MDCE bvba

Nautical Depth

Measuring the Rheological Behaviour Transition

Notes on scientific background and mathematical cable model

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1. Rheological Behaviour Transition. (RBT)

1.1 Definition.

For the definition and description of the Rheological Behaviour Transition, reference is being made to a publication by dr. ir. E.A. Toorman in the periodical ‘Water’, number 66 – September/October 1992, par. 2.3 ‘Sedimentatie’, page 160.

Figure 1 shows the settlement curve of the water / mud interface in an original homogenous mixture.

Three phases during this process can be observed:

- The phase of unhindered or constant settling, is indicated in the figure by the number 1.

  This phase corresponds in a muddy environment with the ‘clear’ water phase. Particles are settling independently from each other.

- The phase of hindered settling, is indicated in the figure 1 by the number 2.

  This phase corresponds in nature with the fluid mud phase. The gravity acting on the particles is hindered by upward flow, particle forces and diffusive forces.

  This is the phase where rheology is the dominant theoretical concept to describe the behaviour of the mud.

  Other secondary concepts are yield shear stress, thixotropy, hysteresis of the viscosity, changing viscosity with share rate, … . Acting forces depend on the share rate. The fluid mud is navigable.

For a characteristic view of the relationship in fluid mud between velocity, shear stress and viscosity, see the figure 2, by Dipl. - Ing. Rewert Wurpts[1].

Another characteristic view for fluid mud, concerning thixotropy and shear rate, is also delivered by Dipl. - Ing. Rewert Wurpts: see figure 3.

An important publication by Prof. Dr. ir. Erik A. Toorman on this subject can be found in Acta Rheologica 36:56-65 (1997): 'Modelling the thixotropic behaviour of dense cohesive sediment suspensions'.

Remark.

The nature of the fluid mud's behaviour – changing viscosity with shear rate and time – implies that the parameter viscosity has to be disregarded for the definition and measurement of the Nautical Depth.

- The phase of consolidation is indicated in the figure 1 by the number 3.

The water / mud interface keeps settling down, although with different, much slower velocities, and the particles keep coming nearer to each other and touch.

At this moment, van der Waals forces intervene dominantly and the mud crosses the 'gel point': a matrix appears, formed by particles in contact / subjected to additional forces. Undrained shear forces of 1 to 2 kPa appear and mark a drastic discontinuity with the fluid mud phase. The mud starts to consolidate.

This phase corresponds therefore with the consolidating mud phase and is characterized by a transition into a completely different field of experience and theory.

In fact the dominant concepts of this phase belong to the field of soil mechanics: consolidating saturated clay, Attenbergh limits, liquid limit, acting forces depending on deformation, …

The passing from the fluid mud phase to the consolidating mud phase is also called the passing of the gel point.

The existence of this matrix is confirmed by the fact that pore pressure in this phase corresponds with an effective stress – see Karl Terzaghi - different from zero.

[1] Terra et Aqua – Number 99 – June 2005, pag. 26

The interface between the fluid mud phase and the consolidating mud phase where this discontinuity appears, is by definition the Rheological Behaviour Transition (RBT).

1.2 Resistivity.

By applying a voltage between two poles in water, a current will be generated with the ions as a transport medium.

Copper is an excellent conductor of electricity because of the much ‘free’ electrons. Pure water on the other hand, is a bad conductor, since not much water molecules are dissociated. In seawater, the ions Na^+ and Cl^- will have this function and in fluid mud even more particles may perform that function.

However, in consolidating mud the particles form a matrix – a solid skeleton structure – under the influence of van der Waals forces. Ions will have less freedom of movement in such an environment and resistivity (conductivity) will be significantly higher (lower) than in water of fluid mud.

This phenomenon has been proved during the trials conducted in October 2008 in Zeebrugge.

Therefore resistivity is a suitable parameter to observe if an environment consists of fluid mud or of consolidating mud.

This property is used by the Rheocable procedure in sounding the RBT, and therefore the Nautical Depth.

1.3 Nautical Depth

The hypothesis, that the level of the Rheological Behaviour Transition actually is the Nautical Depth, was present from early on. In order to verify this hypothesis, life-size experiments were carried out with the TSHD ‘Vlaanderen 18’ in Zeebrugge[2]: see figure 4. This test was carried out in 1989.

[2] These test were carried out also to investigate the influence on a ship’s behaviour in the presence of a fluid mud layer on the seabed, in the perspective of obtaining references fore future laboratory trials. From 1988 onwards up till recent times, these trials have been carried out in the laboratories of Flanders Hydraulics Research, Borgerhout – Antwerp.

The ship was positioned with the keel at the depth of the Rheological Behaviour Transition in the Albert II – dock in the port of Zeebrugge. The dock not used for commercial shipping at that time.

From the central part of the port, where the depth was maintained at -13.5 m, the vessel accelerated and was steered in westerly directions along the longitudinal dock axis to ‘hit’ the RBT in the a.m. dock: see also figure 5.

It was anticipated that the vessel’s speed would decrease significantly when this happened.

Several pilots were aboard, the harbour master of Zeebrugge, representatives of the Board.... And it turned out that the ship was no longer in control!

Rudder hard starboard or hard port had no effect. Propellers full ahead and full astern had no effect. The ship kept moving and chose its own path.

There was some panic on board, until the ship was stopped against the slope, and, by dumping water from the hopper, the ship was quickly back afloat.

When comparing this ship's behaviour with the definition of the Nautical Depth, as formulated by the International Navigation Association PIANC:

Quote:

The Nautical Depth is the level where physical characteristics of the seabed reach a critical limit beyond which contact with a ship’s keel causes either damage or unacceptable effects on controllability and manoeuvrability.

Unquote

It is definitely clear that the Rheological Behaviour Transition is the Nautical Depth.

1.4 The dredging experience.

The existence of a RBT implies the existence of two different mud layers in a zone with sedimentation of predominantly fine materials µ < 60: a fluid mud layer and a consolidating mud layer, the difference being fundamentally the presence of a much higher ‘yield’ stress in the latter.

This phenomenon can indeed be observed on board of a dredger, engaged in dredging operations in muddy areas.

The mixture density and mixture speed histograms are an exact illustration of this fact. The histograms were created using recorded process parameters in a certain dredging area in the port of Zeebrugge, over a period of two weeks in 1997.

While the density provides an unambiguous profile of a normal frequency distribution, one can see that the speed distribution obviously contains two normal frequency distributions: Figures 6 and 7.

The mud displays a liquid state and a consolidating state at the same density.

When dredging fluid mud of density 1.200 kg/m³, the mixture velocity will normally be about 5 m/s.

In the figure 8, a pump curve with a density of 1.200 kg/m³ is represented. Pump specifications are:

- Type IHC 125 – 35 – 60
- Impeller width 1165 mm
- Impeller with 5 blades
- rpm 275
- Dredging depth 15.00 m
- Suction pipe diameter 600 mm

This pump is mounted on board of a dredger of 2.500 m³ hopper capacity.

At 5 m/s, the resistance curve of the dredge line, hits this pump curve at a pressure of 170 kPa see figure 8.

When lowering the suction pipe, at a well defined level the mixture velocity will be reduced to 2 m/s or less, and this over a small increase in depth: the pressure will raise to 215 kPa.

