NTNU – Trondheim
Norwegian University of
Science and Technology

Berm Breakwaters as Protection of Harbours, Artificial Islands and Shorelines in Arctic Areas

Tristan Mennessier

Coastal and Marine Civil Engineering
Submission date: June 2012
Supervisor: Raed Khalil Lubbad, BAT
Co-supervisor: Alf Tørum, BAT

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

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF CIVIL AND TRANSPORT ENGINEERING

Report Title: Berm Breakwaters as Protection of Harbours, Artificial Islands and Shorelines in Arctic Areas	Date:11/06/2012 Number of pages (incl. appendices): 62			
	Master Thesis	X	Project Work	
Name: Tristan Mennessier				
Professor in charge/supervisor: Raed Lubbad				
Other external professional contacts/supervisors: Alf Tørum				

ABSTRACT

The development of Arctic areas raises new challenges in many fields of expertise. This thesis deals with the design of berm breakwaters in such areas.

This thesis investigates through experiments the different ice behaviours such as ride up and pile up to evaluate mainly how efficient are the piling up events to prevent the ice to ride up further. The possible damage to the berm breakwater is also listed.
In the experiments, the ice has been modelled with paraffin. This modelling itself was also investigated to see if it could represent the full scale behaviours. The model ice was pushed against a model berm breakwater and apart from direct observations the force required to push the model ice was also recorded.

This showed that this kind of modelling can actually be used to some extent and that piling up events can be efficient to prevent the ice from riding up.

.

Keywords:

1. Berm breakwaters
2. Ice
3. Experiments

(signature)

NTNU
Norwegian University of Science and Technology

Faculty of Engineering Science and Technology
Department of Civil and Transport Engineering

Division: Marine Civil Engineering
Postal address:
Høgskoleringen 7A
7491 Trondheim
Phone: 73 59 46 40
Telefax: 73 59 70 21

MASTER DEGREE THESIS

Spring 2012

Student: **Tristan Mennessier**

Berm Breakwaters as Protection of Harbours, Artificial Islands and Shorelines in Arctic Areas

Goals

The goal is to improve the design basis of berm breakwaters subjected to ice actions in the Arctic areas.

Gaps

The concept of berm breakwaters may be considered as a good solution for the protection of harbours, artificial islands and shorelines in the Arctic areas. In principle, the berm of the breakwater will help the ice to pile-up which eventually will reduce the incoming ice actions and also increase the overall stability of the breakwater. To verify the efficiency of berm breakwaters in the Arctic and to be able to improve the design, research must be conducted to estimate 1) the global ice actions, 2) the global response of the breakwater to ice action and also to the combined actions from ice and waves, 3) the local ice actions and finally 4) the individual armour stones behaviour.

Research tasks

In this Master thesis, the student will numerically simulate the global response of a berm breakwater to ice actions. If possible, the numerical results should be validated against experimental data. Attempts will also be made to study the behaviour of the individual armour stones.

ACKNOWLEDGEMENTS

This thesis allowed me to work with subjects which are both challenging and up to date. This was possible thanks to the amazing persons who have been by my side and that I would like to thank.

Thanks to Raed Lubbad and Alf Tørum, my supervisors, for their support and the help they have been able to provide me with their broad knowledge.

Thanks to Øivind A. Arntsen, responsible for my master studies, who grant me a place in this programme and without whom all this would have never existed.

Thanks to Muhammad Tedy Asyikin, whose presence contributed to the nice working atmosphere I experienced during this project.

And thanks to all the persons I did not named here but who are always here to answer a question or just relax after some hard work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Roman letters

$D_{n50} = \sqrt[3]{\frac{W_{50}}{\rho_s}}$	the nominal diameter of the median stone
E	the Young's modulus
F_H	the horizontal component of ice action
F_V	the vertical component of ice action
H_B	the breaking load of the ice sheet
H_L	the load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it
H_P	the load component required to push the sheet ice through the ice rubble
H_R	the load to push the ice blocks up the slope through the ice rubble
H_T	the load to turn the ice block at the top of the slope
c	the cohesion angle of the ice rubble.
e	the porosity of the ice rubble
g	the acceleration of gravity
h	the thickness of the ice sheet
h_b	water depth on berm (negative means berm is above S.W.L)
h_r	the rubble height
w	the width of the breakwater

Greek letters

α	the slope angle of the breakwater
μ_i	is the ice-to-ice friction coefficient
ν	is the Poisson ratio (typical value 0.3)
ρ_i	the density of the ice
ρ_s	the density of stone
ρ_w	the density of water
σ_f	the flexural strength of the ice sheet
θ	the angle the rubble makes with the horizontal
ϕ	the friction angle of the ice rubble

1 INTRODUCTION

1.1 Background and motivation

This thesis is the logical next step following my project work. In the project, a literature review has been done to see what is the knowledge we have today about breakwaters and more specifically about berm breakwaters with regards to ice actions.

The efficiency of berm breakwaters to tolerate ice actions has already been proven in 1989 in North Bay, Ontario when a conventional breakwater suffered severe damage while a berm breakwater nearby had almost no damage, see Baird and Associates (1989). In my project work, Mennessier (2011), I have shown that there is today only few literature about the topic of berm breakwaters and this is one of the reason for this thesis. Different scenarios have been discussed concerning the possible loading cases that may be applied to the berm breakwater.

The reason why berm breakwaters are good candidates as protection in Arctic areas is that the ice should have a tendency to pile up on the berm. This means first that the ride up events will be limited and should not cross over the crest of the breakwater as often as for a classical rubble mound structure. Second the piling up could even have a consolidation effect on the breakwater, limiting global failures.

The main goal of this thesis is to verify whether berm breakwaters are actually good candidates for Arctic areas or not. For that purpose, several model scaled experiments have been conducted to see how the ice could behave and what it implies for the breakwater and if the presence of the berm actually increases the protection provided by a breakwater. In those experiments the model ice was actually paraffin. This has been done since the focus was more on the riding and the piling up phenomena which has been assumed not to be strongly dependent on the breaking mechanism. Hence it was not needed to have a model ice with modelled strength and stiffness. The advantage of it is that there is no need for accurate modelling of the ice which is an operation not yet fully understood and the experiments do not either require to take place into a cold laboratory. This however leads to some approximation as well since the breaking of the ice is not taken into account. The use of paraffin thus adds one interesting research task to this thesis, i.e. to see if it was actually viable to use paraffin instead of ice which is complicated to scale down. If such a method can describe the phenomena happening at full scale, it will then be easier to investigate them in the future.

On a first stage, some numerical modelling had been done by using PLAXIS, which is a software used to model soils and their geotechnical properties. The berm breakwater had been modelled in such a way and static forces were applied to see how it would behave. This could show the global displacements but could not describe the movement of just a few stones. Therefore the numerical modelling of the breakwater has been finally replaced by the experiments because global failures have not been observed and the results from the model could therefore not be confronted to the experimental results.

1.2 Organisation of the report

In chapter two the theoretical background concerning the interaction with ice for classical rubble mound and berm breakwaters will be presented. This chapter gives an overview of the challenges which are to be taken into account when building breakwaters in Arctic areas.

The third chapter will explain the experimental setup which has been used so that the experiments can be reproduced and thus it will be possible to compare them with each other.

Chapter four presents some of the results obtained during the experiments and shows the different behaviour observed for both the model ice and the breakwater. The results are discussed and potential explanations concerning them are proposed.

Finally, chapter five summarises the main conclusions of this thesis and suggests several recommendations for further work which mainly aim at an improvement of the presented experiment and proposition to increase the number of cases included in the experiments matrix.

2 THEORY OF ICE INTERACTION WITH RUBBLE MOUND BREAKWATERS

2.1 Classical rubble mound breakwaters

When ice interacts with a rubble mound breakwater, the breakwater may experience different load case scenarios which may lead to different failure modes of the breakwater. MacIntosh et al (1995) and Timco et al (1995) investigated the interaction between level ice and existing breakwaters and they reported several possible loading cases and failure modes.

The scope of this study is limited to the interaction between breakwaters and level ice. Other interaction such as the interaction with ice ridges are out of the scope of this work.

Depending on the loading scenario, several phenomena are expected, which may depend on the ice flexural strength and thickness, as well as the slope inclination.

If the ice start to bend when encountering the structure, the ice sheet will then break and the pieces of broken ice will be pushed along the slope (ride-up) and form a pile of rubble.
In that case, local failures are expected on the structure, such as one rock taking into the rubble and pushed up in the rubble. The load is also separated between a horizontal load from the incoming ice sheet and a vertical load from the rubble on top. This situation is shown in Figure 1.

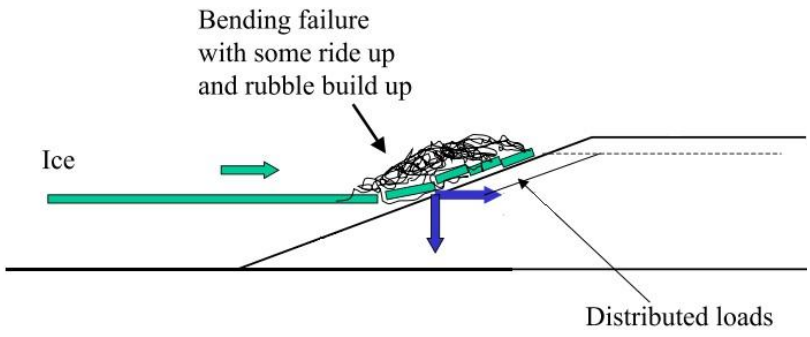


Figure 1 – Initial bending failure and ice ride up on rubble mound structure, Lengkeek et al (2003)

The height of the rubble has an important role in this scenario. Actually, the ice sheet is pushed in between the rocks and the rubble, and a large amount of rubble implies that the ice sheet will be pressed against the armour. The ice will then more likely bring rocks in the ride up.

Even though displacements of a small number of individual rocks might not be an issue for the breakwater itself, this may cause trouble for the structure that the breakwater is supposed to protect. If an armour stone is pushed on the crest of the breakwater, it could damage the structures at this location if any. Rocks could also be pushed far enough to roll on the rear side of the structure and cause damages on the land side.

It is to note that even if large rubble may lead to larger local damage, it also increases the stability of the breakwater.

At the beginning of the process, when there is no rubble, the armour is actually more fragile than when the rubble is present. The vertical load resulting from the rubble accumulation, added to the horizontal one, consolidates the breakwater.

This above case scenario is more likely to take place at the early season. At this stage, the breakwater is actually free of ice and the ice sheet may be more fragile.

In the late season however, the rubble may have consolidated and will form a solid rubble field in front of the breakwater: this is shown in Figure 2. This formation will actually act as a protection, since the ice load is then partially absorbed by the rubble.
In this case, it is possible to assume a complete contact between the rubble field and the armour. This means that there won't be any local damage since the rubble field is not moving. Global failure may however occur if the ice load in front of the rubble is too important. This could lead to global deep sliding of the structure.

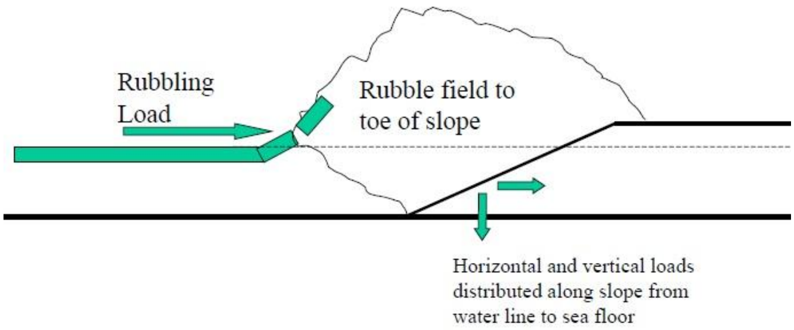


Figure 2 – Grounded rubble field to toe of slope, Lengkeek et al (2003)

In the absence of rubble field in front of the structure and if thick, strong ice comes in direct contact with the breakwater, it may directly penetrate the armour, which is referred to as bulldozing in the literature. Even if this scenario is not the most likely to happen, it has to be considered since the ice will then work in compression. Since the compression strength of the ice is larger than its bending stiffness, it will lead to higher loads.

This may happen in the early season if the conditions allow the ice to grow thick and strong in a short time. This can also happen later, since the rubble field in front of the structure can sometimes not take place or be removed, leaving the breakwater free from its protection.

If the ice directly gets through the armour layer the whole load is in the horizontal direction and decapitation and global failure may occur (Figure 3).

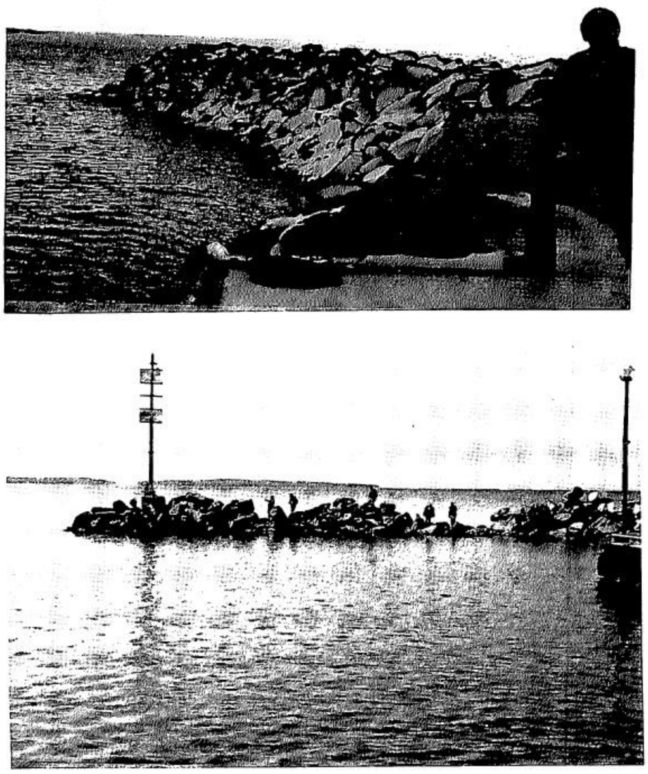


Figure 3 – Photographs showing the as-built and the ice-damaged breakwater at North Bay, Ontario, illustrating the “bulldozing” process. MacIntosh et al (1995)

Some numerical modelling has been done by Lengkeek et al (2003) to show some different loading case scenarios and how the breakwater could fail for each scenario. Figure 4 shows a sketch of the expected failure modes defined as such :

1) local failure of the armour stone due to an ice sheet bending and riding up
2) global slip failure due to a thick ice sheet penetrating through the armour
3) global sliding due to a global distributed load from a consolidated rubble field in front of the structure

As a design recommendation, Lengkeek et al (2003) suggest that the crest freeboard should be twice the ice thickness and the armour layer should be at least one time the design ice thickness.
Those results concern their case of study and should then be modified if you change parameters such as the slope of the structure.

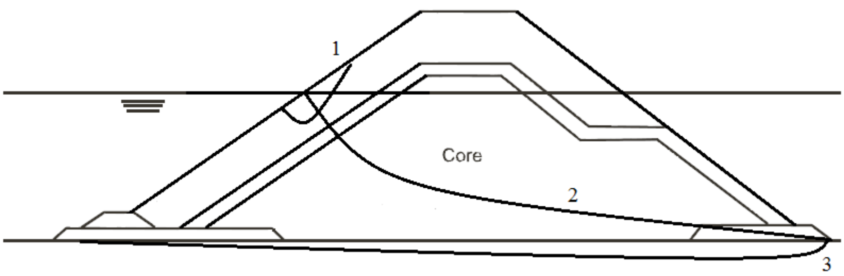


Figure 4 – expected failure modes with different ice loads

Abrasion of the rocks from ice-rock friction does not seem to be an issue. However, as explained before, the ice can push some rocks along the slope, which leads to contacts and friction between the rocks. This could lead to abrasion and should be investigated.

2.2 Berm breakwaters

The loading case scenarios for the berm breakwaters are the same as those for the classical rubble mound breakwaters but it will most likely not lead to the same structure behaviour. Ice may fail in bending and ride-up the front slope and the berm will most likely limit the progression of the ice to the top of the breakwater. This means that there should not be events with simple ride-up, but piling up should take place on the berm and extend to the front of the structure. This would prevent both ice and rocks taken into the rubble from damaging the structures on top or on the rear side of the berm. This scenario is shown on the Figure 5.

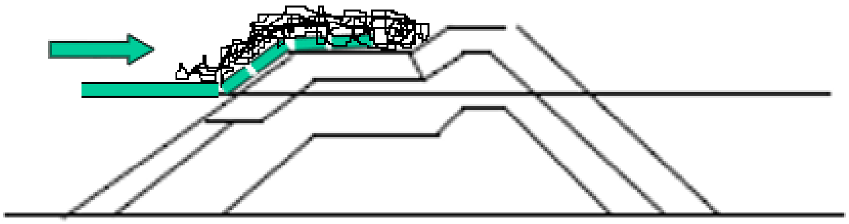


Figure 5 – Ice ride-up and pile-up on the berm.

The berm should lead to more piling-up phenomena since simple ride-up is limited. Furthermore, if some ice reaches the berm, it is more likely to stay there than if it was on a slope and hopefully the increased pile-up will increase the stability of the structure compared to a situation without piling up. The berm breakwater should then have a better stability in average compared to a classical breakwater.

The pile-up formation has been investigated by Gürtner (2009), on a structure called “Shoulder Ice Barrier” (SIB). The results presented below (Figure 7) come from the tests done in the large ice tank of the Hamburgische Schiffbau-Versuchsanstalt (HSVA) as described in Figure 6.
The SIB structure has been derived from the berm breakwater as a possibility to protect drilling platform from ice in shallow water. Though the shape is similar, one of the main differences is that it is a steel structure. Therefore the effect of the roughness and the possible motions of the stones cannot be investigated. But even though the structures are not so similar, the build up of the force can be expected to present the same scheme.

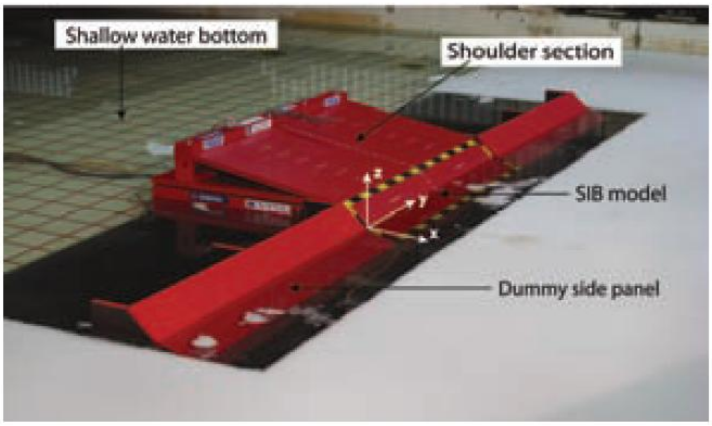


Figure 6 – SIB test set-up, Gürtner (2009)

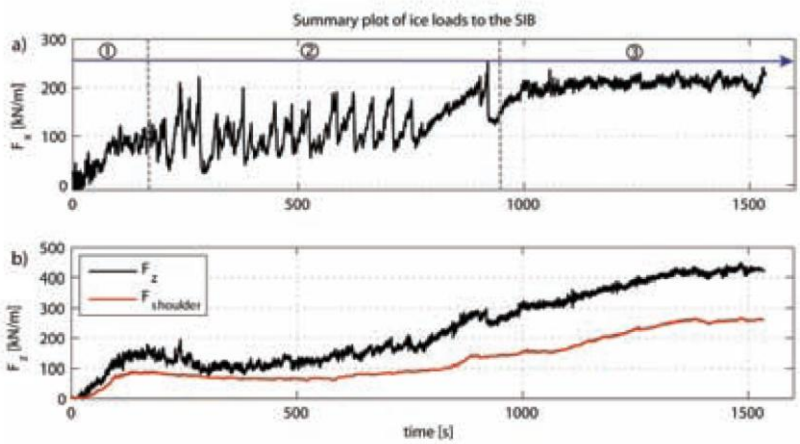


Figure 7 – Force summary plot of one particular test run with set-up according to Figure 24, Gürtner (2009)

Figure 7 represents in a) the force in the horizontal direction and in b) the force for the vertical direction and the force on the shoulder.

