied material flowing down slope as shown in figure1H
    - Mudflow - are basically earth flows containing wet material.
    - Creep- long term deformation of soil particles that might create a downward movement.
- Lateral spreads-ground motions like earthquake or heavy vibrations might create lateral spreads shown in figure2-2J (Highland 2004).

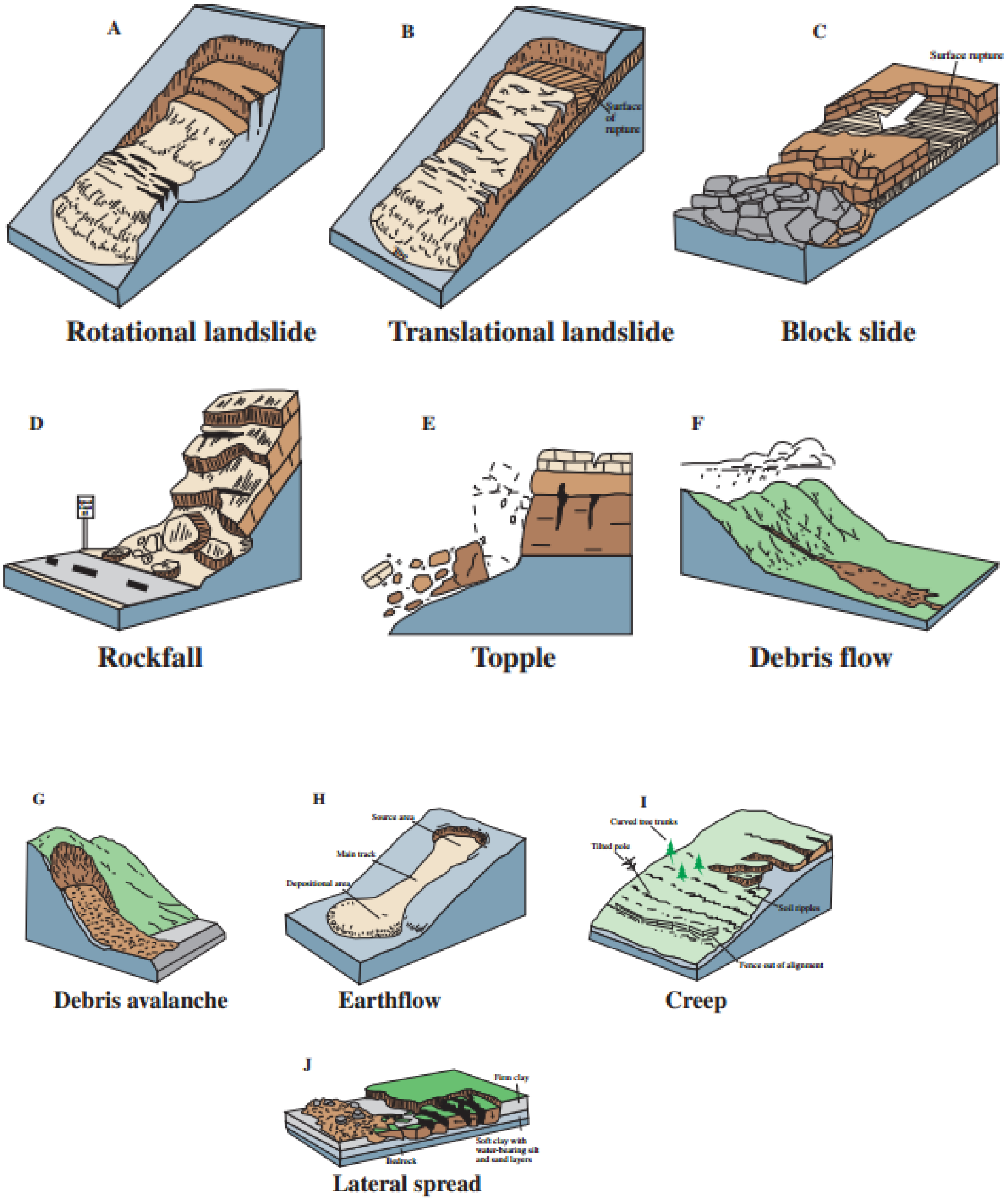


Figure 2-2 Landslide types

In addition to the USGS classification a more detailed classification of flow landslides has been presented (Hungr et al 2001). Accordingly, flow slides can be divided in to 11 classes.

Material	Water Content	Velocity	Name
Silt,Sand, Gravel,Debris (talus)	dry,moist or saturated	Various	Non-liquified sand (silt,gravel,debris)flow
Silt,Sand, Debris,Weak rock	Saturated at rupture surface content	Ex.Rapid	Sand(silt,debris,rock) flow slide
Sensitive clay	at or above liquid limit	Ex.Rapid	Clay flow slide
Peat	Saturated	Slow to very rapid	Peat flow
Clay or Earth	near plastic limit	< Rapid	Earth flow
Debris	saturated	Ex.Rapid	Debris flow
Mud	at or above liquid limit	> Very rapid	Mud flow
Debris	free water present	Ex.Rapid	Debris flow
Debris	partly or fully saturated	Ex.Rapid	Debris avalanche
Fragmented Rock	various,mainly dry	Ex.Rapid	Rock avalanche

Table 2-1 Classification of flow slides

Among the types of slides mentioned in the table above, clay flow slides are the major concern of this work. Clay flow slides are rapid flow of liquefied clay which exhibits water content close to the original. Some clays exhibit a structural collapse during failure and this might result in loss of strength and in turn a rapid movement of the masses might occur .The extra sensitive marine clay (quick clay) slides are moderately over consolidated and once remolded they will become viscous liquid (Locat 1993). A more detail mechanisms of this slides is discussed in the section 2.5.

2.3 Formation and Origin of Quick Clays.

Marine clay deposits accumulated in the sea and fjords following the last ice age lead to sensitive clays. Leaching of ions, by fresh ground water results in the high sensitivity of these clays. Fresh water percolating downwards through the marine deposits due to surface runoff or up wards due to artesian pressures removes the salt ions and leaves behind a unstable, sensitive structure made up flocculated clay minerals. Upon remolding, the clays will lose their structure and surface water is liberated (L'Heureux 2012).A pictorial representation showing where we can find quick clays is shown below (Løken 1983).

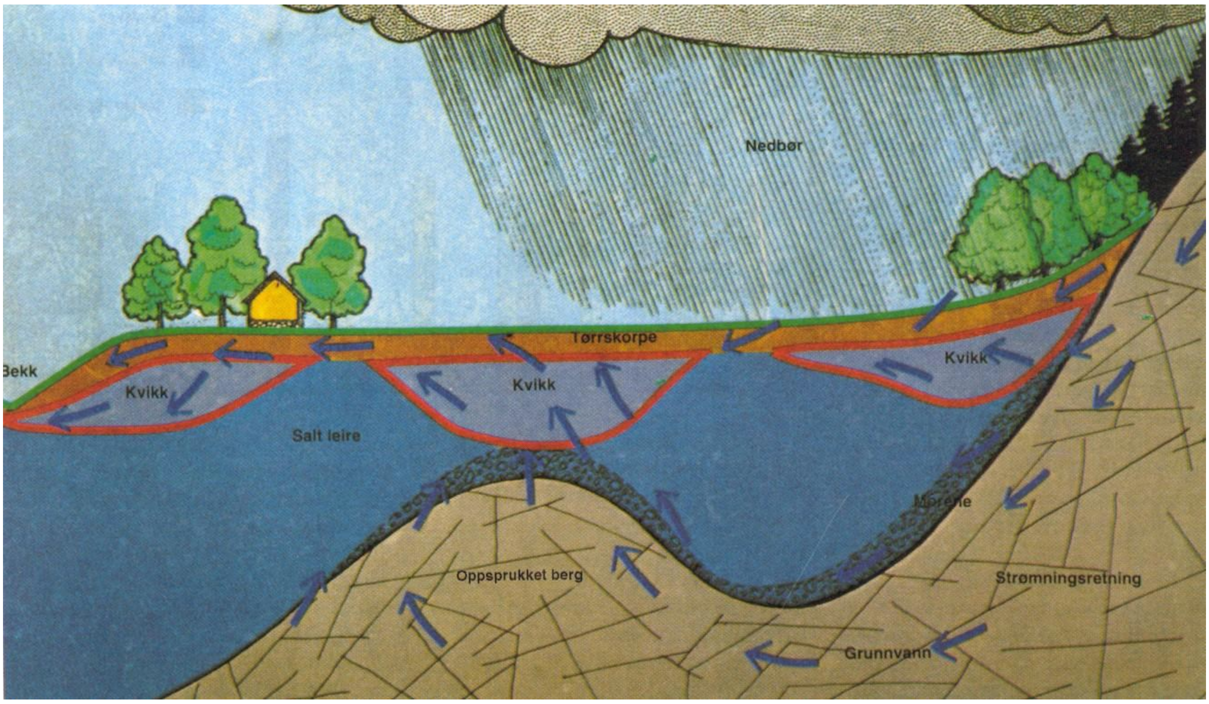


Figure 2-3 Theoretical model showing zones of quick (Løken 1983)

2.4 Characterization of Quick Clays

The Norwegian Water and Energy Directorate (NVE) has set a guideline on how to classify brittle clays. Clays with remoulded shear strength (C_{ur}) less than 2.0 KPa and sensitivity (S_t) greater than 15 are treated as brittle clays. Furthermore, brittle clays can be categorized as quick or sensitive based on the remoulded shear strength. $C_{ur} < 0.5$KPa are termed as quick clays and the remaining as sensitive (NVE 2011).In Sweden clays with sensitivity larger than 50 and $C_{ur} < 0.4$ KPa.

The understanding of the various physical and geotechnical behavior of quick or sensitive clays is important to understand the mechanisms of slides due to such materials. Some aspects that can characterize quick clays are discussed here.

Atterberg limits are water contents that are used to characterize cohesive soils. Atterberg limits include liquid and plastic limits and they are determined at the laboratory. Liquid limit is the water content at which the soil changes from plastic to liquid behavior and Plastic limits are the water content expressed as oven dried soil at which the soil begins to crumble into short pieces when rolled into a thread about 3mm in diameter.

Plasticity index is ($\mathbf{I_p}$) a measure of the plasticity of a soil. Plasticity index is the size of the range of water contents which exhibits plastic property. The plasticity index is the difference between the liquid limit and the plastic limit.

Liquidity index (*$\mathbf{I_L}$*) is used for scaling the natural water content of a soil sample to the limits. It can be calculated as a ratio of difference between natural water content, plastic limit, and plasticity index.

Laboratory tests show the relationship between atterberg limits and salinity (salt content). As mentioned in section 2.1 leaching have resulted in the low salt concentration of such clays. The liquid limit and plastic limits show a decrease for lower salt content in the pore water (Bjerrum 1954).Quick clays have plasticity indices between 8 and 10 % (Trak and Lacasse 1996).

The lower salt concentration also resulted in the lower shear strength of quick clays. As can be seen in the figure below, the lower the plasticity index is the lower is the normalized shear strength value.

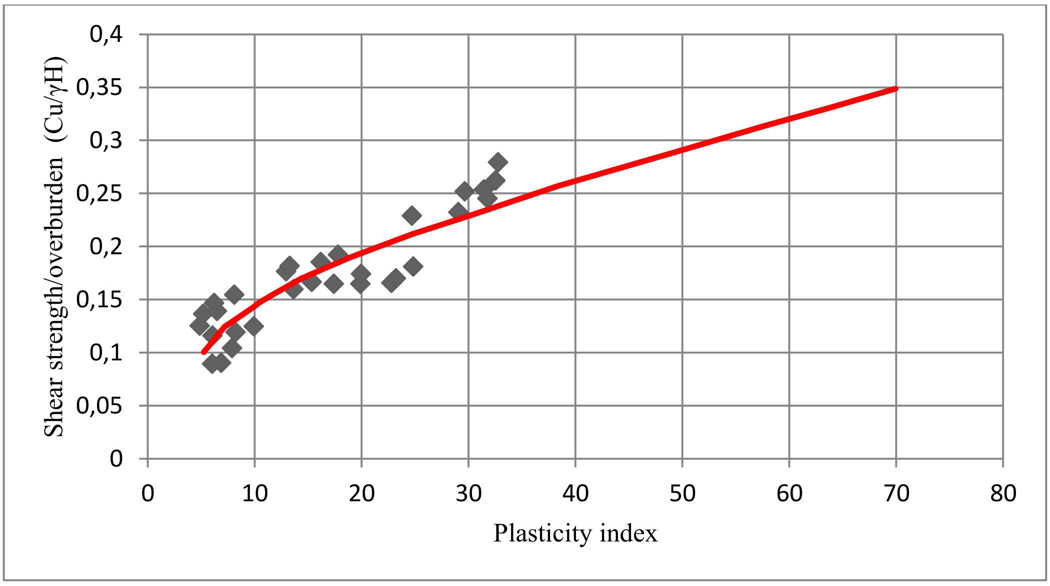


Figure 2-4 Plasticity index vs Shear strength (Bjerrum 1954)

Sensitivity is the ratio between the intact and remoulded shear strength and it gives a more understanding of the behavior of quick clays. A general presentation of sensitivity is presented below (V.Thakur et al 2012).

Sensitivity (St)	**Classification**	**Remarks**
1	Non sensitive	L:low M:medium H:high E:extra S:sensitive Q:quick
1-8	LS	
8-16	HS/ES/SQ	
16-32 (30)	Q/MQ	
>32 (30)	Q	

Table 2.4 Classification of Sensitivity

The liquidity index and sensitivity relations have been studied for clays and are shown in the figure below.

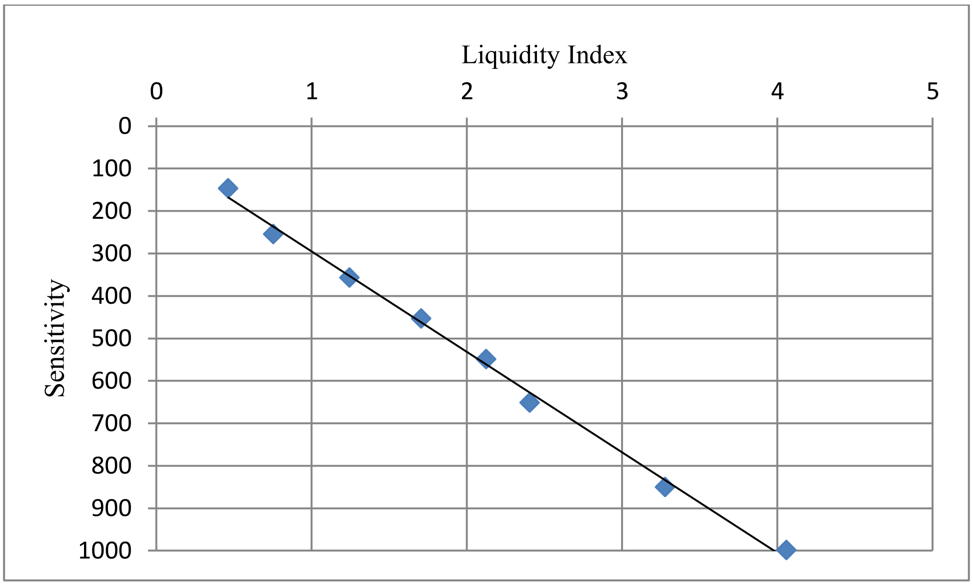


Figure2-5 Relation between Liquidity index and Sensitivity (Bjerrum 1954)

As presented above the characteristics of quick clays will be understood better by studying the relationships among the various parameters that will exhibit the peculiar behavior of such clays.

Quickness test is a new type of test performed on a thoroughly remoulded material placed in a cylinder .The test was done on several samples and it gives a better understanding of the remoulded shear strength and its relationship with flow susceptibility (V.Thakur et al. 2012).The procedure for the test resembles that of a concrete slump test. Cylinders of height 120mm and 45mm and diameter of 100mm and 65mm were used in the test.

The results from the test reveals that samples with C_{ur} values less than 0.2KPa are more like soup while those between 0.4Kpa and 1 Kpa are more of viscous or semisolid. The relationship between C_{ur} and Quickness in % is presented below.

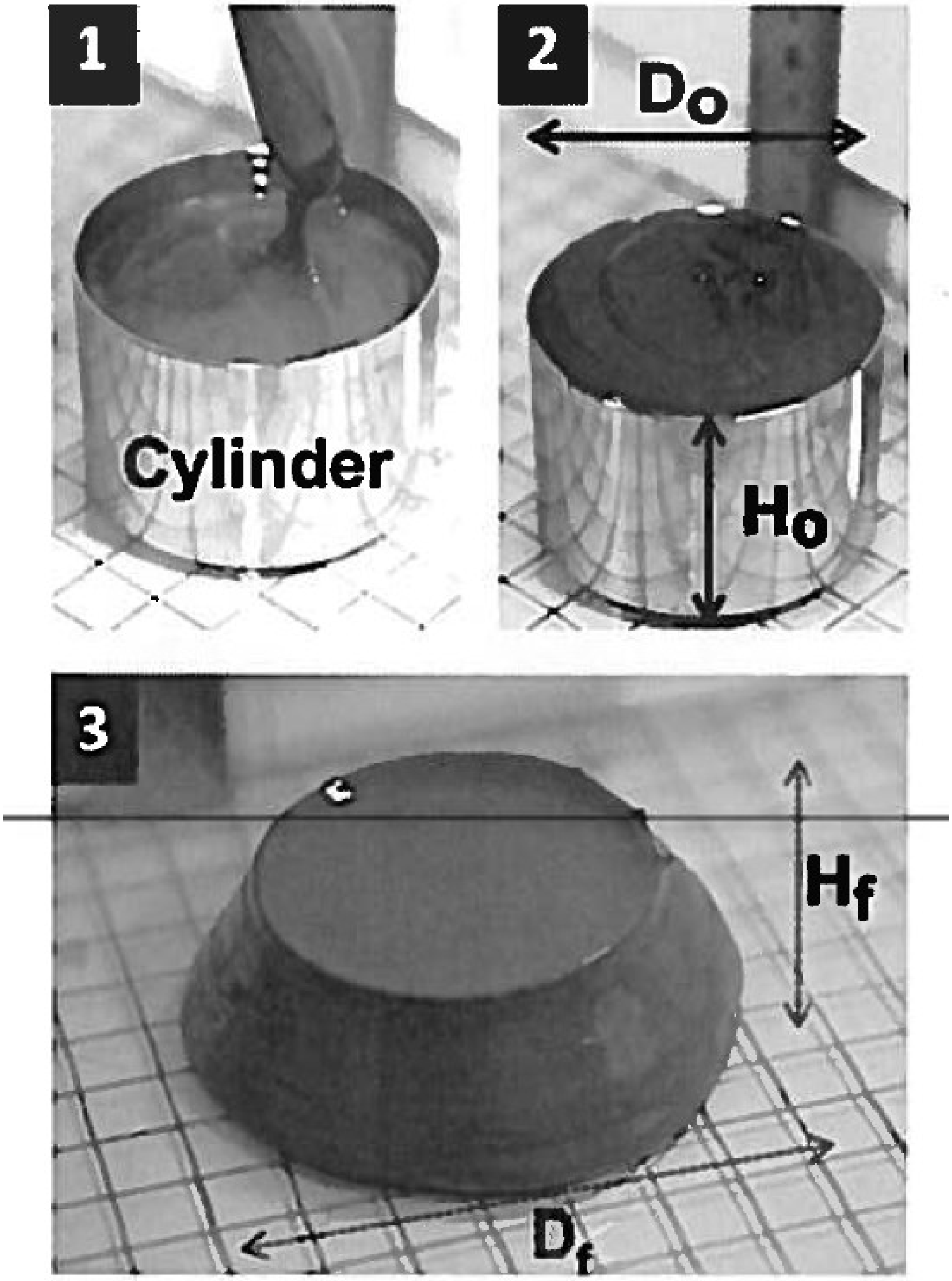


Figure 2-6 Test procedure for Quickness test, Quickness [%] is defined by (1-Hf/H0)x100 (V.Thakur et al. 2012)

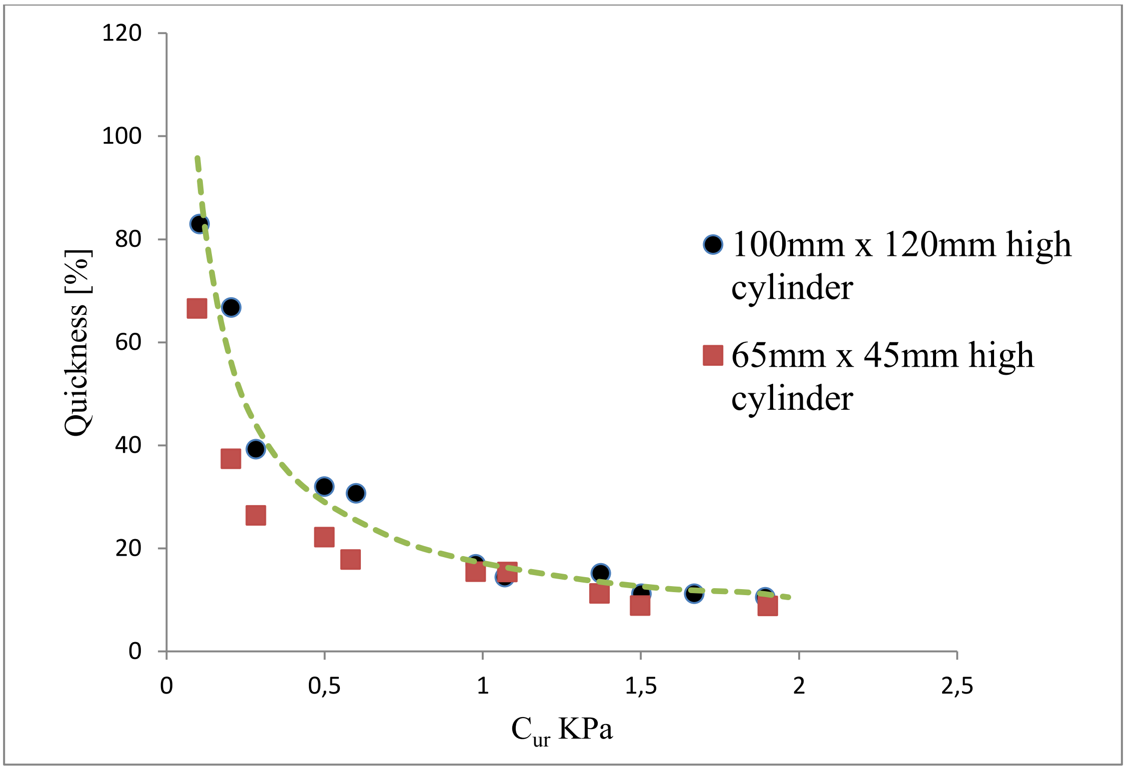


Figure 2-7 Quickness versus Remoulded shear strength

Remoulding energy is the energy needed to remould the slide mass (Tavenas et al. 1983).The remoulding energy can also be defined as the strain energy required to remould the material. An analytical approach has been proposed by (V.Thakur et al. 2012).The approach is based on linear elastic and a linear strain softening behaviour. However, in reality the strain softening part is not a linear curve as shown in the figure below but for the purpose of simplicity it is good to adopt the linear curve.

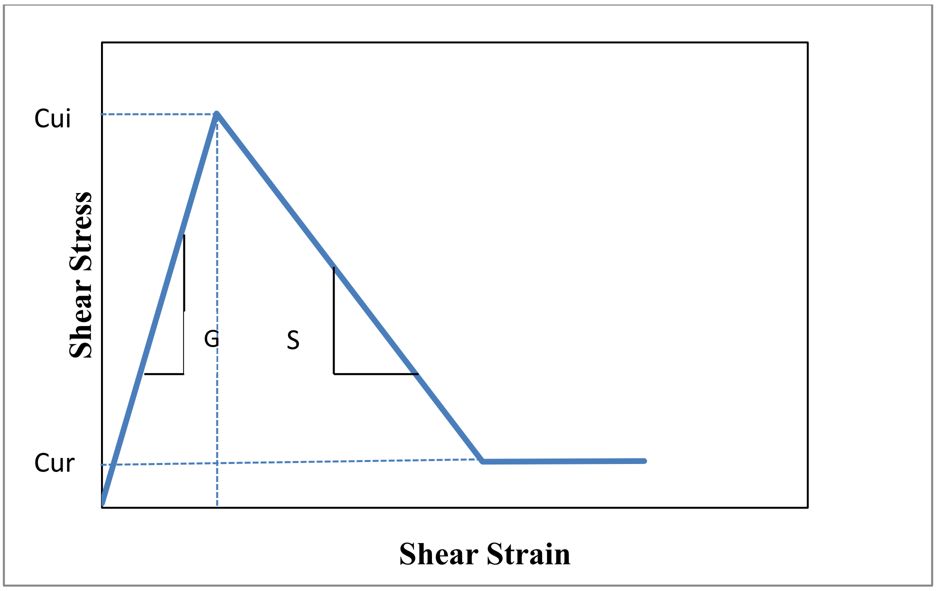


Figure 2-8 Remoulding Energy,G and S represent the hardening and secant modulus

$$\mathrm{Er} = \mathrm{Cur} * \gamma\mathrm{r} - \frac{\mathrm{Cur}^2}{2\mathrm{G}} + \frac{((\mathrm{St}-1)*\mathrm{Cur})^2}{2} * \left(\frac{1}{G} + \frac{1}{S}\right) \qquad (2.4)$$

2.5 Quick Clay Slide Types

Landslides in sensitive clays in general can be classified into three stages:

- Pre failure stage – this is a stable stage where potential triggering factors evolve towards a complete failure.
- Failure stage – the yielding of the available strength.
- Post failure stage – is the state where the slide mass can either stabilize itself or flow some distance along the surface of rupture. The potential aspects of such stage might comprise retrogression or flowability (Locat and Leroueil 1997) .

Based on the mechanism of failure (K.Karlsrud et al.1984) divided Quick clay slides into four major types.

A. Initial Slides-a monolithic rotational slide restricted within a shorter distance.
B. Retrogressive landslides-if an initial slide leaves unstable back scarp there might happen a multiple retrogressive failure until a stable back scarp is formed. The presence of highly sensitive or quick clays in the back scarp might lead to retrogressive failures which lead to rapid flow of the mass down slope. A pictorial representation is shown below.

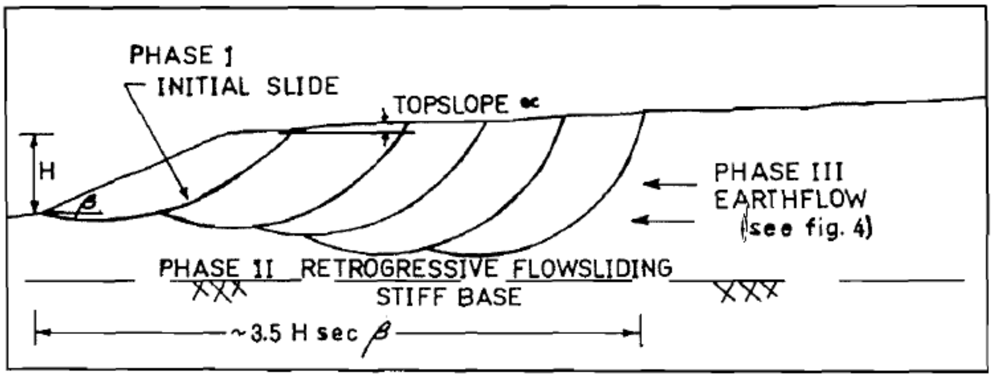


Figure 2-9 Retrogressive Slide (Mitchell and Markell 1974)

C. Monolithic flake type of slides- a large area can slide out as a single monolithic unit. Some Norwegian landslides for example, the 1953 Bekklaget Slide,is such type.

D. Vertical Sinking and lateral Spreading-this type of slide might involve squeezing out of remoulded clay in the down slope. A good example of a spread in sensitive clay material is the 2010 landslide at St-Jude, Quebec, Canada (Locat P et al. 2011).

The slides mentioned from B to D are often very rapid and might cover large areas. Monolithic flake type of slides are common in Scandinavia but are not common in Canada. Spreads accounts 42% of large landslides recorded in Canada (Locat P et al. 2011). The table below shows documented Norwegian quick clay slides.