It is supposed that in both cases – 5 m/s flow and 2 m/s flow – the mixture going through the dredging system is 100 % fluidized: it is fluid mud of 1,2 density.[3]

The difference with respect to the dredge line resistance, is then caused by the energy the pump has to deliver for passing the soil from the consolidating mud phase back to fluid mud phase. Before the consolidating mud can be pumped

[3] Mud, passing through the dredging process at a mixture velocity of 5 m/s, is acting as a Newtonian fluid with low viscosity (water). In this state, pump curves and dredge line resistance curves are the same for the mud as for a sand water mixture of the same density, provided the sand has a d50 of less tan 200µ and that the pumping distances are short as is the case on board of a trailing suction hopper dredger.

through the dredge line system, it has to be fluidized, which consumes extra energy to be delivered by the dredge pump.

Since the power needed to fluidize the mud is proportional to its volume, this extra power is therefore proportional to the rate of flow or to the mixture velocity, implying that the consolidating mud resistance p – q curve is equal to the fluid mud resistance curve plus a constant Δp.

In our numerical case, this constant is 213.44 kPa – 27.49 kPa = 185,95 kPa and can be derived form the curves at mixture velocity equal to 2 m/s.

So, in order to fluidize 1 m³ of mud, the energy needed is apparently 185,95 kJ or the fluidization of 1m³/s requires a power of 186 kW, which is considerable.

1.5 Horizontal movement of a cable in consolidating mud.

If a cable is towed horizontally in a environment of consolidating mud, the energy, needed to do so, will be equal to the energy when towed in an environment of fluid mud with the same density, increased with an amount of energy needed to 'fluidize' the consolidating mud.

From the foregoing example, it is known that this energy is 185,95 Joule/m³.

For a cable with a diameter of 9 cm – this is the diameter of the rubber protection in way of the weight at the end of the cable – alone the force needed to fluidize its own displacement of volume is 1.182 N.

This amount is a minimum because the displacement of the consolidating mud of his own volume, is affecting a considerable larger quantity of mud surrounding the cable.

Later on it will be shown, that this force is more than sufficient to keep the Rheocable positioned on the interface fluid mud / consolidating mud.

1.6 A ship in contact with the consolidating mud.

When the TSHD 'Vlaanderen 18', during the 1989 trials in Zeebrugge, was put in contact with the consolidating mud, the observation was that the ship was out of control. She followed her own course, was not reacting to rudder – and / or propeller manoeuvres.

This can be explained by the fact that the propellers – like dredge pumps, centrifugal pumps in their own way – are unable in that position to ‘mobilize / pump’ a sufficient mass of water for the ship to react.

In a similar way as the dredge pumps, the propellers have to fluidize the consolidating mud, or at least a part of, before the normal pump action can be carried out. The extra power needed reduces this normal pump action drastically with the described consequences for the ship. It must be remembered that rudder action depends entirely on the propeller action.

This fact explains the ship being out of control.

Another observation is that the ship keeps following her own course until she is halted, obviously not by her own means, but by the decreasing depth of the RBT.

TSHD ‘Vlaanderen 18’ was partially loaded with water during the trial, and here mass can be estimated at about 15.000,00 tons, of which about 6.000 tons of her own weight.

When moving with a speed of 4 knots (about 2 m/s), her energy can therefore be estimated at about 30.000 kJ.

Supposing a negative keel clearance with reference to the RBT of 5 cm, the ship will fluidize a volume of 1.15 m^3/s, the vessel’s breadth being 23 m.

She will need to consume 213.9 kJ/s of her energy, meaning that she will be stopped after a distance of 140m: practically her own length.

This is what the vessel halted eventually in Zeebrugge: her keel clearance became negative, towards the end of the dock.

Supposing the keel clearance zero, only friction occurs between the ships bottom and the consolidating mud. This friction is practically non existent or very small, hence the fact that the vessel simply keeps following her course, whilst being unsteerable and unstoppable for the reasons explained.

2. Cable: Model and Discussion.

2.1 Cable configuration: general description

The cable configuration is shown in figure 9.

The cable is of the multi - channel type.

At the forward (inboard) end, the cable is connected to the current generator, to the resistivity meter/logger, to the pressure sensor at the aft end of the cable, including recording and online screen.

For towing purposes, the cable is also connected and secured to the survey vessel by mechanical means.

At the aft end of the cable, the weight is attached to the cable. In the same position is also attached to the cable, the pressure sensor for the measurement of the water column pressure.

This pressure sensor is packed in a watertight casing. Two flexible tubes connect the casing with the pure water phase in order to avoid fluid mud density distortions of the pressure measurement .

Aft of the weight and pressure sensor, follows the ‘resistivity tail’ of the cable. This part of the cable is about 4 to 5 m long. It contains the two current electrodes (the forward and aft one) and the two voltage electrodes (the middle ones).

2.2 The mathematical model.

The cable is divided in 10 pieces of equal length l: cable units U_1 to U_{10}.

The length of the pieces is varying with the total length of the cable.

The cable length is measured between the towing point on board of the survey vessel – usually the cable is fastened for towing purposes at SB or PS of the poop – and the weigh : see figure 9, points A en B.

As a model, each unit is a rigid round rod, connected with hinges at both ends with his neighbours. The diameter of the rod d, is equal to the cable diameter: see also figure 8.

The cable unit is subjected to the following forces: see also figure 10.

- A horizontal force H_i, as a result of the action of cable unit U_{i+1}
- A Vertical force Vi, as a result of the action of cable unit U_{i+1}
- A vertical force q.l, with q the weight per meter under water of the cable and seizing the cable unit in its centre.
- A force F, seizing the cable unit in the centre, in an upward direction perpendicular to the centre line of the unit and equal to

$$F = C_d.\frac{1}{2}.\rho.d.l.(V.\sin\alpha)^2$$

- A horizontal force H_{i-1}, as a result of the action of cable unit U_{i-1}
- A Vertical force Vi+1, as a result of the action of cable unit U_{i11}
- A vertical force W: weight attached at the lower end of the cable
- An unknown force W' caused by the 'resistivity tail' of the cable, symbolized by a horizontal force k . V^2, with the factor k to be determined by trials with the cable floating at different velocities.

Symbols used

L	cable length
l	= L/10, cable unit length
d	cable diameter
H	Horizontal reaction force
V	Vertical reaction force
F	Uplifting force because of velocity
C_d	Drag coefficient (= 1)
ρ	Density
V	Velocity
α	Angle between velocity and cable unit centre line
W	Weight attached at the lower end of the cable in position B
k	factor for unknown force by 'resistivity tail' of the cable

2.3 Calibration of the model.

Two cables were tested free floating: cable 1 on the 3th of October 2008 and cable 2 on the 23th of June, both in Zeebrugge.

The characteristics of these cables are as follows:

	Cable 1	Cable 2	Cable 3
Diameter in mm	23.5	18.5	9.6
Weight under water in kg/m	0.090	0.201	0.309
Length	80.0	66.0	72
k	100	150	125
colour	blue	red	green

Table

For the results of these tests and the calibrations: see figure 11 for cable 1 and figure 12 for cable 2, each representing the trail values and the calculated values, using the model of the former paragraph.

The calibration was done by determining the factor k for each cable.

For cable 1, k is 100.

For cable 2, k is 150.

This difference can be explained by secondary differences in the configuration of the 'resistivity tail': weight, length, …..

Accepting this difference, this cable model is able to reproduce the data of the trials, put together in figure 13: see figure 14.

In figure 14 is added a new cable, with the characteristics as recorded in table: the k factor has been chosen 125, the mean value between 100 and 150. The cable has been chosen in order to allow higher survey velocities at depths of 20m and lower.

The calculation model also allows to visualize the cable curve as it changes with the velocity: see figure15 for cable 1 and figure 16 for cable 2.