Gürtner (2009) divided the process for the horizontal force in three sections. The first phase takes place when the ice impacts directly on the structure, and shows a gradual increase of the force. In phase two, the rubble is forming up and large fluctuations can be seen on the plot. In phase three, the rubble is formed and the force becomes steady. The vertical force, besides, increases gradually until the steady state.

Increasing the probability of piling up also increases the probability of having a consolidated rubble field in front of the structure. This is also improving the stability since the rubble is able to take part of the load from the incoming ice.

Daly et al (2008) conducted laboratory experiments to evaluate the results of different designs. According to them, the placement of the stone as well as the presence of a toe in front of the structure would improve the stability. Improving the placement, which means that you do not have a random position of the stones but a selective placement will result in a better interlocking between the elements and should give a better stability. This is of course to be evaluated with regards to the costs of installation and maintenance of the structure since selective placement of the stone will lead to greater installation costs.

When considering ice actions on berm breakwater, one should not forget that a berm breakwater may or may not be allowed to reshape. This means that the profile of the berm may change, hence a change also in the ice actions and behaviour. This has to be taken into account when designing for the ice actions. Furthermore, if the shape has been allowed to reshape, some abrasion is expected on the stones. Then the abrasion due to the contact between the stones if one of them is taken into the ice and moved along the slope should not be an issue. Those rocks taken into the rubble will also be considered as damage on a non-reshaping berm breakwater on the contrary to those on a reshaping berm.

2.3 Ice action calculation for a rubble slope

Since there is no complete understanding of the ice properties, it is not possible either to predict the behaviour of the ice, meaning that you do not know if the ice will bend and ride-up or simply dig into the armour slope.

For instance Sodhi et al (1996) and Sodhi and Donelli (1999) conducted laboratory experiments about ice action on rip rap and came up with results about what are the effects of a phenomenon (ride-up, pile-up) but there is still no formula capable to predict why such a phenomenon occurs and not another or how large may the rubble pile grow.

The following section describes the calculations of the global ice load from level ice on a sloping structure. The formulas come from the standard ISO/FDIS 19906:2010(E). Note that these formulas are useful only for the loading scenario where level ice rides on the slope. The stone displacements are not considered.

Sloping structures are more likely to make the incoming level ice break in bending, as shown in Figure 8. The interaction between the ice and the structure is quite complicated. It involves failure of the ice sheet, ride-up of the broken ice sheet, piling up of the broken pieces and friction both between the ice and the structure and also between the riding-up pieces and the amount of rubble above. Accumulation of rubble can also take place under the ice sheet.

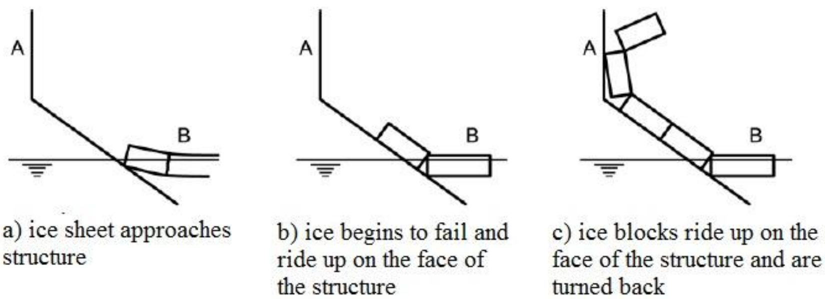


Figure 8 – processes in the interaction between a sloping structure and ice sheet, ISO/FDIS 19906:2010(E)

For level ice, the ISO standard gives formulas to define the horizontal and vertical forces acting on the structure. The definition sketch is given in Figure 9.

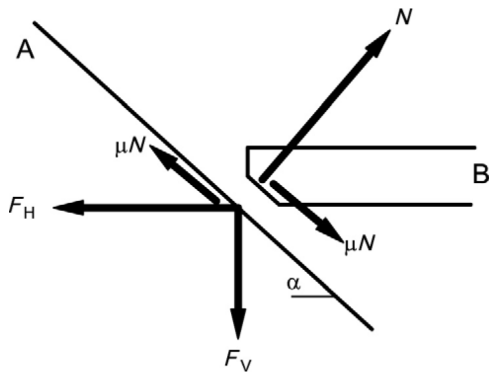


Figure 9 – Ice action components on a sloping structure for a two-dimensional condition, ISO/FDIS 19906:2010(E)

A sloping face of structure ; B encroaching ice sheet ; N normal component of reaction to ice action on structure ; μ ice-structure friction coefficient ; α slope of structure face from horizontal ; F_H horizontal component of ice action ; F_V vertical component of ice action

$$F_H = \frac{H_B+H_P+H_R+H_L+H_T}{1-\frac{H_B}{\sigma_f l_c h}} \tag{1}$$

The corresponding vertical force is

$$F_V = \frac{F_H}{\xi} \tag{2}$$

Where

$$\xi = \frac{\sin\alpha+\mu\cos\alpha}{\cos\alpha-\mu\sin\alpha} \tag{3}$$

H_B is the breaking load, H_P is the load component required to push the sheet ice through the ice rubble, H_R is the load to push the ice blocks up the slope through the ice rubble, H_L is the load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it and H_T is the load to turn the ice block at the top of the slope.
σ_f is the flexural strength of the ice sheet, h is the thickness of the ice sheet.

$$H_B = 0.68\xi\sigma_f\left(\frac{\rho_w g h^5}{E}\right)^{0.25}\left(w+\frac{\pi^2 L_c}{4}\right) \tag{4}$$

$$L_c = \left(\frac{Eh^3}{12\rho_w g(1-\nu^2)}\right)^{1/4} \tag{5}$$

E is the elastic modulus of the ice, ν is the Poisson ratio (typical value 0.3), ρ_w is the density of the water, w is the width of the structure and g the acceleration of gravity.

$$H_P = wh_r^2\mu_i\rho_i g(1-e)\left(1-\frac{\tan\theta}{\tan\alpha}\right)^2\frac{1}{2\tan\theta} \tag{6}$$

h_r is the rubble height, μ_i is the ice-to-ice friction coefficient, ρ_i is the density of the ice, e is the porosity of the ice rubble and θ is the angle the rubble makes with the horizontal.

$$H_R = wP\frac{1}{\cos\alpha-\mu\sin\alpha} \tag{7}$$

$$P = 0.5\mu_i(\mu_i + \mu)\rho_i g(1-e)h_r^2 \sin\alpha\left(\frac{1}{\tan\theta} - \frac{1}{\tan\alpha}\right)\left(1 - \frac{\tan\theta}{\tan\alpha}\right) + 0.5(\mu_i + \mu)\rho_i g(1-e)h_r^2 \frac{\cos\alpha}{\tan\alpha}\left(1 - \frac{\tan\theta}{\tan\alpha}\right) + h_r \mathrm{h}\rho_i g \frac{\sin\alpha + \mu\cos\alpha}{\sin\alpha} \tag{8}$$

$$H_L = 0.5wh_r^2\rho_i g(1-e)\xi\left(\frac{1}{\tan\theta} - \frac{1}{\tan\alpha}\right)\left(1 - \frac{\tan\theta}{\tan\alpha}\right) + 0.5wh_r^2\rho_i g(1-e)\xi\tan\phi\left(1 - \frac{\tan\theta}{\tan\alpha}\right)^2 + \xi cwh_r\left(1 - \frac{\tan\theta}{\tan\alpha}\right) \tag{9}$$

c and ϕ are the cohesion and the friction angle of the ice rubble.

$$H_T = 1.5wh^2\rho_i g\frac{\cos\alpha}{\sin\alpha - \mu\cos\alpha} \tag{10}$$

The horizontal action on the ice sheet influences the flexural failure of the ice sheet. This is considered by using the calculated value of the horizontal action to modify the flexural strength as follows

$$\sigma_f^{(1)} = \frac{F_H}{l_c h} + \sigma_f \tag{11}$$

Where l_c is the total length of the circumferential crack

$$l_c = w + \frac{\pi^2}{4} + L_c \tag{12}$$

Even though those formulas might give an understanding of the ice actions, there are still a lot of uncertainties involved. For instance the ice properties such as the ice-ice friction coefficient or the cohesion angle of the rubble are not known. Another limitation of those calculations is that they are only an estimate of the global load but do not give any information about any local load. They may then be useful to check the global stability of the structure but other formulas are needed to evaluate local damages.

3 EXPERIMENTAL SETUP

Several tests have been conducted to investigate the behaviour of berm breakwaters with regards to ice actions. Those tests have been conducted in a flume which is 60cm wide and where pieces of paraffin, representing the ice, were pushed against a model cross section of the Sirevåg berm breakwater. The force required to push was recorded and the test were also captured on videos. The scale factor used all along the experiments was 70. The following section gives the details of the experimental setup.

3.1 The testing rig

3.1.1 The flume

The flume used was situated in the laboratory of the NTNU Department of Hydraulic and Environmental Engineering. The width of the flume is 60 centimetres. The direction perpendicular to the flume is considered as the y-axis while the longitudinal direction is the x-axis. The flume is shown in Figure 10.

Figure 10-The flume

3.1.2 Towing carriage and force transducers

The model ice was pushed with the use of a linear motion system moving a plate in the x direction. The force required to push was then recorded with two force transducers fixed behind this plate. The reference for the transducers is SN9M/500N from HBM, serial nr: 30879157 and 30879164. The Figure 11 below shows the towing carriage and the force transducers.

Figure 11-Linear motion system and force transducers

The linear motion system used in the x direction was a Rollco QME30-2500. This means that the bearing shafts have a diameter of 30mm and the stroke length is 2500mm.

The motor used to push the model ice was a step motor provided by SINTEF. This motor could not push more than 250 Newtons with a limitation of 1 millimetre per second. It is recommended to use a more powerful motor for further experiments.

3.1.3 Profiler

In order to be able to record any global deformation of the breakwater, a profiler had been installed by SINTEF. This allows to scan the breakwater in x and y directions and make it possible to do a 3D plot of its surface. The photoelectric sensor was a SICK DME 2000 serial.no: 1010578. The motion along the x-axis was assured by the same linear motion system which was used to push the model ice. This system has been described in the section 3.1.2. The system could move along the y-axis thanks to another step motor. The system, as well as the photoelectric sensor, is shown in Figure 12.

Figure 12-XY profiling system and photoelectric sensor

3.1.4 Data acquisition and treatment

The data from the force transducers and the position of the pushing plate was acquired through an HBM MGCplus logger and amplifier system with two DC force amplifiers ML10B and one A/D 8 channel ML801B. The data were then registered on the computer with the use of the software Catman Easy (version 3.1) and analyzed with MATLAB. Figure 13 shows a sketch of the path followed by the data.

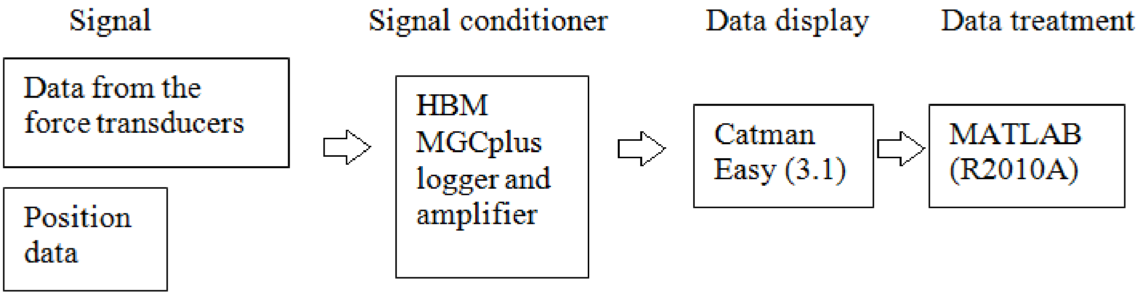


Figure 13-Data acquisition and treatment

On all the experiments it is possible to see that the two force transducers do not record the same amount of force. This means that there is a momentum in the pushing plate but the sum of the two forces allows us to get rid of this. To be interested in only the total force is then an advantage since the force transducers do not require to be placed in a perfectly symmetrical way relatively to the middle of the flume.

The scaling laws used for the experiments were the Froude scaling laws and the scaling number λ was 70. The density of the model ice and the full scale density are considered to be the same. Table 1 shows how this fact is applied to the relevant physical parameter. All the results or parameters given in the next sections are given as model-scaled values unless specified otherwise.

Table 1-Froude scaling multiplication factors

Physical parameter	Unit	Multiplication factor
Length	[m]	λ
Force	[N]	λ^3
Time	[s]	$\sqrt{\lambda}$

3.2 The model berm breakwater

First of all the breakwater design that has been used in all the experiments is the one of the Sirevåg berm breakwater, which is located 70km south of Stavanger, Norway.
This breakwater has been thoroughly investigated by Tørum and al (2003) which means that its behaviour against wave actions is now well known. It has then been decided to use this known structure as a basis for further experiment.

It is important to note that the Sirevåg berm breakwater is a non reshaping breakwater. It is helpful for the experiments since it means we know the profile of the breakwater before any ice action being involved. In case of a static stable reshaping berm breakwater, the ice might actually arrive before the breakwater has reached its static shape. The cross section used in the experiments is presented in the Figure 14 below. Note that the sand and the rock bottom have not been modelled in the experiments. The breakwater has been set perpendicular to the flume direction, occupying the whole width of the flume.

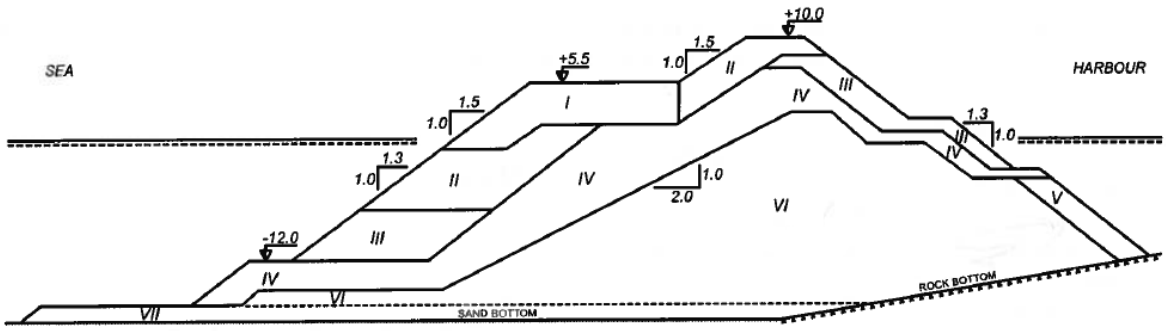


Figure 14-Cross section of the Sirevåg berm breakwater. Characteristics of the stones are given in Table 1 (from Tørum et al (2003))

Table 2 details the characteristics of the stones.

Table 2-Characteristics of the stones for the Sirevåg berm breakwater, from Tørum et al (2003)

	Stone class	**Prototype (tons)**	**Model (kg)**	**Gradation factor $f_g = D_{n85}/D_{n15}$**	**Mean volume reduction factor, k_{mean}**
$\rho_s = 2700 kg/m^3$	I	20-30	0.058-0.087	1.11	0.41
	II	10-20	0.029-0.058	1.15	0.43
	III	4-10	0.012-0.029	1.20	0.42
	IV(filter)	$W_{50} = 1.6$	$W_{50} = 0.004$		
	V&VI (core)	$W_{50} = 1.2$	$W_{50} = 0.0036$		

3.3 The model ice

A key issue of this experimental setup is that it is not ice that has been used but broken pieces of paraffin. This has been done as a try to see if paraffin could represent the ice action, so that it could be reused and facilitate the future investigations about ice actions. The pieces have been broken in forehand in order to remove the breaking mechanisms from the experiments. This has to be done since the paraffin as a different strength from the ice and also since the breaking mechanism has been assumed not to have a major role in the piling and riding up process.

The different parameters that have been changed in the experiments are:

- the thickness of the model ice,
- the length of the pieces (representing a breaking length), and
- the friction.

The lengths that have been used are 7.5, 10.5, 13.5, 16.5, 19.5 and 22.5 centimetres while the two thicknesses used are 1.5 and 3cm. Those thicknesses represent respectively 1 and 2 meters at full scale. This means that for the 3cm thick model ice there is a variation in the breaking length from 3 times the thickness to 7.5 times. And the variation goes from 6 times the thickness to 15 times for the 1.5cm thick pieces.

The friction has been changed by gluing sand to the below water surface of the model ice. The sand used had an average grain size of d=150 micrometer.

The Table 3 below is used to refer to the groups of tests, in parenthesis are given the details of the groups, for instance the tests 4, 17, 18 and 29 belong to TESTS1A.

In the tests with the mention ABC the three lengths 7.5, 10.5 and 13.5 cm have actually been used together. This is simply due to the fact that there was a small lack of paraffin and not enough pieces had been melted.

Table 3-Categorisation of the tests

	Thickness 3cm		**Thickness 1.5cm**	
	d=0	**d=0.00015**	**d=0**	**d=0.00015**
Length(cm)				
7,5	TESTS1A (4, 17, 18, 29)	TESTS1FA (32, 33, 34)		
10,5	TESTS1B (5, 19, 20)	TESTS1FB (35, 36, 37)	TESTS2ABC (27, 28, 9)	TESTS2FABC (50, 51, 52)
13,5	TESTS1C (11, 11bis, 11ter, 30)	TESTS1FC (38, 39, 40)		
16,5	TESTS1D (3, 3bis, 16, 31)	TESTS1FD (41, 42, 43)	TESTS2D (8, 25, 26)	TESTS2FD (53, 54, 55)
19,5	TESTS1E (2, 14, 15)	TESTS1FE (44, 45, 46)	TESTS2E (7, 23, 24)	TESTS2FE (56, 57, 58)
22,5	TESTS1F (1, 12, 13)	TESTS1FF (47, 48, 49)	TESTS2F (6, 21, 22)	TESTS2FF (59, 60, 61)

In all the tests the model ice had a width of 58 centimetres so that it would occupy the whole breadth of the flume. This means that the experiments can be considered as 2D experiments since there is no variation in the y direction.

3.4 Experimental procedure

For each group of tests, the experiment has been repeated at least three times respecting the following pattern.

First of all the breakwater has to be checked. It should be in its original or reference shape so that the results from the different experiments can be compared with each other. Once this has been done, the broken pieces of model ice needed for the experiment can be placed in the flume. It is possible to see in Figure 11 that there is an offset between the end of the stroke and the breakwater so some more pieces were needed in order to push the pieces related to the experiment.

Once the model ice is in place, the software to run the motor, the software to acquire the data and the video camera should be ready. When launched, the software running the motor first waits six seconds. This gives enough time to launch the data acquisition and the camera so that the results on the graphs and the videos will be synchronised.

When the motor stops, the pieces of ice have to be removed carefully if there is a risk that they will slide down when removing the pressure so that any extra damage is avoided. Then if the breakwater presents any damage, pictures are taken. The pushing plate is then put back into place and the process can be repeated.

4 DISCUSSION

As previously mentioned, the experiments have been conducted to evaluate if berm breakwaters are a good option when it comes to coastal defence in Arctic areas. Several issues were of interest. First concerning the ice behaviour, to see if there is actually any piling up taking place which is one of the main reasons why berm breakwaters should be used. Second to see what kind of threats or damage could happen to the breakwater depending on the ice behaviour.

Besides, the new way of approaching those issues, using paraffin as model ice, was also studied to assess if such a method could give reasonable results so there was also some focus on what kind of behaviour can be expected due to this peculiar modelling and in what range does it represent the full scale phenomena.

4.1 Observed ice behaviour

The following phenomena have been observed throughout the experiments:

- Ride-up
- Pile-up
- Stacking
  - Realistic stacking
  - Non-realistic stacking

Those phenomena are described and discussed in the coming sections.

4.1.1 *Ride up*

The easiest phenomenon to categorise is the ride up and a good example of this is the test 18 from the TESTS1A. The picture in Figure 15 shows the situation just before the first release, at around 700 seconds. We can see the force building up between the beginning of the test and this moment and it is this building up that categorizes the ride up.