Year	**Landslide** ***(Ref.^)***	**Type**	**L_R**	**L_F**	**V**	**c_{ur}**	**S_t**	**I_L**	**I_P**
			[m]	[m]	[10^5 x m3]	[kPa]	[-]	[-]	[%]
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[!]	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]	F /FL	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	3-5	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	2-3	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[!]	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

Table 2.5 slides in sensitive clays in Norway

**L_R = Retrogression distance measured from the toe of slope, L_F = run-out distance measured from the toe of slope; H = slope height; V = slide volume; c_{ur} = remolded shear strength along slip surface; S_t = sensitivity, w = water content, w_L = liquid limit, Ip = plasticity index, I_L = liquidity index; NA= Exact year data not available, F= flow slide, FL= flake slide RR= retrogressive slide, RT= rotational slide*

^References: [1]Mayerhof(1957),[2]Egeland and Flateland (1988),[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, [10]Thakur (2012), [11]Furseth (2006),[12]Longva et al. (2003),[13]Holmsen and Holmsen (1946),[14]Karlsreud (1983), [15]Thakur et al. (2012), [16]Huchinson(1961), [17]Karlsrrud (1979), [18]Drury (1968), [19]Nordal et al. (2009), [20]NVE reports, [21]Natterøy(2011), [22]NPRA reports, [23]Sevaldsen (1956), [24]Gregersen (1981), [25]Larsen (2002), [26]NGI(1974), [27]Kenney (1967), [28]Janbu (2005), [29]Bjerrum (1955), [30]Jørstad (1968), [31]Huchinson (1965)

[!] These two names represent the same landslide

2.6 On the mobility of Quick clay slides

Landslides related with quick clays have two main parts, retrogression and flow. The retrogression behavior has been studied in connection with certain parameters. Previous studies made correlations between the potential of retrogression and Stability number ($Ns=\gamma H/Cu$) (Mitchell and Markell 1974).The deduction from thid study was ,if the stability number is greater than 6 ,there will be a potential of retrogression and if it is less than 6 the retrogression will stop. This was based on a collected data of 41 quick clay slides in Canada. However, this is subjected to topographical constraints. The stability number was related with the length of retrogression and presented for Norwegian and Canadian landslide cases in the figure below. The length of retrogression (L_R) was greater than 100m for N_s >4for Norwegian slide cases.

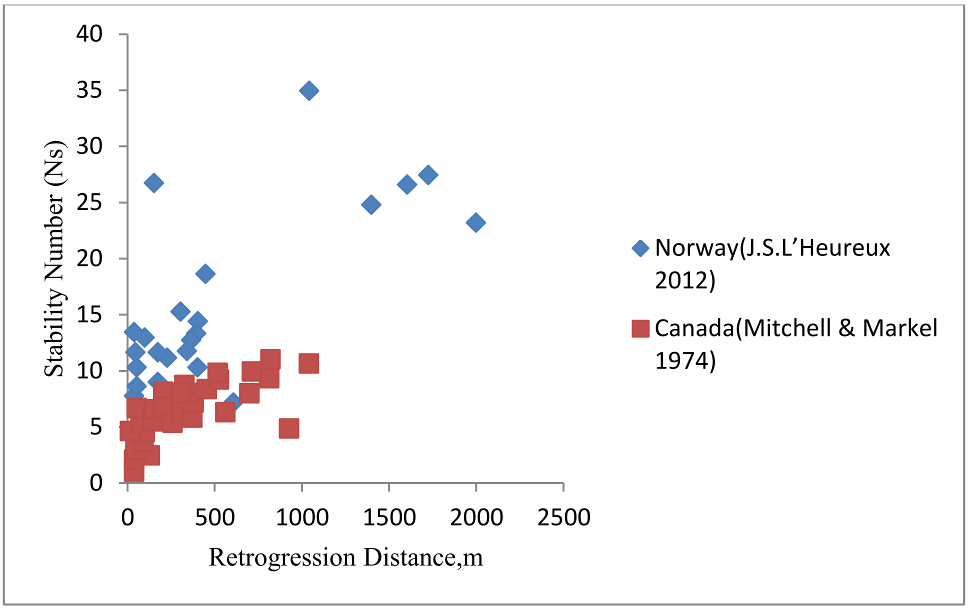


Figure 2-10 Retrogression distance versus Stability number

This correlation failed to describe the retrogressive behavior on some slide cases in Norway. The Lersbakken slide that occurred in 1989 and the Fredrikstad slide which occurred in 1970.

Ground investigations at the Lersbakken slide has shown that the initial slide occurred in the material with remoulded shear strength less than 1KPa and stability number of 7.6.Furthermore, the slide debris has moved 10-15 m away from the slide location. However, no retrogression was observed.

Investigations in the Fredrikstad slide has also shown that the initial slide has occurred in quick clay with remoulded shear strength of 0.5KPa .Besides, the topographical constraint does not exist. But no retrogression was observed again in this case (V.Thakur et al. 2012).

The retrogression distance was studied together with other parameters like remoulded shear strength, liquidity index and sensitivity. Based on collected data such correlations have been done for Norwegian and Canadian quick clays as presented below.

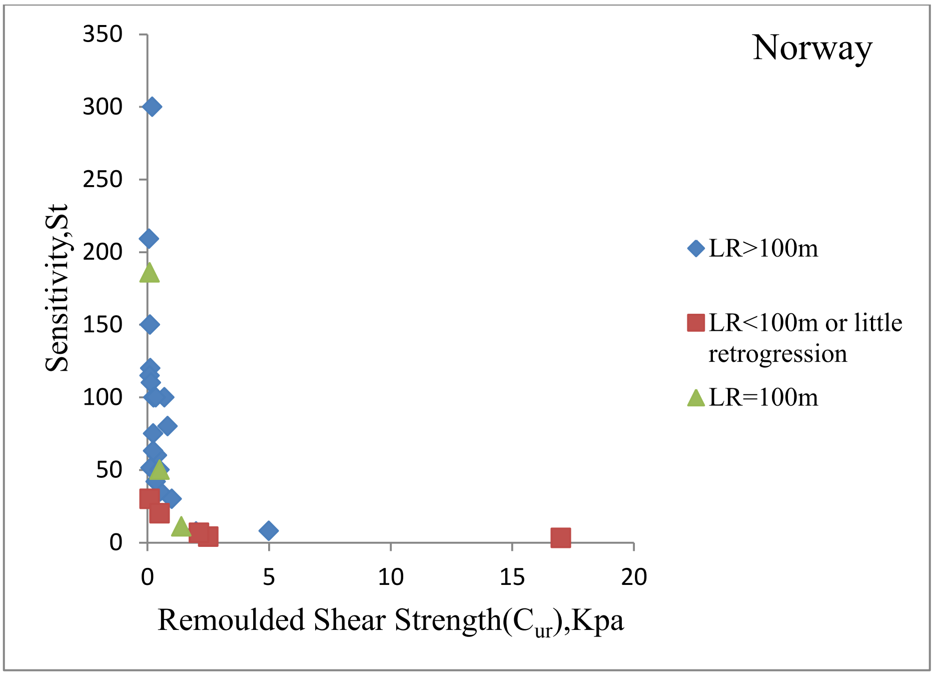


Figure 2-11 Cur versus Sensitivity for Slides in Norway

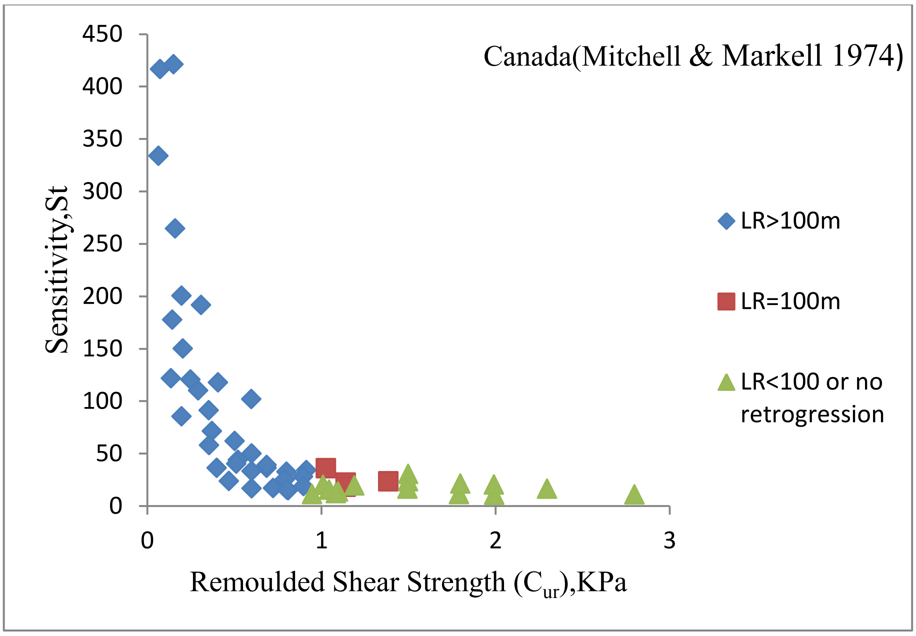


Figure 2-12 Cur versus Sensitivity for Slides in Canada

The retrogression distance in relation to remoulded strength shows the C_{ur} < 1KPa has a higher retrogression distance (L_R>100m) while C_{ur} values greater than 1 shows no retrogression (V.Thakur et al. 2012).For Norwegian slides C_{ur} values less than 0.5 KPa shows retrogression distance greater than 100m.

As shown in the above figures the remoulded shear strength together with sensitivity gives a better understanding of the retrogression behavior of soils. Furthermore, the remoulding energy is an important parameter.

According to (Lebuis et al. 1983) the risk of retrogression is based on the liquidty index,sensitivity and remoulded shear strength.Three conditions can be drawn regarding retrogression (Tavenas et al. 1983).

a) Remoulding energy or the ability of the clay to be remoulded
b) The ability of the clay to flow out of the landslide crater.The consistancy of the remoulded material which is related with the liquididty index and remoulded shear strength.
c) Topographical situation that will enable the evacuation of the debris.

The above mentioned points are the necessary criteria's for the development of retrogressive landslide.

The other part on the mobility of quick clay slides is the flow part. For sub aerial landslides retrogression is more of a problem than the flowability (Locat and Leroueil 1997).This is due to the fact that the slide mass move along a channelized river or stream. However, some of the sub-aerial slides have affected larger areas and the study of the flowability is important in this regard.

On section 2.2 above remoulding energy has been mentioned as one element on the characterization of sensitive clay slides. The available potential energy in a soil mass plays an important role in the flowability (L'Heureux 2012).

The potential energy in a soil mass (Ep) can be given by the following formula:

$$E_p = H_G.\gamma.\mathrm{V} \qquad (2.6.1)$$

Where H_G is the vertical displacement of the center of mass of the slide and V is the volume of slide mass. The available total energy at time t is given by the following formula (L'Heureux 2012).

$$\Delta E_T = \Delta E_P(t) + \Delta E_F(t) + \Delta E_R(t) + \Delta E_k(t) \qquad (2.6.2)$$

The subscripts on the above formula represent the friction, remoulding and kinetic energy respectively. The available energy will be dissipated due to friction, for remoulding and the remaining will be a kinetic energy. The energy is left after dissipation due to friction and remoulding which is the kinetic energy that determines the mobility of the slide mass. The kinetic energy approaching to zero indicates the slide mass will be at rest.

Remoulding index (I_D) introduced to describe the remoulding state (Vaunat and Leroueil 2002).It is the ratio between the potential and remoulding energy. Furthermore, the destruction index was related with the undrained shear strength and plasticity index. Less remoulding energy is needed to for cohesion less materials than for cohesive soils .The overall point in remoulding energy and the available energy is that, the amount of energy left after remoulding should be enough to allow the flow of the slide mass.

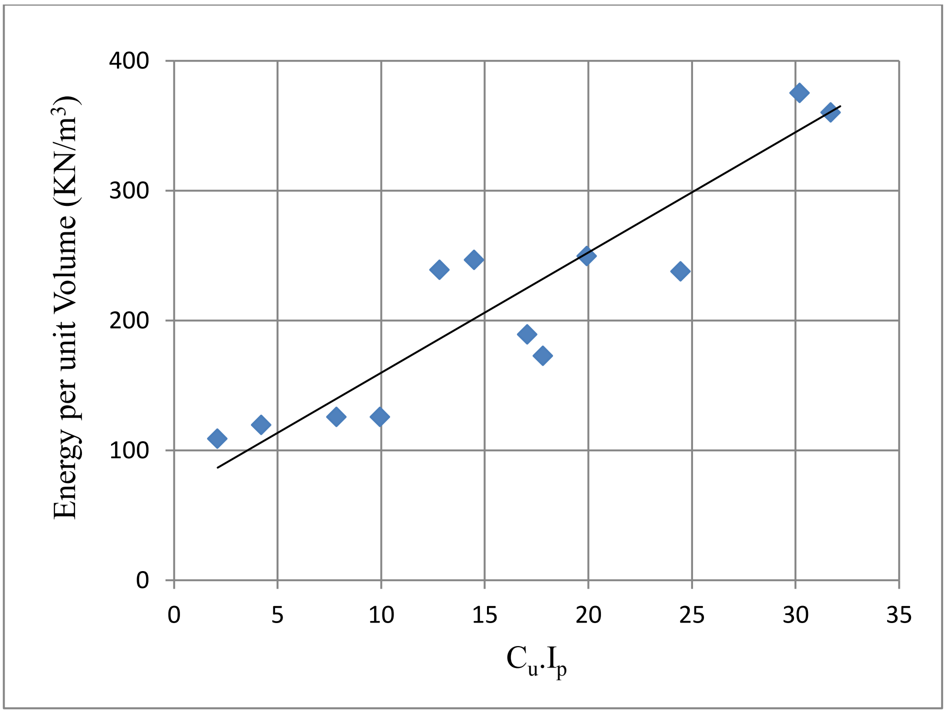


Figure 2-13 Energy required to achieve 75% of remoulding in soft sensitive clay at a given plasticity and undrained shear strength (Leroueil et al. 1996)

2.7 Rheological Properties of Sensitive Clays

Rheology describes the flow nature of liquids or soft solids. The study of the plastic viscosity, yield stress, remoulded strength and their correlations gives a good understanding on the flow nature of sensitive clays. A study was conducted on many samples in Canadian sensitive soils. Remoulded strength and plastic viscosity values were predicted based on the developed correlations. The long run out distance for the well-known slides in Scandinavian and Canada are usually related to the remoulded shear strength or in other words to the viscosity of the soil mass at the post failure stage.

Viscosity of sensitive clays might vary based on soil type, pore water salinity, mineralogy and water content. The main type of flow is described in figure 2-14 below.The slope of each curve represents the viscosity .Curve 2 represents a thickening fluid behavior, in which the viscosity increases with increasing shear rate. Curve 3 represents fluidizing liquids, in which a decrease in viscosity for increasing shear rate is observed. Curve 4 represents Casson fluids, in which the viscosity shows a gradual decrease for an increasing shear rate. Curve 5 represents Bingham fluids for which a constant viscosity after yielding is observed (Locat and Demers 1988).

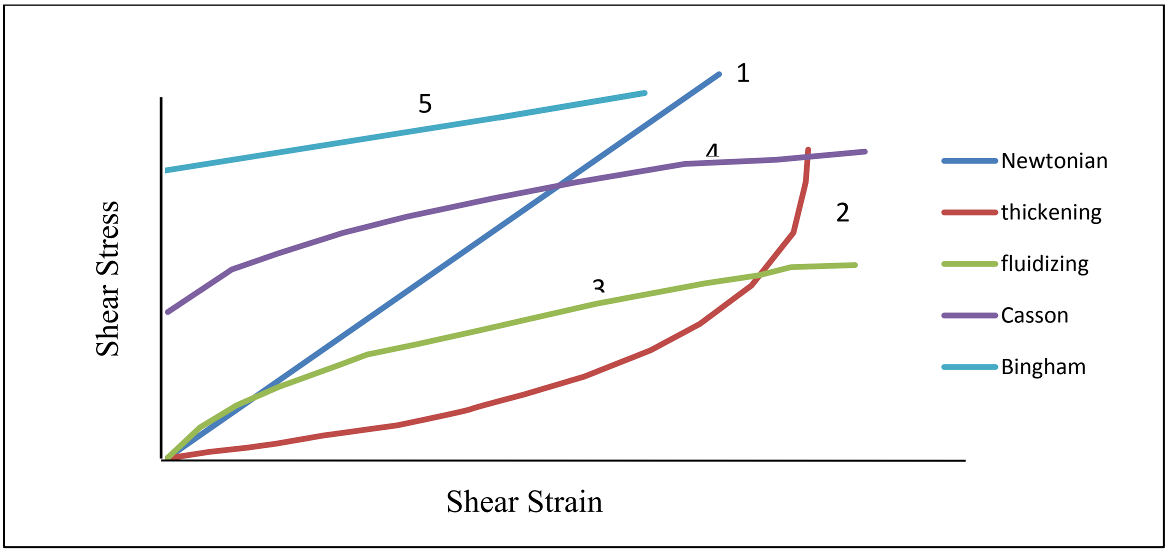
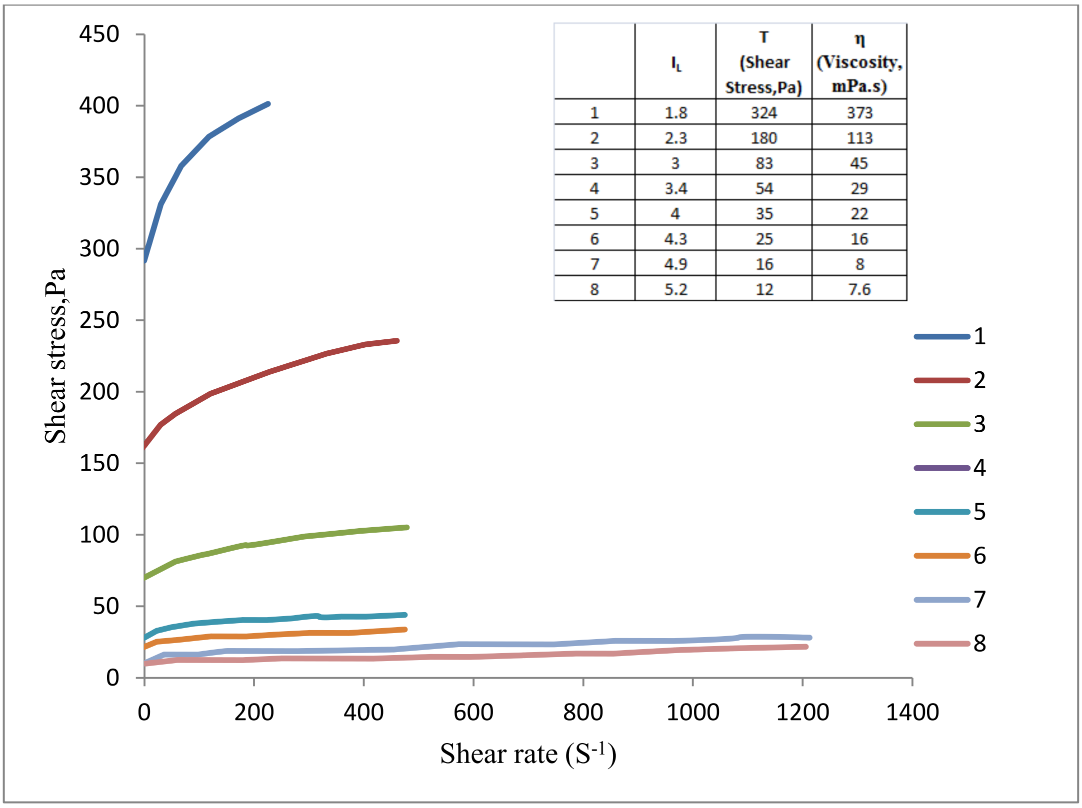


Figure 2-14 Major types of fluid (Locat and Demers 1988)

Based on 70 viscometric laboratory tests on sensitive clays, a gradual decrease in the yield stress for increasing water content or liquidity index was observed. The computation of viscosity was based on the shear stress-shear strain curves developed for the tests. From the curves two types of fluids were observed, Bingham and Casson.



	I_L	T (Shear Stress,Pa)	η (Viscosity, mPa.s)
1	1.8	324	373
2	2.3	180	113
3	3	83	45
4	3.4	54	29
5	4	35	22
6	4.3	25	16
7	4.9	16	8
8	5.2	12	7.6

Figure 2-15 Shear Stress versus Shear strain for various liquidity index values (Locat and Demers 1988)

In the figures below the relation between liquidity index, viscosity, yield stress and remoulded strength is presented.

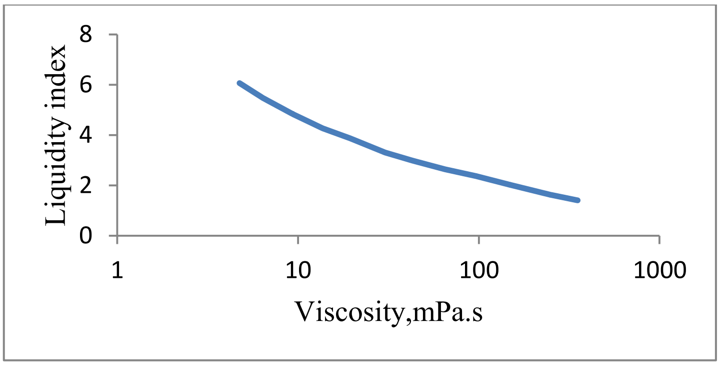


Figure 2-16 Relation between Liquidity index and Viscosity

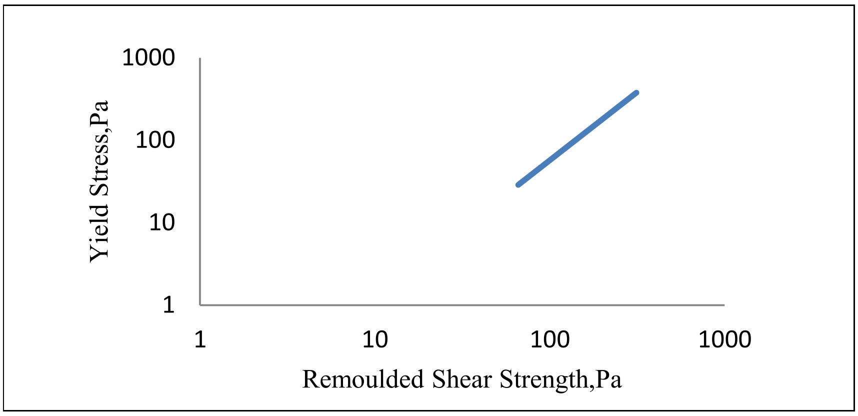


Figure 2-17 Relation between Yield stress and Remoulded shear strength

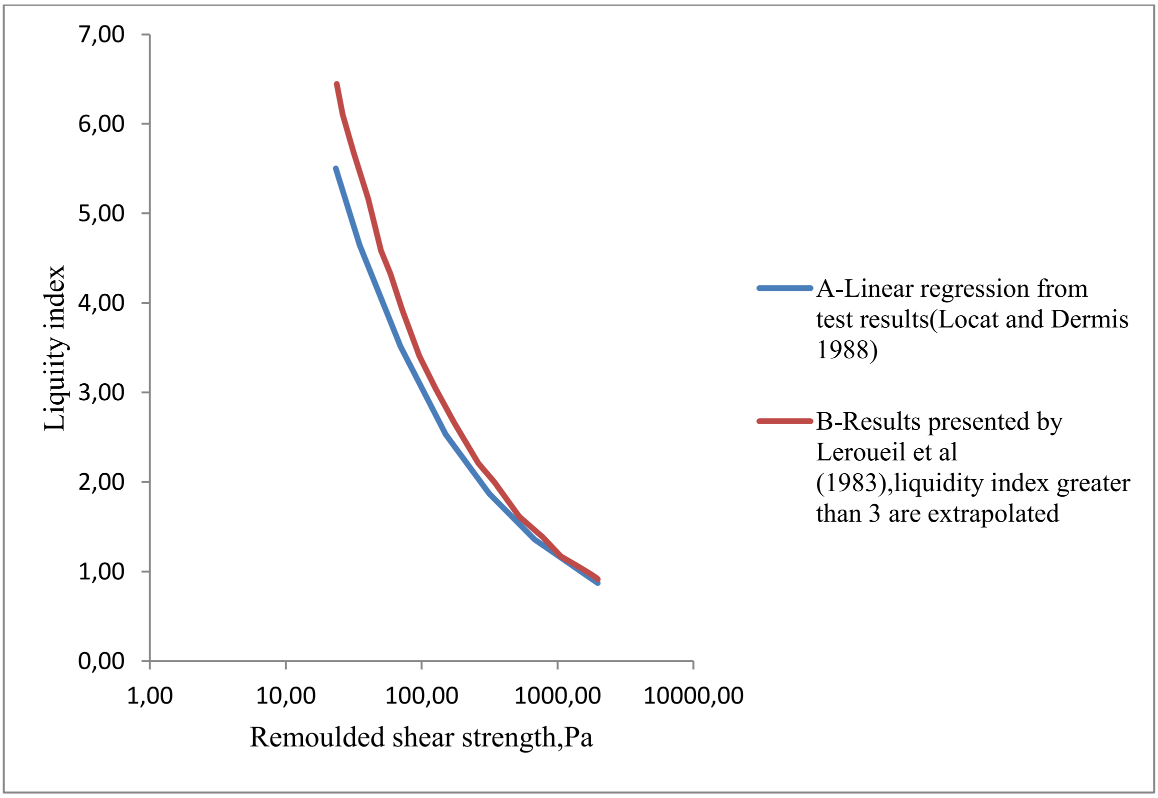


Figure 2-18 Relation between liquidity index and Remoulded shear strength

Two important empirical relations have been developed based the figures shown above.

$$\eta = \left(\frac{9.27}{I_L}\right)^{3.33} \qquad (2.7.1)$$

$$C_{ur} = \left(\frac{19.8}{I_L}\right)^{2.44} \qquad (2.7.2)$$

The relationships presented above are done for Canadian sensitive clays, similar correlations has not been developed for Norwegian sensitive clays. Hence, the above equations will be used for estimating the viscosity and yield stress in computations later in chapter 4.

2.8 Run out Prediction methods

There are four methods that can be used to estimate run out distance of landslides:

a) **Laboratory methods**-laboratory methods can simulate landslides that do not show any scaling effects. Such method has been applied to debris flows consisting of granular materials (Iverson and Denlinger 2001).Rheometric tests have been done to study the mobility of quick clays (Khaldoun et al 2009). The laboratory tests were conducted on samples from Tiller, Trondeheim. A very useful and interesting results were found. Four samples which are different in weight by percentage of quick clay were tested for different yield stress values as shown in the figure below.

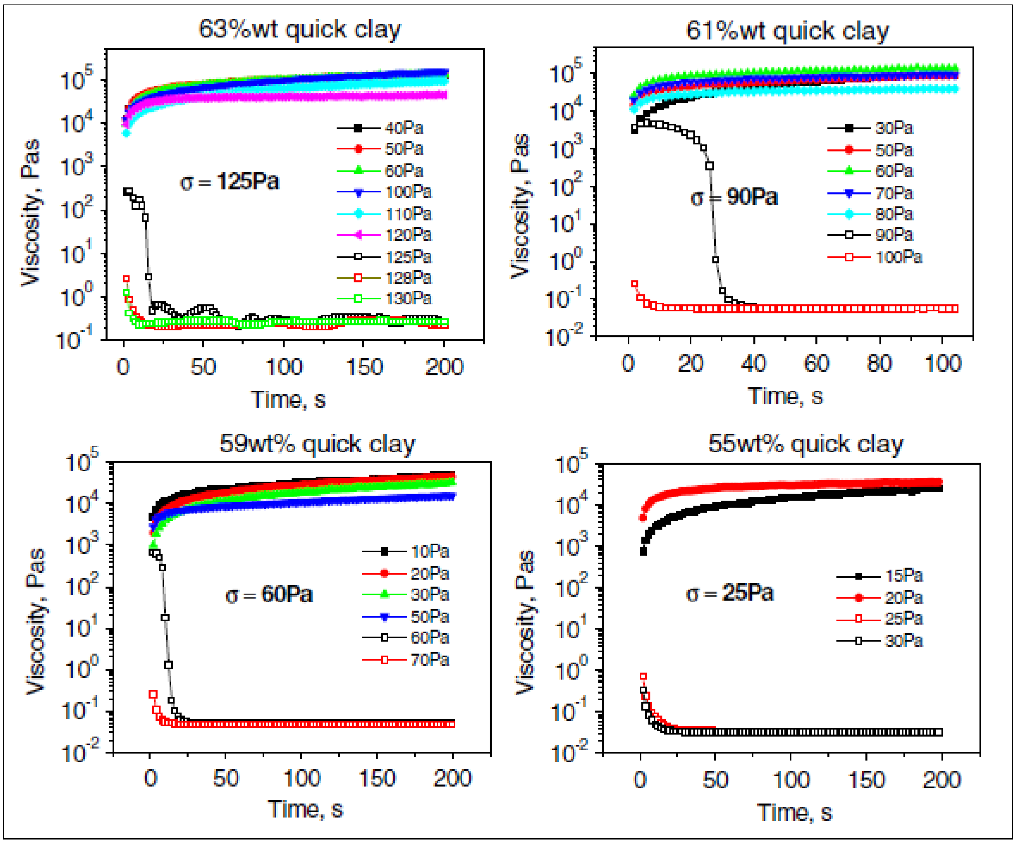


Figure 2-19 Viscosity versus time for varying yield stress values (Khaldoun et al 2009)

Some important findings of the test are:

- Higher water content does not necessarily mean higher mobility, a relatively dry sample 61 % by weight of clays show higher mobility than the 59 % by weight.
- A small stress variation (as small as 1%) can cause a higher change in mobility.