2.4 Discussion of the parameters.

Cable 3 is adopted as the standard.

The parameters which can be changed, in order to influence the position beneath zero level, are the weight at the lower end of the cable and the total length.

Figure 17 shows the result for the parameter length.

At a depth of 20 m, by changing the length with 20 m, the upper limit of the velocity window can be changed by about 1 knots and would allow survey speeds up to 5.5 knots.

Figure 18 shows the result for weight.

At a depth of 20 m, by changing the weight with 10 kg, the upper limit of the velocity window can be changed by plus of minus 0.5 knots and would allow survey speeds up to 5.0 knots.

The effects of changing parameters length and weight can also be considered and calculated. As an example the curve for the cable with a length of 92 m and a weight with 30 kg is added in the figure 11.

At a depth of 20 m, a velocity of 6.3 knots can be reached before the cable would start floating.

2.5 Extra horizontal force.

Figure 19 show the effect of an extra horizontal force on the position of the cable end beneath zero level.

The force of 1.185 N is the minimum force generated by the horizontal movement of the cable in the consolidating mud: see also paragraph 1.5.

This force is sufficient, in an environment of fluid mud, to decrease the vertical position of the cable end up to about -15 m, at a towing speed of 1 knot.

Supposing that the RBT is situated at – 15 m, the cable will not be uplifted until a speed of 5.5 knots is reached.

Indeed, further decreasing of the depth would mean that the cable end changes form the consolidating mud environment to the fluid mud environment: therefore, the cable end – with the weights and the pressure sensor – will stay at the interface, when the towing speed is situated between 1 and 5.5 knots.