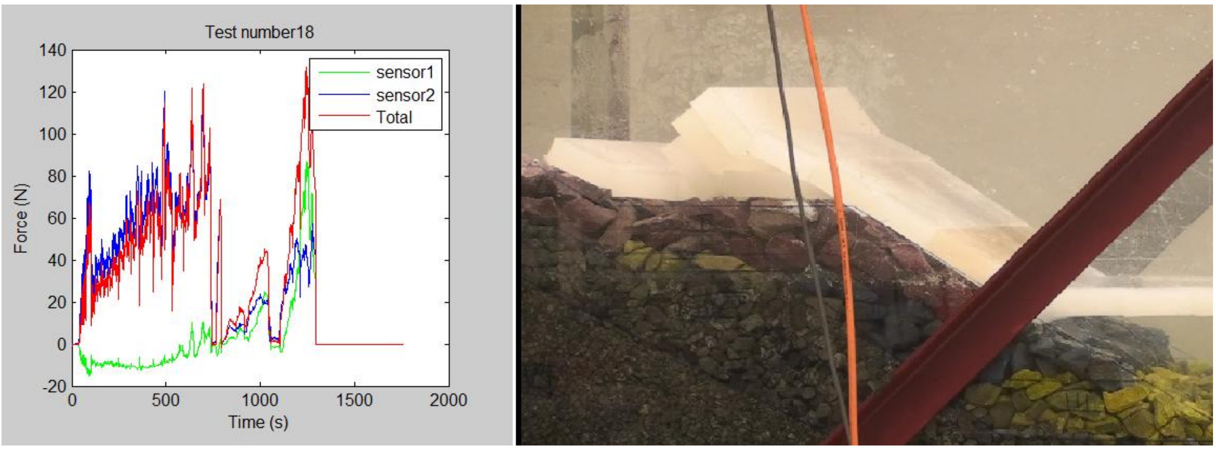


Figure 15-Test18(TESTS1A): Typical ride up phenomenon

The increase in the force during ride up events is completely logical since more and more pieces are taken out of the water and need to be pushed upward. When there are more pieces along the slope, both the weight to push and the resistance due to the contact between the slope and the model ice increase, which leads to a higher recorded force.

Table 4 below shows how many tests in each group presented a ride up. It is possible to note that it may be more likely to have such a phenomenon when the length/width ratio is small. That could explain why there were only few ride up when using the thin model ice. Besides the table also shows that there has been more ride up with the smooth model ice than with the rough one. This should be expected since the rough one requires more force to ride up the slope and is therefore more likely to fail in front of the breakwater instead.

Table 4-occurrences of ride up

<table>
<tr><th></th><th colspan="2">Thickness 3cm</th><th colspan="2">Thickness 1.5cm</th></tr>
<tr><th></th><th>d=0</th><th>d=0.00015</th><th>d=0</th><th>d=0.00015</th></tr>
<tr><th>Length(cm)</th><td></td><td></td><td></td><td></td></tr>
<tr><th>7,5</th><td>XXX</td><td>XX</td><td rowspan="3">X</td><td rowspan="3">XX</td></tr>
<tr><th>10,5</th><td>XXX</td><td>X</td></tr>
<tr><th>13,5</th><td>XXX</td><td>XXX</td></tr>
<tr><th>16,5</th><td>XXX</td><td>X</td><td></td><td></td></tr>
<tr><th>19,5</th><td>X</td><td>XX</td><td></td><td></td></tr>
<tr><th>22,5</th><td></td><td>X</td><td></td><td></td></tr>
</table>

Table 4 shows that there has been almost no ride up for test using the thin model ice. This could be due to the fact that the thin plates are more likely to slide on top of each other since their edge is thinner.

4.1.2 Pile up

The pile up phenomena are of course linked to the ride up events in the sense that a ride up is needed before a pile up event can occur. A ride up event does not however always lead to a pile up on the berm. Table 5 below lists how many tests have shown a pile up.

Table 5-occurrences of pile up

<table>
<tr><th></th><th colspan="2">Thickness 3cm</th><th colspan="2">Thickness 1.5cm</th></tr>
<tr><th></th><th>d=0</th><th>d=0.00015</th><th>d=0</th><th>d=0.00015</th></tr>
<tr><th>Length(cm)</th><td></td><td></td><td></td><td></td></tr>
<tr><th>7,5</th><td>XX</td><td>X</td><td rowspan="3">X</td><td rowspan="3"></td></tr>
<tr><th>10,5</th><td>XXX</td><td>X</td></tr>
<tr><th>13,5</th><td>X</td><td>X</td></tr>
<tr><th>16,5</th><td></td><td></td><td></td><td></td></tr>
<tr><th>19,5</th><td></td><td>X</td><td></td><td></td></tr>
<tr><th>22,5</th><td></td><td></td><td></td><td></td></tr>
</table>

It is interesting to compare with Table 4 and see that overall there has been 11 piling up events for 26 ride up events. There has been however only a few extraneous events which means that the piling of the model ice on the berm is not the only reason for the ice to stop its progress to the rear side of the breakwater. In fact, the model ice can simply break in front of the breakwater during a ride up which is quite likely to lead to an accretion before the slope.

It should also be pointed out that when the model ice starts to break in the first place, the possible ride up taking place afterwards will not lead to a pile up since there will not be enough model ice. The plates have actually to cross the rubble area first and then might reach the berm, but there will not be enough plates left to pile on a berm even they reach it. This might be improved if it was possible to run tests with more model ice.

The different pile up events observed have shown different patterns. Quite often the plate already on the berm and the incoming plate will collide which will lead to an upward displacement for both plates. Then the incoming plate will slide either upward or downward and therefore will pile either on top or below the plates already in place. This is shown in Figure 16.

Figure 16-from left to right: upward force lifting the plates; incoming plate sliding on top; incoming plate sliding below.

Even though pile up events are not that frequent they still represent almost half of the ride up events. This means that the presence of the berm is indeed effective since if it was a classical rubble mound structure this would probably happen at the top of the structure and then the model ice should be more likely to reach the rear side.

4.1.3 Realistic stacking

Another phenomenon which is harder to qualify is the accretion in front of the breakwater.
There are mainly two possibilities to see some accretion taking place, excluding the non realistic one.

Table 6 below shows in how many tests in each group occurred a realistic stacking. This table collides somehow with Table 4 which is quite normal since there can be a realistic stacking either before or after a ride up event.

Table 6-occurrences of realistic stacking

<table>
<tr><th></th><th colspan="2">Thickness 3cm</th><th colspan="2">Thickness 1.5cm</th></tr>
<tr><th></th><th>d=0</th><th>d=0.00015</th><th>d=0</th><th>d=0.00015</th></tr>
<tr><th>Length(cm)</th><td></td><td></td><td></td><td></td></tr>
<tr><th>7,5</th><td>XX</td><td>X</td><td rowspan="3">X</td><td rowspan="3">XX</td></tr>
<tr><th>10,5</th><td>X</td><td></td></tr>
<tr><th>13,5</th><td>X</td><td>XX</td></tr>
<tr><th>16,5</th><td>X</td><td>XX</td><td></td><td>XXX</td></tr>
<tr><th>19,5</th><td>XXX</td><td>XXX</td><td>XX</td><td>XX</td></tr>
<tr><th>22,5</th><td></td><td>XXX</td><td>X</td><td>XXX</td></tr>
</table>

It is possible to see from this table that the model ice is not much influenced by the size of the plates, however it seems like it is influenced by the friction of those. There is actually much more stacking taking place when using the rough model ice.

The first possibility for the stacking to happen is to have a ride up first, and then if there is a release in the force due to some bending for example, the blocks of model ice which are still on the slope and not yet on the berm are likely to slide down and accumulate at the front of the breakwater. The following pieces will then face more difficulties to ride up again and may just keep accumulating at the front of the breakwater. This behaviour is shown in the Figure 17 below.

Figure 17-Possible accretion after ride up. On the left, the test 18 at the moment of the release (about 800s). On the right the same test some minutes after the release

It may happen however that the next pieces just ride on top of the previous ones, creating a double layer of model ice on the slope. In this case, the second layer will have less trouble than the first one since it will be easier to ride up on model ice than on the stones.

The second possibility where accretion can occur is actually when the first pieces of model ice do not manage to ride up on the first place. The accretion will be the first phenomenon taking place. This is shown on the recorded force as basically a curve which is not building up, or for a really short time. The Figure 18 below illustrates this possibility.

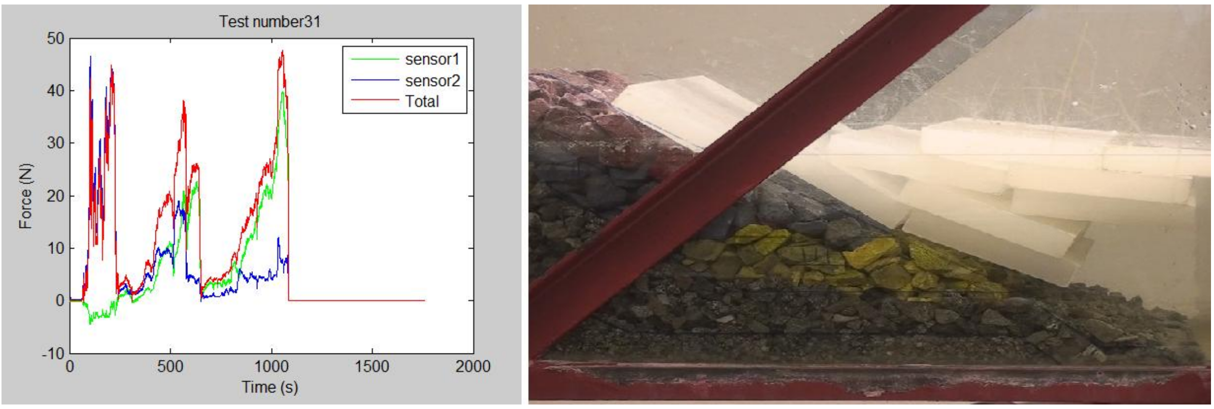


Figure 18-Test 31(TESTS1D): accretion at the front of the breakwater without ride up

On Figure 18 it is possible to see that after 700 seconds, there is actually a riding up pattern taking place. There is actually a ride up but this ride up has to cross over the accretion in front of the breakwater before it can reach the breakwater itself.

This accumulation will therefore act as a barrier in most cases but can in some condition also help the ride up and lead to extraneous events. During the test without added friction, only twice has the model ice reached the rear side of the breakwater and both times it was due to the fact that the first pieces accumulated in a way which helped the ride up. This occurred in tests 3 and 3bis from TESTS1D. Figure 19 below shows a caption of the test 3bis once the ride up has started, at about 700s.

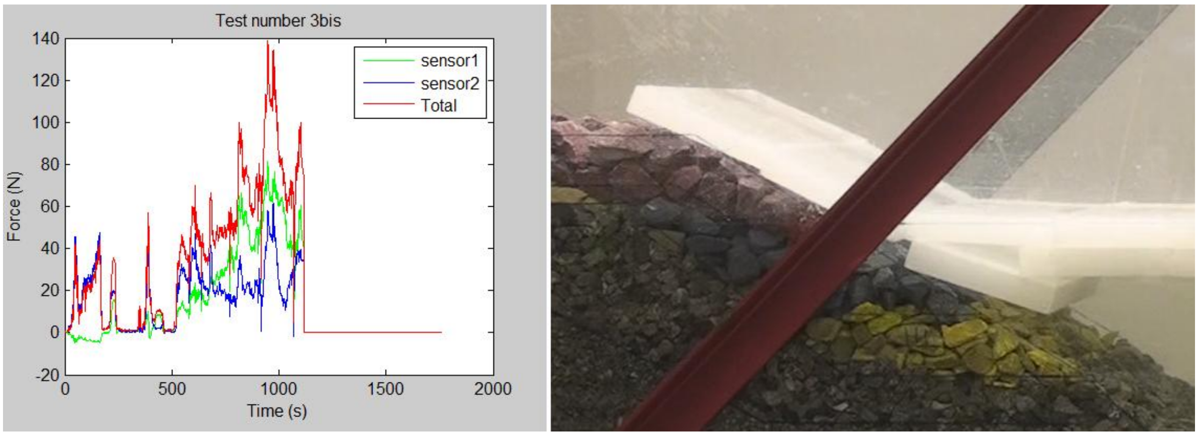


Figure 19-Test 3bis((TESTS1D): start of the ride up

It is possible to see on the graph that the beginning is typical of an accretion occurring on the first place since there is no real building up in the force and that the ride up starts afterwards, from 500 seconds, when the force begins to build up. On the picture on the right the accretion has been formed but this specific accretion actually supports the ride up, smoothening the slope and preventing the model ice from plunging downward.

Figure 20 below shows a caption of the test 3bis at about 1000 seconds. The model ice reached the rear side of the breakwater and actually slid down the rear slope. This event has to be prevented since it would be a threat for anything the breakwater was trying to protect.


Figure 20-Test 3bis: model ice on the rear side of the breakwater

Another thing worth noting from this extraneous event is that it did not require more force than for instance the piling up presented in Figure 15. Therefore it might not possible to detect such events by just looking at the recorded force.

4.1.4 Non realistic stacking

Some non realistic behaviour took place as well in different tests, this is particularly observable for the group TESTS1F. We can see a periodic pattern taking place after the initial peak, and this periodic pattern translates a non realistic stacking in the front of the breakwater showed in Figure 21.

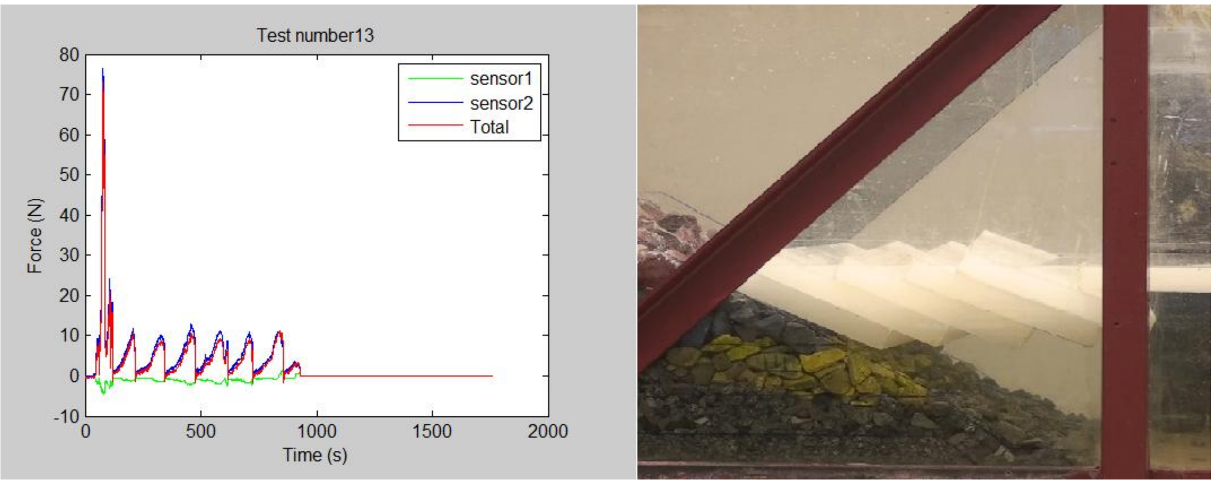


Figure 21-Test 13(TESTS1F): non realistic accretion at the front of the breakwater

Several tests present the same graph and give the same accretion. However, the model ice is stacking in this manner in other tests as well were the forces do not exactly follow the same curve. This is true for the tests 30 and 27. Figure 22 below illustrates it for test 30.

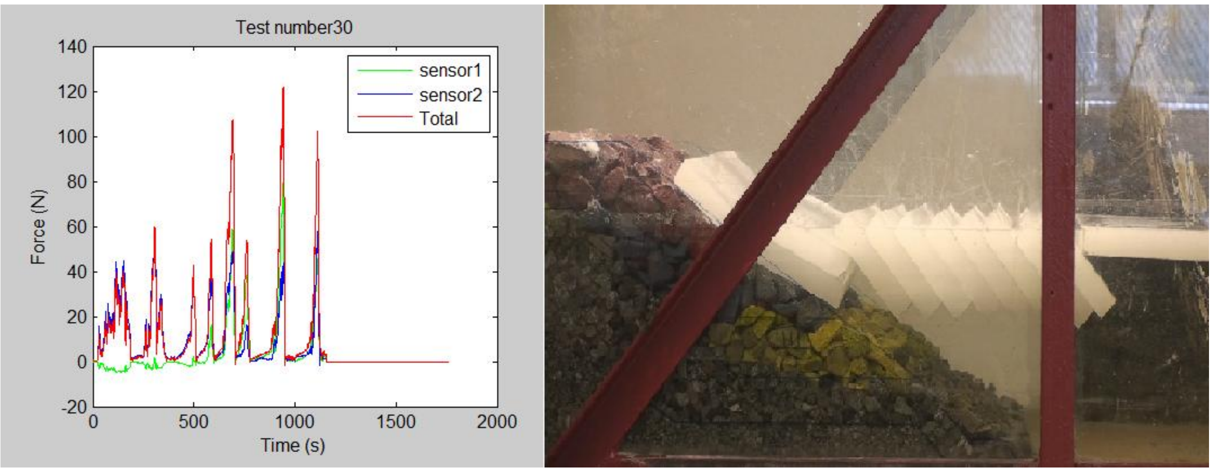


Figure 22-Test 30(TESTS1C): Non realistic accretion in front, different force pattern

Though quite different, the graphs are similar in the sense that both times they present a periodic pattern with a somehow quick frequency. The frequency of the release could be related to the length of the pieces but this requires further investigation.

Table 7 below shows in how many tests a non realistic stacking of either the first type or the second one has been observed, each cross representing a test.

Table 7-occurrences of non realistic stacking

	Thickness 3cm		**Thickness 1.5cm**	
	d=0	**d=0.00015**	**d=0**	**d=0.00015**
Length(cm)				
7,5				
10,5		XX	X	
13,5	X			
16,5			XXX	
19,5			X	X
22,5	XXX		XX	XX

From the results of all the tests with no added friction, it is possible to note that this non realistic pattern is much more likely to happen with the thin model ice than with the thick one. By having a closer look at the tests and at how this pattern takes place this can be understood. Figure 23 below shows three captions where the phenomenon is starting to take place.

Figure 23-non realistic behaviour, detail

As shown, two plates will plunge downward until the first one is stopped by the slope of the breakwater. The second plate exercises then a force almost perpendicular to the slope of the breakwater. By doing so this second plate might start to rip slowly on the edge of the first one if the force required to push it is too high. Then the second plate just slips on the top of the first one. On the picture to the right, it is possible to see that when the force has been released on the first plate, this one will slightly slide down the slope before the second plate blocks it.
Since the thin model ice has a shorter edge, it does not need to rip as long as the thick ice to get on top of the first plate and hence this phenomenon is more likely to occur.

This pattern is more present for large breaking lengths and this is probably due to the fact that the contact between the slope and the plate is larger for large breaking length and the force required to push it is therefore higher. It may be possible to link this phenomenon to the length/width ratio of the plates. On the tests without friction, the pattern took place in TESTS1F for the 3cm thick model ice while it started already in TESTS2D for the 1.5cm thickness. There is actually even an occurrence in TESTS2ABC in the test 27.
The ratios are respectively 7.5 and 9 for TESTS1F and TESTS 2ABC. Those ratios are quite similar so we can expect this phenomenon to happen regularly for tests without added friction when the breaking length is about 8 times the thickness or more.

Concerning the tests with added friction, there has not been as many occurrences as in the tests without friction. The same principle apply though for the length/width ratio since the tests with the highest ratios (TESTS2FF) are the one mainly presenting this pattern, but even then it just appears at the beginning of the test and some other phenomena take place afterwards. Figure 24 below points out how the non realistic pattern appears at the beginning of the tests 60 and 61.