The relation between the slide distance and yield stress on a laboratory build model was also studied and the relations are presented in fig 2-20.As can be seen from the figure below the slide distance increase for very low yield stress values. Very sensitive clays with a very low undrained shear strength values might have higher slide distance. Thus, variation in slope angle and undrained shear strength and viscosity are important parameters regarding mobility.

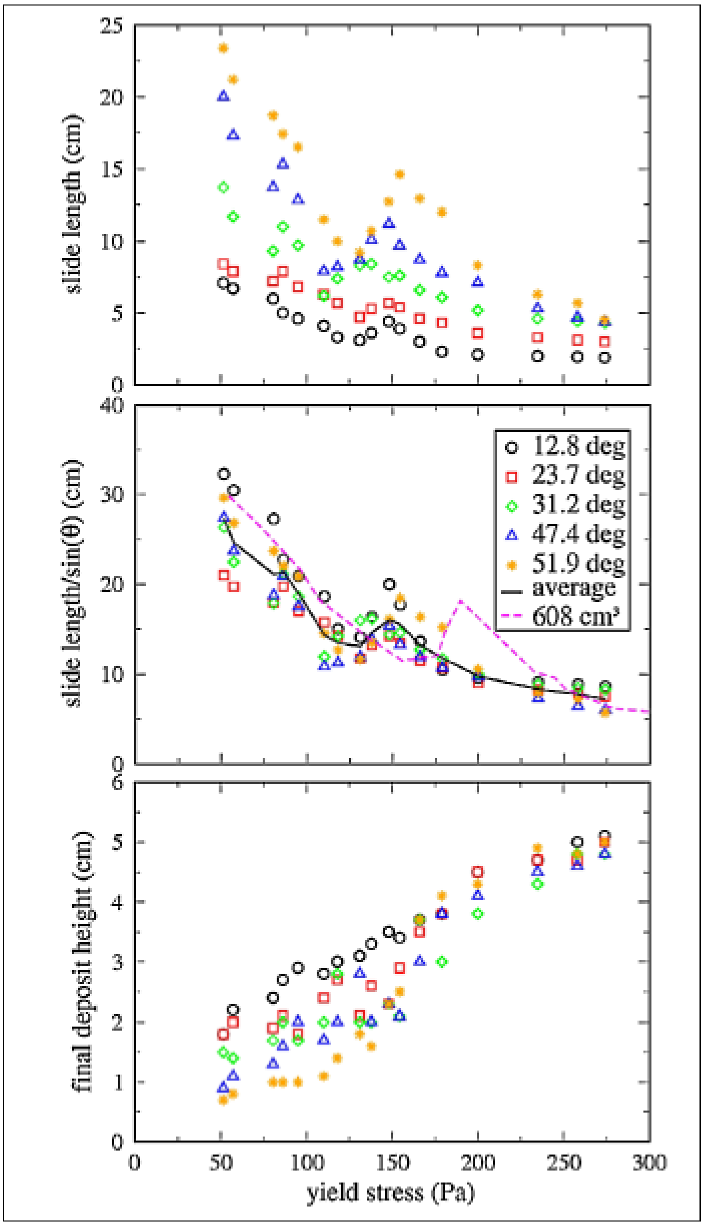


Figure 2-20 Slide length versus yield stress (Khaldoun et al 2009)

b) **Empirical methods**- are based on statically collected data and observations made based on such data .Such method has been applied to quick clay slides and it will be discussed in more details in Chapter 4.

c) **Analytical methods**- are approaches based on physical rules of solid and fluid dynamics. The three main categories of this approach are lumped mass models, 2D models and 3D models. Finite element or finite difference methods might be used to solve such approaches (Hungr et al 2005).

d) **Numerical methods**-are mathematically formulated models that can give results based on constitutive laws. They have been in use for landslide run out prediction .Various numerical models have been developed for run out simulation. Nevertheless, there has not been a specific model developed for quick clay slides. An existing model has been applied for quick clays and will be discussed in more details in Chapter 4.

3. Case Studies

Landslides due to clays in three different locations in Norway has been back analyzed numerically.In addition, a laboratory model land slide has been simulated and back analyzed .The selection of the case studies is done based on the availability of detailed information needed for analysis. Two of the three real case studies are very well documented. There is small availability of information found on the third case. However, a model was developed and studied numerically. The description of each of the case studies is presented below.

3.1 The Byneset Slide

Byneset is a peninsula found in Trondheim municipality in mid Norway. After the glaciaciation era marine clay deposits in the area are exposed due to land uplift, erosion and leaching. As a result, highly sensitivity clays are available in the area.

The Byneset slide has happened in January 2012 about 10 Km south west of Trondheim. The slide had mobilized 2-4.10^5 m^3 of soil mass .There has been similar slide cases happened in the 19th century and several small slides has happened in the area.

The mapping of quick clay areas in Norway done before the slide has designated the area as a potential hazard area. The slide is believed to be triggered due to stream erosion. The slide masses completely evacuated out of the release area (which is about 300m long) as shown in the figure below (Issler et al. 2012).

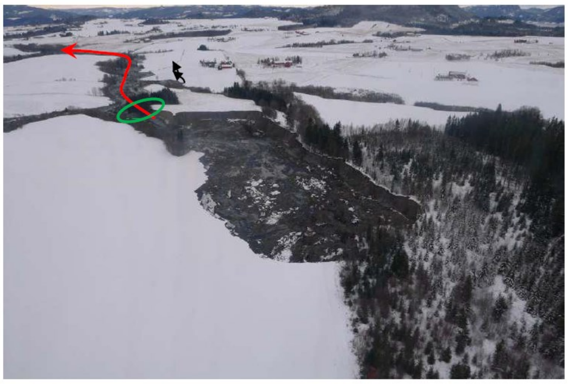


Figure 3-1 Byneset landslide release area (Issler et al. 2012)

The slide mass has traveled down a gentle slope along a dry water canal about 900 meters. Digital elevation model of the area shows the post slide deposits in the figure below.

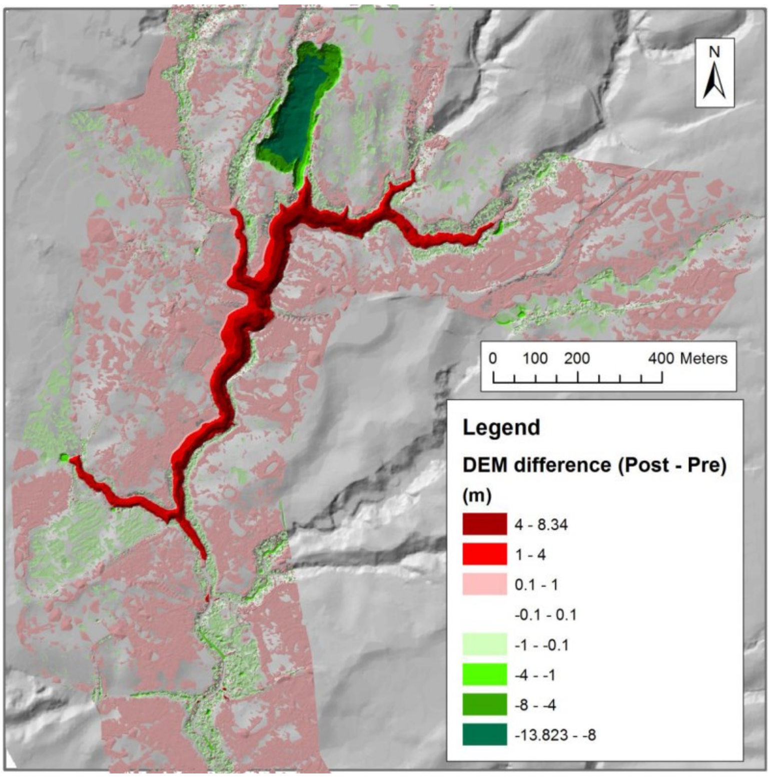


Figure 3-2 Post slide slide digital elevation model (Issler et al. 2012)

Geotechnical investigation has been carried out in the area. The carried out investigation show there are thick layers of soft clay layer in the area. However there is no evidence that the quick clay layer zones deeper than 20m.At the rear of the slide pit is however a rock formation was found. Some of the geotechnical parameters used in the numerical study in Chapter 4 is presented below.

Unit weight	γ	KN/m^3	18,3
Undrained shear strength	C_u	Kpa	10-25
Remoulded shear strength	C_{ur}	Kpa	0,12
Max.Sensitivity	S_t	-	400
Plasticity index	I_p	%	5
Liquidity index	I_L	-	3,8

Table 3-1 Geotechnical Parameters for Byneset

3.2 Finneidfjord Slide

Finneidfjord is found in Northern Norway. In June 1996, a sub marine/sub aerial retrogressive flow of quick clay slide happened along the shore line .The slide has mobilized as much as 1million m^3 of soil mass.

It is believed that the slide has been triggered due to excess pore pressure development after high precipitation. The slide mechanism is categorized into three stages: initial, main and minor slides along the main slide scarp. A swath bathymetry survey indicates the instabilities and slide prior to the main slide. The main slide has retrogressed around 200 to 300 m. The last stage in the slide accounted for smaller debris flows. The slide mechanism and phases are presented in the figure below (Longva et al. 2003).

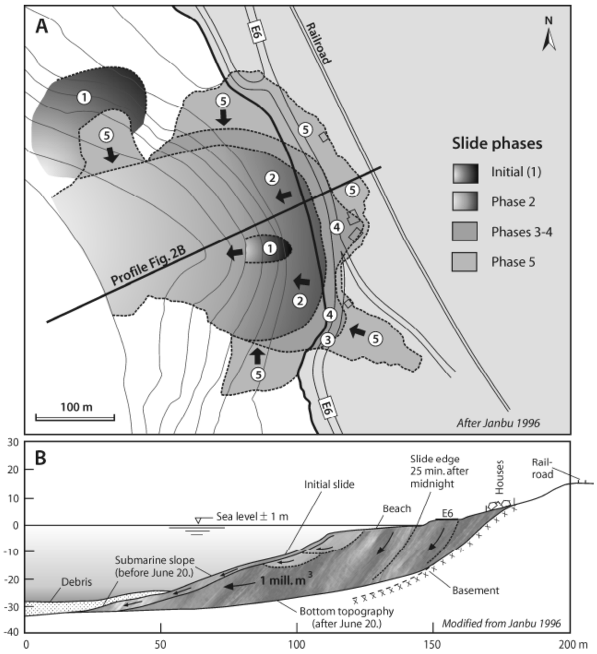


Figure 3-3 (A) The Finneidfjord Slide Phases (B) The Finneidfjord Slide profile

Ground investigation in the area in connection with the construction of E6 highway reveals the area consists of soft sensitive clays. Stability analysis done by Janbu in 1996 (Janbu 1996) shows a low safety margin for the beach slope in the area. Geotechnical parameters used in the numerical study are presented below.

Unit weight	γ	KN/m^3	19
Undrained shear strength	C_u	Kpa	7-10
Remoulded shear strength	C_{ur}	Kpa	0,4
Max.Sensitivity	S_t	-	60
Plasticity index	I_p	%	6
Liquidity index	I_L	-	2,5

Table 3-2 Geotechnical Parameters for Finneidfjord Slide

3.3 Lyngen Slide

A retrogressive landslide has happened in September 03, 2010 in Solhov in Lyngen municipality. The slide has mobilized 200000-300000m^3 of soil mass. The slide happened close to a shore line and all the sliding mass has went to the nearby sea.

Figure 3-4 The slide at Lyngen (aftenposten.no)

The Norwegian Public Roads Administration has made a geotechnical assessment in 1994 in the area for the purpose of road construction. Parameters used in the back analysis are presented in the table below (Issler et al. 2012).

Unit weight	γ	KN/m^3	20
Undrained shear strength	C_u	Kpa	7
Remoulded shear strength	C_{ur}	Kpa	0,14
Max.Sensitivity	S_t	-	51
Plasticity index	I_p	%	-
Liquidity index	I_L	-	2,1

Table 3-3 Geotechnical Parameters for Lyngen Slide

The slide area contours has been used to plot the slide surface which are used for numerical computation. Since the slide mass has all flown to the sea an ideal terrain contours has been made to study the flow of the slide mass.

3.4 Laboratory model landslide

A laboratory model landslide has been scaled up and back analyzed numerically to study the flow behavior of soft sensitive clays (Appendix 1).The landslide model was built in the laboratory and run out distances at different shear strength values has been compared with numerical simulation.

The laboratory land slide has a 2liter volume, 90cm long and a slope of 8.53 degrees. The details of the model experiment and numerical back calculation are explained in appendix 1.

4. Run out Prediction

The post failure movements of quick clay slides that involve flows cover longer distances in some cases based on the topography and other governing parameters discussed in chapter 2.There are several ways to estimate landslide run out distance, some of the methods were mentioned in section 2.8.The movement of flow is complex that there is no single error free method to depict the real cases. However, the existing methods can give a good systematic approach to assess the impact of a landslide hazard (Quan 2012).

4.1 Empirical Methods

There are several methods for estimating landslide run out distance empirically. Three types of empirical methods will be discussed here based on methods presented by Hunger et al (2005). The application of such methods is relatively easier. However, the interpretation of such methods lacks consistency among researches in the area.

4.1.1 Geomorphological approach

This method involves identification and interpretation of recent and ancient landslide deposits. Future travel distance estimation is based on such data. Field work and photo interpretation are the main sources of the data analysis. The outer deposit margins of previous landslides will give an indication to the potential reach of a present landslide in a given terrain. The challenge in such a method is to identify earlier landslide deposits (Hungr et al. 2005).

4.1.2 Geometrical approach

Geometrical method also called travel angle method is based on the geometrical characteristics of landslides. The correlation between the angle of reach (the tangent of the height of drop of the slope and the run out distance) called ’’fahrbschung’’ and the volume of landslide mass has been studied. Besides, the topography and obstacles of flow was incorporated in the study (Corominas 1996).

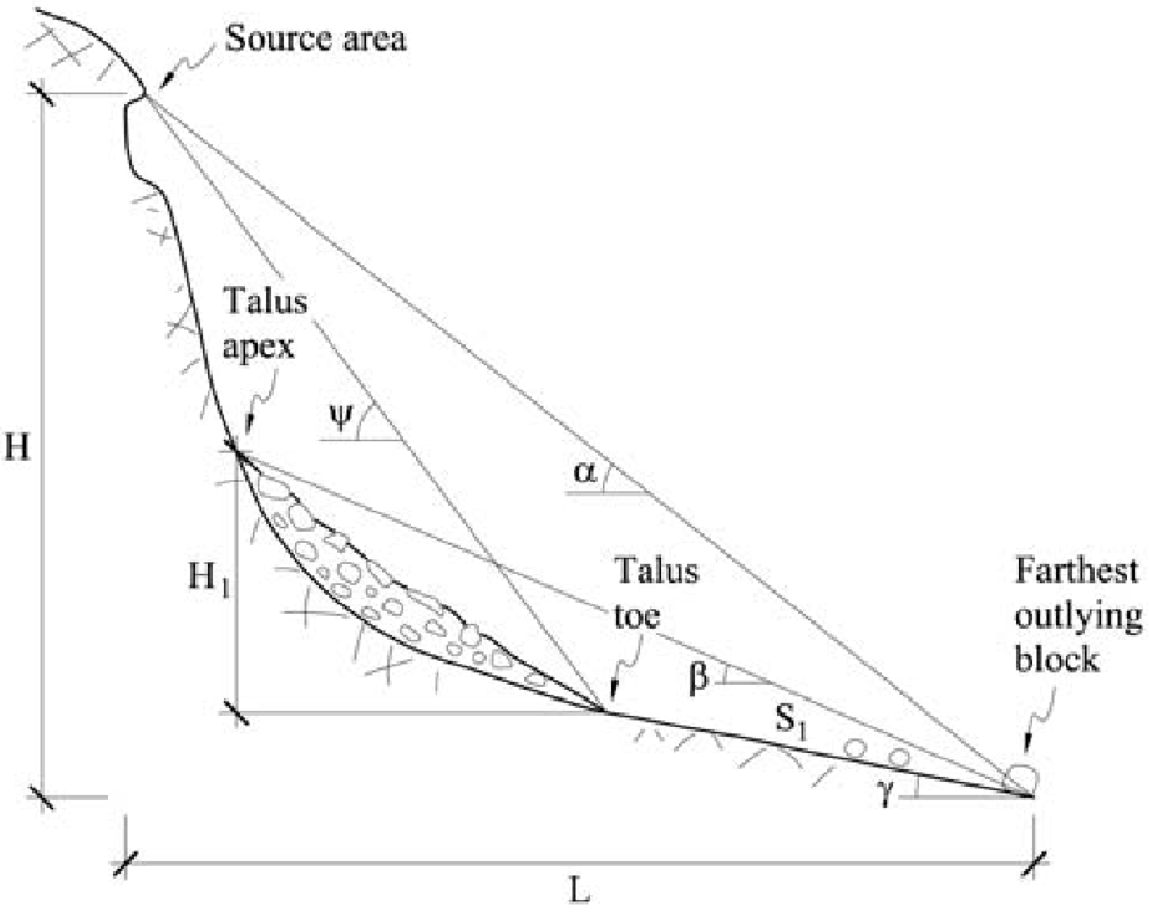


Figure 4-1 (H),travel distance (L),reach angle (α),shadow angle (β),source-talus angle (ψ),substrate angle (γ) and shadow distance (S1) (Hungr et al. 2005).

A statical analysis was made on 204 collected data. The collected data was categorized into four major classes of landslides, namely

- Rock falls
- Debris flows
- Earth flows
- Translational slides

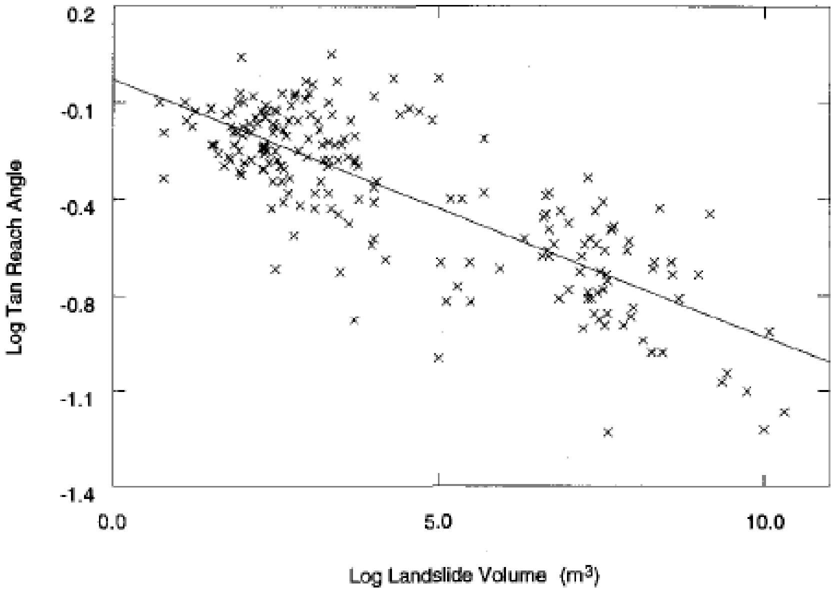


Figure 4-2 Volume versus reach angle

For each of the above mentioned types there has been an empirical correlation developed considering the topographic constraints (Figure 4.3).

Despite the various conflicting deduction about the relation between the reach angle and volume of slide among many researchers, the figure above has shown a good relationship. For the four categories mentioned above, there is an empirical equation developed as shown below:

Table 4-1 Regression equation between volume and travel distance

Rock falls	log (H/L)= -0,109log vol +0,210 r^2=0.759
Debris flows	log (H/L) = -0,105log vol – 0,012 r^2=0.763
Earth flows	log (H/L) = -0,070 log vol – 0,214 r^2=0,648
Translational slides	log (H/L) = -0,068 log vol -0,159 r^2=0.670

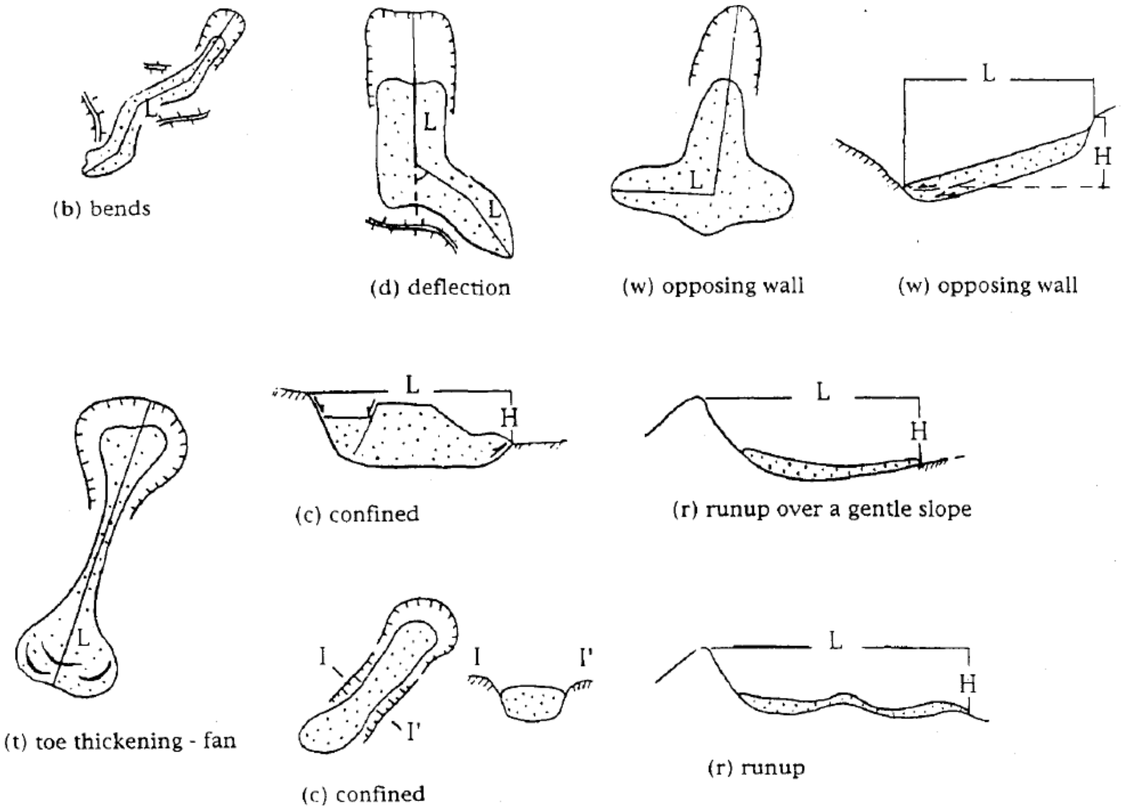


Figure 4-3 Obstructions of flow

Quick clay slides can be categorized based on earth flows among the categories. The empirical formula has been used for quick clay slide case to see the run out distances.The volume versus the length flow as per the formula suggested above was computed for 12 Norwegian landslide cases.

Year	**Landslide**	**Type**	**L_R**	**L_F**	**$L= L_R+ L_F$**	**H**	**V**	**$L=1.636Vol^{0.07}/H$ (Coromias 1996)**
			[m]	[m]	**[m]**		[m3]	[m]
1974	Båstad	F	230	700	930	20	1500000	89
1953	Bekkelaget	FL/F	145	20	165	16	100000	59
1928	Brå	FL	197	300	497	79	500000	325
1980	Fredrikstad	RR	45	22	67	8	100000	30
1959	Furre	FL /F	300	90	390	19	3000000	88
1974	Gullaug	F /FL	150		150	30	900000	128
1967	Hekseberg	FL	700	300	1000	27	200000	103
1944	Lade	FL	40	62	102	5	500000	20
1954	Lodalen	FL	40	10	50	10	100000	37
2010	Lyngen	F	153	411	564	26	220000	100
1965	Selnes	F	230	400	630	10	140000	38
1959	Vibstad	F	250	250	500	25	1000000	107

Table 4-2 Empirical run out prediction

The estimated runs out distances have a higher variation with the observed data. Only for landslide cases with a higher slope height and higher volume the above empirical formula gave a closer result but it failed to give a reasonable value for most of the cases. The higher scatter in the data used for deriving the empirical relations might give optimistic results (Hunger et al 2005), whereas in reality the landslide mass travels more beyond the computed run out distances.

NVE suggests using 15 times the slope height to estimate the run out distance; such relation e could lead to erroneous conclusions. Since some quick landslide cases, for example Byneset slide, has happened in a very gentle slope but the slide mass has travelled more than 800 meters.

4.1.3 Volume based approach

Volume change method considering material entrainment has been studied previously. However, in this section the volume based approach will solely be restricted to correlations developed between the length flow and normalized volume (volume divided by width) for Canadian and Norwegian slides.

J.S L'Heureux (L'Heureux 2012) has made correlations for Norwegian quick clay slide cases based on collected landslide data and comparison was made between the length flow and normalized volume. Due a scatter in the data a unique empirical relation could not be derived, rather, an empirical relation was given for the upper boundary as shown in the figure below.

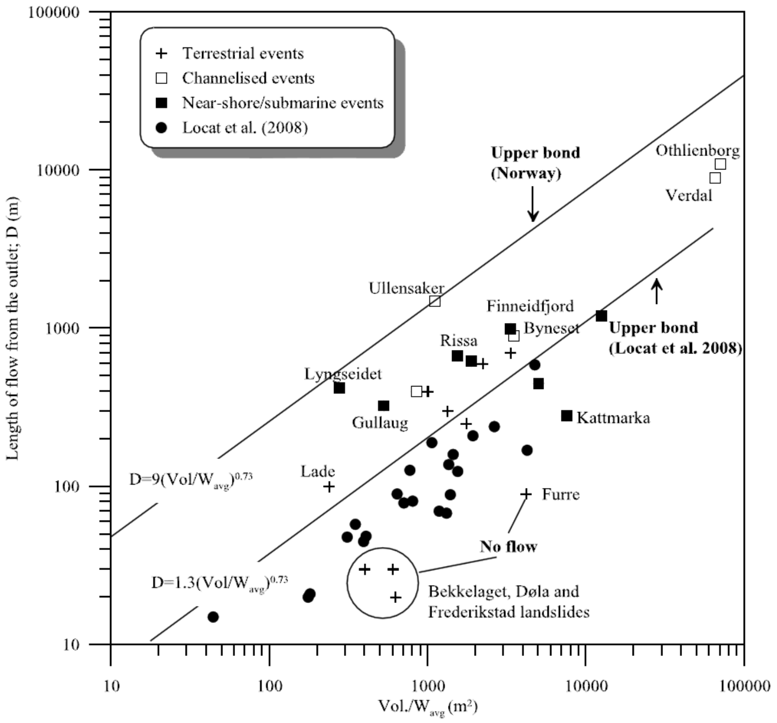


Figure 4-4 Volume versus length of flow

$$Lf = 9 * \left(\frac{Vol}{W\ avg}\right)^{0.73} \quad (4.1.3.1)$$

$$Lf = 1.3 * \left(\frac{Vol}{W\ avg}\right)^{0.73} \quad (4.1.3.1)$$

Equation 4.1.3.1 is an estimate for Norwegian slide and Equation 4.1.3.2 is for slides in Canada.

The other worth mentioning point regarding run out distance is the relationship between the retrogression and the flow distance or the run out distance. As shown in the figure below there is a linear relation between the two, in case of Norwegian and Canadian landslide cases.

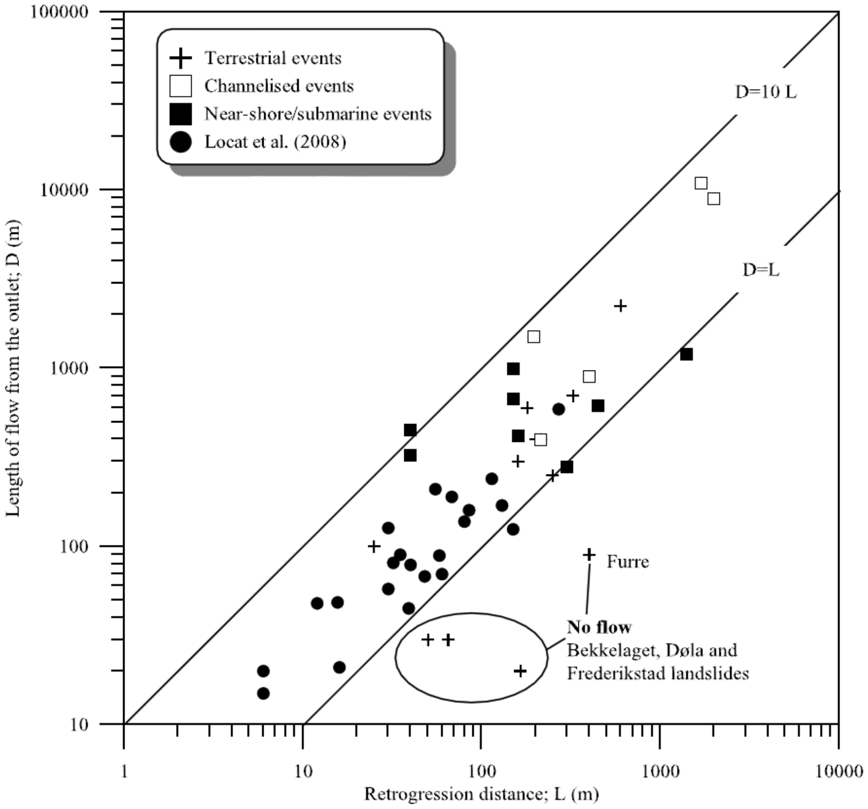


Figure 4-5 Relation between retrogression and flow distance

The above figure shows a linear relationship between the retrogression and flow distances. Retrogression does not always mean there will flow as can be seen also for some cases but in general there exists a linear relationship among them.