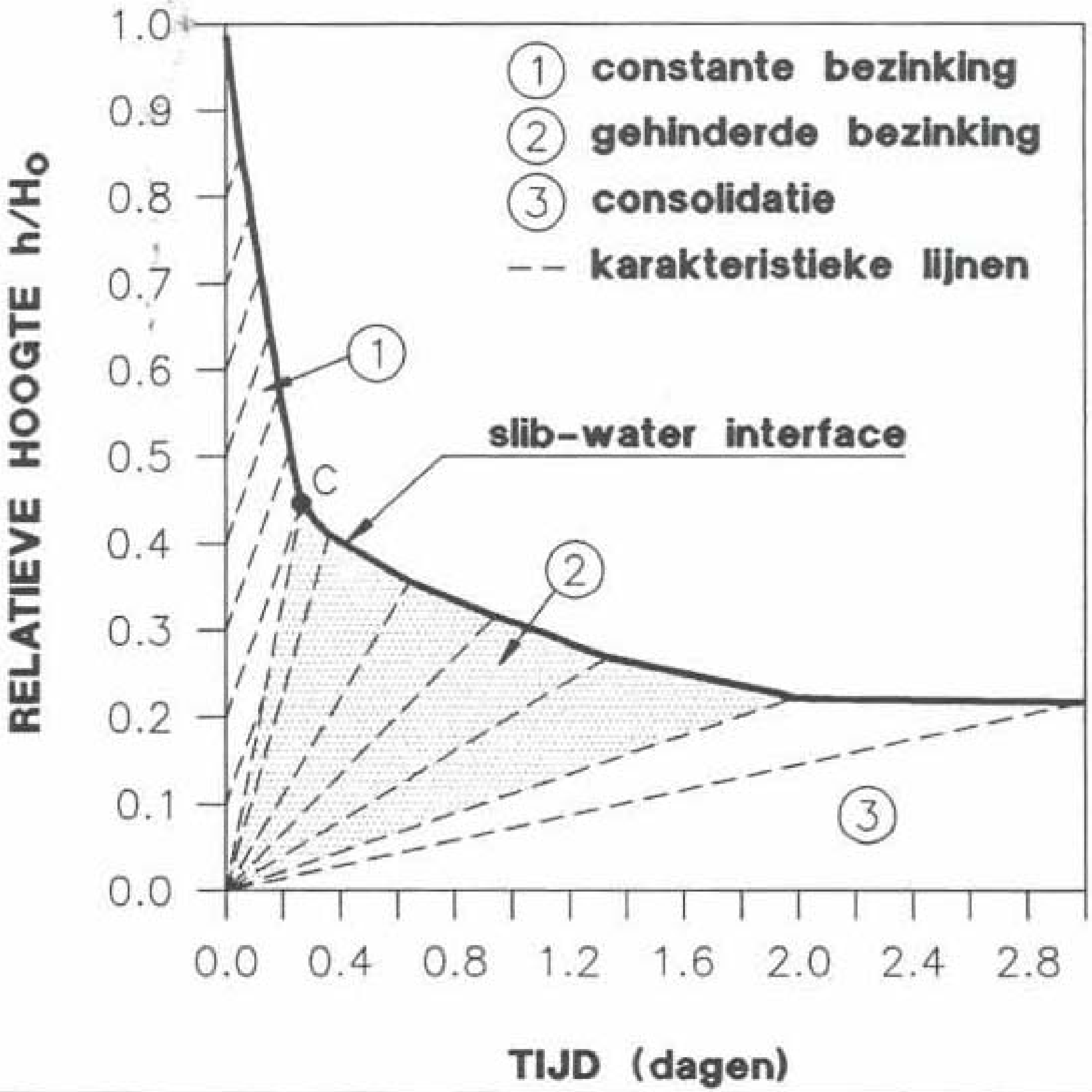
Marc Druyts

Peteralv Brabers

Bruges, November 13, 2009

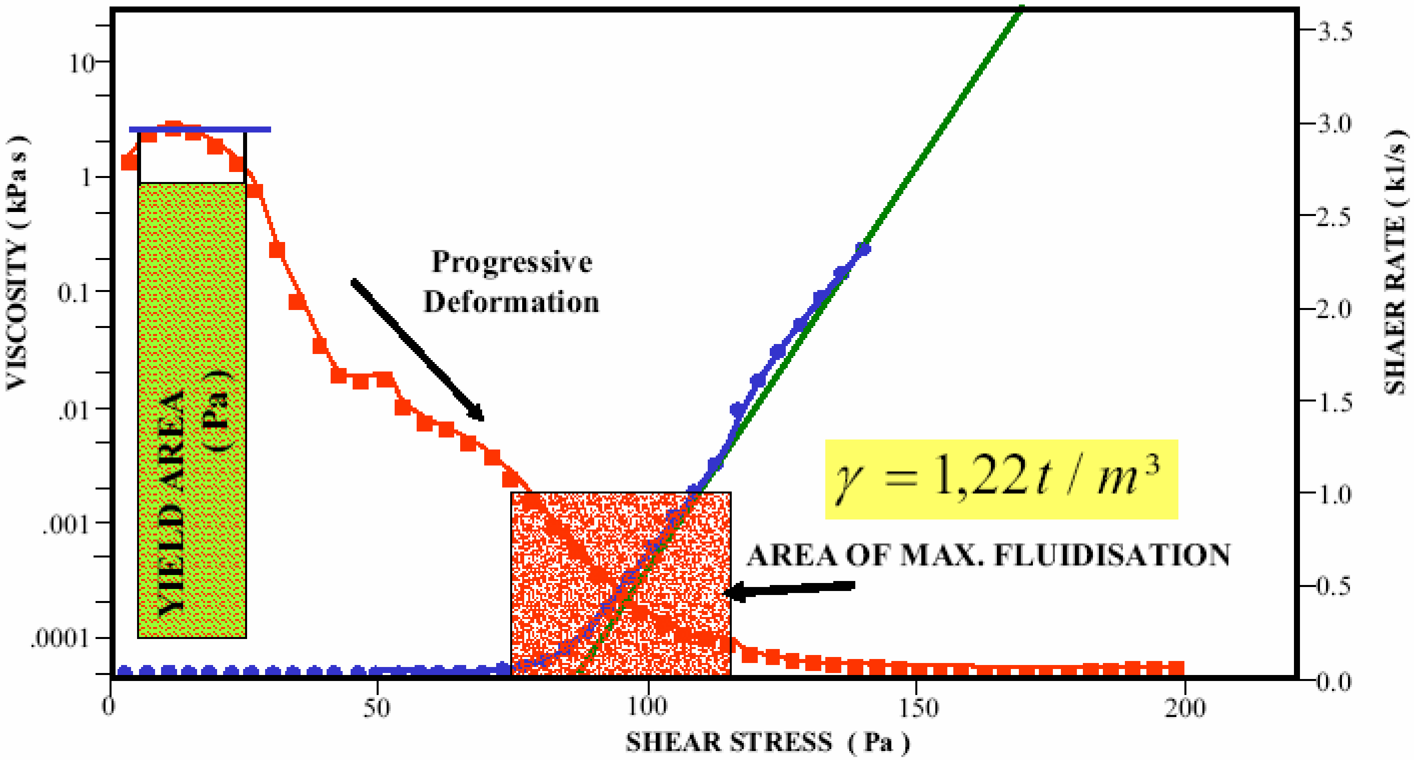
3. **Figures**

Fig. 2: Bezinkingscurve en karakteristieke lijnen (streeplijnen). Het compressiepunt C bevindt zich aan de overgang van (1) naar (2).