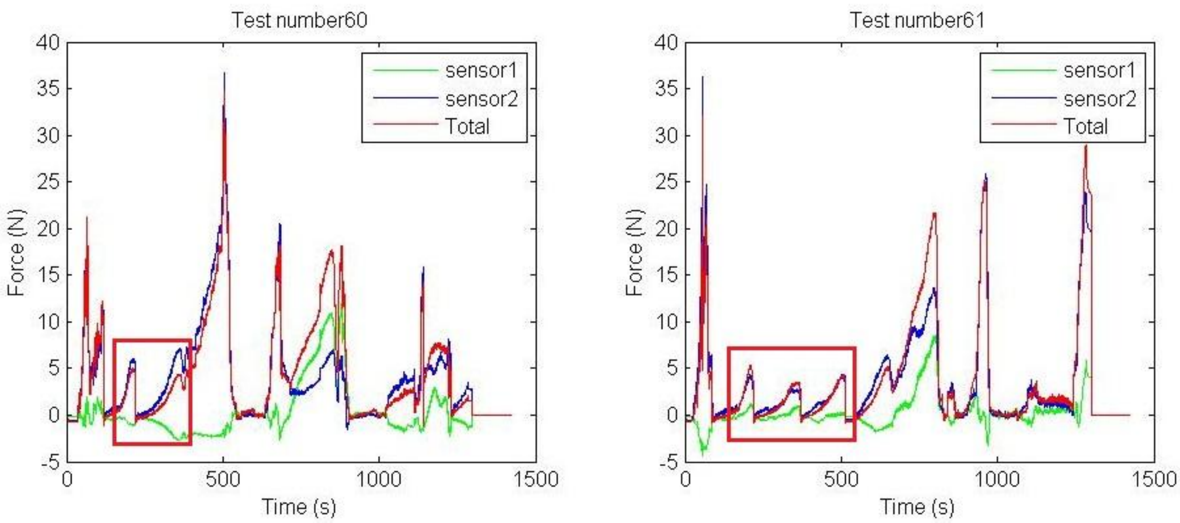


Figure 24-Tests 60 and 61 (TESTS2FF): non realistic accretion at the beginning of the tests.

At first, more non realistic accretion was expected since the added friction implies that more force will be required to push the first plate. One possible explanation could be that even if the phenomenon starts to take place, the first plate will not slide the slope when the friction is released as shown in Figure 23, leading to a slightly different situation.

4.2 Observed response from the breakwater

Having categorized the events occurring for the model ice, it is possible to see what kind of response those can trigger when it comes to the breakwater itself and the resultant damage.

First of all it is important to state that no global failure of the breakwater has been observed. This might however be an error induced by the motor used to push the model ice. Actually the motor would start vibrating at a high frequency when the load was exceeding 250N and these vibrations most probably helped the model ice to either ride up or plunge instead of directly digging through the slope.

The behaviours that have been observed from the breakwater are the following:

- Armour stones rolled upward
- Damage to the crest
- Damage to the toe

4.2.1 Armour stones rolled upward

This first kind of damage occurs during the ride up events. In the case of a ride up some armour stones can be moved up the slope by the model ice. Figure 25 below illustrates this phenomenon which presents caption of test 17. A stone is moved several diameters uoward before taking another place on the slope. Though it does not require a large amount of force to push a stone upward, a movement of more than one diameter could be considered as extraneous since it has been observed only twice throughout all the tests. Furthermore, in the case of the Sirevåg berm breakwater, the motion of a stone is directly considered as damage since the breakwater is not supposed to reshape.

Most stones in direct contact with the model ice will often tilt a little when a plate slide over them but they will move back as soon as the force is released. This kind movement leads therefore to no permanent damage.

Figure 25-Test 17(TESTS1A): a stone is moved up the slope

4.2.2 Damage to the crest of the breakwater

This kind of damage is linked to extraneous event since it occurs only if a ride up reaches the crest of the breakwater. Once the model ice has reached the top of the breakwater, the stones from the crest are quite likely to be pushed downward along the rear slope of the breakwater. Figure 26 below shows the damage which took place at the crest during test 3bis.

Figure 26-Test 3bis(TESTS1D): stones from the top of the breakwater have been dragged downward the rear slope

This damage is problematic for different reasons. The first is that it weakens the top of the breakwater which means that it will become easier and easier for the model ice to cross it or damage it further. The second is that the stones which are dragged down, even though in Figure 26 they stopped on the next layer of stones, they might go further down and do some high damage to any boat or structure on this side of the breakwater.

It is interesting to see that the ride up events have generally been less damaging the berm when using the rough model ice. In many cases, only one piece of model ice managed to reach the berm and did not endanger the crest of the rear side. Considering all the tests performed with added friction, only four times has a piece touched the crest of the breakwater, but even then there has been no damage affecting the crest. At no occasion has a piece reached the rear side of the breakwater. Figure 27 below shows the end of the tests 34 and 39 which presented the furthest ride up on the tests with added friction.

Figure 27-Test34(TESTS1FA) on the left and test39(TESTS1FC) on the right. Most advanced ride up events during tests with added friction.

4.2.3 Damage to the toe of the breakwater

Another kind of damage that can occur concerns the lower part of the slope and the toe. These parts can actually be at risk when some accumulation of model ice is taking place especially when the model ice starts plunging instead of riding up. The model ice may then scrap the stones downward and reduce the overall stability of the slope. Figure 28 below shows such an event which took place during test 15.

Figure 28- test 15(TESTS1E): Accumulation in front of the breakwater scrapping the toe of the breakwater. The red arrow shows the movement of the model ice

The results of this event for the toe of the breakwater are shown in figure 29 below.

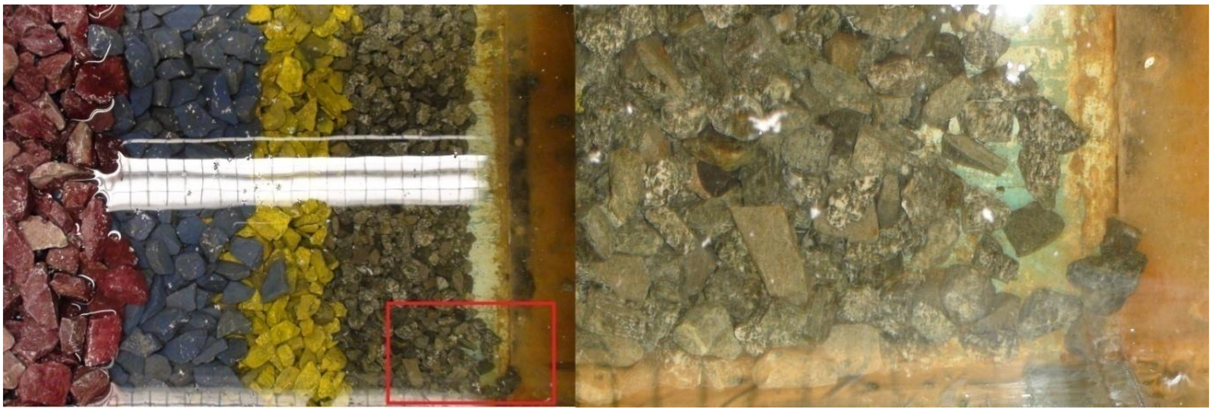


Figure 29-Damage at the toe of the breakwater after test 15

In Figure 29 it is also possible to see that some stones from the layer II (blue ones) have been moved downward. Such displacement arrived quite often and occurred when there is a release in the force due to the bending of the model ice (either upward or downward) in front of the breakwater. The plates which are stacked on the slope will then slide downwards and regularly take some stones with them. However, it is not likely to happen that easily with ice since the ice can get frozen with the stones on the slope and therefore will stick to it.

In the tests where there is added friction, the plates have a tendency to be more attached to the armour stones, these kind of damage are therefore reduced which makes it more coherent when compared to the full scale phenomena since the ice is not supposed to slide down so fast but should be in most cases stuck to the slope.

4.3 Analysis of the force signal

It is possible to extract some information directly from the recorded force. As previously shown, ride up events and stacking can to some extent be detected only by looking at the signal. There can however be large variations for the same kind of event and even if the ice behaviour can be described, it is difficult to tell what the response from the breakwater is.

For instance in Figure 30 below we can see two ride up events with also some accretion in the front of the breakwater. One major difference that is visible directly is that there is some pile up in test 34 while there is not any in test 39

Figure 30- Test34(TESTS1FA) on the left and test39(TESTS1FC) on the right

Those events are interesting since they are in fact quite different. In test 34, the model ice went straight up to the berm and started then to pile up while continuing to ride up until it failed in front of the breakwater. In test 39 on the contrary the model ice first started to accumulate in front of the breakwater and it is this accretion which helped the rest of the plates to ride up afterwards. This can be seen in the recorded force as well as shown in Figure 31. The force starts building up from the beginning in the test 34 while there are clear releases in test 39. It is also possible to note that the force in test 34 goes up to 250N which is twice as much as the force that has been recorded in test 39. The two reasons for it are first that in test 39 there is no piling up, and hence a smaller amount of model ice to push to reach the top and second that the accretion in front of the breakwater makes the slope easier to ride up on for the model ice.
This shows again that even if the shape of the graph can be used to analyse what kind of event is taking place, it might be complicated to decipher it if there is not any other information which has been recorded by other means.

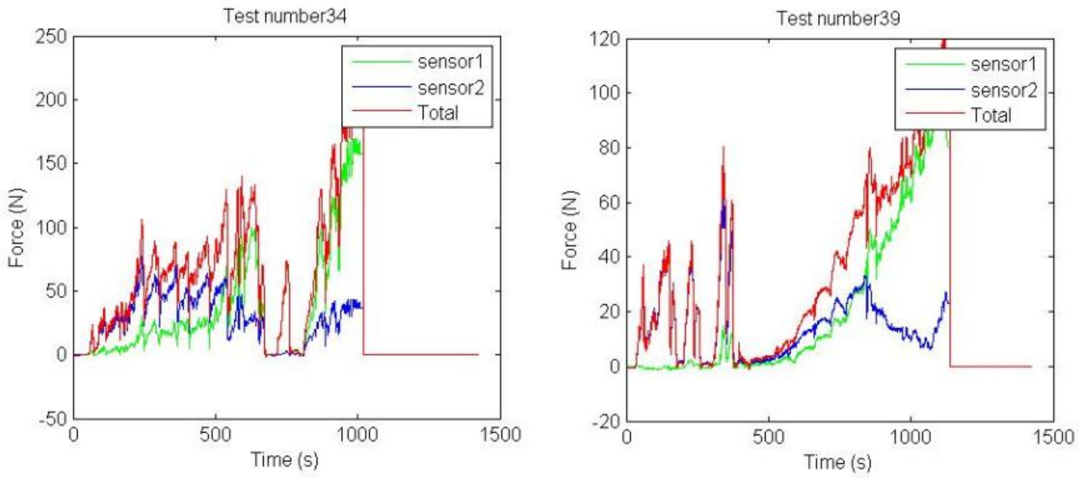


Figure 31-Recorded force for the tests 34 and 39

The fact that the recorded force alone cannot translates everything that is happening is also shown through Figure 32 and 33. Those are pictures and the recorded force from test 59. The force never reached more than 30N but as it can be seen in the Figure 32 a stone has been moved over several diameters upward. Such movement of one particular stone cannot actually be expected to show up in the graph. The weight of one plate of model ice in this case is about 1.7 kg while the weight of a stone is less than hundred grams.

Figure 32- Test 59 (TESTS1FF): motion of an individual stone

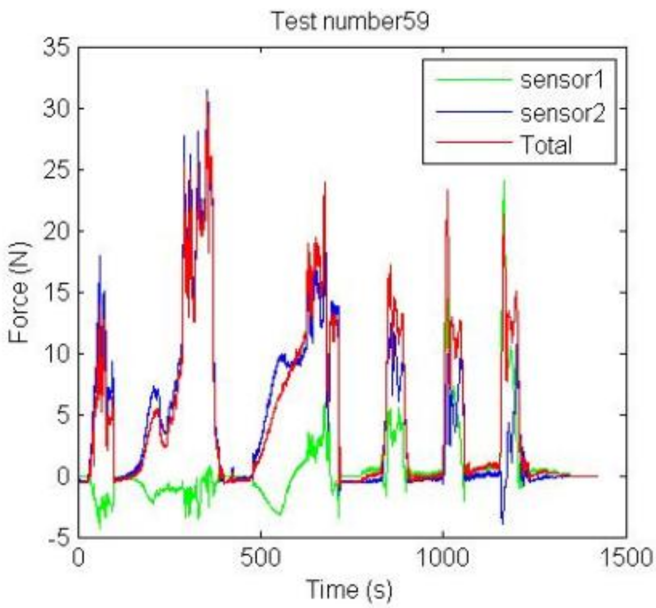


Figure 33 Test 59(TESTS1FF): recorded force

To make a comparison of all the different tests that have been conducted, even though the force cannot translate all phenomena taking place it is interesting to see what is the maximal force recorded for each test. Table 7 below shows the mean of the different maxima for all the series with the standard deviation in parenthesis.

Table 8-Mean maximal force for each series. Standard deviation in parenthesis.

	Thickness 3cm		**Thickness 1.5cm**	
	d=0	**d=0.00015**	**d=0**	**d=0.00015**
Length(cm)				
7,5	150 (33)	191 (20)	52 (23)	57 (21)
10,5	186 (67)	162 (33)		
13,5	125 (7)	135 (13)		
16,5	104 (46)	101 (39)	19 (5)	28 (2)
19,5	78 (11)	128 (13)	32 (12)	58 (32)
22,5	54 (22)	79 (16)	33 (9)	33 (2)

This shows how the force is increasing when decreasing the breaking length, especially for the test with the thick model ice where the three smallest lengths are separated. The relation between the length and the force is even more visible when shown on a graph as presented in Figure 34 below. From this picture it is also possible to see that the force required to push the model ice when the friction is increased is slightly higher, which was expected.

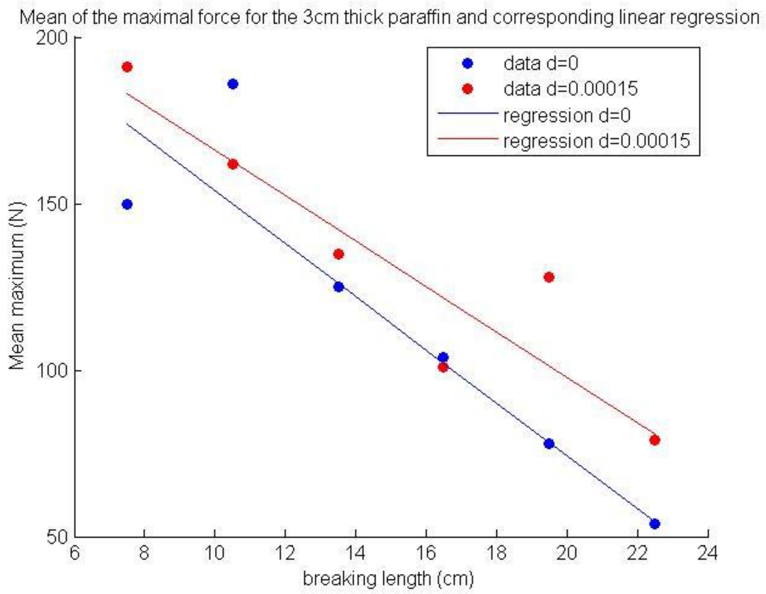


Figure 34- mean maximal force for the 3cm thick ice and linear regression.

Figure 34 could also be related to another phenomenon related to the drifting speed of the ice. At full scale, the ice with a higher drift speed will indeed tend to have a shorter breaking length and will also apply a higher load on the breakwater.
It is also possible to compare the force that has been recorded to what could be expected when using the ISO formula (1) presented in the section 2.3.
To calculate the forces we can use the test 18 presented in Figure 15. This figure is repeated below in Figure 35 for convenience. This case has been taken since it is an ideal case with

ride up and pile up where the model ice is parallel to the slope. It might be much harder to define the parameters in case of a test such as the one presented in Figure 18.

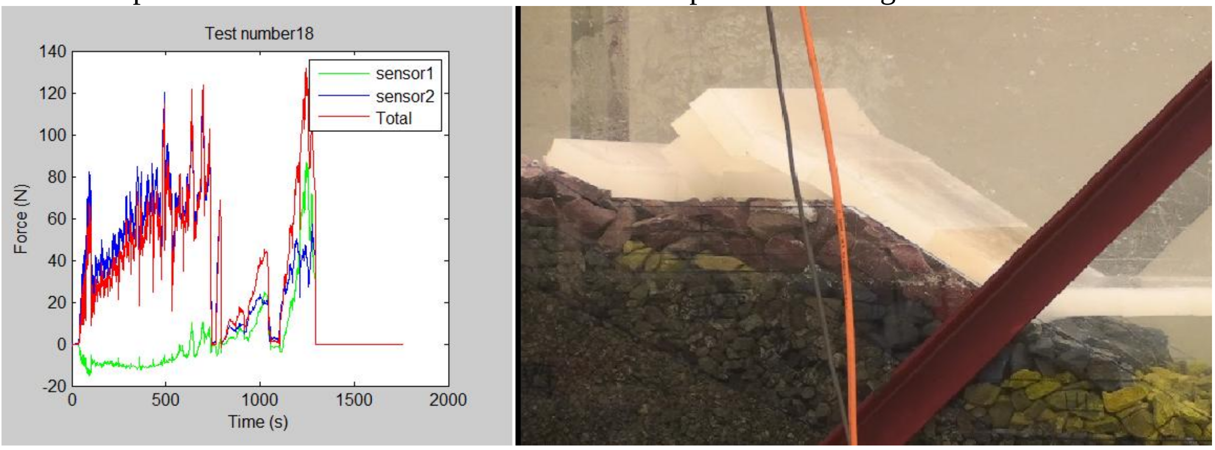


Figure 35- Test18(TESTS1A)

In that case the slope angle and the rubble angle are similar, which leads to simplification in the formula. Furthermore since we do not consider the breaking mechanism, we can put $H_B = 0$. This leads to :

$H_B = 0$
$H_P = 0$
$H_L = 0$

$$H_R = w * h_r \mathrm{h} \rho_i g \frac{\sin\alpha + \mu\cos\alpha}{\sin\alpha} * \frac{1}{\cos\alpha - \mu\sin\alpha}$$

$$H_T = 1.5 w h^2 \rho_i g \frac{\cos\alpha}{\sin\alpha - \mu\cos\alpha}$$

$$F_H = w * h_r \mathrm{h} \rho_i g \frac{\sin\alpha + \mu\cos\alpha}{\sin\alpha} * \frac{1}{\cos\alpha - \mu\sin\alpha} + 1.5 w h^2 \rho_i g \frac{\cos\alpha}{\sin\alpha - \mu\cos\alpha}$$

The parameters presented in Table 8 are used. Those are directly taken from the experiment which means that the result is model scaled as well.

Table 9-parameters corresponding to the test 18

g	9.81	μ_i	0.4
α	37°	μ	0.5
h	0.03 meter	θ	37°
h_r	0.1 meter	w	0.6 meter
ρ_i	900 kg	ρ_w	1000kg/m3

This gives the result

$$F_H = 0.0919 kN = 91.9 N$$

This is in the same range as the result presented in Figure 35 so it should be possible to predict how much force will be recorded in a test. Even though it could be a good approximation, it is possible to see that the simplified formula does not take the breaking length into account though the Figure 34 showed us that there was most probably a correlation between this length and the recorded force.

5 CONCLUSION AND RECOMMENDATION FOR FURTHER WORK

5.1 Conclusion

From the experiments that have been conducted several conclusions can be drawn.

- First concerning the potential use of berm breakwaters in Arctic areas, it has been shown that in many cases the ride up events are stopped by the piling up. This is important since it is one of the main reason berm breakwaters should be used instead of classical rubble mound structures. The efficiency of the piling up should be questioned however since it can happen that the model ice piles up but that it does not prevent the ride up to go further.

- Then about the use of paraffin in the modelling, it has been shown that the different expected behaviour such as forming some rubble in front, riding up and piling up have been observed. This means that it is actually possible to use this kind of modelling and that it would translate some of the phenomena happening at full scale. However this method has limits since the size of the plates can lead to a non realistic behaviour of the model ice as shown in Figure 21.