4.2 Numerical Methods

Numerical methods application on landslide run out analysis is usually based on distinct element or continuum mechanics models. Distinct element (mass point models) comprises a sliding and a turbulent behavior based on the formulation given by Voellmy (1955).

Continuum mechanics approach, which is the most commonly used, applies the conservation of mass, momentum and energy for the slide dynamics and rheological properties for the flowing material. Hungr (1995) proposed continuum based depth average models (Quan 2012).

4.2.1 Review of existing numerical tools

The classification of dynamic run out models can be based on: solution dimension (1D or 2D), a solution reference frame (Eulerian or Langrangian) or basal rheology. The following table presents some of the various numerical tools available for debris flow analysis.

Model	**Rheology**	**Solution approach**	**Reference frame**	**Variation of Rheology**	**Entrainment rate**
MADFLOW (Chen and Lee,2007)	Frictional, Voellmy and Bingham	Continuum Integrated	Lagrangian with mesh	no	Defined
TOCHING (Crosta et al,2003)	Frictional (elastoplastic model)	Continuum Differential	Differential (adaptive mesh)	yes	Process based
RAMMS (Christen et al,2010)	Voellmy	Continuum Integrated	Eularian	yes	Process based and defined
DAN3D (Hunger and McDougall,2009)	Frictional, Voellmy, Bingham, Newtonian and Plastic	Continuum Integrated	Lagrangian meshless	yes	Defined
FLATMODEL (Medina et al,2008)	Frictional and Voellmy	Continuum Integrated	Eulerian	no	Process based
SCIDDICA s3-hex (D'Ambrosio et al,2003)	Energy based	Cellular Automata	Eulerian	no	Process based
3dDMM (Kwan and Sun,2006)	Frictional and Voellmy	Continuum Integrated	Eulerian	yes	Defined
PASTOR model (Pastor et al,2009)	Frictional, Voellmy and Bingham	Continuum Integrated	Lagrangian meshless	yes	Defined
MassMov2D (Begueria et al,2009)	Voellmy and Bingham	Continuum Integrated	Eulerian	yes	Defined
RASH3D (Pirulli and Mangeney 2008)	Frictional, Voellmy, Quadratic	Continuum Integrated	Eularian	no	No entrainment rate is used
FLO-2D (O'Brien et al.,1993)	Quadratic	Continuum Integrated	Eularian	no	No entrainment rate is used
TITAN2D (Pitman and Le,2005)	Frictional	Continuum Integrated	Lagrangian with mesh	no	No entrainment rate is used
PFC (Poisel and Preh, 2007)	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 (Kelfoun and Druitt,2005)	Frictional and Voellmy	Continuum Integrated	Eulerian	no	No entrainment rate is used

Table 4-3 Dynamic run out models (Quan 2012)

An International Forum on Landslide Disaster Management held in 2007 (Hungr et al. 2007)applied the above mentioned numerical tools on twelve different cases .The main results of such study comprise the following key points:

- Run out modelling is affected by topography and the computation domain.
- Mesh refinements improve the modelling results.
- Computational efficiency. Some of the numerical tools need much time and memory space than the others.
- Momentum based approach in formulating the equations of motion is still a reliable method.
- Eulerian and Lagrangian solution approaches have their advantages and dis advantages, however, the existing models are consistent in using these solution methods.
- Most of the run out models give reasonable results in back calculating a well-documented event. Nevertheless, inconsistencies were observed in forward analysis.
- Calibration of the models requires detailed several case studies.

4.2.3 Application of DAN3D run out model to sensitive clays

A dynamic three dimensional numerical analysis model developed by Hunger and McDougall (McDougall and Hungr 2004) has been used in this work to assess the run out distance of landslides due to sensitive clays.

4.2.3.1 Theoretical Background

The model was developed based on a semi empirical approach concept of “equivalent fluid” defined by Hungr (1995) .An equivalent fluid is a hypothetical material governed by a simple rheology representing the heterogeneous and complex landslide materials shown in the figure 4.6 below.

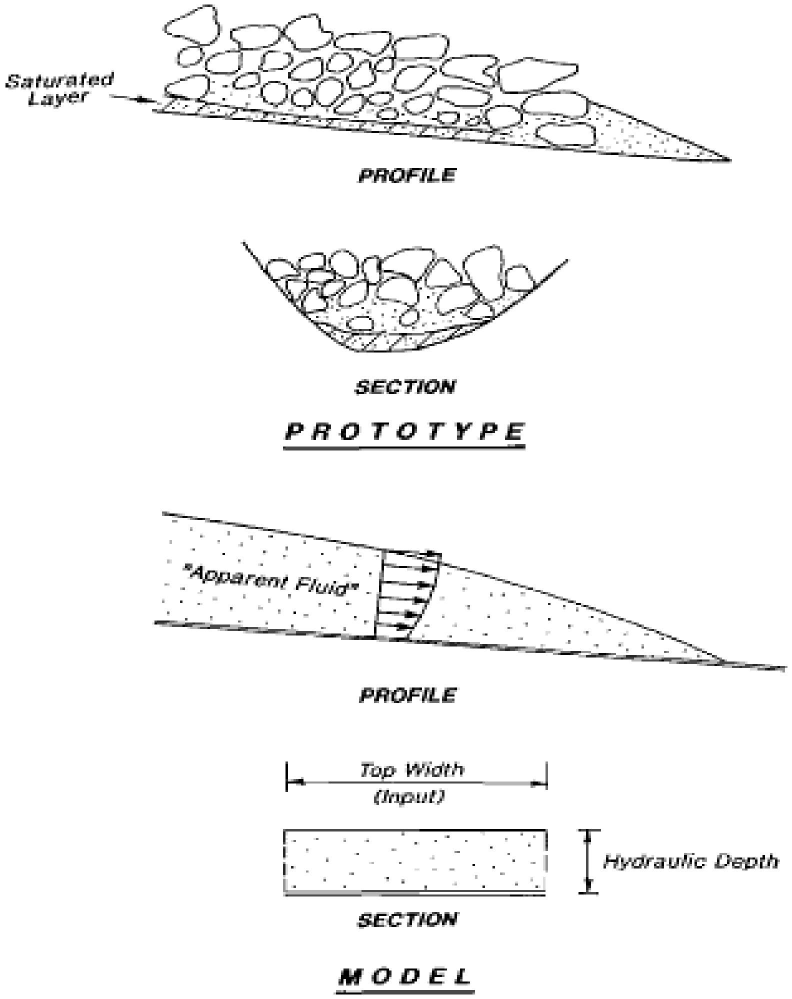


Figure 4-6 A homogeneous apparent fluid replacing the slide mass

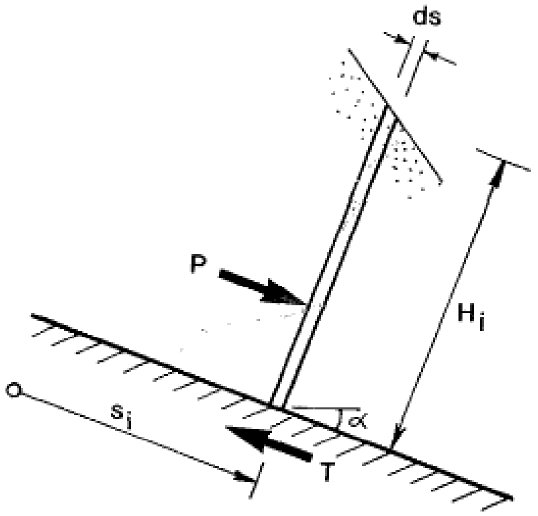


Figure 4-7 Forces acting on a sliding block

The solution used in the model is a mesh less Lagrangian solution scheme called smoothed particle hydrodynamics. Smooth particles are number of elements of the divided slide mass which has a finite volume. The reference columns (figure 4-8) will indicate the position of particles. The volume of the particles can be altered due to material entrainment.

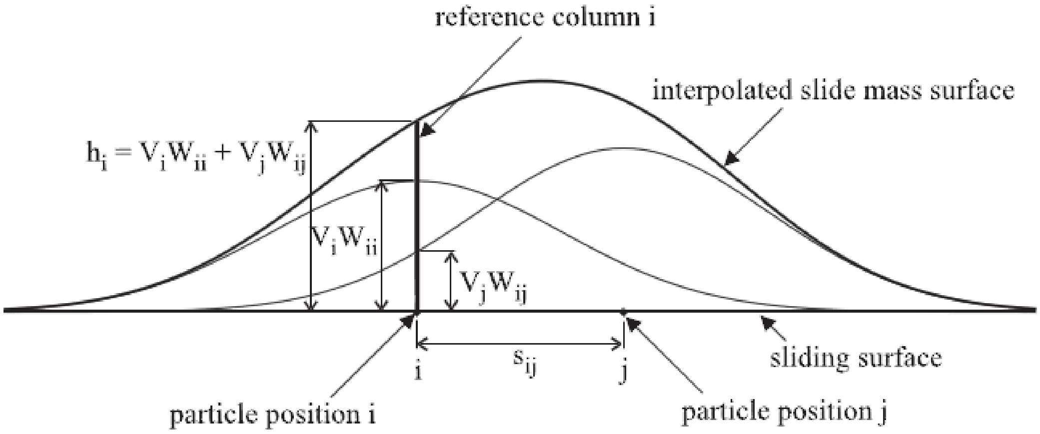


Figure 4-8 A physical representation of Smoothed particle hydrodynamics

The depth and depth gradient of each particle at a given time can be estimated based on the reference column locations satisfying continuity and equation of motion. Numerical integration of the momentum balance equations will be used to determine the local instantaneous acceleration. In short time step, the flow velocities are updated and the columns advance to a new positions. The figure above presents a simplified illustration.

Figure 4.6 shows the forces acting on a sliding mass.The flow resistance term T depends on the rheology of the material and other parameters like geology and topography. Five types of rheologies are defined and can be implemented in DAN3D simulations:

I. ***Plastic flow***: it is related with a pseudo-static motion of liquefied soil, the base shear resistance is assumed to be equivalent to a constant yield strength value.

$$\tau = -c \qquad (4.2.3.1)$$

Where τ is the shear resistance along the bed

II. ***Bingham model***: is a combination of plastic and viscous behavior. A Bingham fluid is assumed to be viscous above a threshold yield stress and rigid below a threshold value. The basal resistance term is given by:

$$\tau^3 + 3\left(\frac{\tau_{yield}}{2} + \frac{\mu_{Bingham}}{2} V\right)\tau^2 - \frac{\tau_{yield}}{2} = 0 \qquad (4.2.3.2)$$

where τ_{yield} is the Bingham yieldstress ,$\mu_{Bingham}$ is the Bingham viscosity ,V is the velocity and τ is basal shear resistance.

III. ***Frictional basal resistance:*** is given by the difference between normal stress and pore pressure at the bed.

$$\tau = -(\sigma_z - u)\tan\phi \qquad (4.2.3.3)$$

Where ϕ is the dynamic basal friction angle, u is the pore pressure and σ_z is stress normal to the bed.

IV. ***Voellmy resistance model***: is a combination of turbulent and frictional behavior .The basal resistance is given by:

$$\tau = -\left(\sigma_z f + \frac{\rho g v^2}{\xi} V\right) \qquad (4.2.3.4)$$

Where *f* is the friction coefficient and ξ turbulence parameter.

V. ***Newtonian flow***: is the function of the velocity and viscosity parameter. It is given by:

$$\tau = \frac{3V\mu}{H_i} \qquad (4.2.3.5)$$

Where μ is the viscosity and *V* is the velocity of the sliding mass.

Among the five rheologies described above plastic and Bingham rheology are theoretically suitable for geotechnical analysis and were used in the simulations of landslides.

4.2.3.2 Building and Parameterizing a model in DAN3D

The input files needed to be used in DAN3D simulations are topography files in ASCII format namely path topography and source depth.

- Path topography file: is a grid file representing a surface where the sliding mass flows.
- Source topography file: is also called release area which is a vertical depth file of the slide mass at initial conditions. This can be obtained by deducting the post slide digital elevation model (DEM) from the pre slide DEM (DAN3D user manual).

These two inputs have to prepared in a separate mapping tool (Surfer version 11 from Golden software's was used for these purpose) in grid format so as to run the simulations. A detailed description on preparing the input files is given in appendix 2.

After preparing the input files proper parameterization has to be done in the various input fields. In general the parameters required can be classified into 2:

I. ***Material properties***: these include unit weight, shear strength, viscosity, rheology (one among the five mentioned in section 4.2.3.1 one has to be selected) and friction and internal friction angle. For the case studies presented in chapter 3 the selection of the model parameters were based on laboratory tests and empirical relations. The following table summarizes the parameters used in this study.

Table 4-4 Input parameters and defintions

	Definition	Byneset	Finneidfjord	Lyngen	Lab model	Remark
Rheology	see section 4.2.3.1	Plastic	Plastic and Bingham	Plastic	Plastic	Bingham rheology has been tested on all cases but the simulation stopped at the start except for Finneidfjord slide.
Unit weight (KN/m^3)		20	19	20	20	
Shear strength (KPa)	Undrained strength of liquefied material, in case quick clays remoulded shear strength is used	0,12	0,4 and 0,08	0,14	0,1 - 2	For byneset and the laboratory model land cases varying remoulded shear strength values were used. Different remoulded shear strength values were reported for Finneidfjord slide thus 0,4Kpa is used with Plastic rheology whereas 0,08Kpa was used for Bingham rheology.
Viscosity(KPa.s)	the dynamic viscosity of a material	$1,95 \times 10^{-4}$	$7,85 \times 10^{-3}$	$14,1 \times 10^{-3}$		Derived from equation 2.7.1
Internal friction angle	The amount of internal friction. This value is used to compute tangential stress components in the model.	20	20	20-25	20	Varying internal friction angle was used for Lyngen slide.

The input parameters mentioned in table 4-4 are based on the selected rheologies' (Plastic and Bingham). There are other material parameters which are not mentioned in the above table for other rheology types.

II. ***Control parameters***-these comprise model time and time stepping. The default value for time stepping is 0, 1 second but lesser time stepping gives better accuracy of the simulation results. The model time can be increased until a maximum of 2000 seconds. The simulation can be stopped or be given lesser time based on judgment.

5. Results and Discussion

The simulations in DAN3D were run for the different cases mentioned in chapter 3.The results are presented and discussed subsequently. In appendix 1 flow contours for Byneset slide and for the laboratory model landslide are presented .The flow contours presented for the two cases are plotted as a percentage of the computation time. Flow contours at different simulation times are plotted for the three cases in the next sections.

5.1 Byneset slide simulation

The input parameters used for Byneset slide are shown in table 3.1.The analysis was done at varying shear strength values to study the effect of the flow dependency on shear strength value. In chapter two the remoulded shear strength value and it's relation with retrogression distance has been mentioned. The remoulded shear strength value affects the run out distance as well.

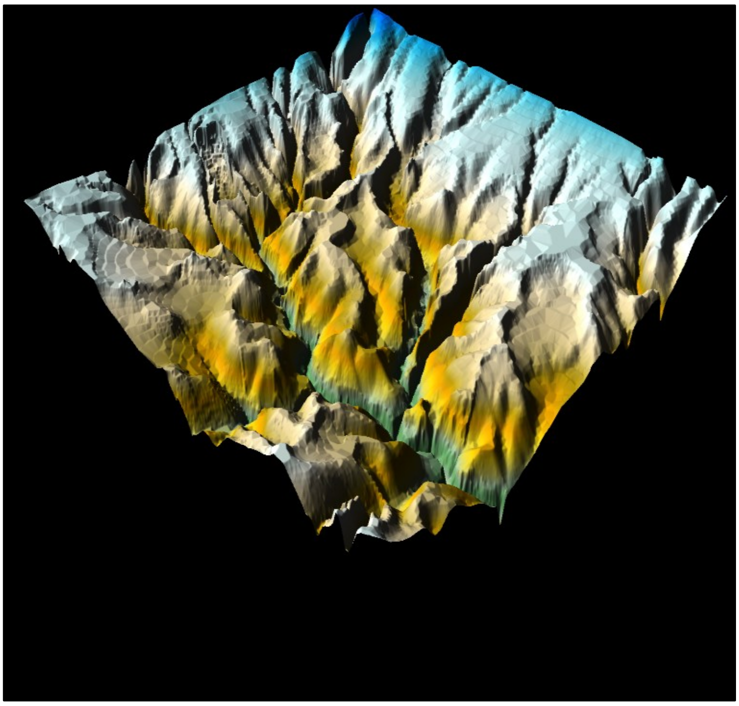


Figure 5-1 Three dimensional surface map for Byneset slide

The simulation was first done at the remoulded shear strength value 0,12KPa.The flow contours and the plots showing velocity and run out distance are shown in figures 5-2, 5-3 &5-4. The run out distance at the yield strength value fits quite well with the actual observed results from the actual landslide (see figure 3.2).However, the simulation results gave higher velocity for a sub-aerial land slide. The basal resistance in Plastic rheology is assumed to be a constant value which is the same as the yield strength .Nevertheless, the basal resistance shear strength along the slide surface can be higher than the remoulded shear strength value (yield strength value for quick clay slides is taken to be the remoulded shear strength based on their linear relationship mentioned in section 2.7) of the sliding mass. Figures 5.5 and 5.6 show the reduction in the run out distance and velocity for increasing remoulded shear strength value.

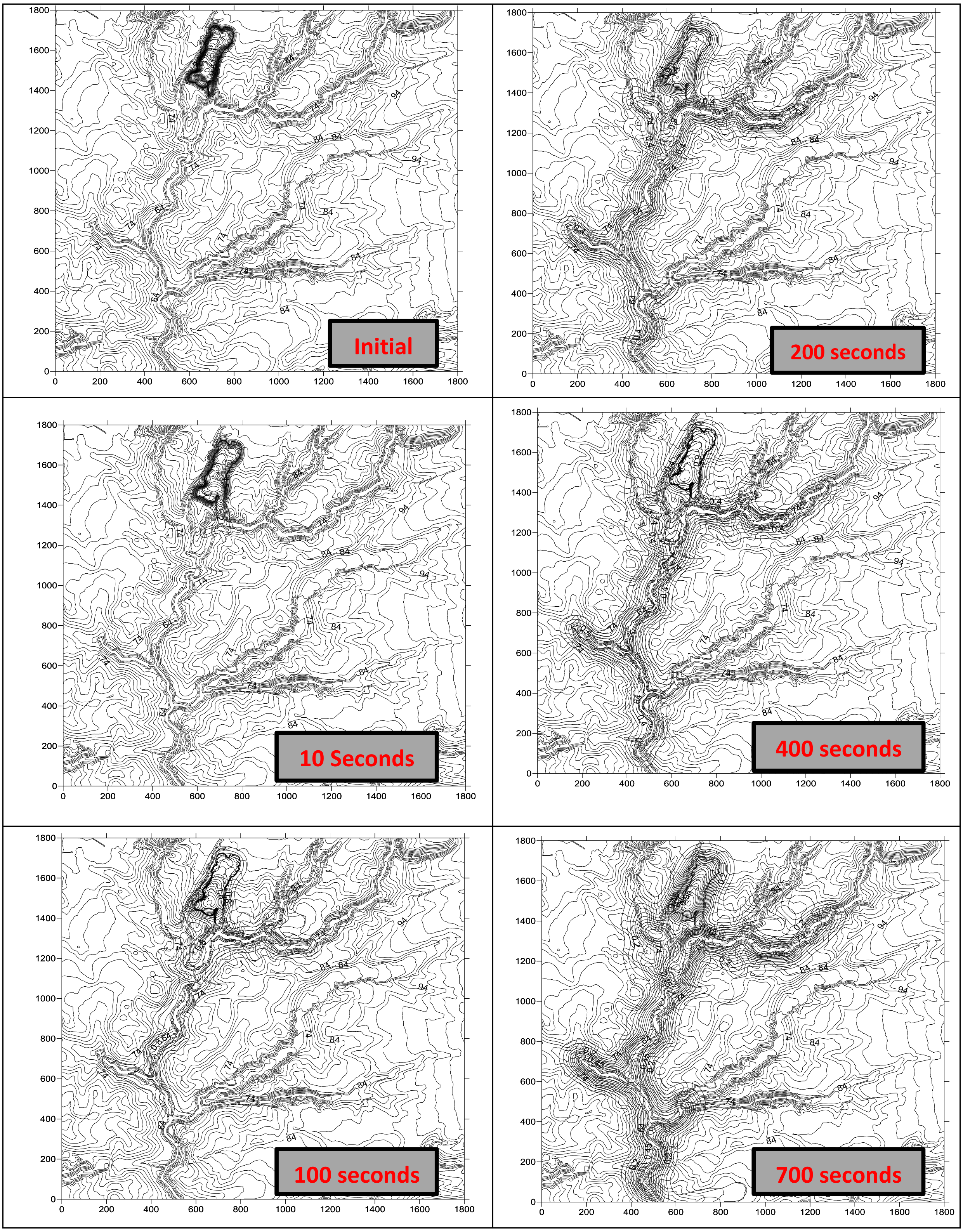


Figure 5-2 Flow contours Byneset slide

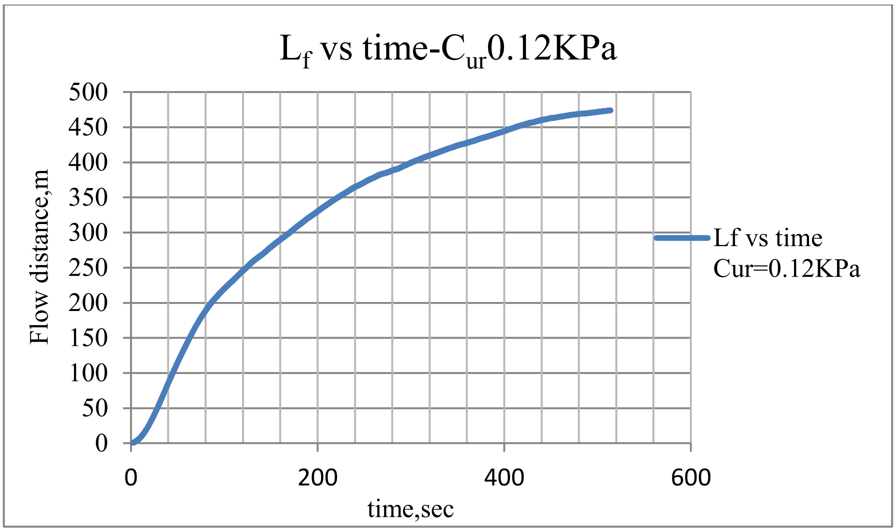


Figure 5-3 Horizontal flow distance versus time

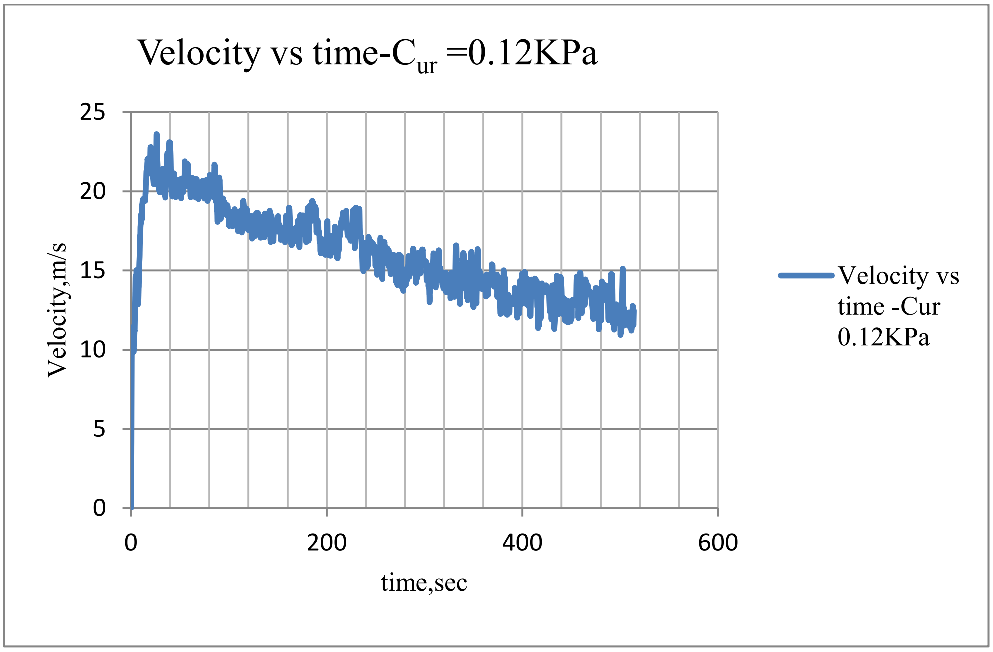


Figure 5-4 Velocity versus time

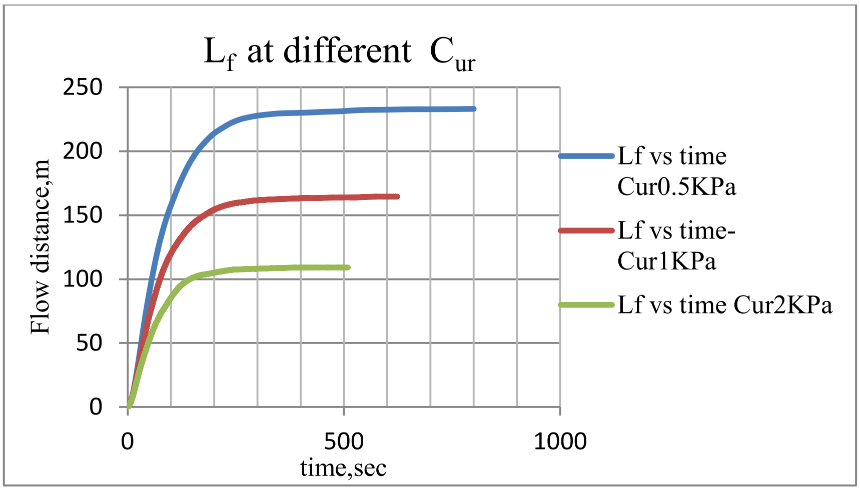


Figure 5-5 Horizontal flow distance vs. time at varying shear strength values

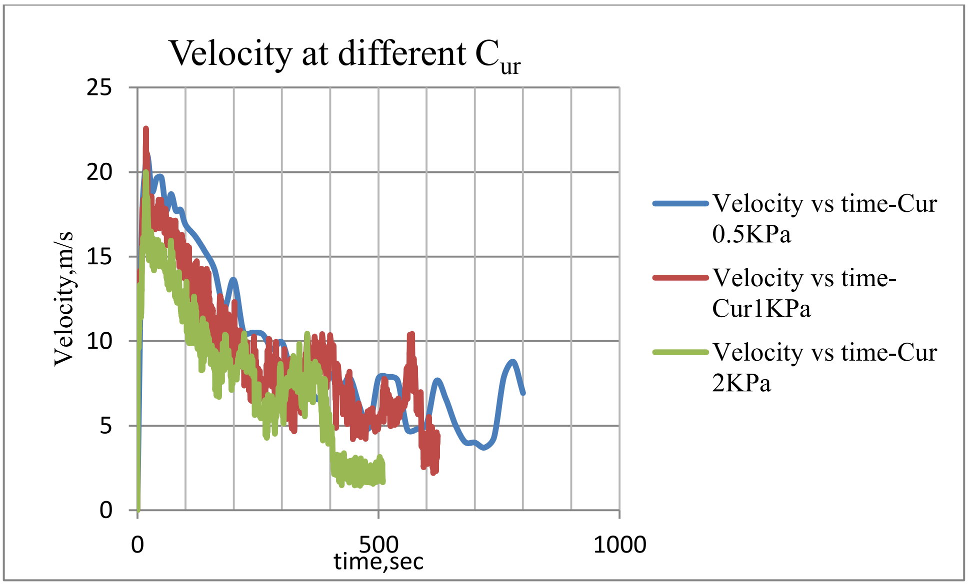


Figure 5-6 Velocity vs. time at varying shear strength values

The run out distances plotted above are the projected horizontal distances. Since the flow along the other direction was relatively small,the main direction was taken into consideration. The run out distances can be seen on the flow contour plots also. The flow distances were computed from both directions on the other slide cases in the next sections.