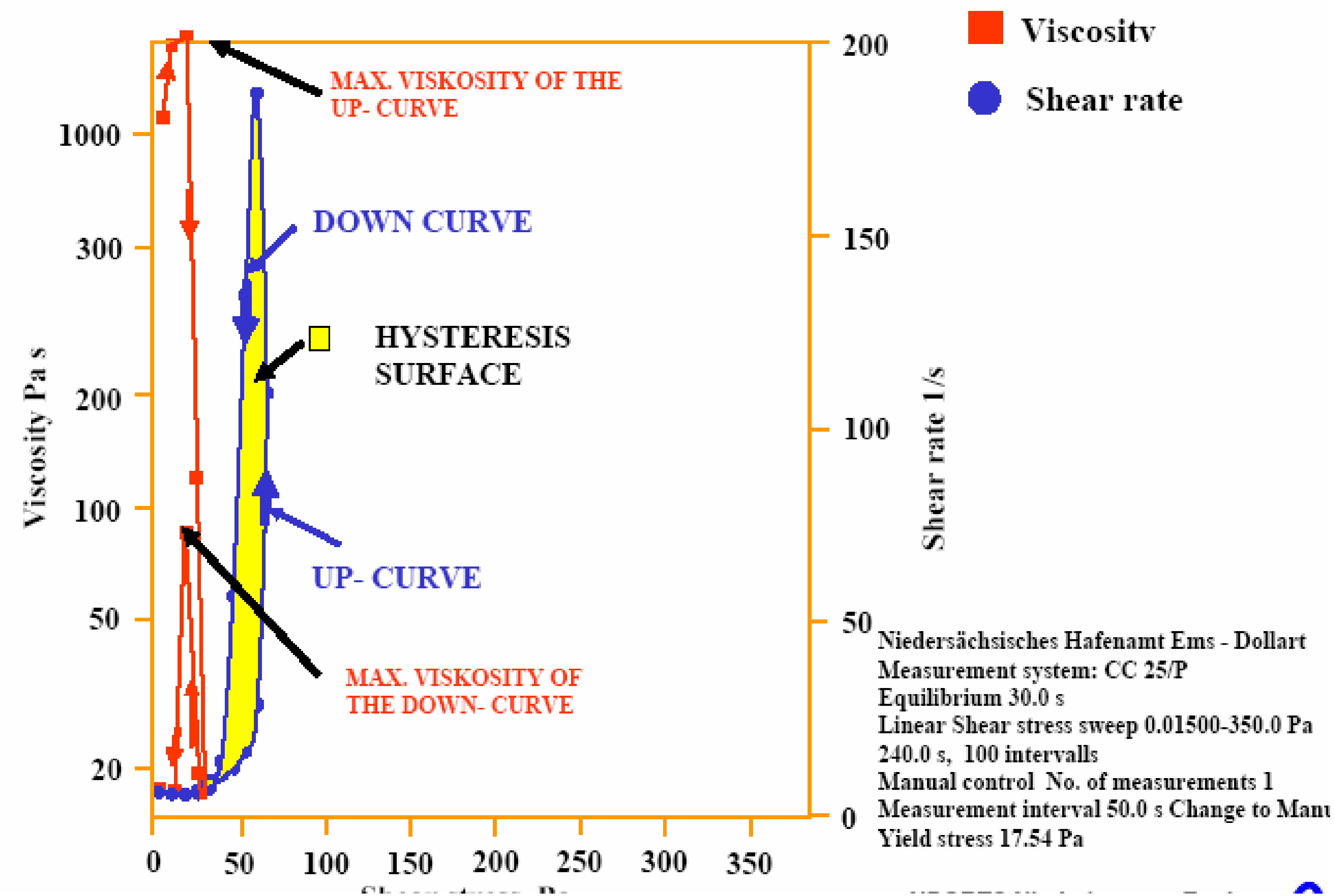
Water nr. 66 - september/oktober 1992

Port of Emden, 24.03.1999
Yield Stress

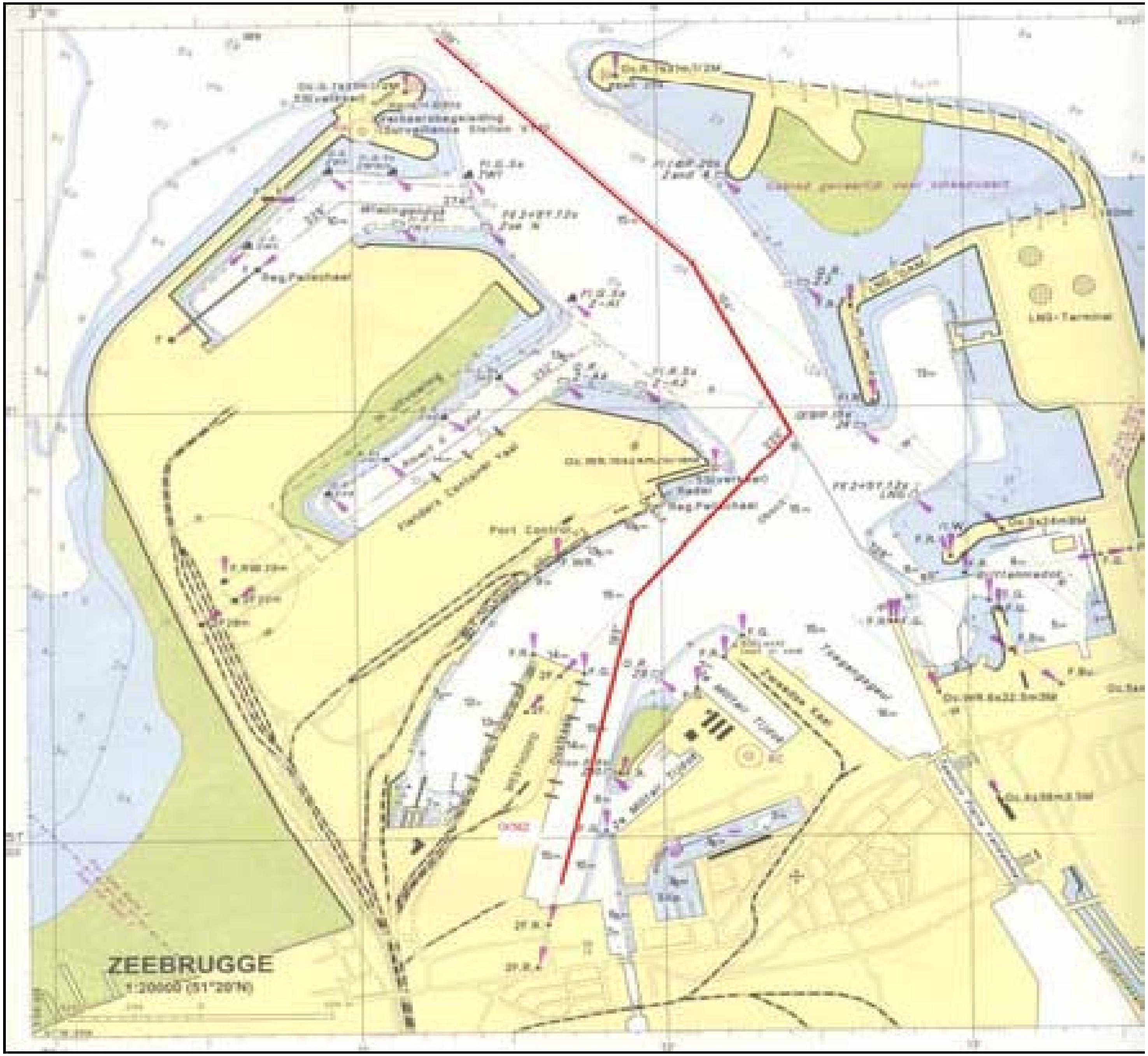


Emden 24.03.1999
Measurement system CC 25/P
To gap 25.00.2.50 N
Equilibrium 50.0 s
1.000 - 200.0 Pa Up linear
120.0s in 50 intervalls
Manual control No. Of measurements 1
Measurement interval 50.0s Change to Manual
Yield stress 10.97Pa

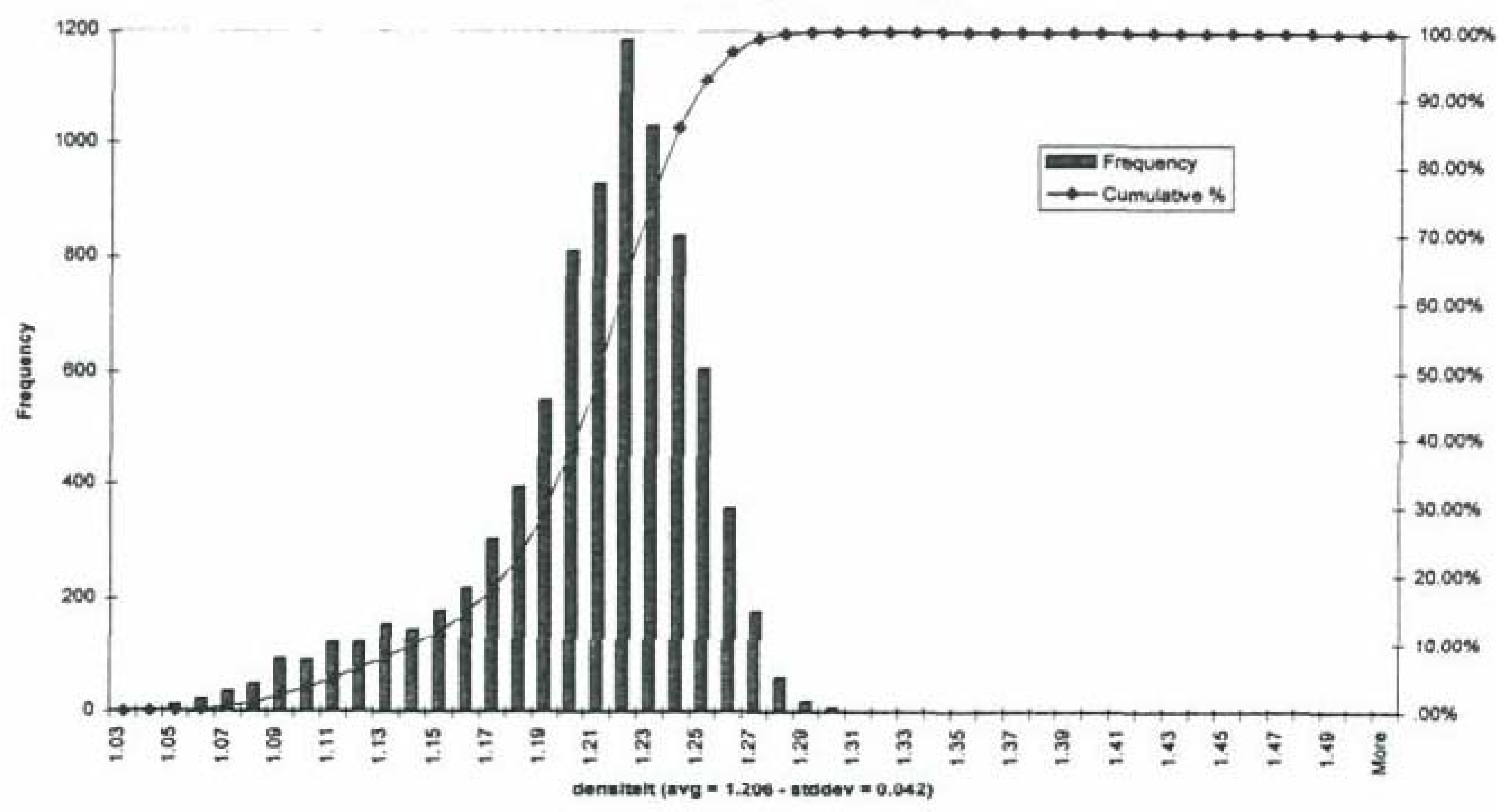
THIXOTROPY



Viscosity
Shear rate
MAX. VISKOSITY OF THE UP- CURVE
DOWN CURVE
HYSTERESIS SURFACE
UP- CURVE
MAX. VISKOSITY OF THE DOWN- CURVE
Viscosity Pa s
Shear rate 1/s
1000
300
200
100
50
20
200
150
100
50
0
0
50
100
150
200
250
300
350
Niedersächsisches Hafenamt Ems - Dollart
Measurement system: CC 25/P
Equilibrium 30.0 s
Linear Shear stress sweep 0.01500-350.0 Pa
240.0 s, 100 intervalls
Manual control No. of measurements 1
Yield stress 17.54 Pa