- Last about the friction. The increased friction led to less unrealistic pattern of the model ice and less unrealistic damage on the slope since the plates are not sliding down as fast as with smooth ice. The use of friction looks actually promising to better represent the phenomena happening at full scale.

5.2 Recommendation for further work

From the former conclusions it is possible to give some recommendation for further work.

- First concerning the experiments themselves, a more powerful motor should be used. On one hand this might lead to some global failure of the berm and therefore it would actually be possible to investigate how such failures occur. On another hand it would then be possible to add a dimension to the testing matrix by using different speed and evaluate the impact of the speed on the behaviour of both the ice and the breakwater.

- Second it would also be interesting to run much more tests in order to have more data concerning the piling up events and further to be able to analyse them with statistical tools. That would be helpful to see for instance how much damage should in average be expected due to the movement of the armour stones when they are dragged by the riding up model ice.

- Others possibilities to widen the range of phenomena covered by the experiments could be to modify either the friction or the concentration of the model ice in the flume. As we have seen, the friction has an impact on the kind of observed behaviour and its variation could therefore lead to new phenomena and could also make the experiments even more representative of the full scale behaviours.

REFERENCES

Daly, S.F., Zufelt, J., Zabiinski, L., Sodhi, D. and Bjella, K.(2008): Estimation of ice impacts on armor stone revetments at Barrow, Alaska. Proceedings of the 19th IAHR International Symposium on ice, Vancouver, British Columbia, Canada, July 6 – 11, 2008.

Gürtner, A. (2009): Experimental and numerical investigations on ice-structure interaction. PhD-thesis, Norwegian University of Science and Technology, Department of Civil and Transport Engineering, January 2009.

Lengkeek, H.J., Croasdale, K.R. and Metge, M. (2003): Design of ice protection barrier in Caspian Sea. Proceedings 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE03); June 8-13, 2003, Cancun, Mexico.

MacIntosh, K.J., Timco, G.W. and Willis, D.H. (1995): Canadian experience with ice and armour stone. Proceedings of the 1995 Canadian Coastal Conference, Dartmouth; Nova Scotia, October 1995. Vol. 2, pp 597-606.

Mennessier, T. (2011): Berm breakwater as protection of harbours, artificial islands and shorelines in Arctic areas, Project woark, Norwegian University of Science and Technology, Department of Civil and Transport Engineering, December 2011

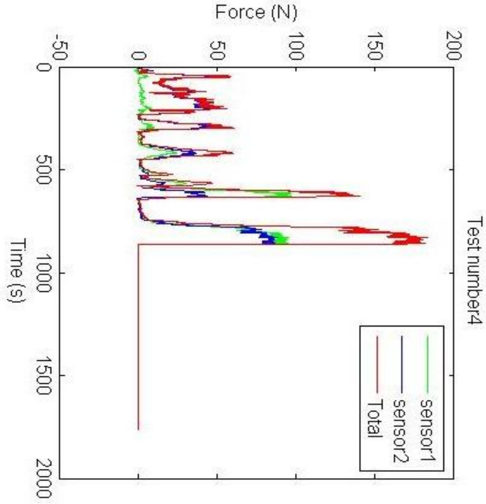
Sodhi, D.S., Borland, S.L. and Stanley, J.M. (1996): Ice action on riprap. Small-scale tests. US Army Corps of Engineers, Cold Regions Research&Engineering Laboratory. CRREL Report 96-12.

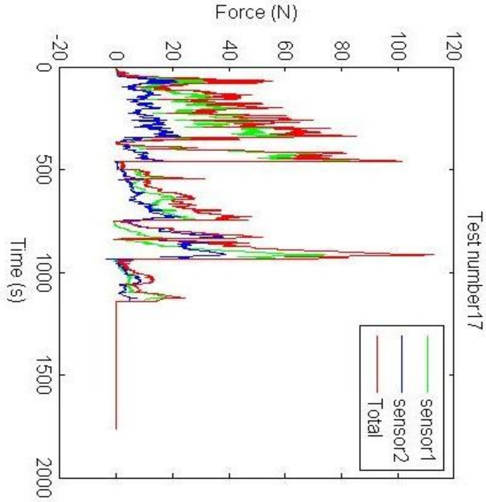
Sodhi, D and C. Donelly (1999). Ice effects on riprap: small-scale tests. Proceedings 10th International Conference on Cold Regions Engineering, Lincoln, NH, Aug. 16-19, 1999. Putting research into practice. Edited by J.E. Zufelt, p.824-837. Publisher: American Society of Civil Engineers. Reston, VA, USA.

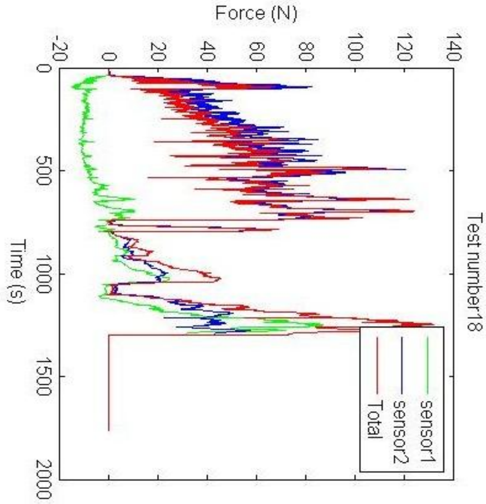
Timco, G. W., Willis, D.H. and Wright, B.D. (1995): Ice action on armor rocks with application to an artificial island concept. Proceedings of the Second International Conference on Development of Russian Arctic Offshore, RAO'95, St. Petersburg, Russia, 1995.

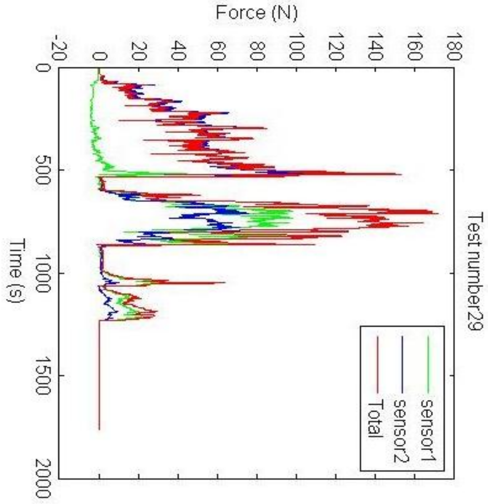
ANNEXE: RECORDED FORCE FOR ALL THE TESTS

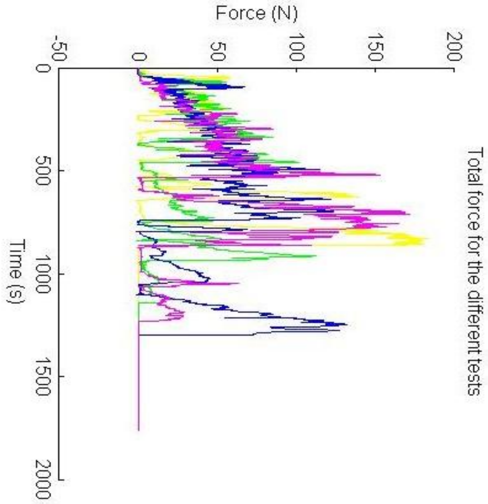
TESTS1A



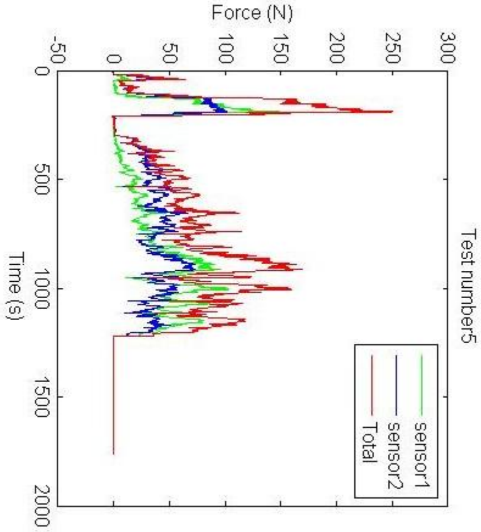




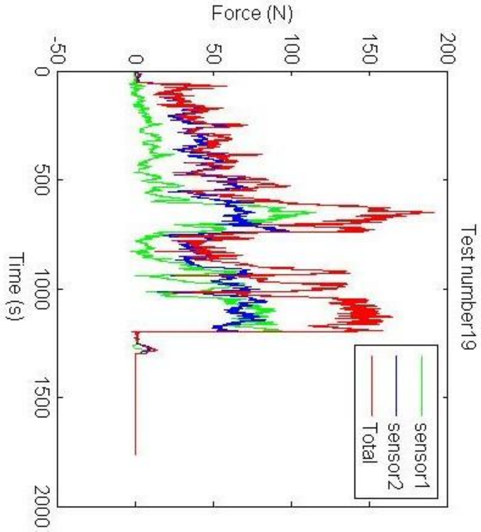




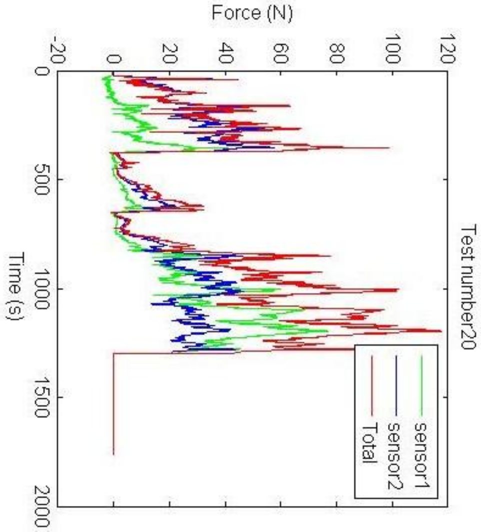
TESTS1B



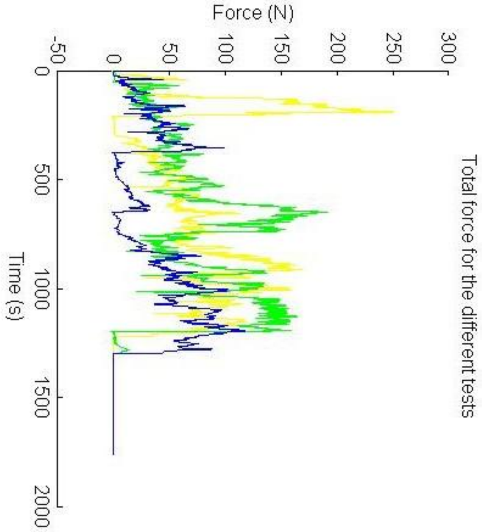
Test number5
Force (N)
Time (s)
sensor1
sensor2
Total



Test number19
Force (N)
Time (s)
sensor1
sensor2
Total

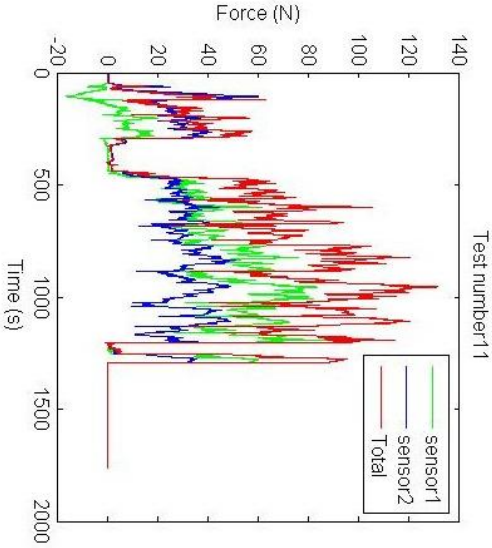


Test number20
Force (N)
Time (s)
sensor1
sensor2
Total

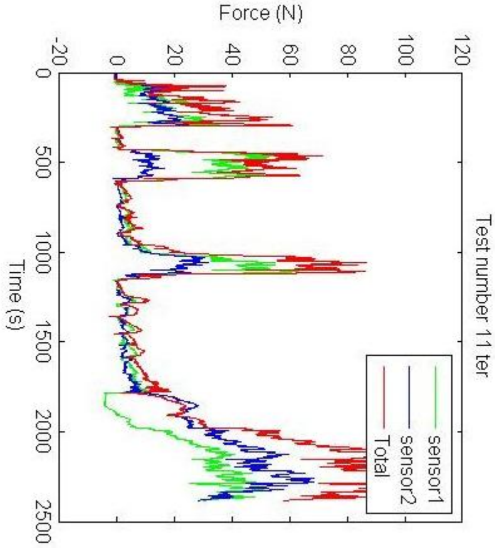


Total force for the different tests
Force (N)
Time (s)

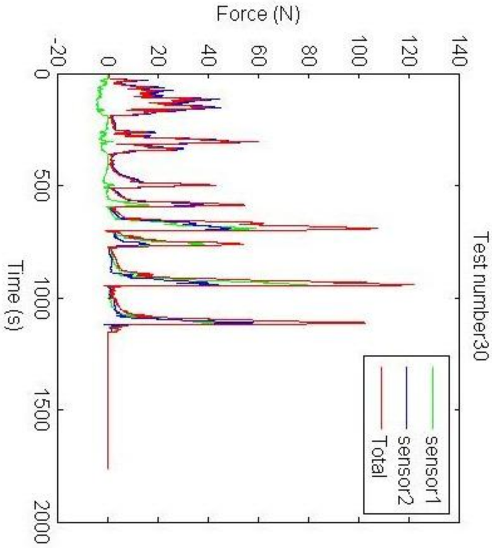
TESTS1C



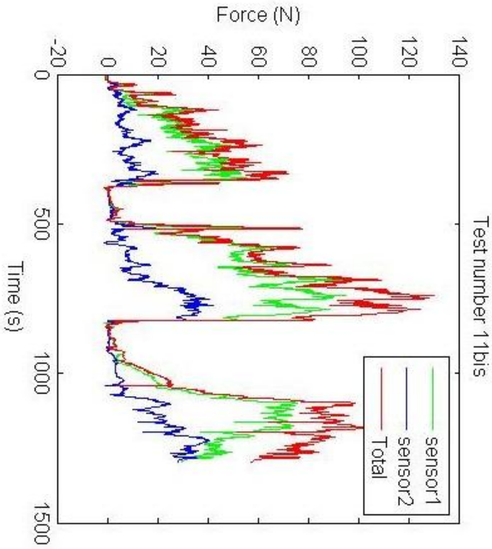
Test number11
Force (N)
Time (s)
sensor1
sensor2
Total



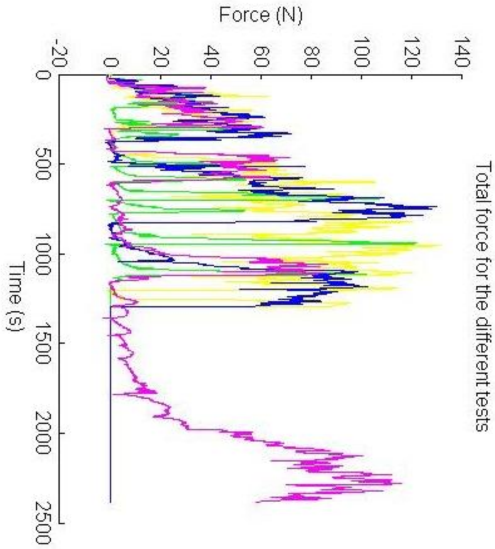
Test number 11 ter
Force (N)
Time (s)
sensor1
sensor2
Total



Test number30
Force (N)
Time (s)
sensor1
sensor2
Total

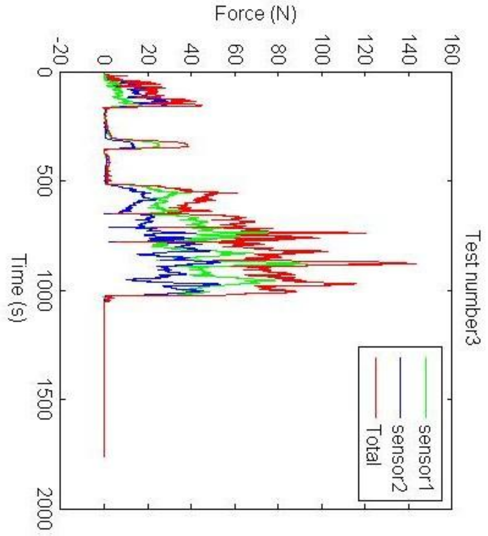


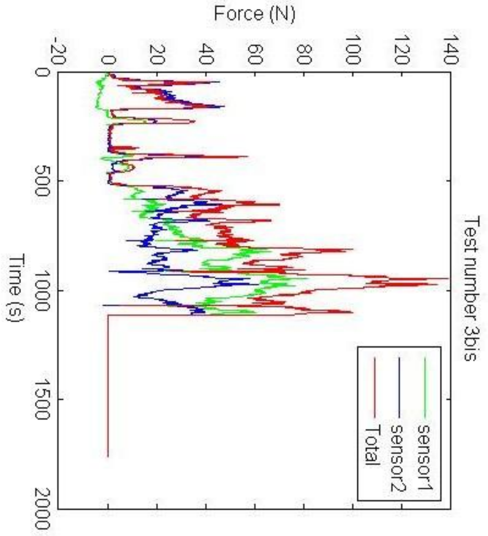
Test number 11bis
Force (N)
Time (s)
sensor1
sensor2
Total

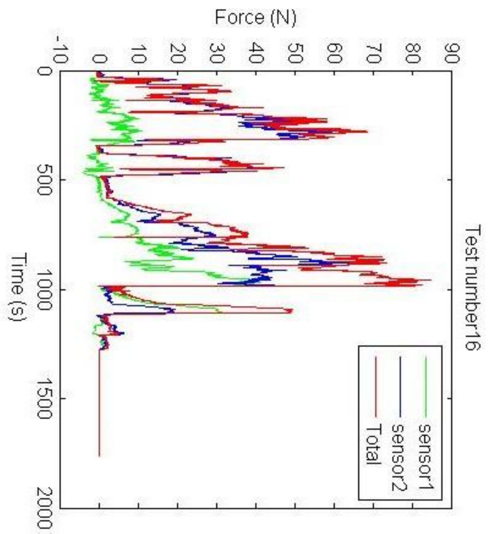


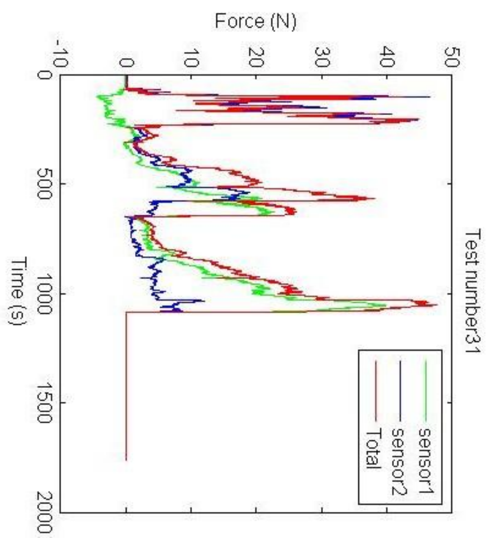
Total force for the different tests
Force (N)
Time (s)