5.2 Finneidfjord slide simulation

The Finneidfjord Slide is a subaqueous failure. Since DAN3D does not consider hydrodynamic effects in subaqueous failures, adjustments were made on the input topographic contours (Issler, et al. 2012). The planar topographic situation (as can be seen on the 3D surface map in figure 5.6) and the higher slide mass volume has contributed to the higher run out distance.

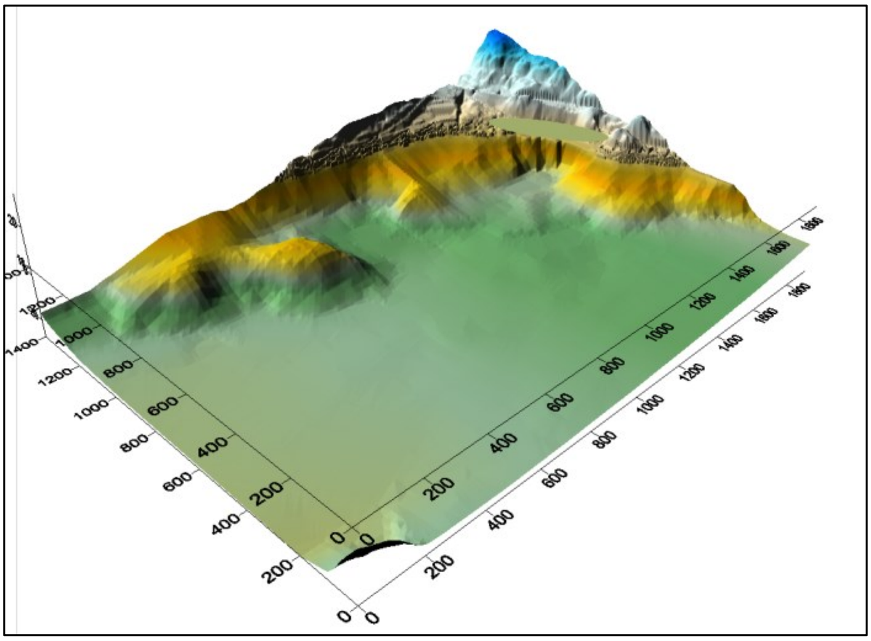


Figure 5-7 Three dimensional surface map for Byneset

The flow contours for plastic rheology is shown in the figure 5-7 below. The velocity in this case is very high as the case for the Byneset slide. The slide debris has higher run out than what was reported in table 2.1.

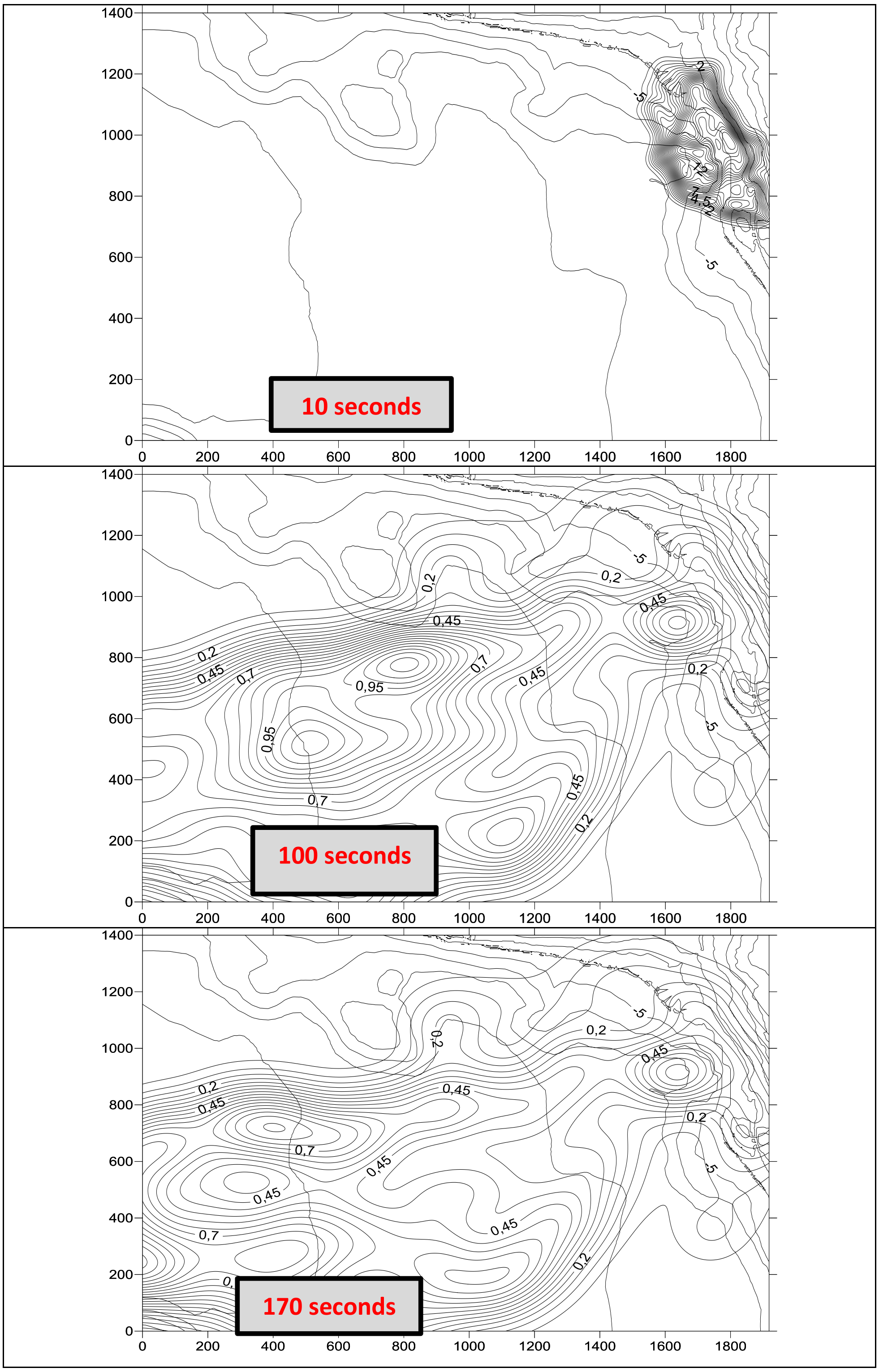


Figure 5-8 Flow contours-Plastic rheology

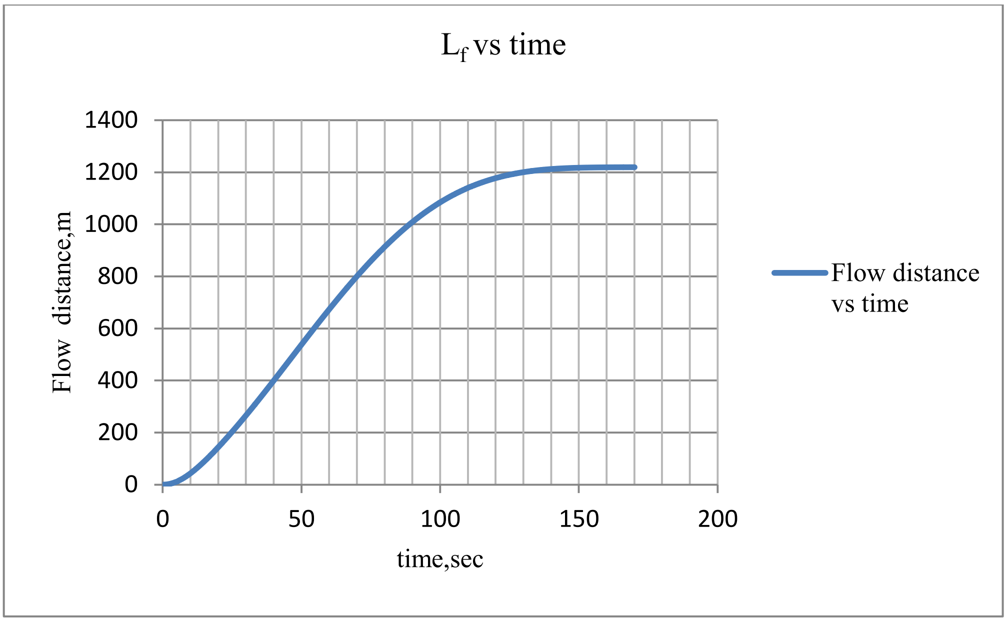


Figure 5-9 Flow distance vs. time

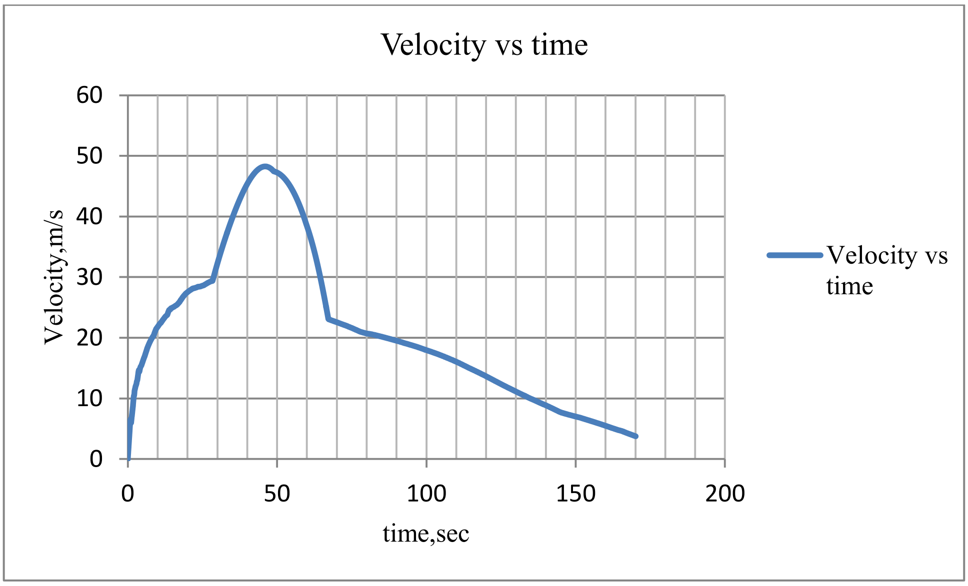


Figure 5-10 Velocity vs time

The analysis was done on Bingham rheology as well. The value of the remoulded shear strength used in such analysis was 0,08KPa (Issler, et al. 2012).The slide mass has travelled a lesser distance on Bingham rheology. The simulation on Bingham rheology worked on this case only. The flow contour, run out distance and velocity are shown in the figures below.

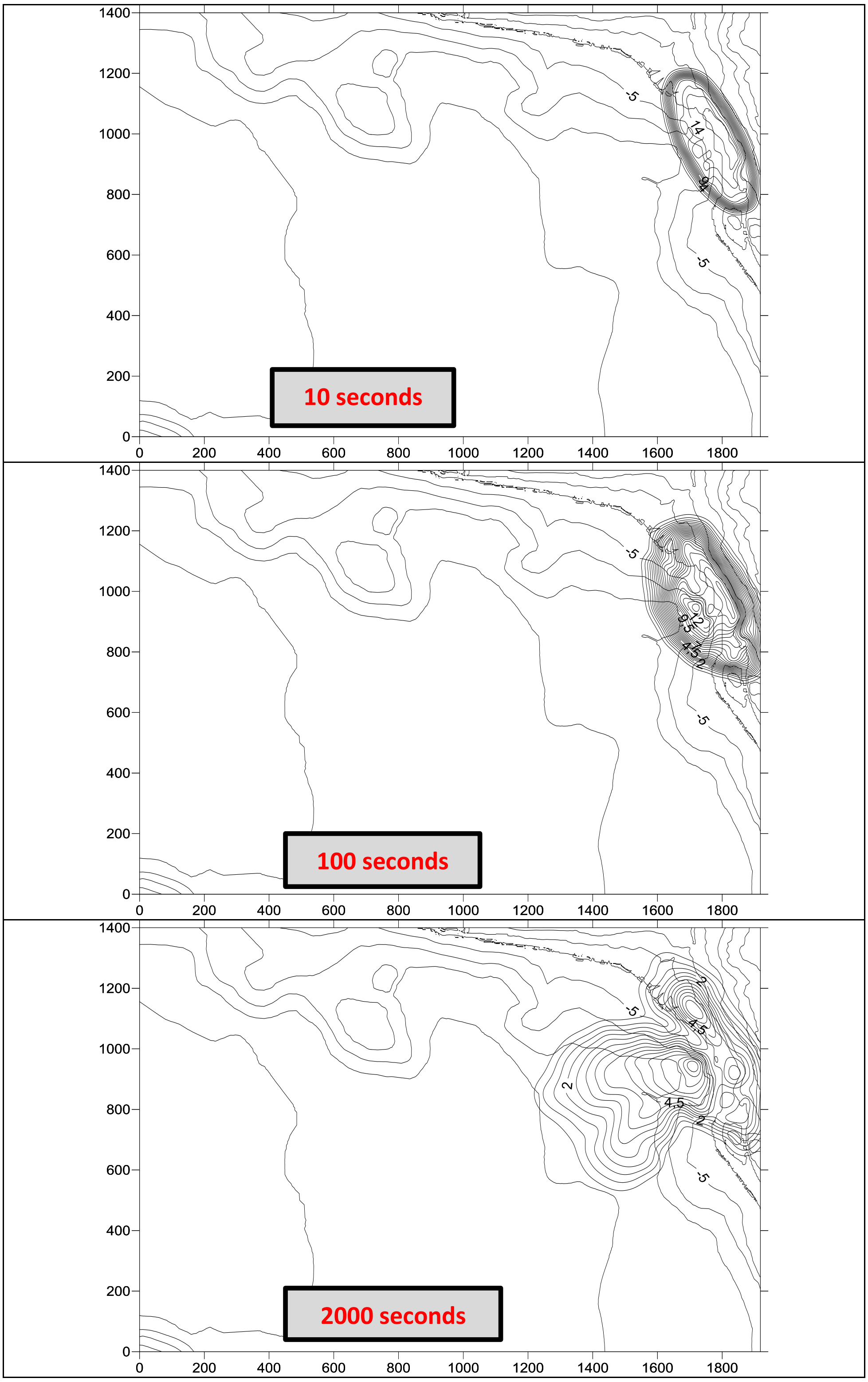


Figure 5-11 Flow contours-Bingham rheology

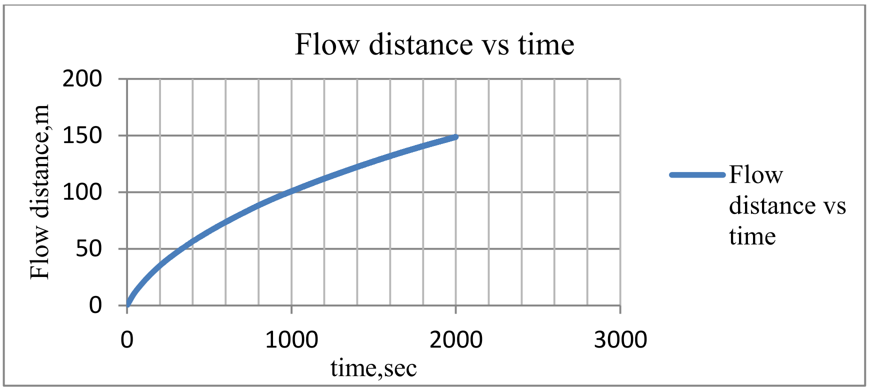


Figure 5-12 Flow distance vs time

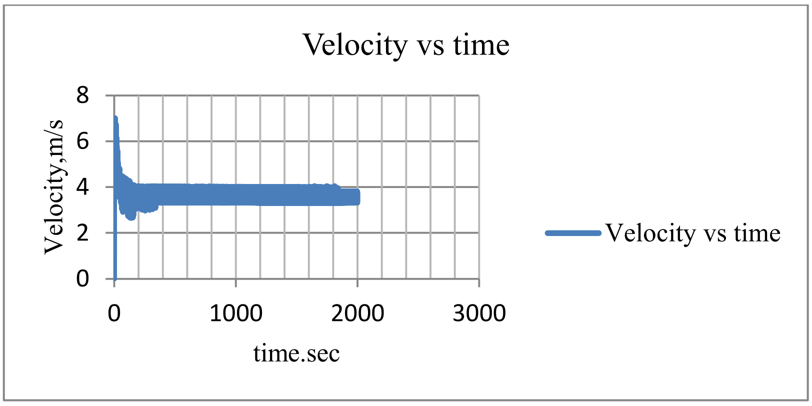


Figure 5-13 Velocity vs. time

The two major material input parameters needed for Bingham rheology are remoulded shear strength and viscosity. In table two 37 landslide cases has been mentioned for Norwegian quick clays. The remoulded shear strength value for most Norwegian quick clay slides, are seldom lower than 0,1KPa, for example very low remoulded shear strength value was reported for Duedalen slide.

The other parameter needed for Bingham rheology is the viscosity. The empirical relation given in equation 2.7.1 is based on tests on Canadian sensitive clays. There has been no such relation developed for Norwegian sensitive clays yet. The assessment of the Bingham rheology needs further investigation on the parameters especially on viscosity parameter. In comparison with Plastic rheology the run-out distance is much less even at such low shear strength value.

5.3 Lyngen slide simulation

The Lyngen slide is a retrogressive slide. In DAN3D simulations, it is not possible to simulate such slide types because prior to the analysis the path topography and release area have to be defined. However, using the original terrain contour maps all the mass retrogressed was designated as it is released at once like for Byneset slide case. The main objective here is to evaluate the topographic and other parameter effects on the run out distance. The contours showing the original terrain are shown in appendix 2.In addition; a hypothetical surface was made as path topography by combining with original terrain. This is due to the fact that the slide mass has flown to the nearby sea as mentioned in section 3.3. The slide surface is shown in the three dimensional terrain maps in figure 5-13.

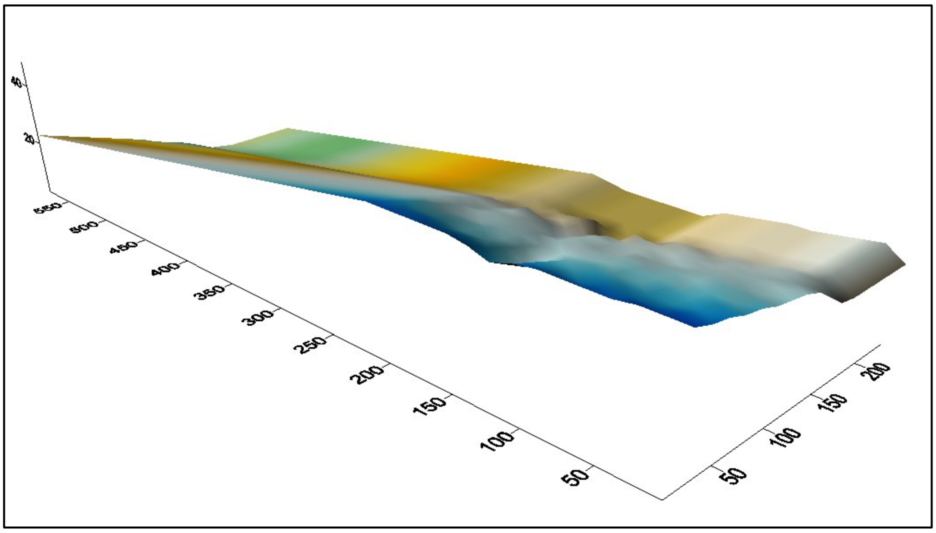


Figure 5-14 Three dimensional Surface map Lyngen slide

The simulation was run at varying internal friction angle while keeping the remoulded shear strength value to be constant (0.14KPa). The results as shown in table 5-1 below gave an insignificant variance on the run out distance.

Internal friction angle(°)	**L_f(m)**
20	1296,266
21	1316,243
22	1350,649
23	1350,717
24	1365,653
25	1343,328

Table 5-1 Internal friction angle vs flow distance

The varying shear strength value gives different results on the run out distance as for Byneset case. The figures below show the flow contour run out distance and velocity.

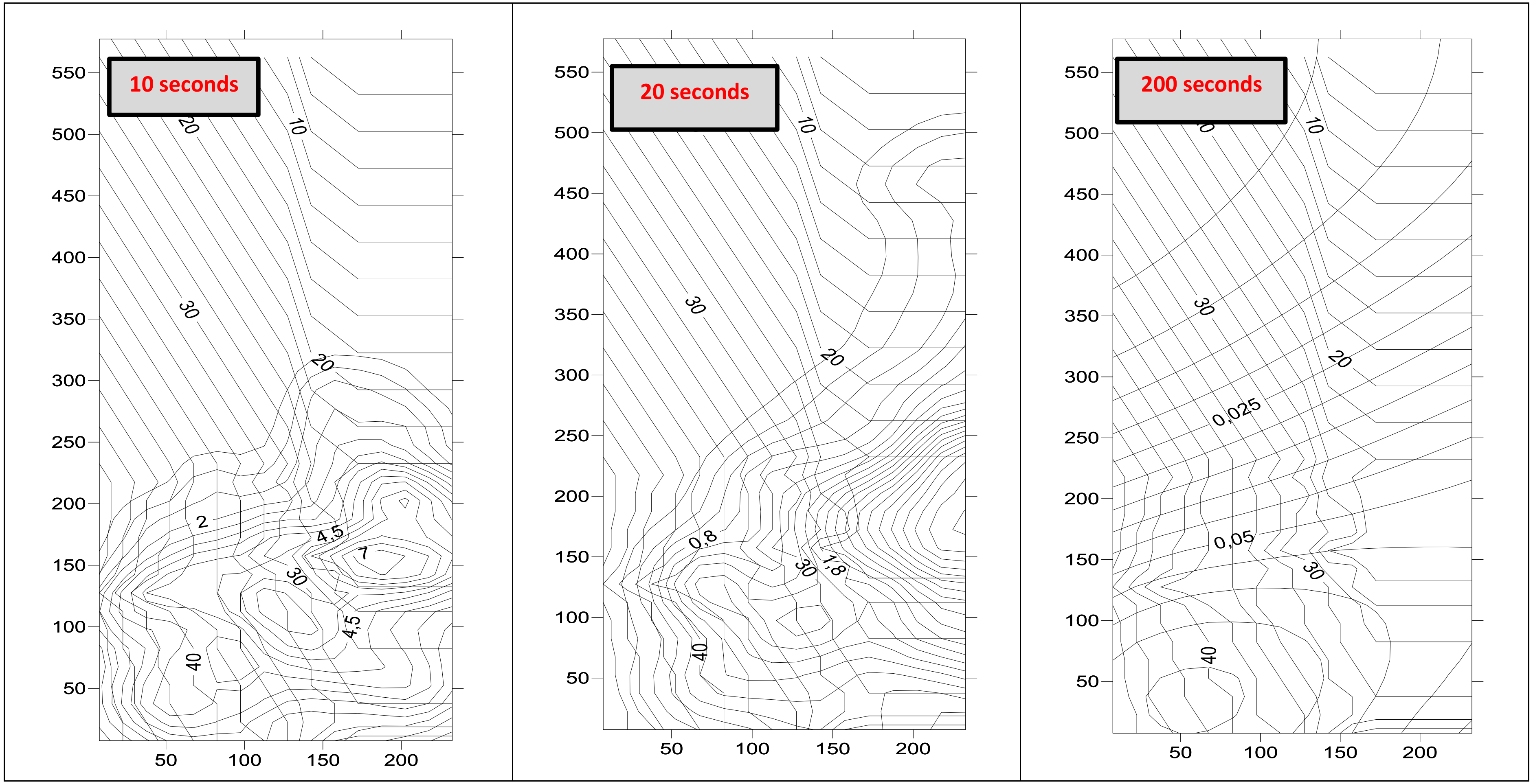


Figure 5-15 Flow contours-Lyngen slide

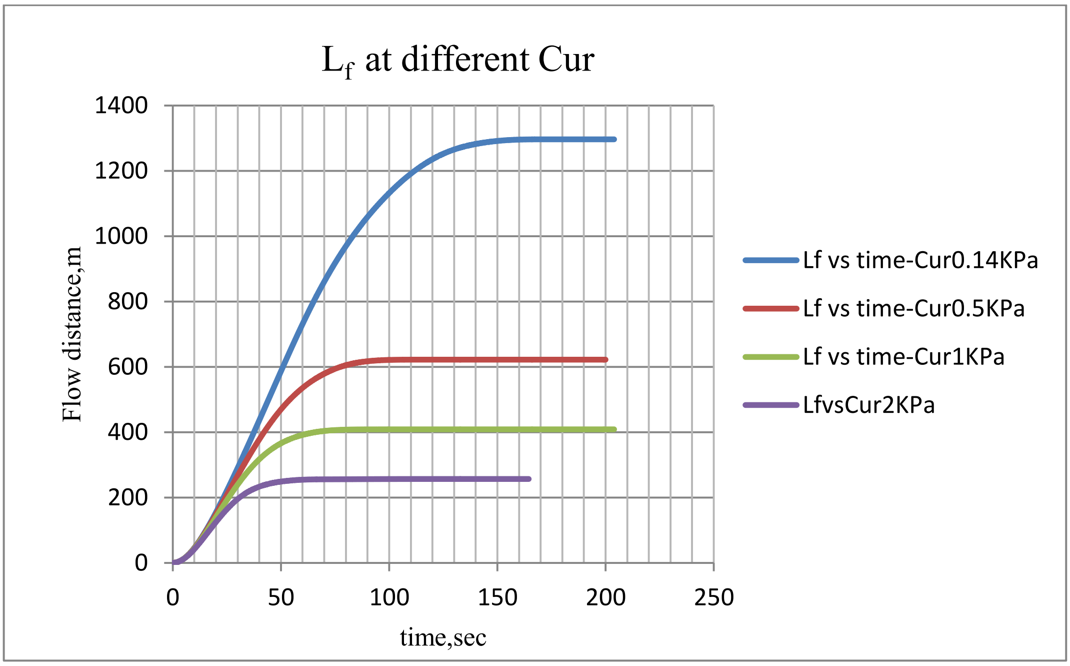


Figure 5-16 Flow distance vs time

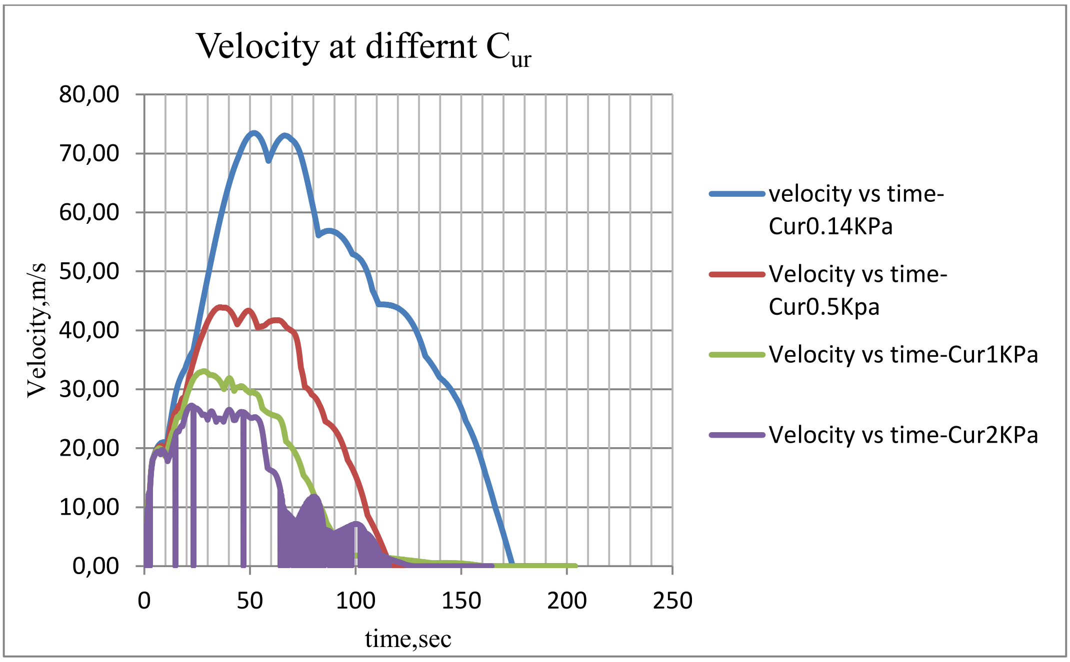


Figure 5-17 Velocity vs. time at varying shear strength values

The run out distance decreases with increasing shear strength value. The run out distances are higher even though the slide mass volume is 5 times less than for Finneidfjord slide case.

This prevails the topographic situation plays an important role on the run out distance. The velocities obtained are very high in this case study which is not realistic and needs calibration and further investigation.

5.4 Laboratory model simulation

The laboratory model's prior aim was to evaluate the effect of remoulded shear strength on run out distance. This has been illustrated on the laboratory model experiment mentioned on appendix1.The back analysis was done by scaling up the laboratory model (Appendix 1 figure 8). The results from the analysis gave a similar trend for the two cases mentioned above.