ZEEBRUGGE
1:20000 (51°20'N)
LNG-Terminal
Port Control

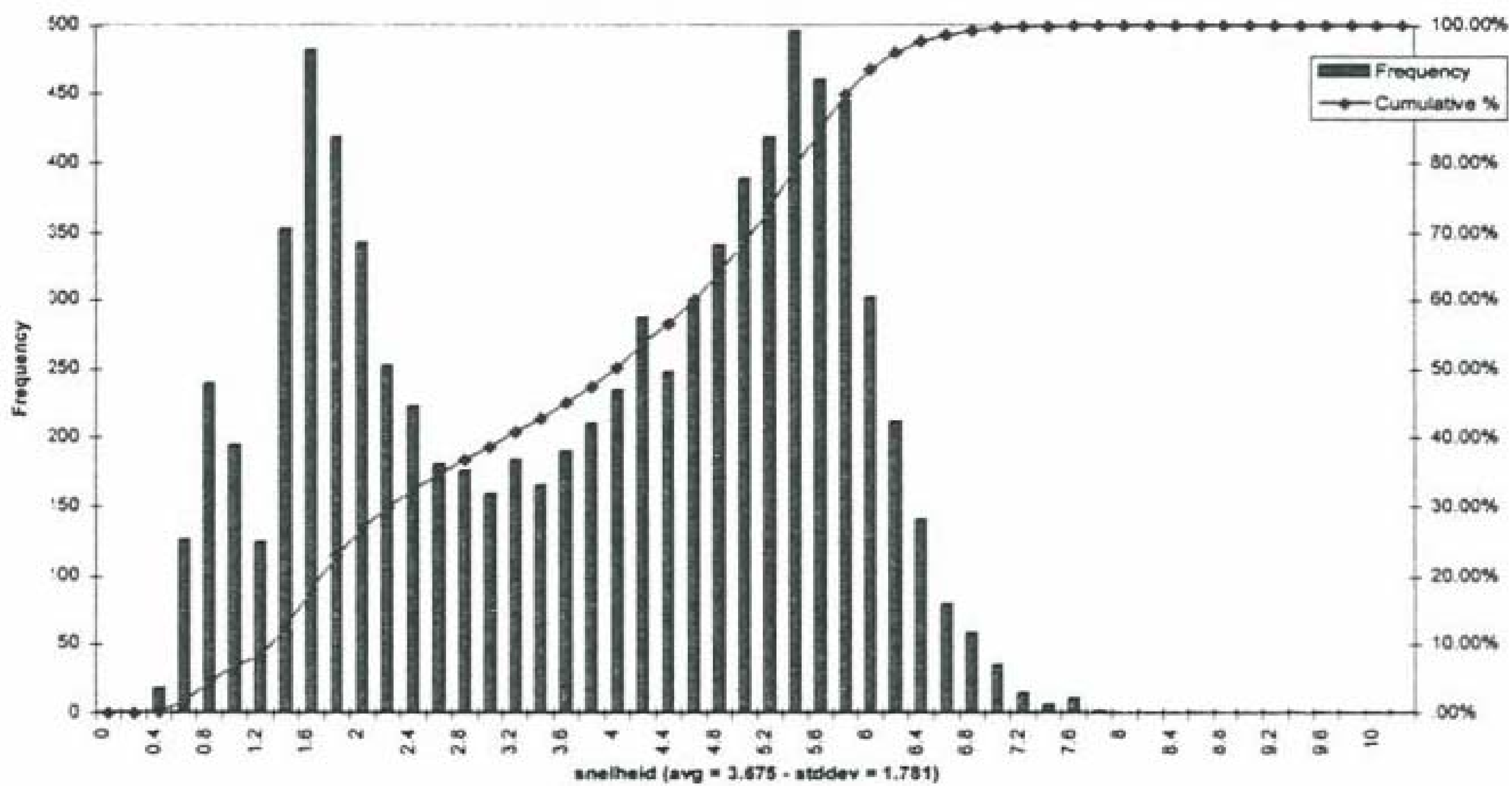
Mixture Density Histogram



Histogram Densiteit

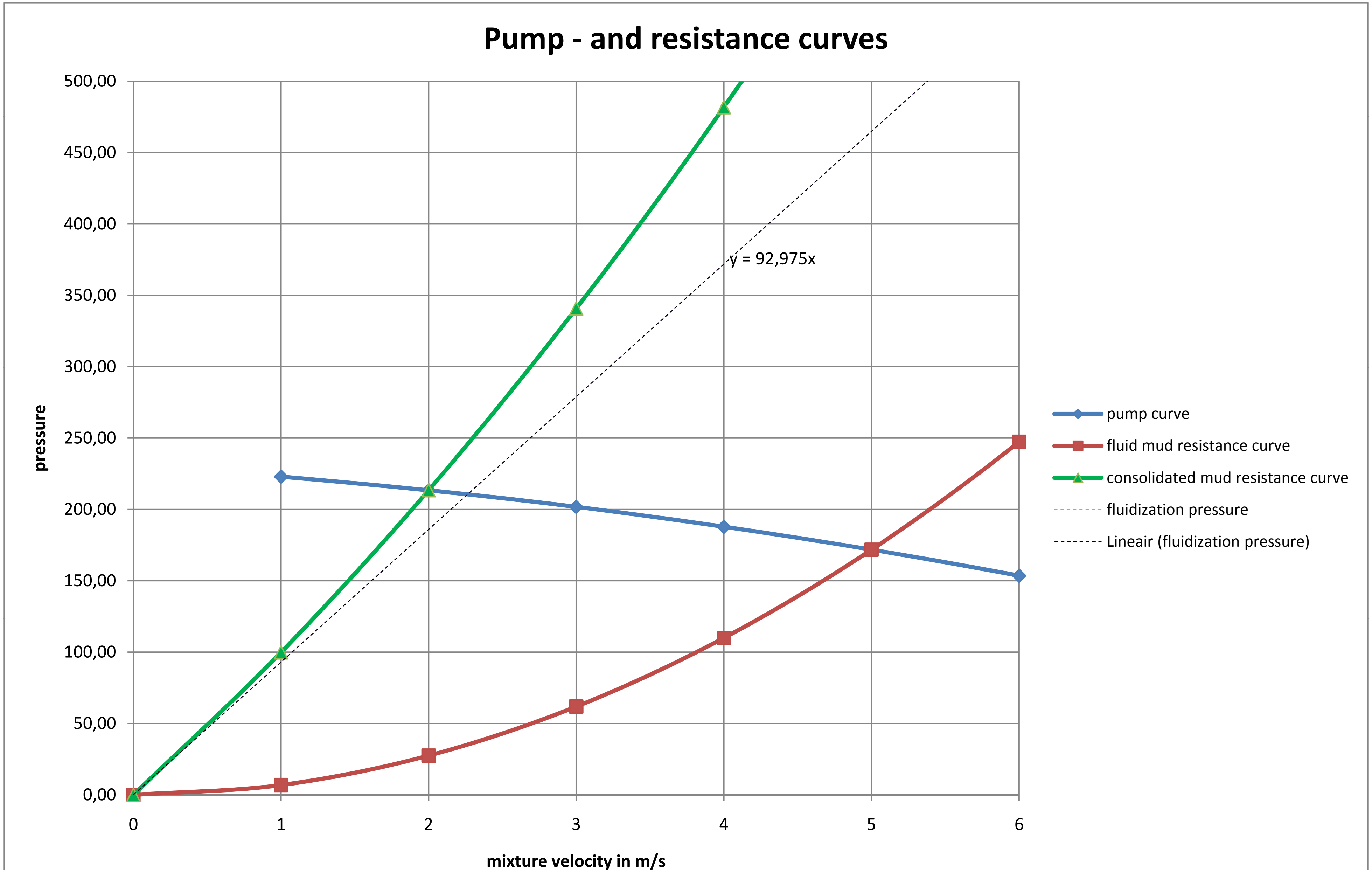
Sleephopperzuiger 2000m³ weken 47-48 1997 8494 samples