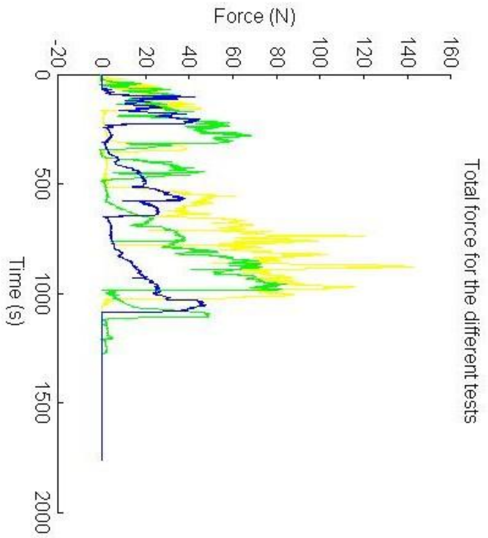
TESTS1D


Test number3
Force (N)
Time (s)
sensor1
sensor2
Total

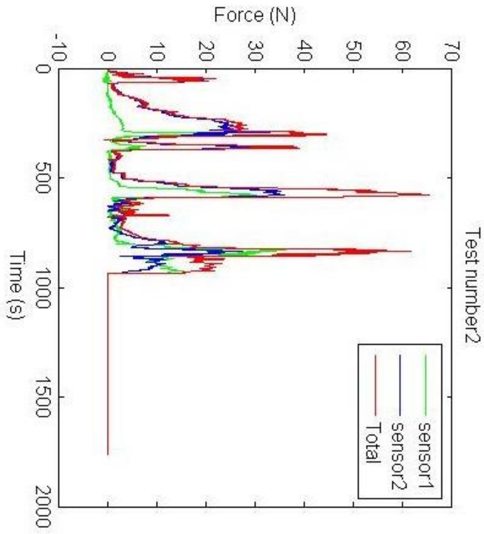

Test number 3bis
Force (N)
Time (s)
sensor1
sensor2
Total


Test number16
Force (N)
Time (s)
sensor1
sensor2
Total

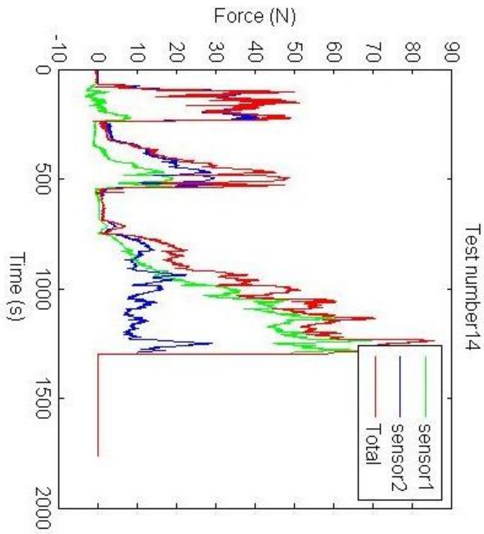

Test number31
Force (N)
Time (s)
sensor1
sensor2
Total


Total force for the different tests
Force (N)
Time (s)

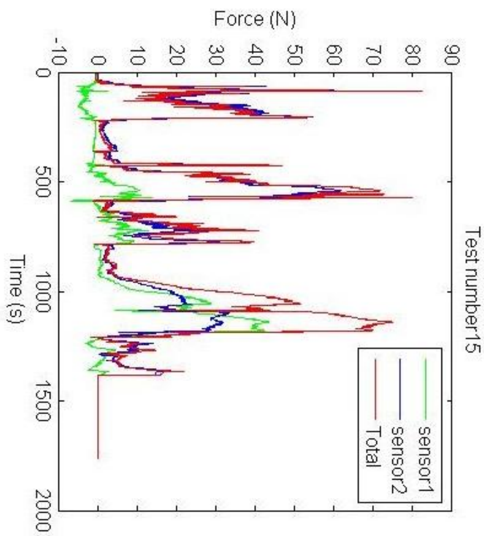
TESTS1E



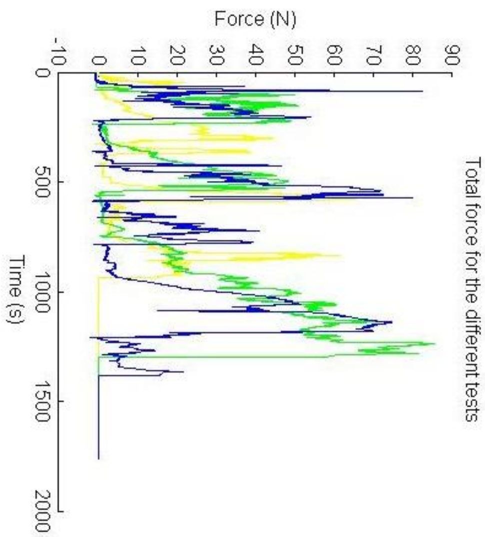
Test number2
Force (N)
Time (s)
sensor1
sensor2
Total



Test number14
Force (N)
Time (s)
sensor1
sensor2
Total

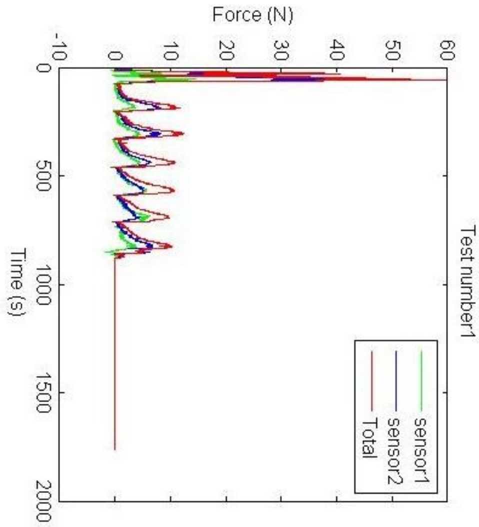


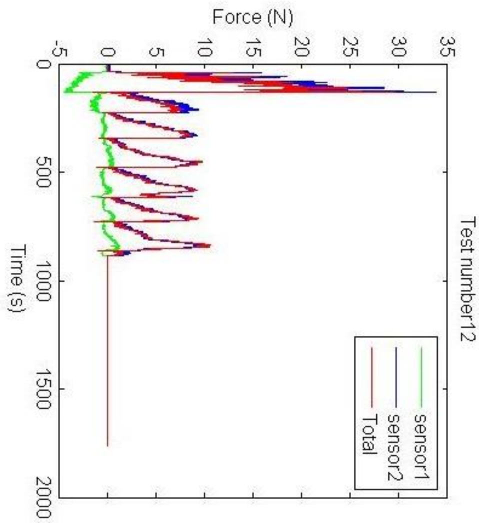
Test number15
Force (N)
Time (s)
sensor1
sensor2
Total

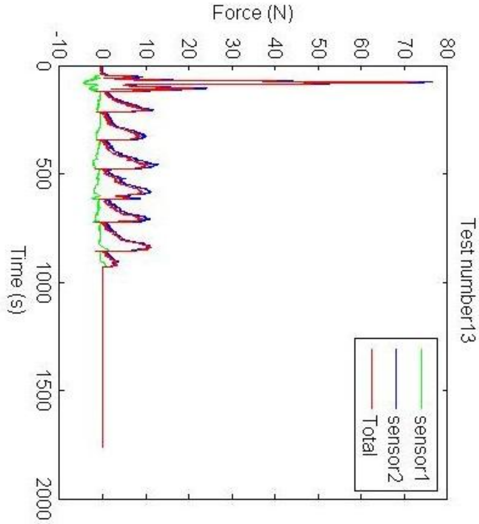


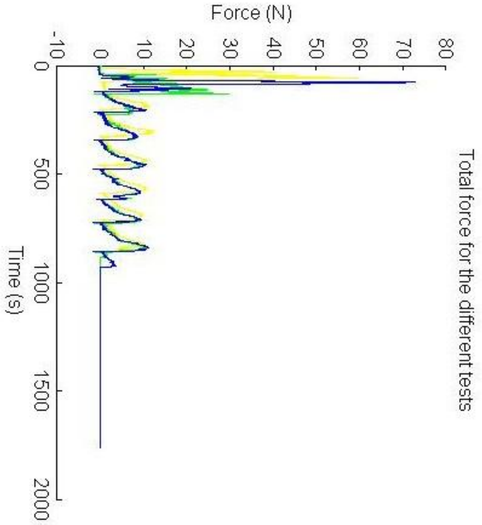
Total force for the different tests
Force (N)
Time (s)

TESTS1F

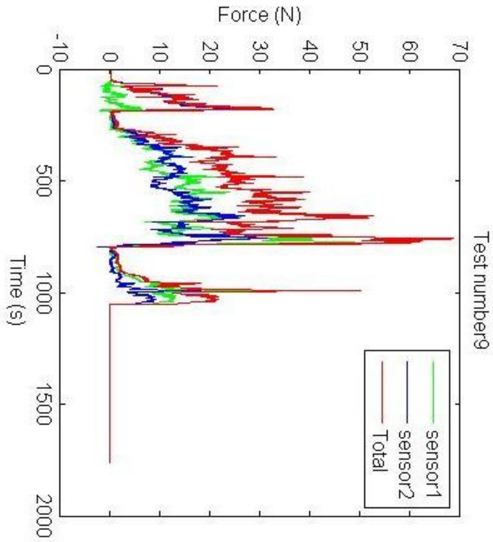

Test number1
Force (N)
Time (s)
sensor1
sensor2
Total


Test number12
Force (N)
Time (s)
sensor1
sensor2
Total

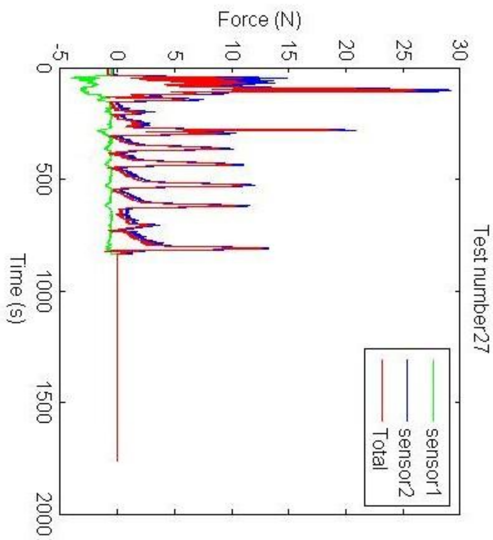

Test number13
Force (N)
Time (s)
sensor1
sensor2
Total


Total force for the different tests
Force (N)
Time (s)

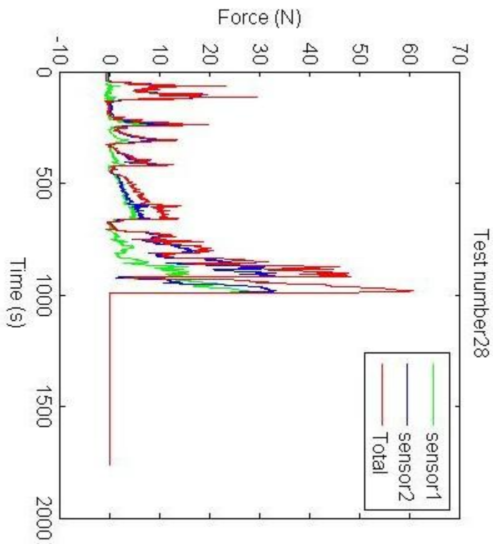
TESTS2ABC



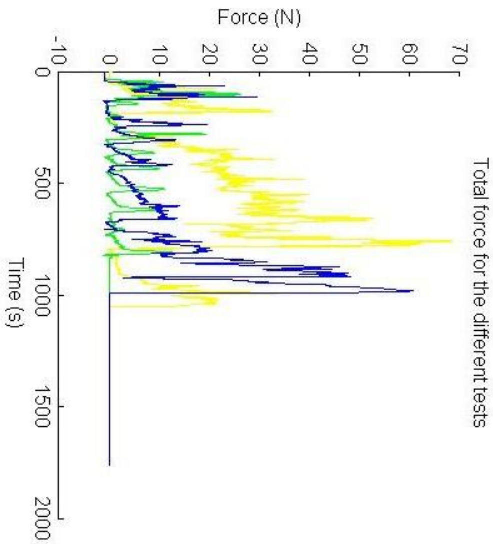
Test number9
Force (N)
Time (s)
sensor1
sensor2
Total



Test number27
Force (N)
Time (s)
sensor1
sensor2
Total

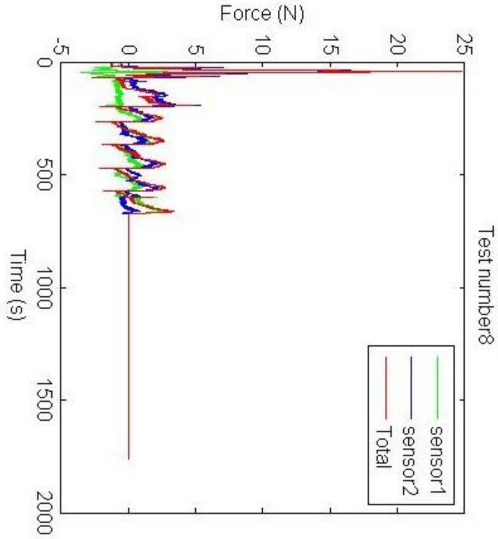


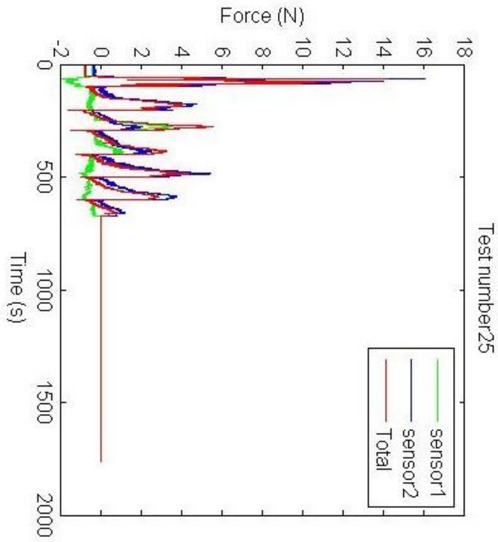
Test number28
Force (N)
Time (s)
sensor1
sensor2
Total

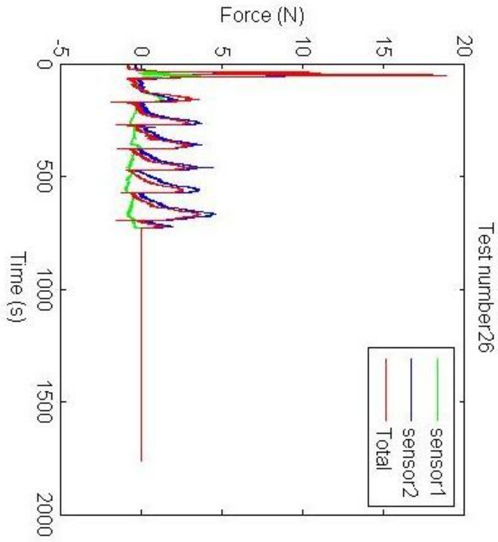


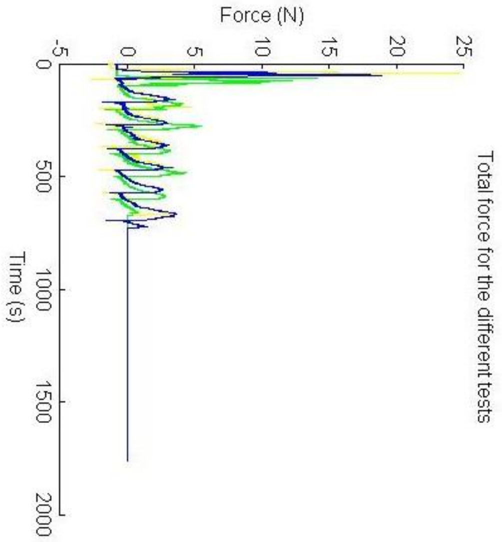
Total force for the different tests
Force (N)
Time (s)

TESTS2D

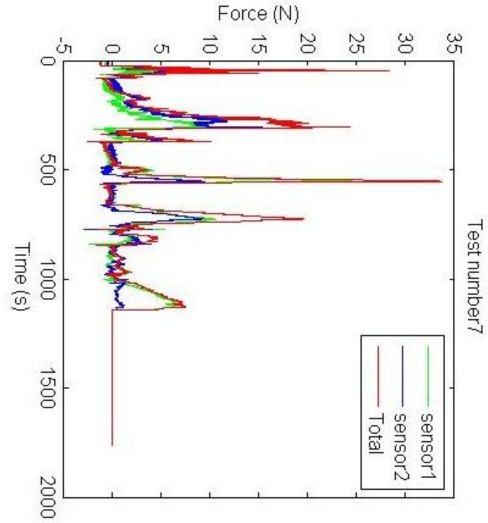

Test number8
Force (N)
Time (s)
sensor1
sensor2
Total

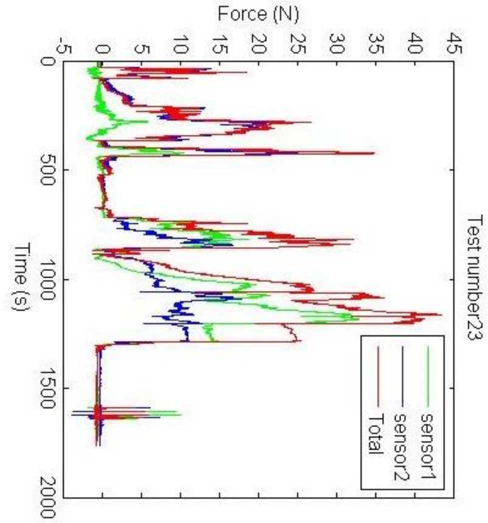

Test number25
Force (N)
Time (s)
sensor1
sensor2
Total

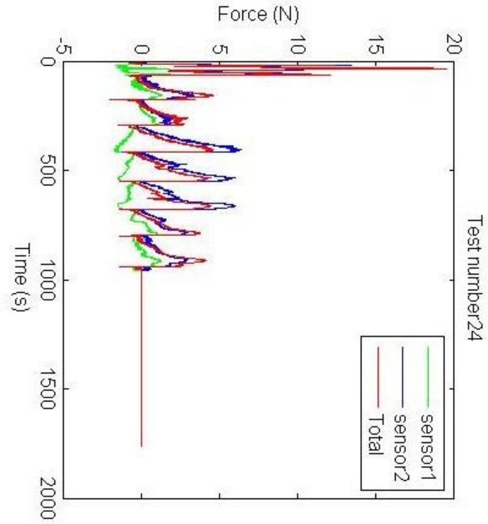

Test number26
Force (N)
Time (s)
sensor1
sensor2
Total

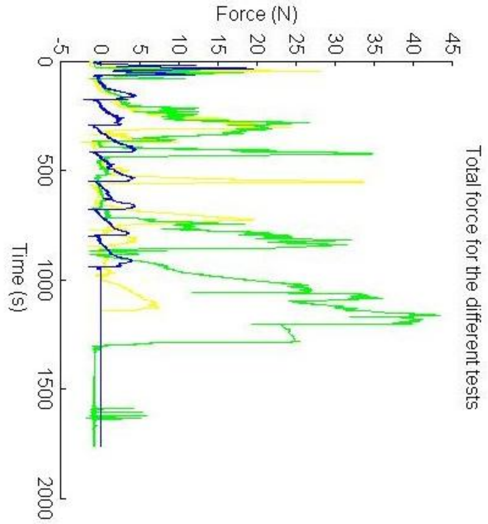

Total force for the different tests
Force (N)
Time (s)