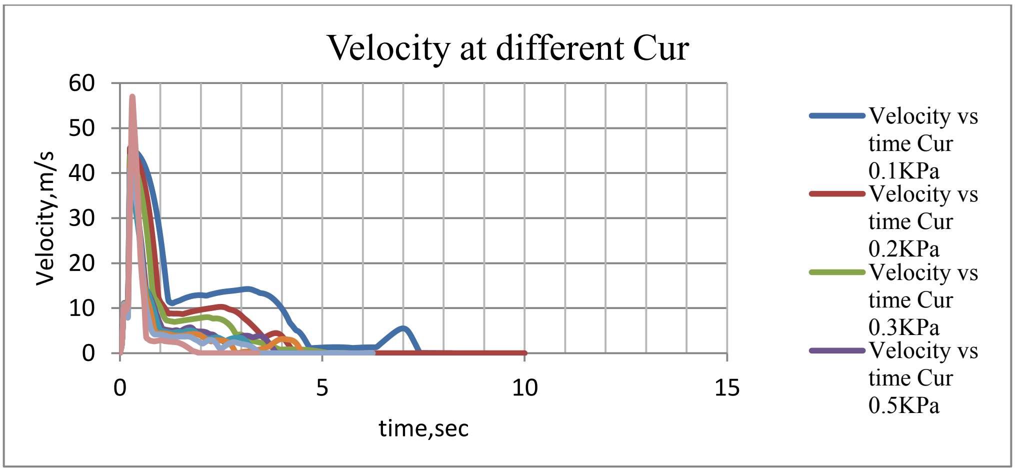


Figure 5-18 Velocity vs. time at varying shear strength values

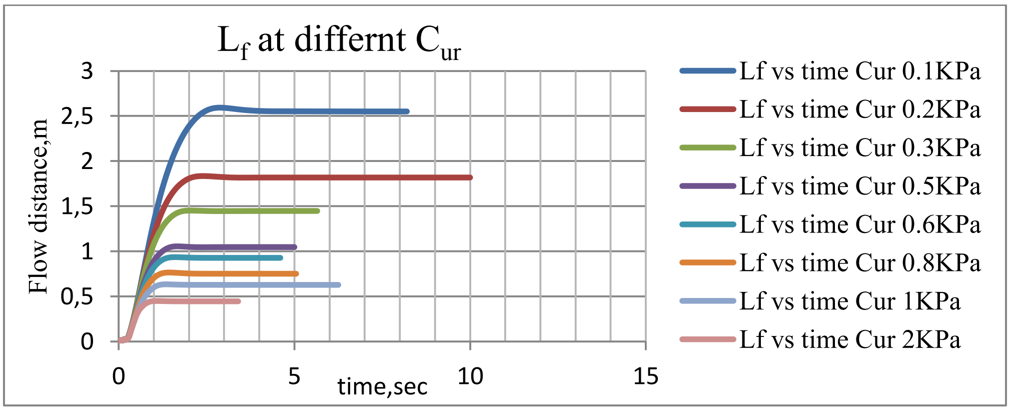


Figure 5-19 Flow distance vs. time

In the paper presented in appendix 1 calibration has been done to fit the simulated results with the laboratory test.This has been done due to the over estimation of the run out distance for higher remoulded shear strength values.

6. Conclusion and future work

The analysis results in DAN3D are generally based on topography, remoulded shear strength, viscosity and rheology type .The main outputs which are important in the study of debris flow analysis are the run out distance and the debris velocity. The run out distance for channelized flows like Byneset gave closer value, while in Finneidfjord case it gave higher results. The velocity from the analysis was higher than expected. Although there is no recorded data for quick clay slide velocities, the results are unrealistic. The flow dependency on remoulded shear strength value was observed in the simulations as well. The theoretical definition for Plastic and Bingham rheologies seem that both can be used for quick clay slide debris flow analysis. However, Bingham rheology stopped for the three cases at the initial simulation time. Enormous landslide cases have been back analysed (McKinnon 2010) based on Voellmy and Frictional rheologies but almost no cases have been studied on Plastic and Bingham rheologies.

The challenges on simulating quick clay slides lies into three major parts:

- The slide mechanism and the properties of quick clays. In section 2.5 the slide mechanisms has been mentioned, retrogressive and flake and flow type of slides are difficult to simulate and back analyse since such slides involve different steps.
- Sub aqueous failures cannot be analysed directly in this model unless a calibration is done to consider the hydro dynamic effects.
- The need for detailed information on the pre and post slide terrain models. Although taking topographical considerations is an advantage, the lack availability of such data might give unreasonable results.

In the future, more studies have to be done to characterize quick clay flow behaviour especially for Norwegian quick clays to determine the viscosity parameter more precisely. The dynamic analysis model shall be made to incorporate the sensitive clay slide debris flows. Laboratory and full scale tests have been done to verify the model applicability. Such kinds of tests have to be developed in order to incorporate and enhance the model applicability to quick clay slides.

References

Bjerrum, L. (1954). Geotechnical properties of Norwegian marine clays. Geotechnique **4**(2): 49-69.

Corominas, J. (1996). The angle of reach as a mobility index for small and large landslides.Canadian Geotechnical Journal **33**(2): 260-271.

DAN3D user manual, Documentation for DAN3D 2009,O.Hungr Geotechnical Engineering Inc,copyright 2010

Gregersen, O. (1981). The Quick Clay Landslide in Rissa, Norway. Norwegian Geotechnical Institute 135**:** 1-6.

Highland, L. (2004). Landslide Types and Processes. from http://pbs.usgs.gov/fs/2004/3072/.

Hungr, O. (1995). A model for the runout analysis of rapid flow slides, debris flows, and avalanches. Canadian Geotechnical Journal **32**(4): 610-623.

Hungr, O., Corominas, J.,Eberhardt,E. (2005). Estimating landslide motion mechanism, travel distance and velocity.Landslide Risk Management: 99-128.

Hungr, O., Evans, S., Bovis ,M.J and Hutchinson ,J.N. (2001). A review of the classification of landslides of the flow type. Environmental & Engineering Geoscience **7**(3): 221-238.

Hungr, O., Morgenstern, N.,Wong, HN. (2007). Review of benchmarking exercise on landslide debris runout and mobility modelling. Proc. the 2007 International Forum on landslide disaster management.

Issler, D., Cepeda, J. M., Byron, Q. L.,Venditti,V., Karlsrud,K (2012) .Back-analyses of run-out for Norwegian quick-clay landslides, Norwegian Geotechnical Institute Report 20120753-01-R.

Iverson, R. M. and R. P. Denlinger (2001). Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory.Journal of Geophysical Research: Solid Earth (1978–2012) **106**(B1): 537-552.

Janbu, N. (1996). Raset I Finneidfjord. Unpublished expert´s report prepared for the County Sheriff of Nordland.

Karlsrud, K., Aas,G.,Gregeresen,O. (1984). Can We Predict Landslide Hazards in Soft Senstive Clays. Norwegian Geotechnical Institute Publication **158**.

Khaldoun, A., Moller, P.,Abdoulaye,F., Bert,D., Yves,M.,Jon,O.F. (2009). Quick clay and landslides of clayey soils.Physical review letters **103**(18): 188301.

L'Heureux, J.-S. (2012). Characterization of historical quick clay landslides and input parameters for Q-Bing, Norwegian Geotechnical Institute.

Lebuis, J., J.-M. Robert, Rissmann, P (1983). Regional mapping of landslide hazard in Québec. Symposium on slopes on soft clays. Linkoping, Swedish Geotechnical Institute Report. **17:** 205–262.

Leroueil, S., J. Vaunat, Picarelli, L.,Locat, J.,Faure, R.,Lee, H (1996). A geotechnical characterisation of slope movements. the 7th symposium on landslides, Trondheim.

Locat, J. (1993). Considerations on viscous flows. International Workshop on Rapid Gravitational Movements:CEMAGREFF, Grenbole University Press.

Locat, J. and D. Demers (1988). Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays.Canadian Geotechnical Journal **25**(4): 799-806.

Locat, J. and S. Leroueil (1997). Landslide stages and risk assessment issues in sensitive clays and other soft sediments. Proceedings of the International Workshop on Landslide Risk Assessment, Hawaii. Edited by D. Cruden and R. Fell. AA Balkema, Rotterdam, The Netherlands.

Locat, P., Fournier, T., Robitaille, D., & Locat, A. 2011. Glissement de terrain du 10 mai 2010, St-Jude, Montérégie. Rapport sur les caractéristiques et les causes. Ministères des Transports du Québec, report MT11-01. (In French)

Longva, O., N. Janbu, Blikra, LH.,Bøe, R. (2003). The 1996 Finneidfjord slide; seafloor failure and slide dynamics. Submarine Mass movements and their consequences, Springer**:** 531-538.

Løken, T. (1983). Kvikkleire og skredfare – hvor og hvorfor?Norges almenvitenskapelige forskningsråd **28**: 7-12.

McDougall, S. and O. Hungr (2004). A model for the analysis of rapid landslide motion across three-dimensional terrain.Canadian Geotechnical Journal **41**(6): 1084-1097.

McKinnon, M. (2010). Landslide runout: statistical analysis of physical characteristics and model parameters.Masters Thesis of The University Of British Columbia.

Mitchell, R. and A. Markell (1974). Flowsliding in sensitive soils.Canadian Geotechnical Journal **11**(1): 11-31.

Natterøy, A. (2011). Skredkatalog om kvikkleire. NTNU Institutt for geologi og bergteknikk.

NVE (2011). Vudering av områdestabilitet ved utbygging på kvikkleire og andre jordarter med sprøbruddegenskaper. Vedlegg 1 til NVEs retningslinjer:Fkom-og skredfare i areaplanar.

Quan, L. (2012). Dynamic numerical run-out modeling for quantitative landslide risk assessment. Thesis of University of Twente, ITC **206**: 1-237.

Tavenas, F., Flon, P., Leroueil, S. & Lebuis, J. 1983. Remoulding energy and risk of slide retrogression in sensitive clays. In: Proceedings of the Symposium on slopes on soft clays, Linköping, Sweden. Swedish Geotechnical Institute, SGI Report No. 17, pp. 423–454.

Thakur ,V., Oset, F., Aabøe, R.,Berg, P.O., Degago ,S., Wiig, T., Lyche E.,.Haugen, E.E.D., Sæter, M.B., Robsrudet ,A.(2012). A critical appraisel of the definition of Brittle clays. Slop stability and landslides.

Trak B. & Lacasse S. (1996). Soils susceptible to flow slides and associated mechanisms. In: Proceedings of the Seventh International Symposium on Landslides, Trondheim, Norway, Balkema, Rotterdam, Vol. 1, pp. 497–506

Vaunat, J. and S. Leroueil (2002). Analysis of post-failure slope movements within the framework of hazard and risk analysis. Natural Hazards **26**(1): 81-107.

Appendix 1: Run-out of sensitive clay debris -A paper submitted to ’’ *Geotechnical Engineering Journal by South Asian Geotechnical Society*.’

Run-out of sensitive clay debris: significance of the flow behavior of sensitive clays

V. Thakur[1] and D. Nigussie[2]

[1]*Aalesund University College and Norwegian Public Roads Administration*

[2]*Norwegian University of Science and Technology*

E-mail: vikas.thakur@vegvesen.no

ABSTRACT: *Geohazards in the form of massive flow slides in sensitive clay deposits have been responsible for the loss of human lives and damage to nearby infrastructure. The run-out of sensitive clay debris involved in such flow slides is, among others, largely influenced by the remolded shear strength (c_{ur}) of the sensitive clays. The present work studied this factor using a small-scale model referred to as the run-out test. The results demonstrated that sensitive clay debris with $c_{ur} < 0.3$ have a potential for a longer run-out, whereas a very short run-out was observed for the sensitive clay debris with $c_{ur} > 1$ kPa. These observations were back-calculated using the three-dimensional numerical tool DAN3D.*

1. INTRODUCTION

Rapidly developing flow slides in sensitive clay deposits possess substantial destructive capabilities, resulting in the loss of life and destruction of surrounding properties. In the last 40 years, there have been one or two sensitive clay landslides per decade with volumes exceeding 500,000 m^3. In Norway alone, several hundred people have died in such landslides in sensitive soft clay slopes, and as recently as 1893, the Verdal landslide killed 116 people (Furseth, 2006; Walberg 1993; Issler et al. 2012, Oset et al. 2013). Geotechnical assessments of such flow slides include an estimation of the retrogression and prediction of the run-out of the slide debris. Although the estimation of landslide retrogression in sensitive clays has received considerable attention (*e.g.,* Lebuis and Rissmann 1979; Tavenas et al. 1983; Karlsrud et al. 1985; Trak and Laccasse 1996; Leroueil et al. 1996; Vaunat and Leroueil 2002; Thakur and Degago 2012), an appropriate method for investigating the run-out of sensitive clay debris remains the focus on ongoing research (*e.g.,* Mitchell and Markell 1974; Karlsrud 1979; Edger and Karlsrud 1982; Norem et al. 1990, Trak and Lacasse 1996; Locat and Leroueil 1997; Hutchinson 2002; Vaunat and Leroueil 2002; Hungr 2005; Locat and Lee 2005; Khaldoun et al. 2009; L'Heureux 2012; Issler et al. 2012; Thakur et al. 2013a&b).

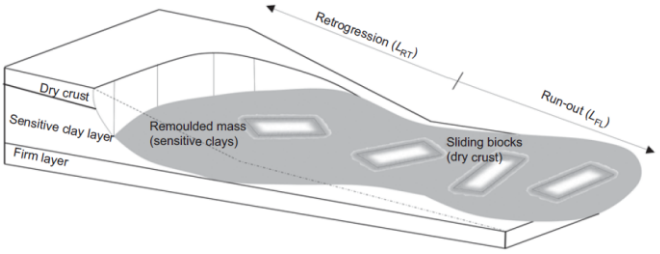


Figure1: Flow slides in sensitive clays (Thakur and Degago, 2013).

The run-out of sensitive clay debris is dependent on several factors, including the thickness of the dry crust, sensitive clay layers, boundary conditions, and topographical aspects that may allow sensitive clays to 'escape' from the slide scarp (Mitchell & Markell, 1974; Lebuis and Rissmann 1979; Tavenas et al., 1983; Karlsrud et al., 1985; L'Heureux 2012, Thakur et al. 2012, Thakur et al., 2013a&b). However, the ability of the clay debris to disintegrate and thus flow is one of the decisive factors in determining the run-out. Recent studies by Thakur et al. (2012), Thakur and Degago (2012), and Thakur et al. (2013a&b) have shown that seemingly small variations in the remolded shear strength (c_{ur}) have significant effects on the flow behavior of sensitive clays. Based on these studies, this paper presents work aimed at experimentally and numerically describing how the flow behavior influences the run-out distances of sensitive clay debris under given topographical settings. This study further investigates whether all sensitive clay debris has the same potential for run-out.

2. BACKGROUND

Highly sensitive clays are mainly found in Canada, Norway, and Sweden. Sensitive clays are often categorized using the term sensitivity (S_t), which is the ratio between the undrained shear strength (c_u) measured in the intact state (c_{ui}) and the remolded (c_{ur}) sensitive clay using the fall cone method. Rosenqvist (1953) demonstrated that the sensitivity of Norwegian marine clays is related to the leaching of salts by fresh groundwater within the grain structure. Bjerrum (1955, 1961) demonstrated that highly sensitive clays may have salt contents as low as 0.5%, whereas marine clays commonly have salt contents of 3% or more.

Figure 2 :A highly sensitive clay in the intact (left) and fully remolded states (right).

Transformation from an intact material to a fully remolded state at their natural water content is a typical characteristic of highly sensitive clays (Figure 2). Such peculiar behavior is mainly responsible for the large run-out of the debris involved in flow slides in sensitive clays. To understand this aspect, a brief review of literature on the prediction of run-out distances and the characteristics of sensitive clays in their intact and remolded states is presented here.

2.1 Review of run-out calculation methods

Over the years, many different run-out and intensity calculation methods have been developed to perform debris-flow hazard assessments (e.g., Dai et al. 2002, Hungr et al. 2005, Rickenmann 2005). The methods available for run-out estimation can be divided into four different classes: empirical, analytical, simple flow routing, and numerical.

Empirical relationships are the most commonly adopted techniques for estimating the run-out distance of slide debris. Mitchell and Markell (1974), Hsü, (1975), Karlsrud (1979), Edger and Karlsrud (1982), Karlsrud et al. (1985), Cannon (1993), Corominas, (1996), Locat and Leroueil (1997), Rickenmann (1999), Fell et al. (2000), Fannin and Wise (2001), Legros, (2002), Hutchinson (2002), Vaunat and Leroueil (2002), Bathurst et al. (2003), Crosta et al. (2003), Hungr (2005), Locat and Lee (2005), L'Heuruex (2012), and Thakur and Degago (2013a&b), among others, have reported empirical correlations for estimating the run-out distance for various geomaterials, including sensitive clays.

Ricknemann (1999) proposed an expression (Equation. 1) based on a worldwide dataset including 154 debris flow events. This function includes the vertical drop, *H*, and the maximum run-out distance L_{FL} and is mainly linked with the debris-flow volume, *V* (Figure 3).

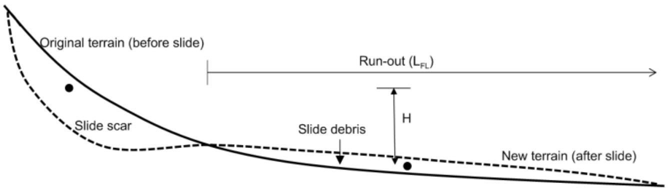


Figure 3: The idealized run-out of the debris from a slide event.

$$L_{FL} = 1.9\ V^{0.16}\ H^{0.83} \qquad (1)$$

Corominas (1996) compared a dataset of 52 debris flows, debris slides, and debris avalanches that occurred in the Pyrenees to 19 worldwide events and proposed the following relationship:

$$L_{FL} = 1.03\ V^{-0.105}\ H \qquad (2)$$

Locat et al. (2008) proposed a correlation between the run-out distance and normalized slide volume for Canadian sensitive clays based on collected landslide data. A unique empirical relation could not be derived due to scatter in the data; instead, upper and lower limits were suggested. The upper limit is given as follows:

$$L_{FL} = 1.3\left(\frac{V}{W_{avg}}\right)^{0.73} \qquad (3)\mathrm{Lf} = 9^{*}\left(\frac{\mathrm{Vol}}{\mathrm{Wavg}}\right)^{0.73}$$

Similarly, L'Heureux et al. (2012) suggested the following relationship for Norwegian sensitive clays:

$$L_{FL} = 9\left(\frac{V}{W_{avg}}\right)^{0.73} \qquad (4)$$

Equations 3 and 4 suggest that the run-out distance for sensitive clays generally increases with an increasing volume of the slide debris (V) per unit width (W_{avg}).

Another important relationship that has been noted is that the run-out distance in sensitive clays is closely related to the retrogression distance (L_R). Locat et al. (2008) suggested a maximum run-out distance for Canadian landslides as:

$$L_{FL} = 8.8\ L_R^{0.8} \qquad (5)$$

L'Hueruex et al. (2012) suggested a maximum run-out distance for Norwegian landslide as:

$$L_{FL} = 9\ L_R \qquad (6)$$

The major advantage of these empirical relationships is their simplicity. The only required input data are the longitudinal profile of the flow path and the landslide volume. In contrast, empirical relationships are often established using large datasets of observed debris flows without considering the specific characteristics of the sliding debris or topographical aspects that may influence the dynamic behavior and trajectory.

The limitations of the empirical approach are often compensated for using analytical models. Analytical approaches have been developed for rock avalanches (Körner, 1976; Hungr et al., 2005), flow slides (Hutchinson, 1986), snow avalanches (Voellmy, 1955; Perla et al., 1980), and debris flows (Rickenmann, 1990).

Sassa (1988) proposed an analytical model so called the friction or sled model. The landslide is represented by a mass concentrated at one point, and the total vertical drop and the total horizontal travel distance of the mass are respectively noted H and L. The sliding resistance T obeys the law:

$$T = \mu N, \qquad (7)$$

Where μ is the friction coefficient, *N* is the normal force exerted by the mass on the sliding surface. The loss of potential energy to the energy dissipated by friction was considered to be equal. Accordingly:

$$H/L = T/N = \mu \qquad (8)$$

μ is usually consider to be equal to the tangent of the friction angle φ of the material. Scheidegger (1973) proposed to estimate the run-out distance of rock falls:

$$L_{FL} = L_T\,(1 - H_T\,L_T^{-1})\,tan\varphi_m \qquad (9)$$

Here, the reach angle (φ_m) is expressed by arctan (H_T / L_T). H_T and L_T are respectively the vertical and horizontal distances from the head of the landslide source to the distal margin of the displaced mass.

An approach based on the energy balance is suggested by Scheidegger (1973), Hsü (1975), Sassa (1988) Vanaut and Leroueil (2002), and Thakur and Degago (2013) for the estimation of run-out in sensitive clay debris. The approach by Thakur and Degago (2013) suggests, in flow slides of sensitive clays, the change in potential energy before and after the slide is transformed to a different form of energy that results in disintegration of the soil to its remolding state and slide movement (kinetic and frictional energy). The available potential energy is a function of slope geometry and soil density. The available potential energy to be transformed and the disintegration energy have huge significance in deciding the extent of landslides in sensitive clays. It also implies that, for a given change in potential energy, sensitive clays with higher disintegration energy result in smaller slide movement than sensitive clays with lower disintegration energy. The slide movement is characterized by the run-out distance and the retrogression distance, which is controlled by the amount of energy transferred to kinetic and frictional energy during the slide process.

Over the past two decades, a large number of numerical models have been developed for other landslide types or snow avalanches. Although the constitutive behavior of slide debris remains an open topic for discussion, quasi-two-dimensional numerical models (e.g., BING (Imran et al. 2001) and NIS (Norem et al. 1987, 1989)) and quasi-three-dimensional models (e.g., DAN3D (McDougall and Hungr, 2004; McDougall, 2006), MassMov2D (Beguería et al., 2009), LS-RAIPD (Sassa, 1988; Sassa 2004; Sassa et al. 2010) and RAMMS (Christen et al. 2002)) are commonly used to estimate run-out distances. Importantly, none of these tools were developed for the estimation of the run-out distance of sensitive clay debris flows.

2.2 Characterization of sensitive clays

A characterization of sensitive clays is presented in Figures 4, 5 and 6 using the index properties obtained for more than 500 samples taken from 130 boreholes throughout Norway.

Norwegian sensitive clays follow the A-line, PI = 0.73 (LL - 20), on Casagrande's plasticity chart (Figure 4). Here, PI and LL refer to the plasticity index and liquidity limit, respectively. Norwegian sensitive clays having $S_t > 15$ are typically low-plasticity materials, with plasticity index, PI (I_P), values of less than or approximately equal to 10, meaning that they transform into brittle materials when subjected to external loading.

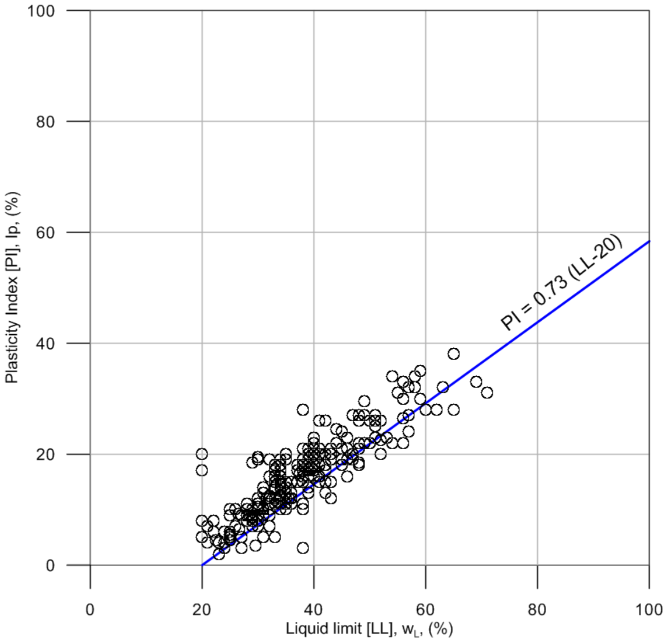


Figure 4: Norwegian sensitive clays plotted on Casagrande's plasticity chart.

Sensitive clays are uniquely related to their S_t and LL (w_L) values, and the majority of highly sensitive clays have a water content (w) > w_L (Figure 5). A ratio $w/w_L > 1.0$ characterizes open void structures that allow sensitive clays to be metastable in nature. These clays are susceptible to flow slides when their liquidity index (I_L) is greater than 1.2 (Lebuis and Rissmann 1979; Leroueil et al. 1983; Burland, 1990;). The friction angle φ varies between 25° and 28° when these clays are normally consolidated, although φ decreases with increasing w/w_L, as shown in Figure 6.

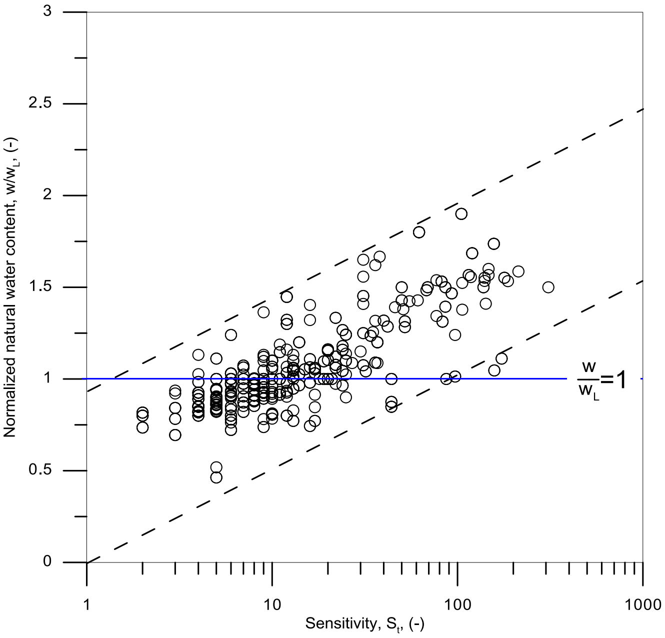


Figure 5: The relationship between soil sensitivity and the normalized natural water content for Norwegian sensitive clays.

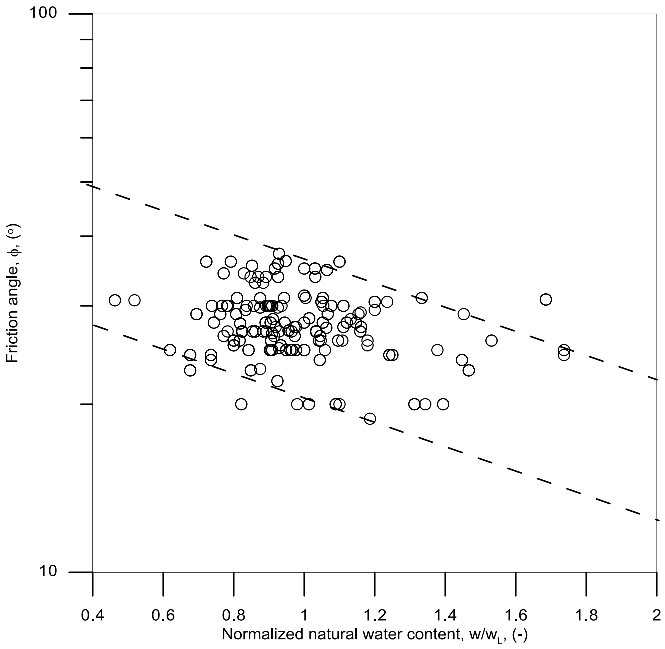


Figure 6: The relationship between the friction angles measured from consolidated triaxial tests under the undrained condition and the normalized natural water content for Norwegian sensitive clays.

It has been well documented (*e.g.,* Lacasse et al., 1985; Lunne et al. 1997) that routine sampling procedures (e.g., using 54-mm cylinders) lead to sample disturbances in sensitive soft clays. In turn, sample disturbances lead to, among other problems, the underestimation of the pre-consolidation pressure, c_{ui} and the rate of strain softening. Figure 7 illustrates the effect of sample disturbance in soft sensitive clay from the Kløfta roadway project in Norway. The figure shows that a 54-mm sampler induced a large amount of disturbance in the sample. Consequently, the stress-strain-deformation characteristics obtained from laboratory tests are not representative of the true response of the material in the field. Therefore, larger-diameter samplers, such as 76-, 95-, or 230-mm samplers, are becoming increasingly popular in Norway. In addition, the sample quality also influences S_t. Table 1 presents a comparison between the measured c_{ui} and S_t values from a block sample and from 54-mm diameter samplers from the Kløfta roadway project in Norway. The measured value of c_{ur} = 0.2 kPa was clearly unaffected by the type of sampling. The measured c_{ui} for a block sample was 27 kPa, whereas 54-mm-diameter samples at the same depth had c_{ui} values of 8.6 and 11.7 kPa. The range of error for the S_t values in Table 1 was on the order of 300%, which has a significant effect in the interpretation and design procedures. Consequently, c_{ui} and S_t are influenced by sample disturbance, whereas c_{ur} is not dependent on the quality of the sample.