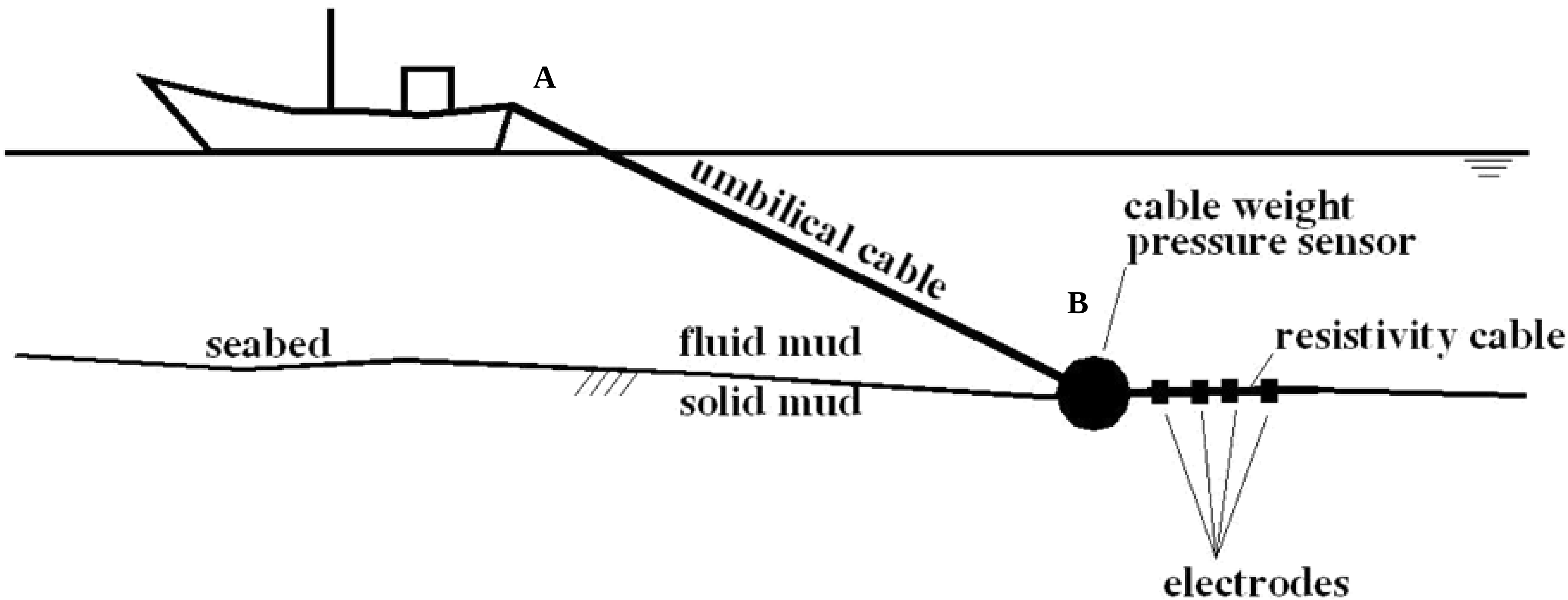
Mixture Velocity Histogram

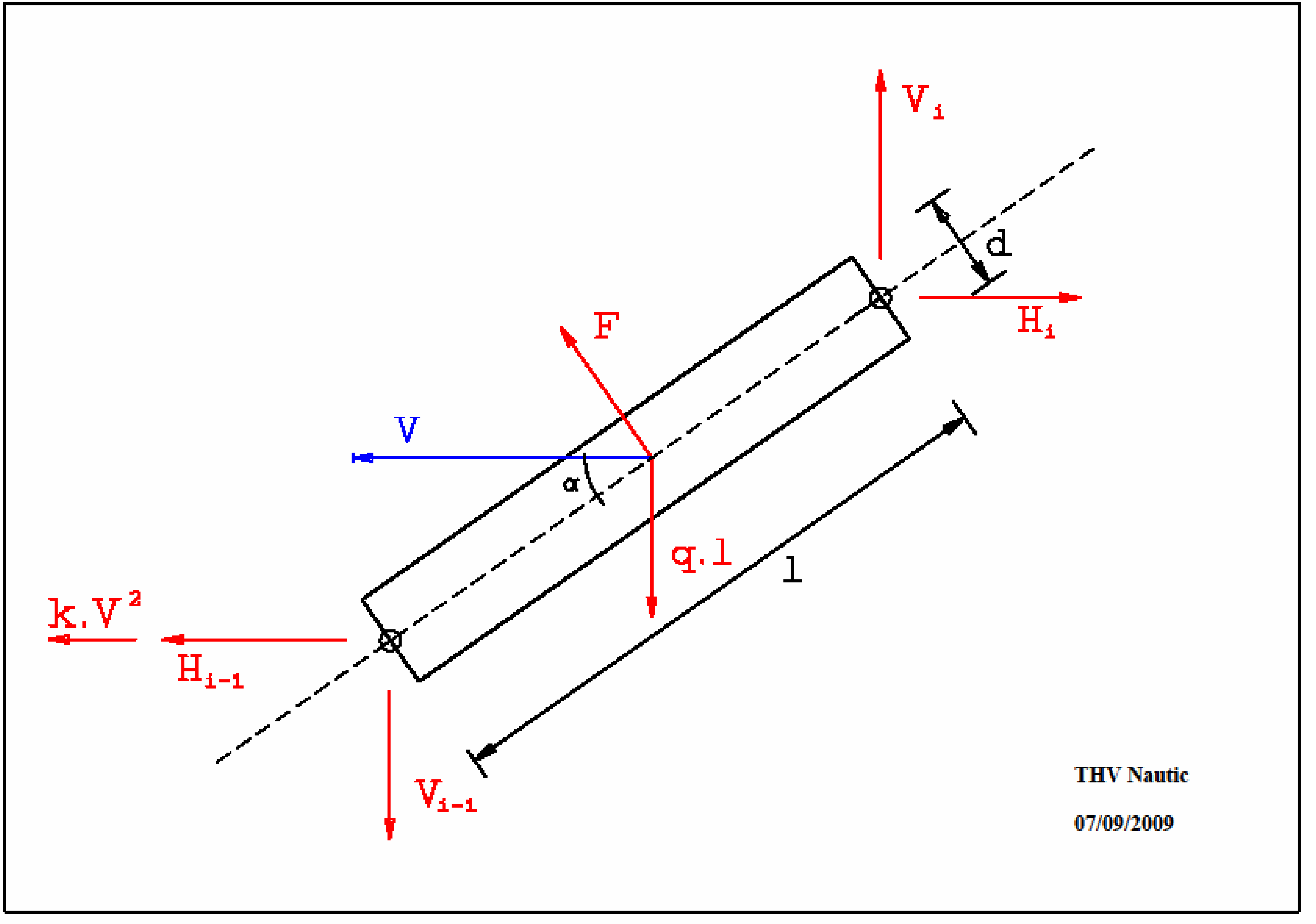


Histogram Mengselsnelheid

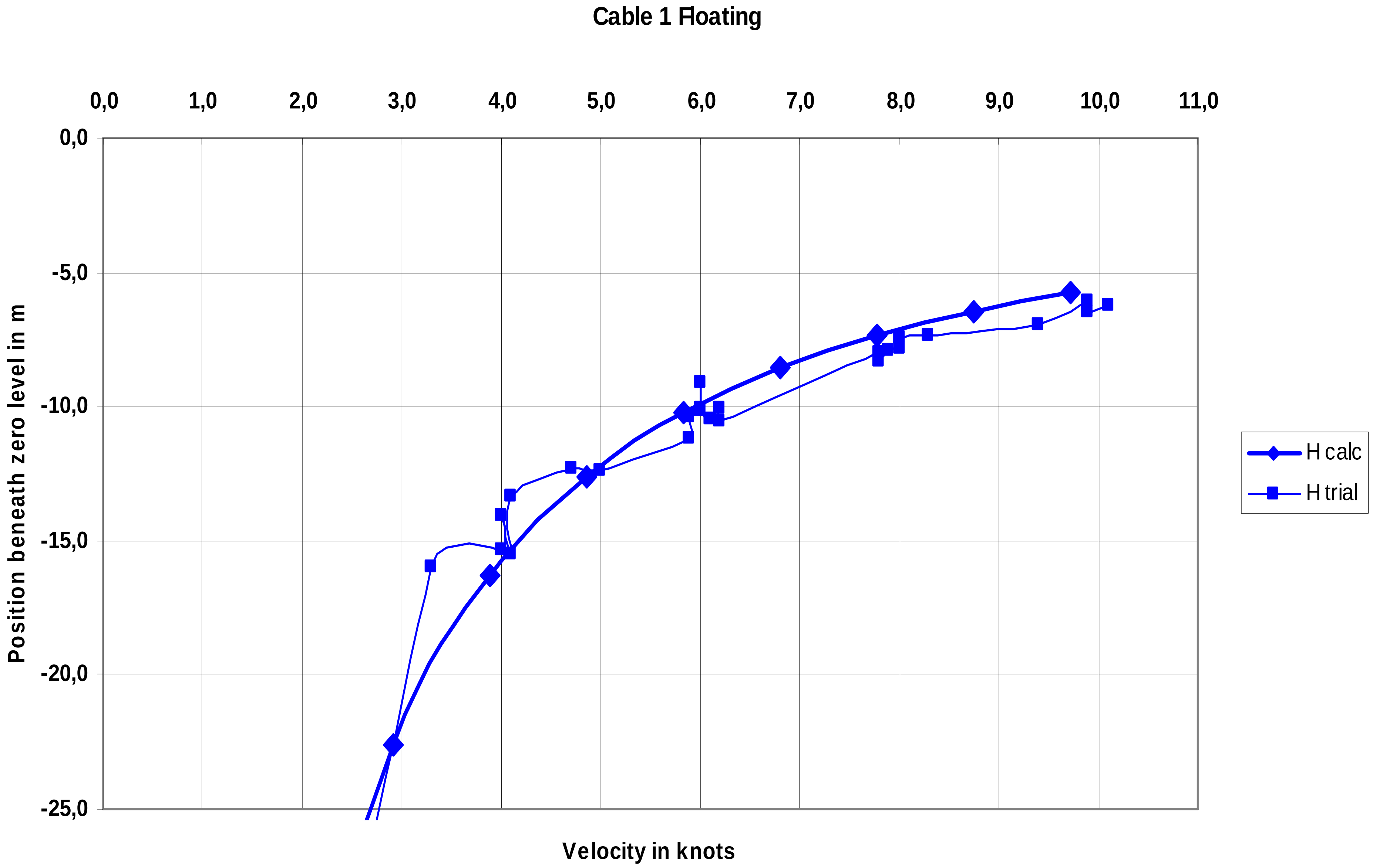
Sleephopperzuiger 2000m³ weken 47-48 1997 8494 sample


Pump - and resistance curves
500,00
450,00
400,00
350,00
300,00
250,00
200,00
150,00
100,00
50,00
0,00