TESTS2E

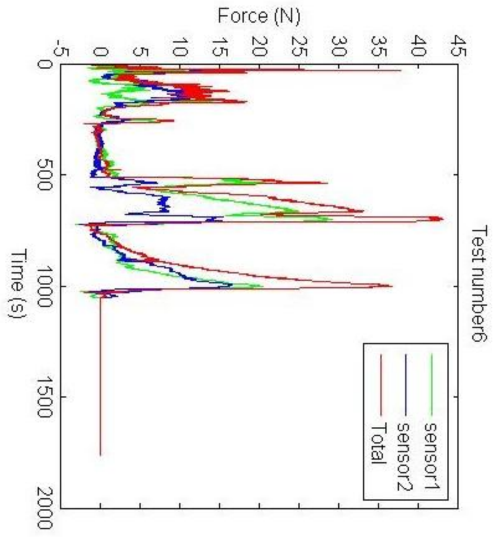

Test number7
Force (N)
Time (s)
sensor1
sensor2
Total

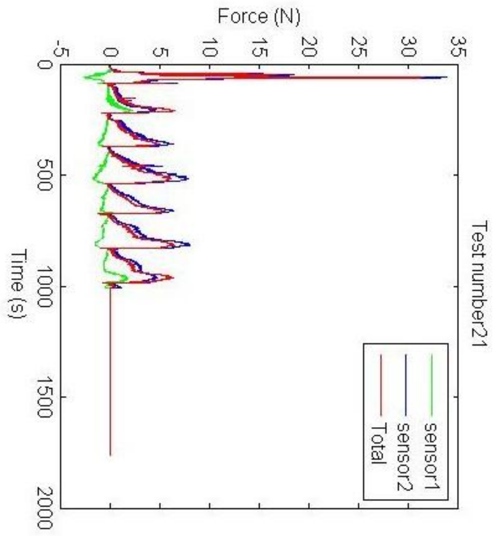

Test number23
Force (N)
Time (s)
sensor1
sensor2
Total

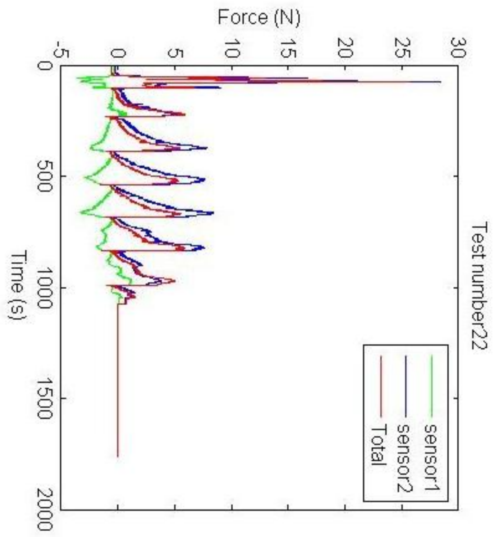

Test number24
Force (N)
Time (s)
sensor1
sensor2
Total

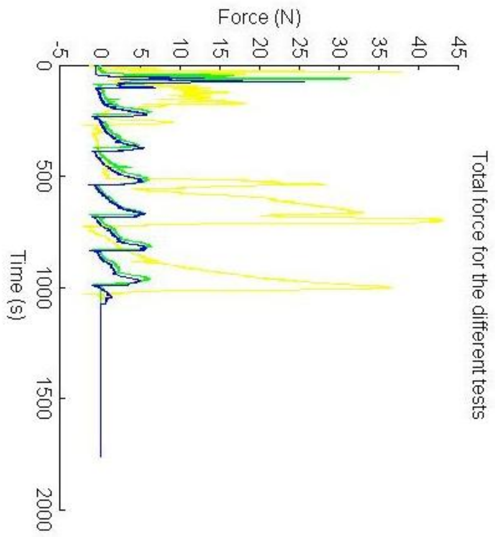

Total force for the different tests
Force (N)
Time (s)

TESTS2F

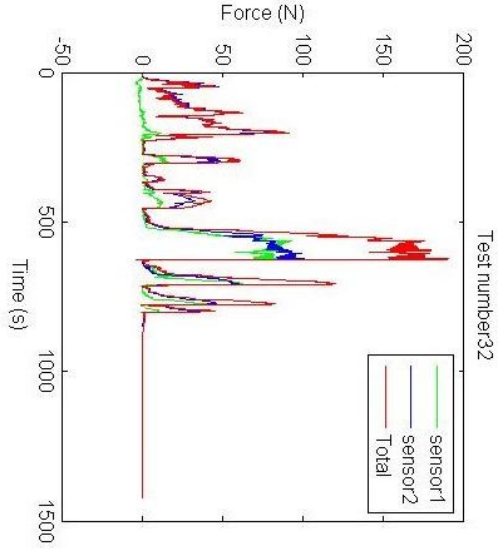

Test number6
Force (N)
Time (s)
sensor1
sensor2
Total

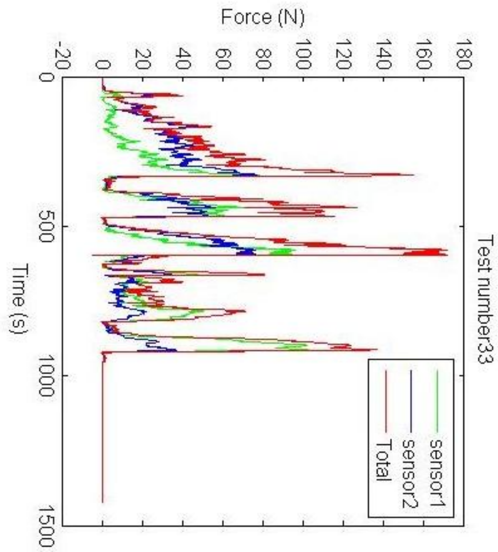

Test number21
Force (N)
Time (s)
sensor1
sensor2
Total

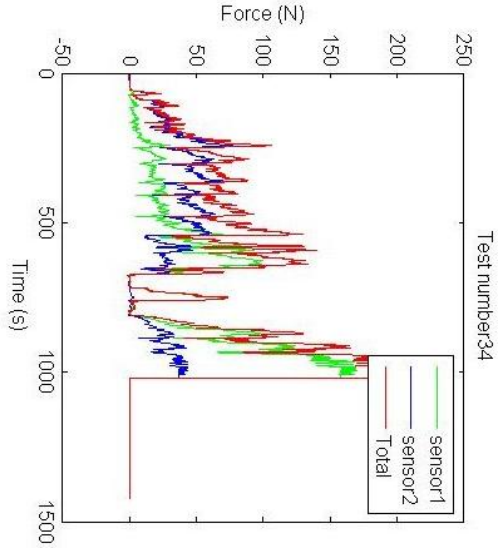

Test number22
Force (N)
Time (s)
sensor1
sensor2
Total

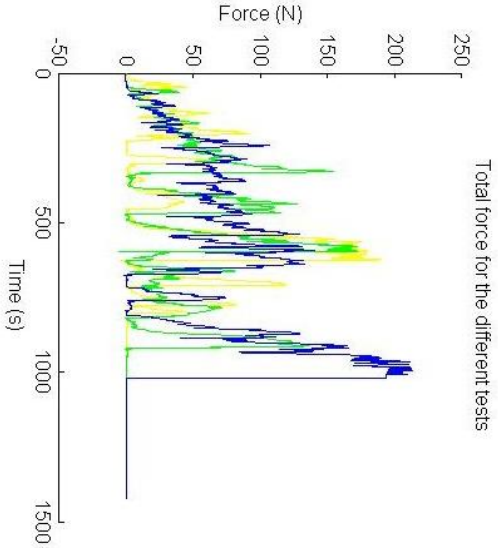

Total force for the different tests
Force (N)
Time (s)

TESTS1FA

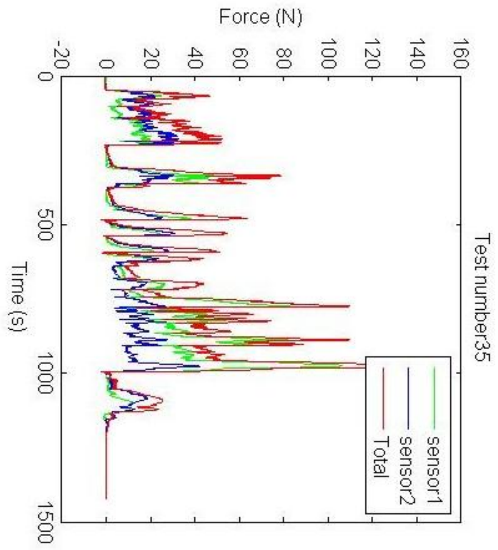

Test number32
Force (N)
Time (s)
sensor1
sensor2
Total

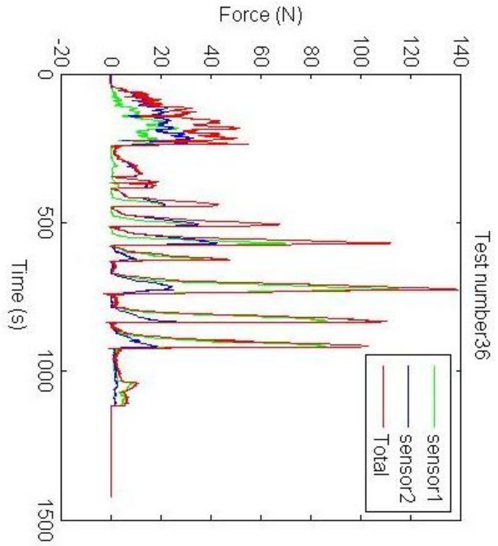

Test number33
Force (N)
Time (s)
sensor1
sensor2
Total

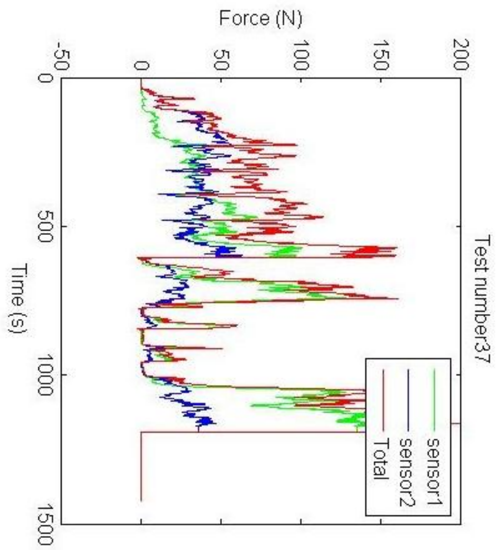

Test number34
Force (N)
Time (s)
sensor1
sensor2
Total

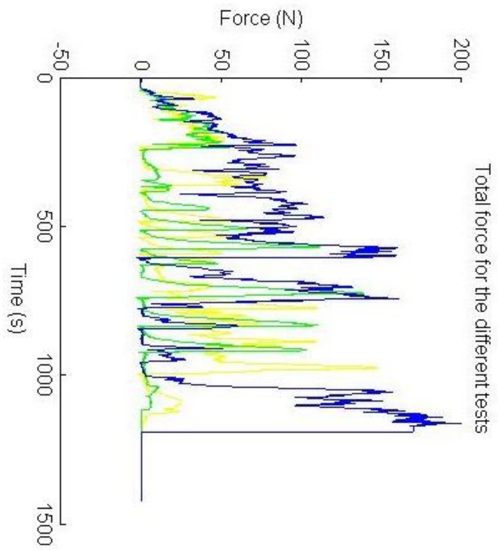

Total force for the different tests
Force (N)
Time (s)

TESTS1FB

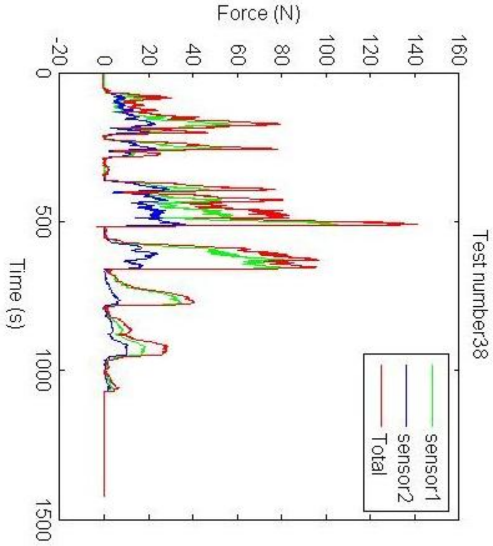

Test number35
Force (N)
Time (s)
sensor1
sensor2
Total

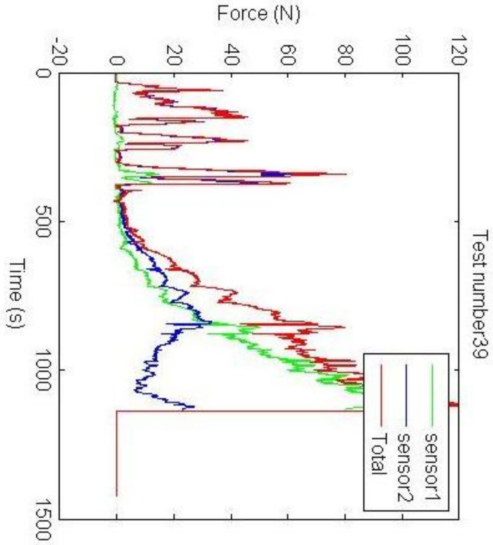

Test number36
Force (N)
Time (s)
sensor1
sensor2
Total

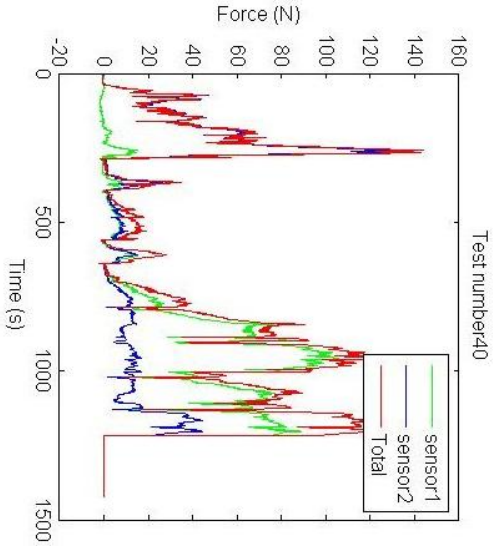

Test number37
Force (N)
Time (s)
sensor1
sensor2
Total


Total force for the different tests
Force (N)
Time (s)

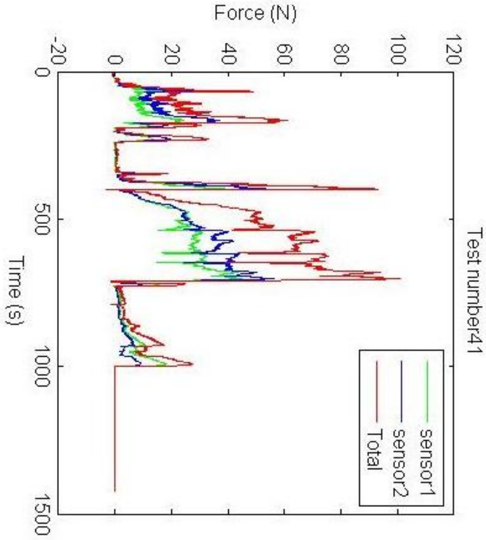
TESTS1FC

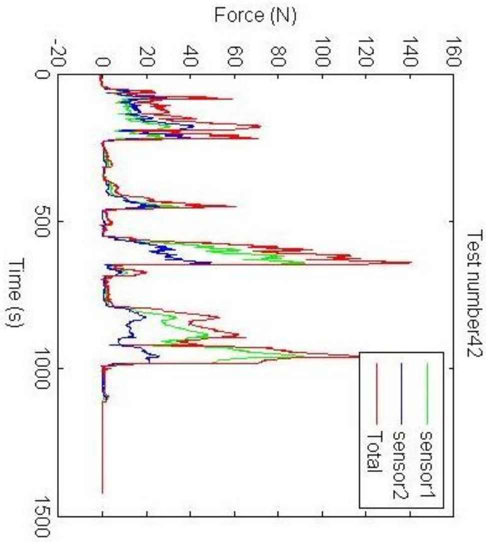

Test number38
Force (N)
Time (s)
sensor1
sensor2
Total

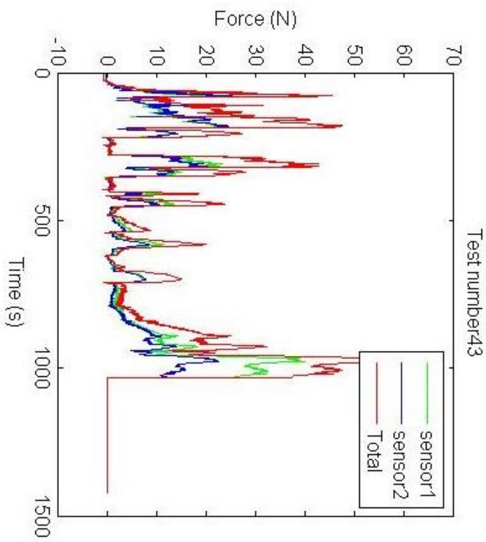

Test number39
Force (N)
Time (s)
sensor1
sensor2
Total

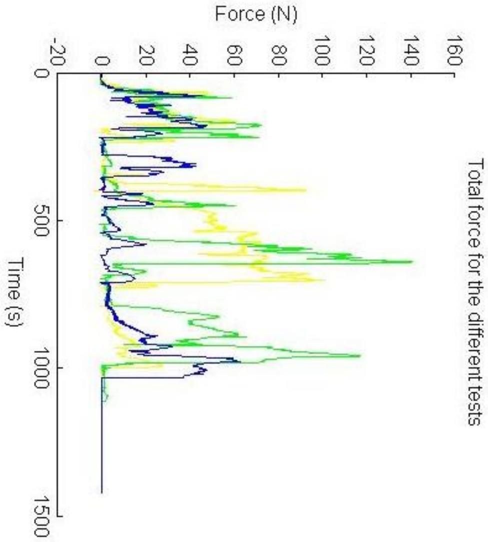

Test number40
Force (N)
Time (s)
sensor1
sensor2
Total

TESTS1FD

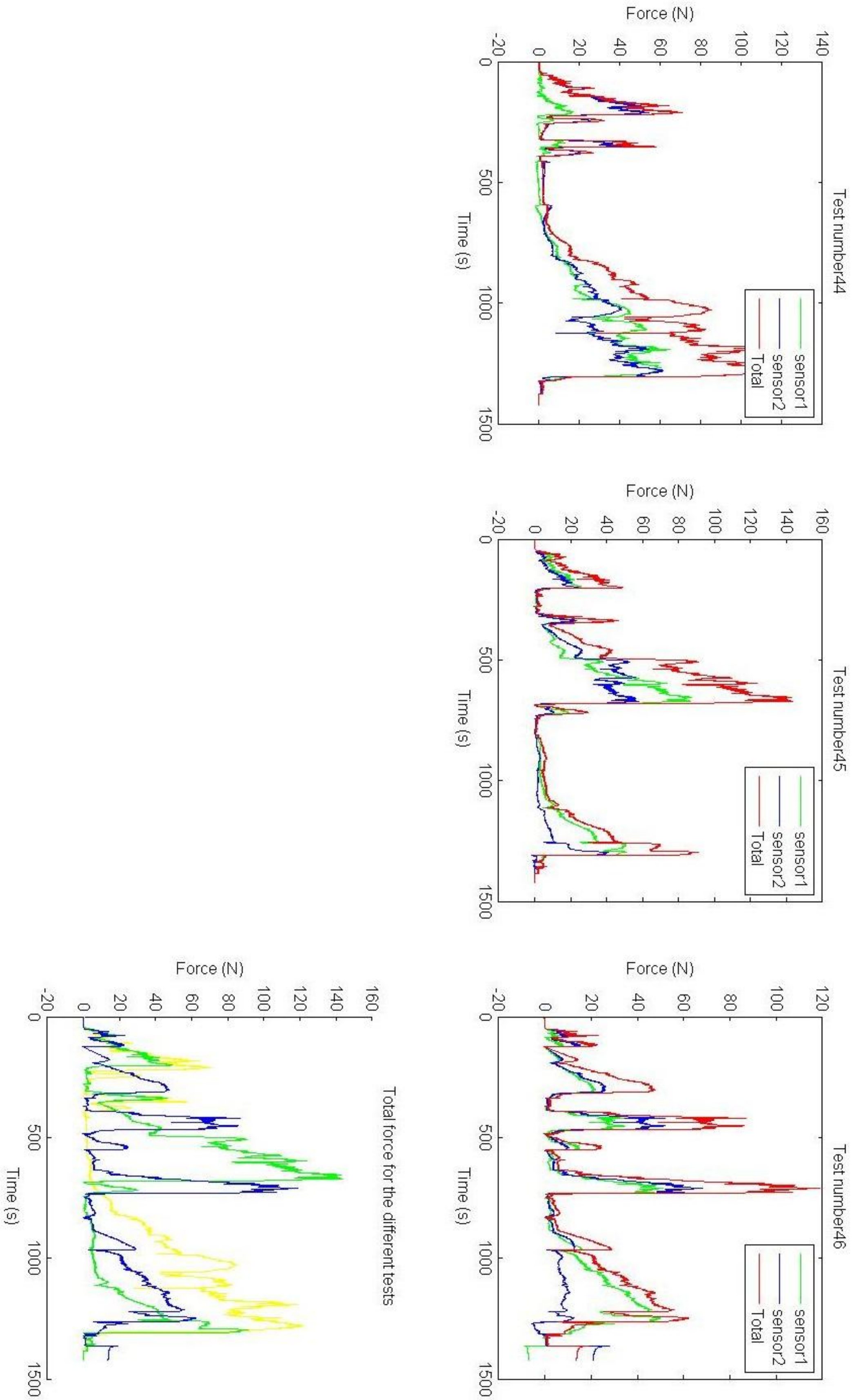

Test number41
Force (N)
Time (s)
sensor1
sensor2
Total


Test number42
Force (N)
Time (s)
sensor1
sensor2
Total

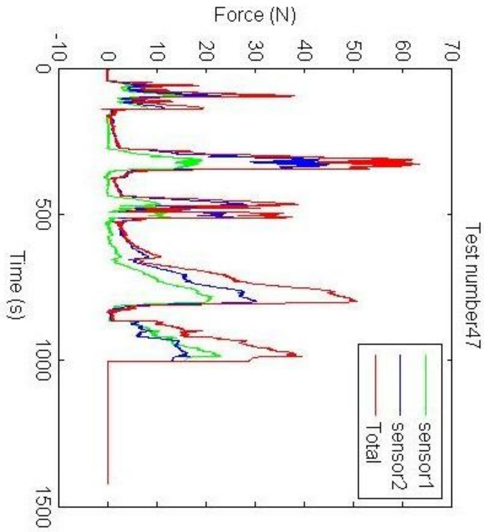

Test number43
Force (N)
Time (s)
sensor1
sensor2
Total


Total force for the different tests
Force (N)
Time (s)