Table1. The effects of sample disturbance

Depth (m)	c_{ui} (kPa)	c_{ur} (kPa)	S_t (-)
18.5^A	27	0.2	135
18.5^B	8.6	0.2	42
18.5^B	11.7	0.2	58

^{A} Block sample; ^{B} 54-mm-diameter sample

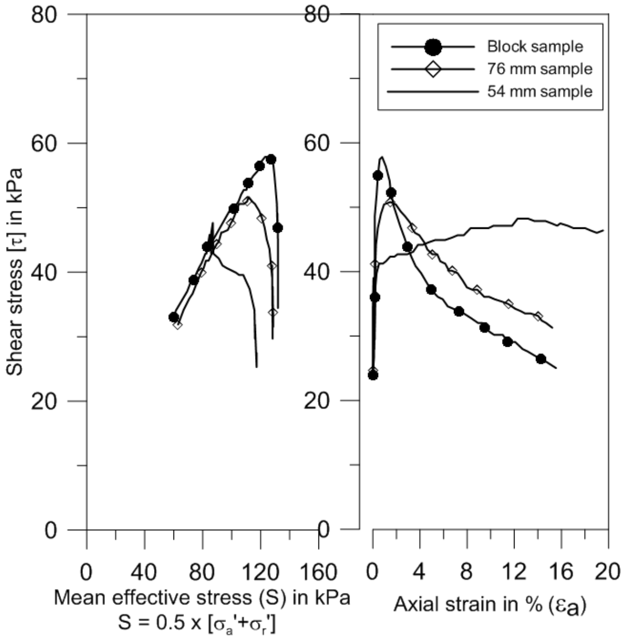


Figure 7: The effects of sample disturbance illustrated using anisotropically consolidated undrained triaxial tests on soft sensitive clays sampled using different samplers. Here, σ_a' and σ_r' are the effective stresses in the axial and radial directions, respectively. The presented results are from a Kløfta roadway project in Norway (Source; SVV, 2009).

During a landslide, the flow behavior of slide debris can be quite complex and various types of behavior can exist depending on natural water content, salt content, and liquidity index of the soil (Locat and Demers, 1988). Locat and Demers, (1988) and Locat and Lee (2005) suggests that the study of the plastic viscosity, yield stress, remolded strength, and their correlations provides a good understanding of the flow characteristics of slide debris. They have presented the rheological properties of Canadian sensitive soils. Such studies are yet to done for Norwegian sensitive clays. The literature reports a large discrepancy between laboratory and back-calculated field values of viscosity and the measured shear stress. As the objective of this paper is to discuss the correlation of the flow potential of sensitive clay debris and their remolded shear strengths, no further discussion is presented with regard to rheological models and their applicability to run-out distance modeling.

3. LABORATORY MODEL TEST

In this section, a simple test procedure used to estimate run-out distances is presented. The model test aims to provide the basis for understanding of the run-out of fully remolded sensitive clay debris using a small-scale laboratory model. Thakur and Degago (2012) have presented a similar test, the quickness test, to define the collapse behavior of remolded sensitive clays. However, the quickness test is not meant to model the run-out.

3.1 Test procedure

The model test is based on the concept of a dam breach. The model test is performed by filling a box with remolded sensitive clay, slowly releasing the filled mass from one end (gate), and measuring the run-out distance as the material is subjected to flow. The open-ended box used in this study has a length (L_o) = 200 mm, height (H_o) = 150 mm, and width (Wo) = 100 mm. An overview of the model used in the study is presented in Figure 8. The thoroughly remolded material is placed into the box and leveled off and then allowed to flow outward as the gate is slowly lifted upward with minimum disturbance to the sample. The flow length or the run-out (L_{FL}) is observed and measured along a gently inclined ramp. An inclination of 8.5° was chosen.

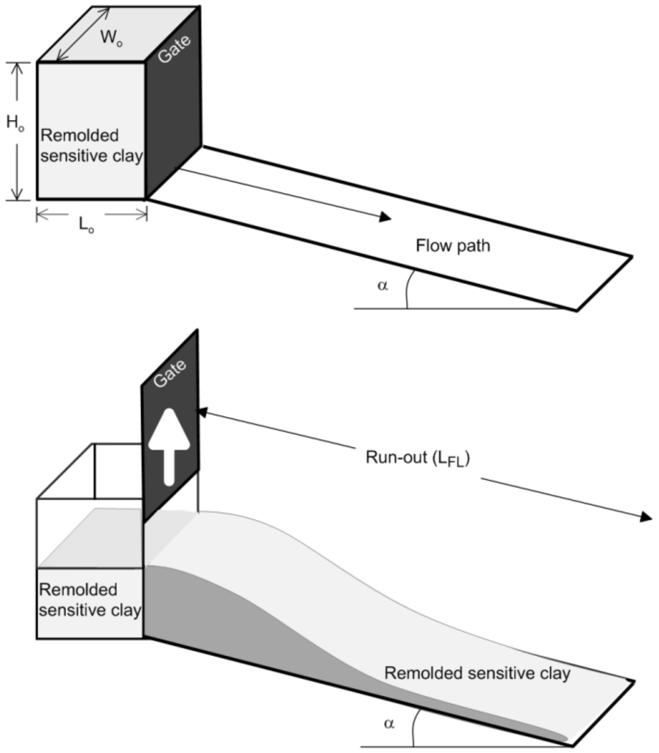


Figure 8: The run-out model test set-up.

3.2 Characterization of the tested materials

The model tests were performed on sensitive clay samples collected from three different landslide locations in central Norway. These sites have been studied extensively in connection with landslide hazards. The laboratory index properties of the sampled material are presented in Table 2. The liquid limit (w_L), c_{ui} and c_{ur} of the tested material were obtained using the fall-cone method, as described by the National Standard NS 8015 in Norway. The remolded shear strength (c_{ur}) of sensitive clays is dependent on the natural water content, which is illustrated in Figure 9 for all three clays. The tested sensitive clays had different salt contents, clay fractions, and mineral compositions, which in turn led to the same c_{ur} values at different water contents (w).

Table 2 Engineering characterization of the tested material

Properties	**Byneset**	**Lersbekken**	**Olsøy**
Sampling depth (H) [m]	4 – 12	6 – 10	4 – 15
Clay fractions (< 2 μm) [%]	30 – 55	30	50 – 65
Water content (w) [%]	27 – 48	22 – 34	28 – 38
Plasticity index (I_P) [%]	3 – 15	5 – 7	3 – 10
Liquidity index (I_L) [-]	0.9 – 5.4	0.7 – 2.0	0.6 – 3
Undisturbed undrained shear strength (c_{ui}) [kPa]	5.2 – 72	12 – 58	60 – 100
Remolded undrained shear strength (c_{ur}) [kPa]	0 – 3	0 – 2	0 – 2.1
Sensitivity (S_t) [-]	4 – 400	16 – 29	30 – 100
Over consolidation ratio (OCR) [-]	1.1 – 3.3	1.8 – 2.0	2– 4
Salinity (g/l)	0.6 – 0.74	1.5 – 1.6	0.9 – 2.0

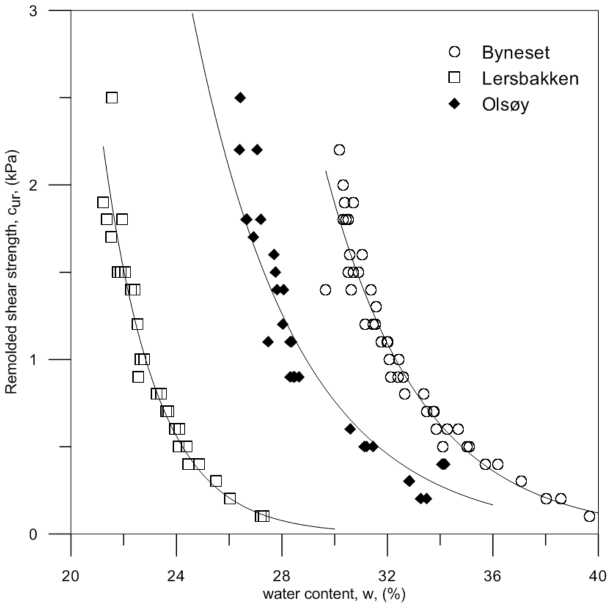


Figure 9: The remolded shear strength as a function of the water content for the tested sensitive clays.

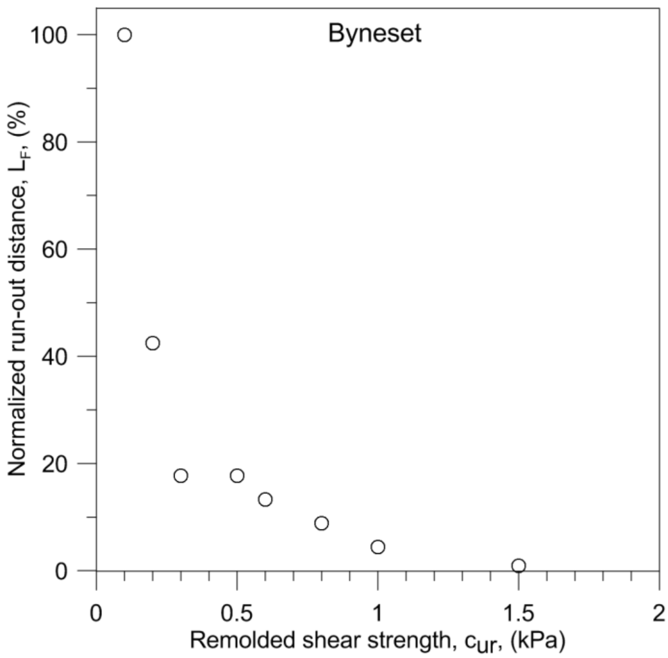


Figure 10: L_F versus c_{ur} values determined for soil samples collected from the Byneset landslide location.

3.3 Results and observations

Run-out model tests were performed on more than 35 different remolded sensitive clay samples extracted from the Lersbekken, Byneset, and Olsøy landslide locations. The observations during a run-out test conducted on Byneset, Lersbekken and Olsøy clay indicated that sensitive clays with c_{ur} = 0.1 kPa behaved as fluids, and therefore, the highest run-outs were observed for this particular c_{ur}. Importantly, the lowest possible c_{ur} value that can be measured using the fall cone apparatus is 0.1 kPa. Sensitive clays having c_{ur} = 0.1 kPa behave like water, and therefore, the run-out in such materials will depend on the available slide volume (remolded sensitive clay debris) and the formation of the terrain. Because the aim at this stage of the study was to visualize the run-out of sensitive clays at different c_{ur} values but not to predict the run-out distance for c_{ur} = 0.1 kPa, the run-out (L_{FL}) at c_{ur} = 0.1 kPa was considered as a reference value for comparison with the run-outs observed at the other c_{ur} values. For this purpose, a normalized run-out, (L_F), which is the ratio of the flow length at a given c_{ur} to the run-out at c_{ur} = 0.1 kPa, was used in this study. The relationship between L_F and c_{ur} is presented in Figures 10-12.

Interestingly, remolded sensitive clays having $c_{ur} \sim 0.5$ kPa are not as fluid as they were originally assumed, and sensitive clays with 0.5 kPa < c_{ur} < 2.0 kPa were semisolid in nature. This behavior can be observed in terms of L_F: L_F is reduced from 100% to approximately 18% for the Byneset clay, 22% for the Lersbakken clay, and 20% for the Olsøy clay when c_{ur} is increased from 0.1 to 0.3 kPa. L_F was further reduced by less than 95% when c_{ur} was increased to 1.0 kPa for all of the tested clays.

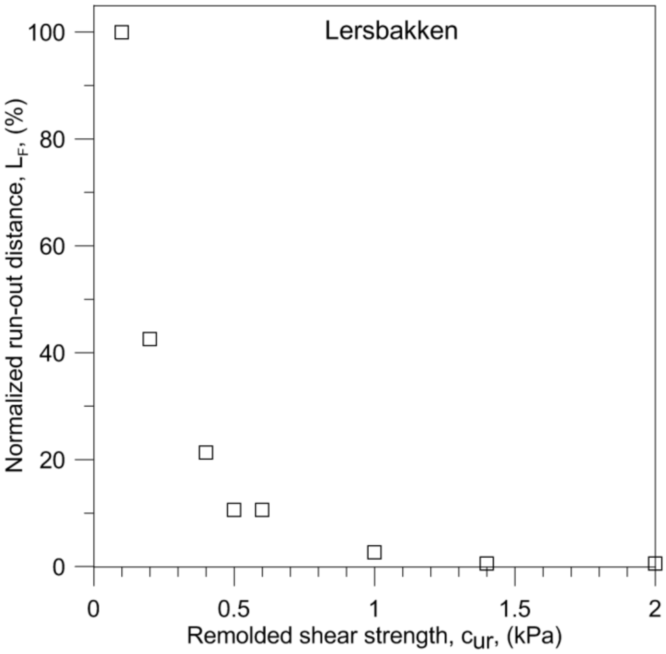


Figure 11: L_F versus c_{ur} values determined for soil samples collected from the Lersbakken landslide location.

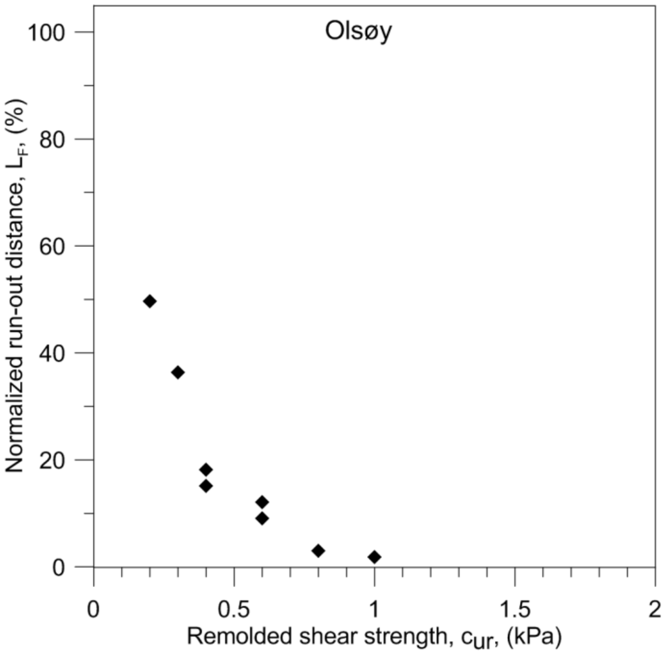


Figure 12: L_F versus c_{ur} values determined for soil samples collected from the Olsøy landslide location.

The observed behavior is in line with Mitchell and Markell (1974); Lebuis and Rissmann 1979; Locat et al. (2008); Thakur et al. (2013a&b) who reports that sensitive clays having c_{ur} > 1.0 kPa are less likely to experience a flow slide and therefore no run-out of the slide debris.

The results show that the run-out distances or flow lengths observed for the Lersbekken, Byneset, and Olsøy clays are identical. A combined plot with data for all three landslide locations is shown in Figure 13. For clay samples with c_{ur} > 1.0 kPa, very little run-out was measured. Interestingly, the run-out behavior of sensitive clay changed dramatically within the range c_{ur} < 0.3 kPa. The results of the run-out tests shown in Figure 16 clearly demonstrate that the Lersbekken, Byneset, and Olsøy materials had nearly identical responses.

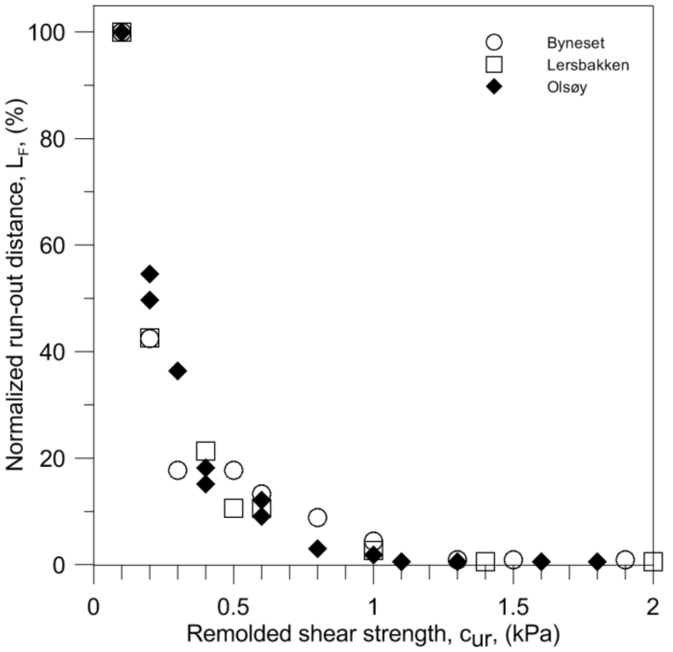


Figure 13: Compilation of L_F versus c_{ur} values registered on soil samples taken from the three landslide locations.

4. BACK-CALCULATION OF THE MODEL TEST RESULTS USING DAN3D

As mentioned earlier, several numerical tools are available to simulate debris flow and flow slides in a variety of geomaterials, except sensitive clays. Issler et al. (2012) suggested that DAN3D is the most appropriate tool and has the greatest potential to model run-out in sensitive clays. Therefore, DAN3D was chosen in this work to study the effect of the c_{ur} value of sensitive clays on the run-out distance.

4.1 Brief description of DAN3D

Dynamic Analysis of Landslides (DAN) is a quasi-two-dimensional model that was developed by Hungr (1995) and was further extended to DAN3D by McDougall and Hungr (2004) and McDougall (2006). The version of DAN3D used in this study was kindly provided by Prof. Oldrich Hungr for use in research. The basic premise of the analysis is that as a result of sliding or other failure, a pre-defined volume of soil or rock ("the source volume") changes into a fluid and flows downslope, following a path of a defined direction and width. A digital terrain model of the landslide path and a digital elevation model of the depth in the release area (“landslide scar”) are prerequisite as the input. The run-out estimation can be performed using several alternative rheological relationships, including Frictional, Plastic, Newtonian, Bingham, and Voellmy models:

Plastic model

$$\tau = \tau_y \qquad (10)$$

Frictional model

$$\tau = (1 - r_u)\,\sigma_n \tan \varphi \qquad (11)$$

Newtonian model

$$\tau = 2\mu v/h \qquad (12)$$

Bingham model

$$\tau = \tau_y + 2\mu v/h \qquad (13)$$

Voellmy model

$$\tau = \sigma_n \tan \varphi + \gamma v^2/\xi \qquad (14)$$

where τ is the bed shear stress, τ_y is the yield shear strength, r_u is the pore pressure ratio, σ_n is the bed-normal total stress, φ is the apparent friction angle, γ is the unit weight of the slide debris, μ is the viscosity, v is the depth-averaged flow velocity, and ξ is the turbulent friction coefficient (in m/s^2). In general, there is a lack of knowledge about parameter like φ, μ, ξ and v for remolded Norwegian sensitive clay debris. Accordingly, the Newtonian model and the the Voellmy model or the Friction model could not be used in this study. Issler et al. (2012) suggests that the Bingham model is not suitable for sensitive clay debris. Therefore, despite its simplicity, the plastic model was chosen in this study.

4.2 Back-calculation of the model tests

Because all of the normalized run-out behaviors were nearly identical for all three clays, the model tests for the Byneset clay were chosen for the back-calculation. The back-calculation of the model tests in DAN3D require input files containing information regarding the topography and initial conditions (Figure 14) of the model tests in the form of three ASCII grid files. The calculations were performed using the plastic model (Equation 10) for various τ_y values. The τ_y was considered to be equal to c_{ur}. The input parameters were configured according to Table 3.

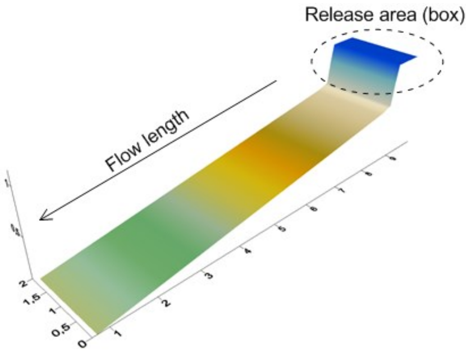


Figure 14 The path topography defined in the DAN3D calculations.

4.3 Simulation results and discussion

Thakur et al. (2013a&b) and Thakur and Degago (2012) reported that sensitive clays having c_{ur} > 1.0 kPa are less likely to experience a flow slide, i.e., zero retrogression after an initial slide and no run-out of the slide debris. This finding was confirmed by the model test results. Therefore, a back-calculation was performed at c_{ur} values up to 1.0 kPa. The numerically calculated run-out results for sensitive clay debris, in the form of a flow depth contour map for c_{ur} = 0.1, 0.3, and 1.0 kPa, are shown in Figure 15. The calculation results are in agreement with the model tests; i.e., lower c_{ur} values yield a higher L_{FL}. A comparison between the numerical calculation and the results from the model tests, presented in Figure 16, indicate an identical trend between the laboratory observations and numerical simulation. In particular, for c_{ur} < 0.3 kPa, there was good agreement between the back calculation using the plastic model and the laboratory test results. The run-out distance was drastically reduced with small increases in c_{ur}. Note that this particular range of c_{ur} is of interest because the majority of large flow slides in Norway (*e.g.*, the landslides in Verdal (1893), Braa (1928), Selnes (1965), Hekseberg (1967), Baastad (1974), Rissa (1978), Kattmarka (2009), Lyngen (2010), and Byneset (2012)) having L_{FL} > 200 m had $c_{ur} \leq 0.3$ kPa.

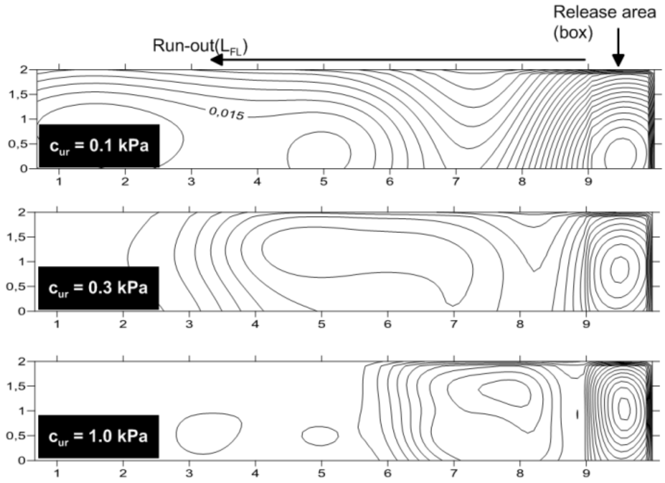


Figure 15 Run-out at various c_{ur} shown in a form of contour maps.

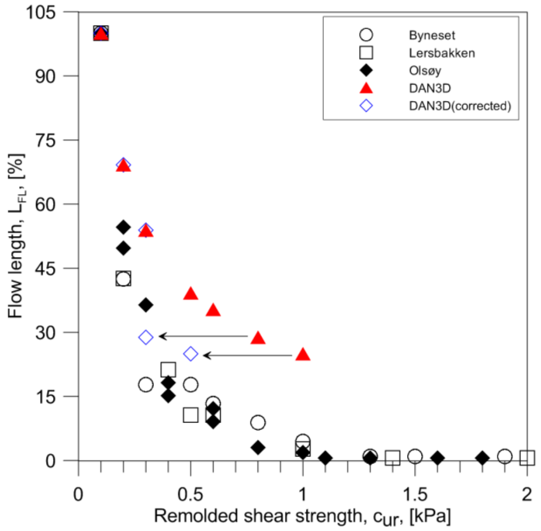


Figure 16 Back-calculated L_F for c_{ur} values for the Byneset sensitive clay along with the model test results.

However, the numerical results appear to have over-predicted the flow length for sensitive clay debris having $c_{ur} > 0.3$ kPa. Such over-prediction is attributed to the choice of constitutive model. The plastic model in DAN3D assumes zero friction between the slide debris and sliding plane (or bed) along the flow path. In contrast, there will always be some degree of frictional resistance along the sliding plane in the model test, which will counteract the flow of sensitive clay debris. The amount of frictional resistance will depend on the roughness of the bed, slope of the sliding plane, thickness of the slide debris, and the internal friction of the material. In the case of sensitive clay debris having relatively low c_{ur} values, the friction resistance between the contact surfaces will be less important because the inter-particle friction between the sliding material will be sufficiently low (similar to that of water) that the contact friction will have little influence on the flow. In contrast, semisolid sensitive clays with larger c_{ur} values (>0.3 kPa) will flow similarly to a monolithic mass, and therefore, the friction at the contact plane will have a decisive role in the run-out process. For comparison purposes, a simple correction is applied to the numerical results. The correction (τ_y^*) is assumed to be equal to the shear stresses that may result on the sliding plane due to the weight of the slide debris itself. Accordingly, τ_y^* per m^2 can be expressed as $\gamma.H_o.\sin\alpha$, where γ is assumed as 20 kN/m^3, H_o is 0.15 m, and α is 8.5°, resulting in an additional resistance of approximately 0.45 kPa. A new set of calculations that incorporate the additional τ_y^* were performed for sensitive clay debris having c_{ur} >0.3 kPa. The new results are presented in Figure 16 as DAN3D (corrected). Despite several approximations the new results exhibit a better fit with the results of the model tests.

This simple exercise demonstrates the importance of considering the effect of bed friction in numerical calculations. This simple back-calculation has encouraged the authors to study the run-out simulation for a complex case. Therefore, a back-calculation of a large flow slide, the Byneset landslide, occurred on the early morning of January 1, 2012 is presented in the next section.

5. BACK-CALCULATION OF THE BYNESET FLOW SLIDE

The Byneset flow slide took place in a highly sensitive clay deposit, and it is believed that the slide was initiated due to natural erosion at the toe of the slope. Byneset is located approximately 10 km west of Trondheim. The flow slide was approximately 150 m in width. The flow slide retrogressed backward to a distance approximately 450 m from the toe of the slope. The total run-out of the sensitive clay debris was approximately 870 m from the toe of the slope. The volume of the slide debris was estimated to be on the order of 3-3.5 × 10^5 m^3. A detailed ground investigation was performed by the authorities soon after the flow slide, and the results were presented by Thakur (2012). An overview of the geotechnical properties of the sensitive clay deposit from the flow slide area is presented in Table 2. Photos taken immediately after the flow slide illustrate that the slide masses evacuated the slide scar almost completely, as shown in Figures 17 and 18. The slide debris followed a water canal over a distance of approximately 870 m. Due to low discharge in the canal, water is not expected to have played an important role in the run-out of the slide debris. Completely remolded sensitive clay debris were observed along the entire flow path. A typical area of the flow is shown in Figure 19.

Figure 17 The Byneset flow slide (Source NVE, 2012). A closer view of the slide area and the gate.

The Byneset flow slide was back-calculated using DAN3D. The remolded shear strengths of the sensitive clay involved in the flow slide were as low as 0.1 kPa. Accordingly, several simple approximations were made to back-calculate the flow slide:

(1) The slide debris obeys the plastic model.

(2) The effects of friction along the contact surface between the flow path and slide debris were neglected.

(3) External factors, such as the effects of vegetation and water or snow along the flow path, were not considered in the model.

(4) It was assumed that the run-out is solely controlled by the remolded shear strength and topography of the area.

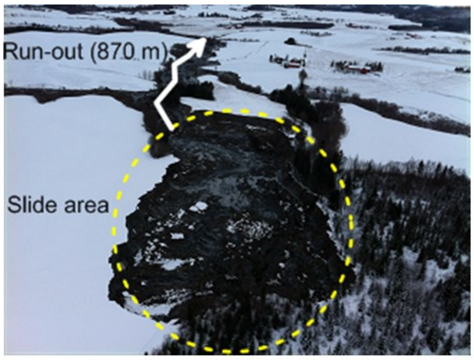


Figure 18 The extent of the Byneset flow slide (Source NVE, 2012).

Figure 19 The remolded sensitive clay debris along the flow path. (Source NVE, 2012).