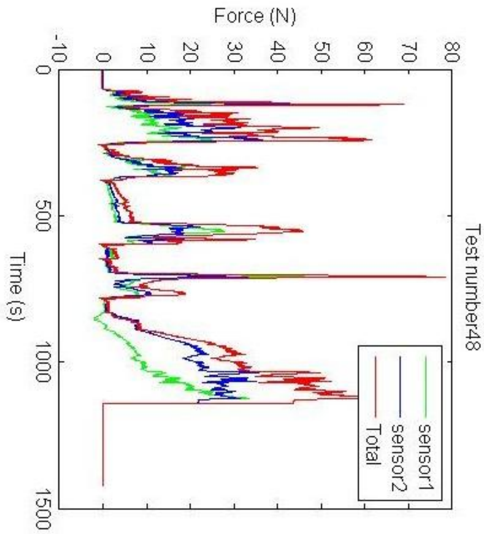
TESTS1FE


Test number44
Test number45
Test number46
Total force for the different tests
Force (N)
Time (s)
sensor1
sensor2
Total

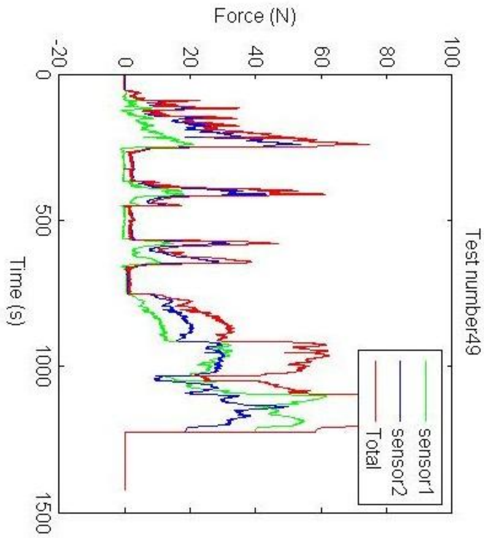
TESTS1FF



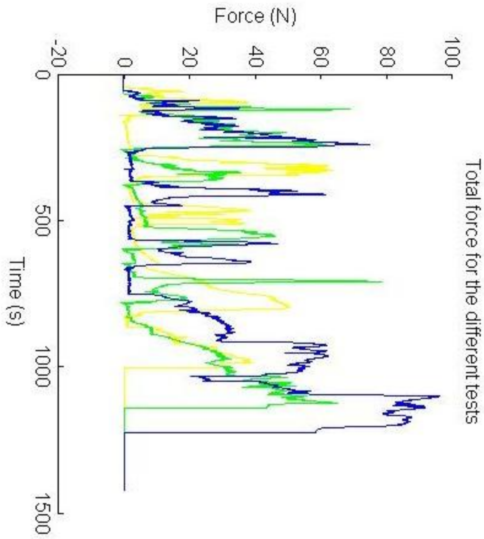
Test number47
Force (N)
Time (s)
sensor1
sensor2
Total



Test number48
Force (N)
Time (s)
sensor1
sensor2
Total

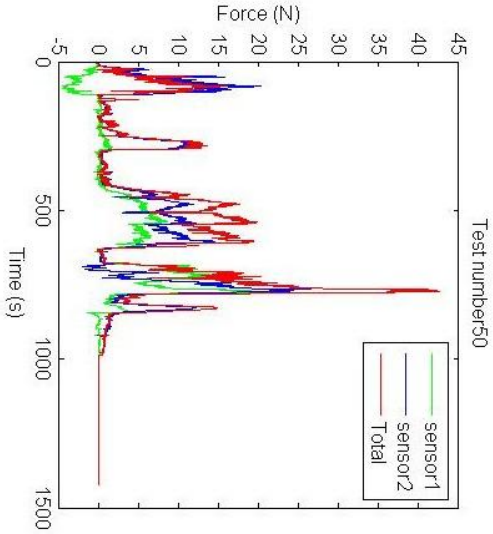


Test number49
Force (N)
Time (s)
sensor1
sensor2
Total

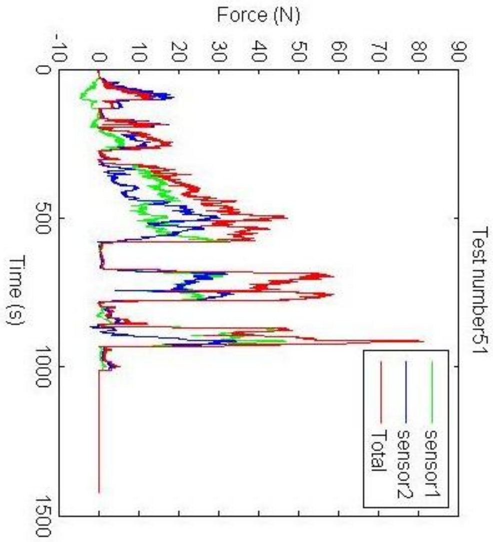


Total force for the different tests
Force (N)
Time (s)

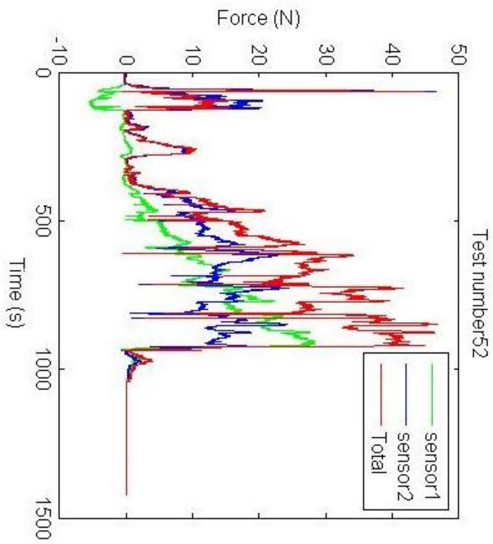
TESTS2FABC



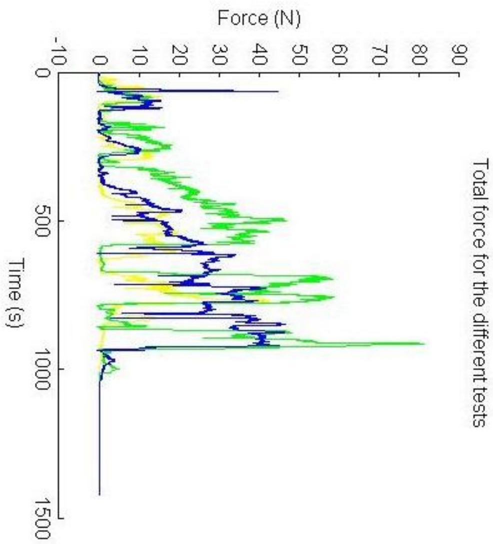
Test number50
Force (N)
Time (s)
sensor1
sensor2
Total



Test number51
Force (N)
Time (s)
sensor1
sensor2
Total

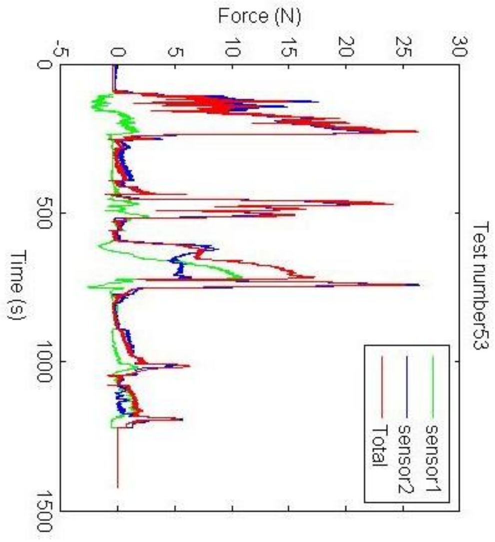


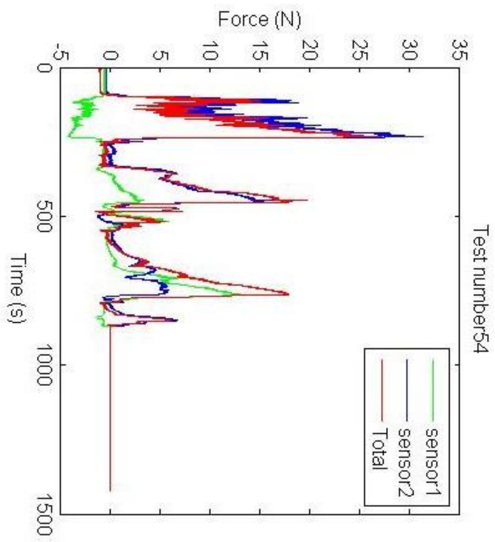
Test number52
Force (N)
Time (s)
sensor1
sensor2
Total

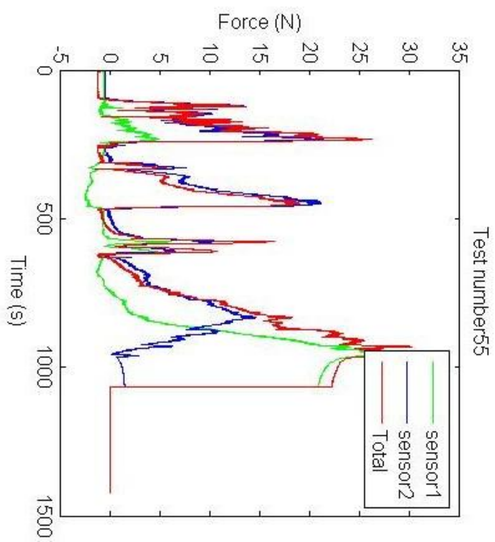


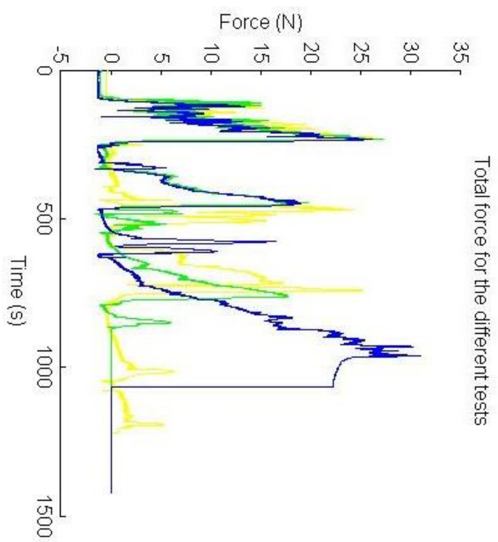
Total force for the different tests
Force (N)
Time (s)

TESTS2FD

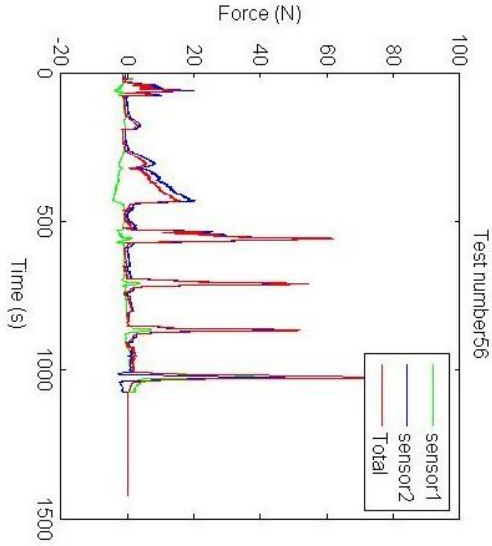

Test number53
Force (N)
Time (s)
sensor1
sensor2
Total

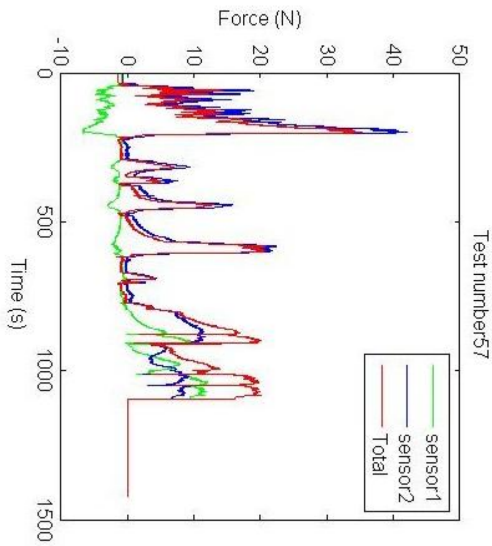

Test number54
Force (N)
Time (s)
sensor1
sensor2
Total

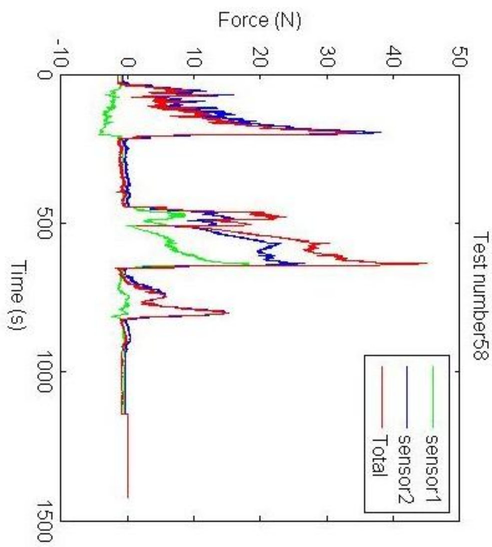

Test number55
Force (N)
Time (s)
sensor1
sensor2
Total

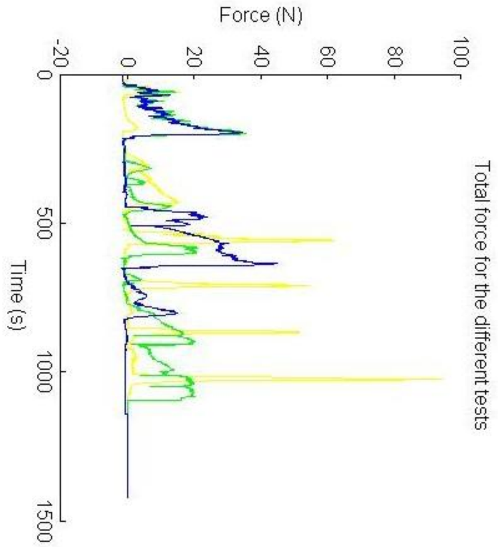

Total force for the different tests
Force (N)
Time (s)

TESTS2FE

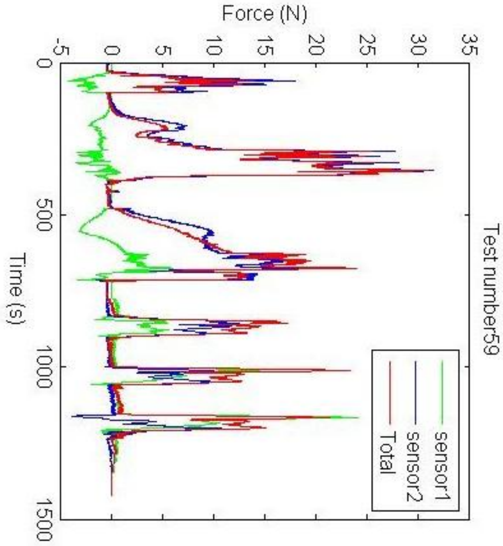

Test number56
Force (N)
Time (s)
sensor1
sensor2
Total

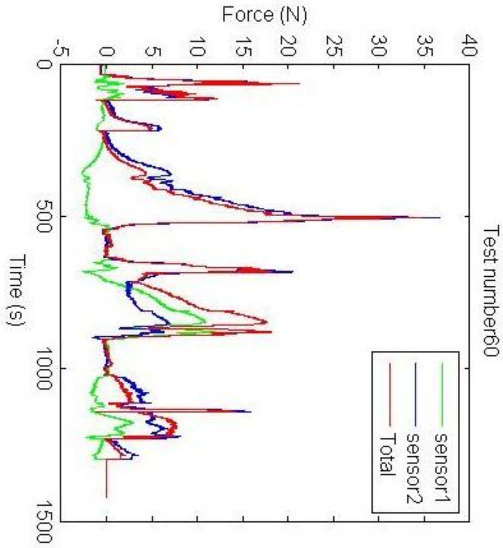

Test number57
Force (N)
Time (s)
sensor1
sensor2
Total

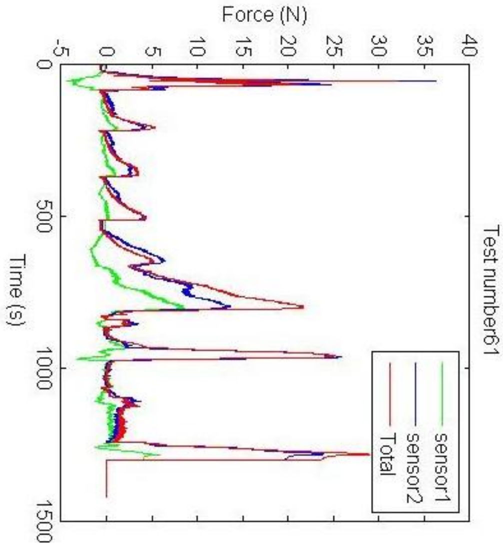

Test number58
Force (N)
Time (s)
sensor1
sensor2
Total

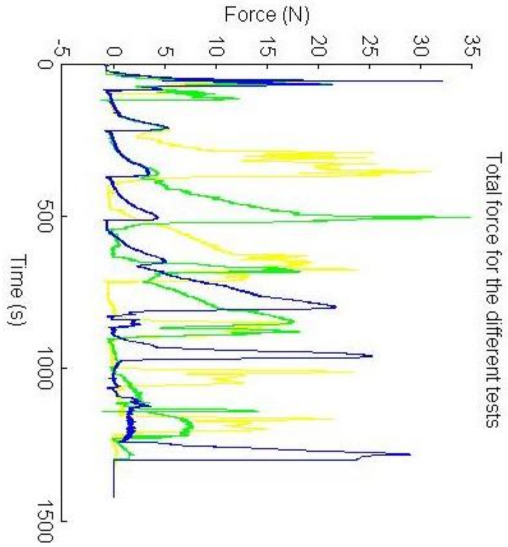

Total force for the different tests
Force (N)
Time (s)

TESTS2FF


Test number59
Force (N)
Time (s)
sensor1
sensor2
Total


Test number60
Force (N)
Time (s)
sensor1
sensor2
Total


Test number61
Force (N)
Time (s)
sensor1
sensor2
Total


Total force for the different tests
Force (N)
Time (s)