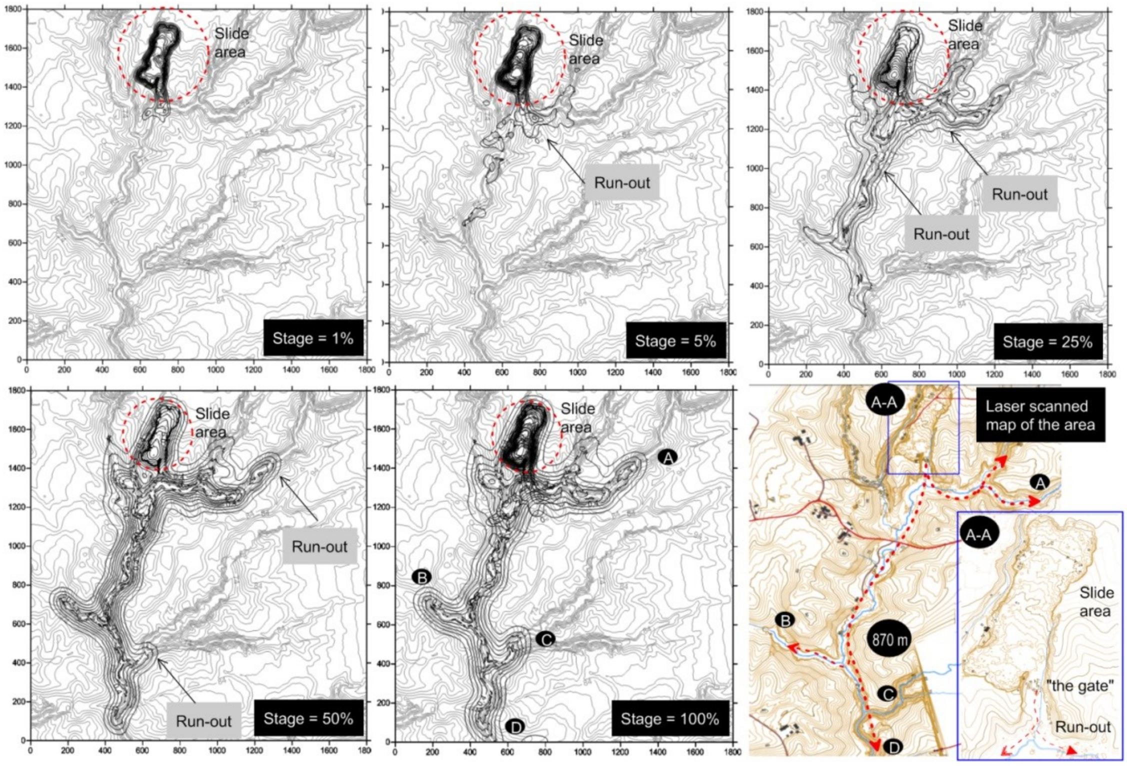


Figure 20: Back calculation of the Byneset flow slide. Run-out of sensitive clay debris, shown as a flow/deposit contour map at different stages of the simulation. The lower right figure shows the new topography of the area after the flow slide.

The results at stages of 1%, 5%, 25%, 50%, and 100% (at the end) of the calculation are shown in Figure 20. The different stages of the simulation give an idea over how the slide debris must have run-away from the slide area along the canal. The total run-out of the slide debris obtained at the end of the simulation (100%) is quite similar to that observed in the field. To support this similarity, a topographical map of the area is shown in the same figure (lower left). The extent of the run-out of the sensitive clay debris on the map is marked as A, B, C, and D. the actual mapping and the calculated run-out distance using the plastic model are quite similar. . The velocity of the slide debris was between 15 and 20 m/s, which is a relatively high velocity for such sub-aerial flow slides. It is difficult to verify the obtained velocity, as actual measurements are not available. However, slide debris involved in the Rissa landslide (1978) in Norway also had a velocity of approximately 11-12 m/s. Therefore, it is possible to conclude that the obtained velocity for the Byneset flow slide is reasonable. In summary, the back- calculated run-out distance is in agreement with the field evidences.

8. CLOSING REMARKS

This work presents a simple laboratory procedure that focuses on the effect of the remolded behavior of sensitive clays in terms of the run-out distance. Model tests were performed on more than 35 samples from three landslide sites. These results demonstrate that sensitive clays with $c_{ur} < 0.3$ kPa can be susceptible to large run-out, whereas the run-out is drastically reduced with increasing c_{ur}. This relationship was validated by back-calculating the model test and the Byneset flow slide using the DAN3D software. The numerical results demonstrated that the plastic model in DAN3D can be a good alternative for use with sensitive clays having $c_{ur} < 0.3$ kPa. However, the run-out distance can be over-estimated by the plastic model for sensitive clays having c_{ur} larger than 0.3 kPa in the absence of an appropriate correction with respect to the frictional resistance along the sliding surface. Further studies should be performed to test the other models in DAN3D using reliable input parameters. The model tests shall be carried on for different α values and using different volume of sensitive clay debris to study scale effects.

9. ACKNOWLEDGEMENT

The authors wish to acknowledge the National research program “Natural hazards: Infrastructure for Floods and Slides (NIFS)” for supporting this work. The authors would like to thank Morten Hoel, Annette Kleppe and Erlend Hundal from the University College Sor - Trondelag for helping with the laboratory testing.

10. REFERENCES

Bathurst, J.C., Burton, A., and Ward, T.J. (2003) “Debris flow run-out and landslide sediment delivery model tests”. Journal of Hydraulic Engineering, 123-5, pp410–419.

Begueria, S., Van Asch, Th.W.J., Malet, J.P., and Gröndhal, S. (2009) “A GIS-based numerical model for simulating the kinematics of mud and debris flows over complex terrain”. Natural Hazards and Earth System Sciences 9, pp1897-1909.

Bjerrum, L. (1955) “Stability of natural slopes in quick clay”. Géotechnique, issue 5-1, pp101–119.

Bjerrum, L., (1961) “The effective shear strength parameters of sensitive clays”, Proc. 5th International Conference Soil Mechanics Foundation Engineering Paris, pp23–28.

Bjerrum, L., and Kjærnsli, B. (1957) “Analysis of the stability of some Norwegian natural clay slopes”. Géotechnique, issue 7-1, pp1–16.

Burland, J. B. (1990) “30th Rankin Lecture: on the compressibility and shear strength of natural clays”. Géotechnique, issue 40-3, pp329–378.

Cannon, S.H. (1993) “An empirical model for the volume-change behavior of debris flows”, In: Shen, H.W., Su, S.T., Wen, F. (Eds.), National Conference on Hydraulic Engineering. ASCE, San Francisco, pp1768–1773.

Christen, M. Bartelt, P., and Gruber, U., (2002) “AVAL-1D: An Avalanche Dynamics Program for the Practice”, In: International Congress Interpraevent 2002 in the Pacific Rim - Matsumo, Japan, Congress publication, 2, pp715-725.

Corominas, J., (1996) “The angle of reach as a mobility index for small and large landslides”. Canadian Geotechnical Journal, 33-2 , pp 260–271.

Crosta, G.B., Cucchiaro, S., and Frattini, P., (2003) “Validation of semi-empirical relationships for the definition of debris-flow behavior in granular materials”, In: Rickenmann, D., Chen, C. (Eds.), 3rd Int. Conf. on Debris-Flow Hazards Mitigation. Millpress, Davos, pp821–831.

Dai, F.C., Lee, C.F., and Ngai, Y.Y., (2002) “Landslide risk assessment and management: an overview”. Engineering Geology, 64-1, pp65–87.

Edgers L., and Karlsrud, K., (1982) “Soil flows generated by submarine slides”, NGI Publication 143.

Fannin, R.J., and Wise, M.P., (2001) “An empirical–statistical model for debris flow travel distance”. Canadian Geotechnical Journal, 38, pp982–994.

Fell, R., Hungr, O., Leroueil, S., and Reimer, W., (2000) “Keynote Lecture – Geotechnical engineering of the stability of natural slopes, and cuts and fills in soil”, GeoEng 2000, issue 1, p21–120.

Furseth A (2006). Skredulykker i Norge. Tun Forlag, Oslo.

Hsü, K., (1975) “Catastrophic debris streams (Sturzstroms) generated by rock falls”. Geological Society of America Bulletin, 86, pp129–140.

Hungr, O. (2005) “Classification and terminology”. Debris-flow hazards and related phenomena. Springer. ISBN 3-540-20726-0, pp9–24.

Hungr, O., Corominas, J., and Eberhardt, E., (2005) “Estimating landslide motion mechanism, travel distance and velocity”, In: Hungr, O., Fell, R., Couture, R., Eberhardt, E. (Eds.), Landslide Risk Management. Taylor & Francis Group, Vancouver, pp99–128.

Hutchinson, J. N. (2002) “Chalk flows from the coastal cliffs of northwest Europe, Catastrophic landslides: Effects, occurrence, and mechanism”s. Geol. Soc. of Ame. Reviews in Eng. Geo., pp257–302.

Hutchinson, D. J. (1961) “A landslide on a thin layer of quick clay at Furre, central Norway”. Geotechnique, issue11-2, pp69–94.

Hutchinson, J.N., 1986. A sliding-consolidation model for flow slides. Canadian Geotechnical Journal 23, 115–126.

Imran, J., Parker, G., Locat, J., and Lee, H., (2001) “1D numerical model of muddy subaqueous and subaerial debris flows”. Journal of Hydraulic Engineering, 127-11, pp959–968.

Issler, D., Cepeda, J.M., Luna B.Q. and Venditti, V., (2012) “Back-analyses of run-out for Norwegian quick-clay landslides”. NIFS report. Available at www.naturfare.no

Karlsrud, K. (1979) “Skredfare og planlegging”, Lecture notes NIF-Course, Hardanger.

Karlsrud, K., Aas, G., and Gregersen, O. (1985) “Can we predict landslide hazards in soft sensitive clays? Summary of Norwegian practice and experience”. NGI Publication nr 158.

Karlsrud, K., Lunne, T., and Brattlien, K., (1996) “Improved CPTU interpretation based on block samples”, In Proceedings of the 12th Nordic Geotechnical Conference, Iceland, issue 1 pp195–201.

Khaldoun, A., Moller, P., Fall, A., Wegdam, G., De Leeuw, B., Méheust, Y., Fossum, J. O. and Bonn, D., (2009) “Quick clay and landslides of clayey soil”. Phys. Rev. Lett. 103, 188301.

Körner, H.J., (1976) “Reichweite und Geschwindigkeit von Bergstürzen und Fliessschneelawinene”. Rock Mechanics, 8, pp225–256.

L’Heureux, J. S., (2012) “A study of the retrogressive behaviour and mobility of Norwegian quick clay landslides”, Proc. 11th INASL, Banff, Canada, issue 1, pp981–988.

Lacasse, S., Berre, T., and Lefebvre, T., (1985)” Block sampling of sensitive clays”, International Conference of Soil Mechanics and Foundation Engineering, issue 2, pp887–892.

Lebuis. J., and Rissmann, P., (1979) “Les coulées argileuses dans le région de Québec et de Shawinigan. In: Argiles sensibles, pentes instables, mesures correctives et coulées des régions de Québec et Shawinigan”, Geo. Assoc. of Canada Guidebook, pp19–40

Legros, F., (2002) “The mobility of long-runout landslides”. Engineering Geology, 63, pp301–331.

Leroueil, S., Locat, J., and Vaunat, J., (1996) “Geotechnical characterisation of slope movements”, Proceedings of the 7th International Symposium on Landslides, pp53–74.

Leroueil, S., Tavenas, F., and Le Bihan, J.P. (1983) “Propriétés caracteristiqués des argiles de I’est du Canada”. Canadian Geotechnical Journal, issue 20, pp681–705.

Locat, A., Leroueil, S., Bernander, S., Demers, D., Locat, J., and Ouehb, L., (2008) “Study of a lateral spread failure in an eastern Canada clay deposit in relation with progressive failure: The Saint-Barnabé-Nord slide”, Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management, pp89-96.

Locat, J., and Demers, D. (1988) "Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays". Canadian Geotechnical Journal, issue 25, pp799–806.

Locat, J., and Lee, H. J. (2005) "Subaqueous debris flow". Debris-flow hazards and related phenomena. Springer. ISBN 3-540-20726-0, pp203–246.

Locat, J., and Leroueil, S. (1988) "Physicochemical and mechanical characteristics of recent Saguenay Fjord sediments". Canadian Geotechnical Journal, issue 25, pp382–388.

Locat, J., and Leroueil, S., (1997) "Landslide stages and risk assessment issues in sensitive clays and other soft sediments", Proc. International Workshop on Landslide Risk Assessment, (Cruden and Fell ed.) Hawaii, Balkema, Rotterdam, pp261-270.

Locat, P., Leroueil, S., and Locat, J., (2003) "Characterization of a submarine flow-slide at Pointe-du-Fort, Saguenay Fjord, Quebec, Canada", Proceeding of the 1st Symposium on Submarine Mass Movements and their Consequences, pp521–529.

Locat, P., Leroueil, S., and Locat, J., (2008) "Remaniement et mobilité des débris de glissements de terrain dans les argiles sensible de l'est du Canada", Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management. Presse de l'Université Laval, Québec, pp97–106.

Lunne, T., Berre, T., and Strandvik, S., (1997) "Sample disturbance effects in soft low plastic Norwegian clay", In Proceedings of the Conference on Recent Developments in Soil and Pavement Mechanics, pp81–102.

McDougall, S., (2006). "A new continuum dynamic model for the analysis of ex-tremely rapid landslide motion across complex 3D terrain". PhD thesis, University of British Columbia, Vancouver, Canada.

McDougall, S., and Hungr, O., (2004) "A model for the analysis of rapid landslide motion across three-dimensional terrain". Canadian Geotechnical Journal, 41, pp1084–1097.

Mitchell, R.J., and Markell, A.R. (1974) "Flow slides in sensitive soils". Can. Geot. Journal, issue 11-1, pp11–31.

NGF (1974). Guidelines by Norwegian Geotechnical Society.

Nordal, S., Alen, C., Emdal, A. Madshus, C., and Lyche E. (2009) Landslide in Kattamrka in Namsos 13. March 2009. Transportation Ministry, Norway, 2009, Report ISBN 978-82-92506-71-4.

Norem, H., Irgens, F. and Schieldrop, B., (1987) "A continuum model for calculating snow avalanche velocities", In: Avalanche formation, movement and effects, Proceedings of the Davos symposium, September 1986. IAHS publication no. 162, pp 363-379

Norem, H., Locat, J., and Schieldrop, B. (1990) "An approach to the physics and the modeling of submarine flowslides". Marine Geotechnology, 9, pp93–111.

NVE (2012). Kvikkleireskred ved Esp, Byneset I Trondheim. Norwegian Water and Energy Directorate (NVE), Oslo, Norway. NVE Report no. 1-2012 prelim-inary version 2012-01-09, 79 pp.

Oset, F., Thakur, V., Dolva, B. K., Aunaas, K., Sæter, M. B., Robsrud, A., Viklund, M. Nyheim, T., Lyche, E. and Jensen O. A. (2013) "Regulatory framework for Regulatory framework for road and railway construction on the sensitive clays of Norway". Natural Hazards book: Advances in Natural and Technological Hazards Research, ISSN: 1878-9897 (Print) 2213-6959 (Online).

Perla, R., Cheng, T.T., and Mc Clung, D.M., (1980) "A two parameter model of snow avalanche motion". Journal of Glaciology, 26-94, pp197–208.

Rickenmann, D., (1990) "Debris Flows 1987 in Switzerland: modelling and fluvial sediment transport". In: Sinniger, R.O., Monbaron, M. (Eds.), Hydrology in Mountainous Regions; Lausanne Symposium. IAHS, Lausanne, pp371–378.

Rickenmann, D., (1999) "Empirical relationships for debris flows". Natural hazards, 19-1, pp47–77.

Rickenmann, D., (2005) "Run-out prediction methods", In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Springer, Berlin, pp305–324.

Rickenmann, D., (2005) Hangmuren und Gefahrenbeurteilung. Kurzbericht für das Bundesamt für Wasser und Geologie. Unpublished report, Universität für Bodenkultur, Wien, und Eidg. Forschungsanstalt WSL, Birmensdorf, 18p.

Rickenmann, D., Laigle, D., McArdell, B., and Hübl, J., (2006) "Comparison of 2D debris-flow simulation models with field events". Computational Geosciences 10-2, pp241–264.

Rickenmann,D., and Koch, T.,(1997) "Comparison of debrisflowmodeling approaches", In: Chen, C. (Ed.), 1st Int. Conf. on Debris-Flow Hazards Mitigation, San Francisco, pp 576–585.

Rosenqvist, I. T. (1953) Considerations on the sensitivity of Norwegian clays. Geotechnique 3, 195–200.

Sassa, K. (1988) "Special lecture: Geotechnical model for the motion of landslides", In: C. Bonnard (ed.), Proc. of 5th Symp. on Landslides, Balkema, Rotterdam, pp37–55.

Scheidegger, A. E. (1973) "On the prediction of the reach and velocity of catastrophic landslides". Rock Mechanics, 5, pp231–236.

SVV (2009). Technology report 2425. Norwegian Roads Authority.

Tavenas, F., Flon, P., Leroueil, S., and Lebuis, J., (1983) "Remolding energy and risk of slide retrogression in sensitive clays", Proceedings of the Symposium Slopes on Soft Clays, Linköping, pp423–454.

Thakur V (2012) Landslide at Byneset. NIFS report. ISBN nr 978-82-410-0822-1. Available at www.naturfare.no

Thakur, V., and Degago, S.A. (2012) "Quickness of sensitive clays". Géotechnique Letters, issue 2-3, pp87–95.

Thakur, V., and Degago, S.A. (2013b) "Disintegration of sensitive clays". Géotechnique Letters, issue 3-1, pp20–25.

Thakur, V., Degago S, Oset, F., Dolva, B. K., Aabøe, R., Aunaas, K., Nyheim, T., Lyche, E., Jensen O. A. Viklund, M., Sæter, M. B., Robsrud, A., Nigguise, D., and L'Heureux J.S. (2013b) "Characterization of post-failure movements of landslides in soft sensitive clays". Natural Hazards book: Advances in Natural and Technological Hazards Research, ISSN: 1878-9897 (Print) 2213-6959 (Online).

Thakur, V., Oset, F., Aabøe, R., Berg, P. O., Degago, S. A., Wiig, T., Lyche, E., Haugen, E. E. D., Saeter, M. B., and Robsrud, A. (2012) "A critical appraisal of the definition of Brittle clays (Sprøbruddmateriale)", Proc. 16th Nordic Geotechnical Meeting Copenhagen, issue 1, pp451– 462.

Trak, B., and Lacasse, S., (1996) "Soils susceptible to flow slides and associated mechanisms", Proceedings of the 7th International Symposium on Landslides, Trondheim, issue 1, pp 497–506.

Vaunat, J., and Leroueil, S. (2002) "Analysis of Post-Failure Slope Movements within the Framework of Hazard and Risk Analysis". Natural Hazards, issue 26, pp83–102.

Voellmy, A., 1955. Über die Zerstörungskraft von Lawinen. Schweizerische Bauzeitung 73, 212–285.

Appendix 2: Preparation of Input files for DAN3D Analysis using ArcGIS10 and Surfer 11

The back analysis done for Lyngen slide and for lab model slide preparation requires input data necessary for DAN3D simulation .ArcGIS 10 and Surfer 11(Golden Software, Inc) were used based on NGI Report number 20092228-00-2-R.

Lyngen Slide

1. Original terrain contour-the dotted line shows the slide boundary

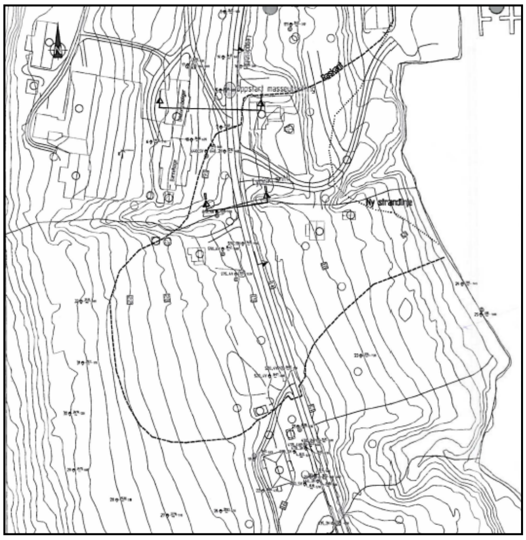


Figure A2-1 Pre slide contour map

2. The original contour was gridded as shown below and elevation points at each grid intersection was recorded :

Figure A2-2 Pre slide gridded contour map

3. The recorded elevation points are recorded and in note pad file using the following format:
   ncols <value> [these are the number of columns]
   nrows <value> [these are the number of rows]
   xllcorner <value> [this is the x coordinate of the center or lower-left corner of the lower-left cell]
   yllcorner <value> [this is the y coordinate of the center or lower-left corner of the lower-left cell]
   cellsize <value> [this is the resolution of your data]
   nodata_value [0]

25	23	21	19	16	14	11	9	7	3	2	1
25	23	20	18	15	14	12	10	9	4	3	0
25	23	20	18	15	14	12	10	7	5	4	0
25	22	19	18	16	14	12	10	7	6	5	0
25	22	19	17	16	14	11	8	7	2	0	0
24	21	19	17	15	14	13	11	9	5	5	0
22	19	16	15	15	14	12	11	9	8	4	3
24	22	20	18	16	15	12	11	10	8	7	4
25	22	20	19	17	16	14	11	10	9	7	5
25	22	21	19	18	16	14	12	11	9	7	6
25	23	21	19	18	17	15	13	11	10	8	6
25	23	21	20	18	17	16	14	12	10	9	7
26	23	21	20	19	18	16	15	13	11	10	8
26	24	22	21	19	18	16	15	14	11	10	9
26	24	23	21	20	18	17	16	14	10	6	5

This elevation points were scaled up to create raster data in ArcGIS

4. Gridded raster data set was created in ArcGIS from the text file provided in step 3:

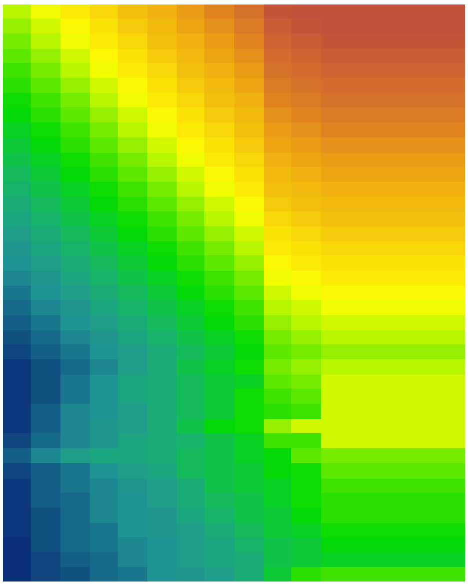


Figure A2-3 Raster data

5. The raster data shown above is comprised of the original terrain and hypothetically drawn area. Contour map generated from the raster is shown below. The dotted area designates the ideal slide surface merged with the original terrain map from figure A-1.

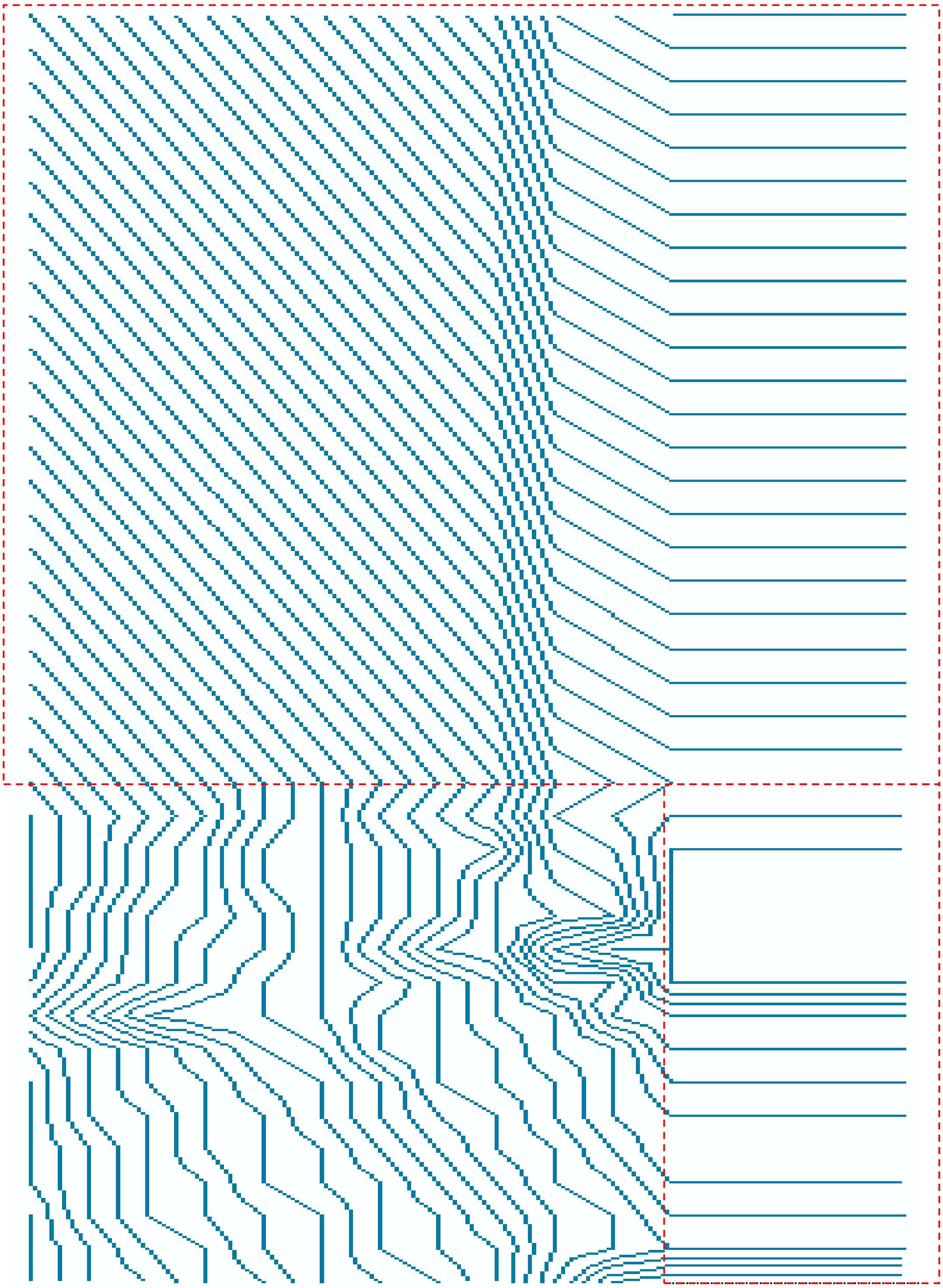


Figure A2-4 Contour map

6. The dotted line in figure A-1 shows the boundary of the slide.The area was plotted in ArcGIS to designate the release area.

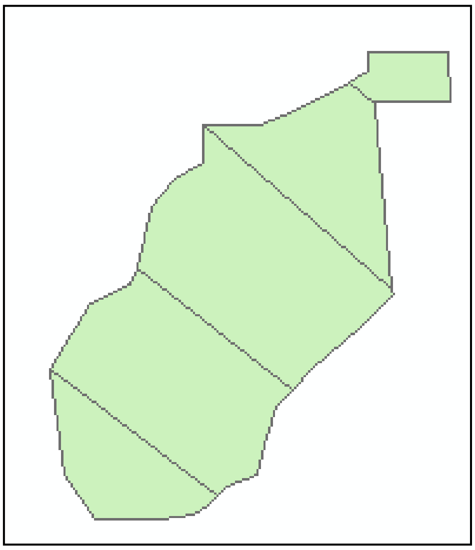


Figure A2-5 Release area

7. The release area was changed to raster data and depth data was given.The volume of the release area was checked in ArcGIS. Then the raster data from the release area was merged with the raster data created in step 4.
8. The two raster data sets in step 3 and 7 are changed to text files. These two files were opened in Surfer 11.
9. The two grid files were used to create the release area and path topography .The two plots shown below were used in DAN3D

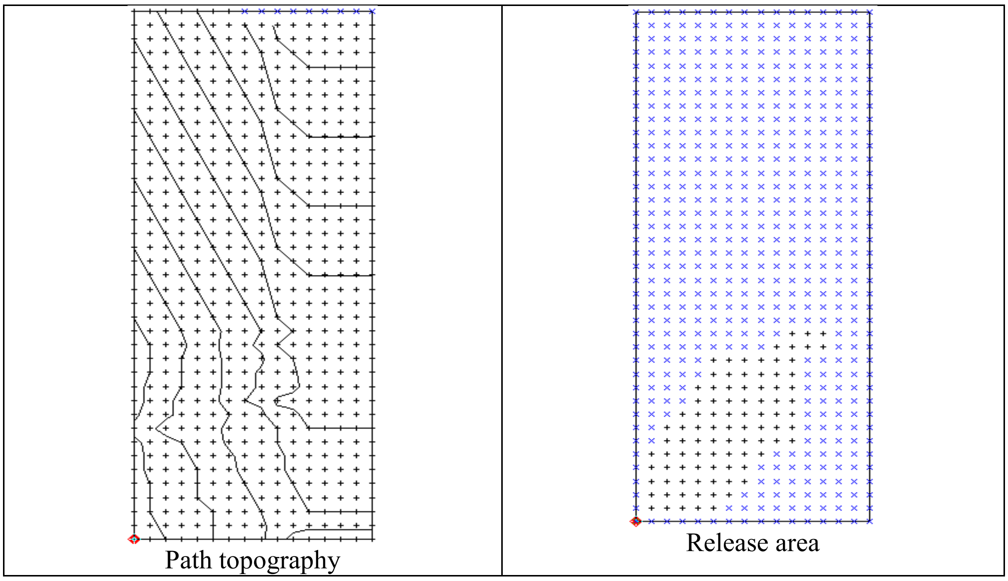


Figure A2-6 Grid files for DAN3D