pressure
0
1
2
3
4
5
6
mixture velocity in m/s
y = 92,975x
pump curve
fluid mud resistance curve
consolidated mud resistance curve
fluidization pressure
Lineair (fluidization pressure)

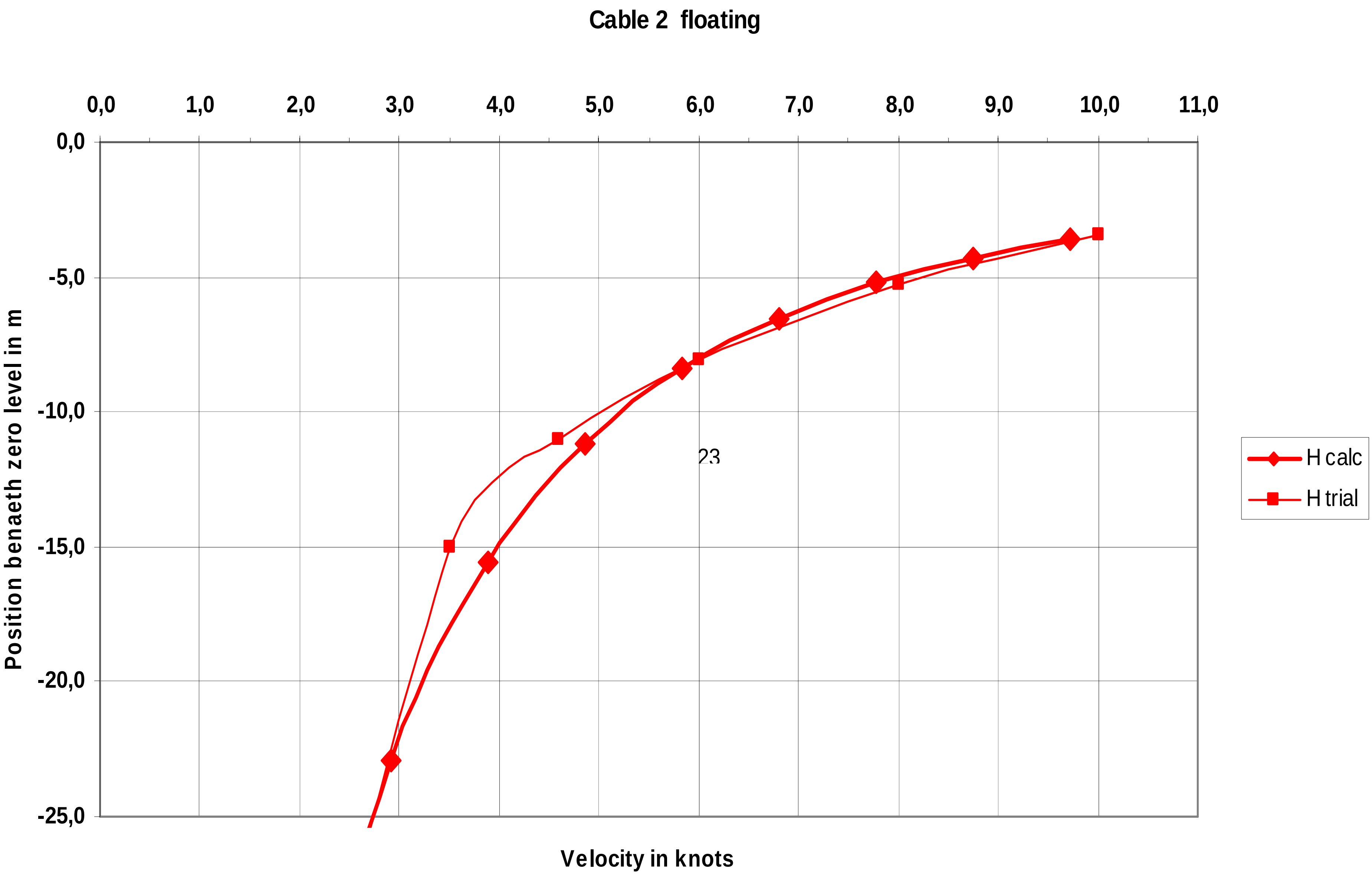

A
umbilical cable
cable weight
pressure sensor
B
seabed
fluid mud
solid mud
resistivity cable
electrodes



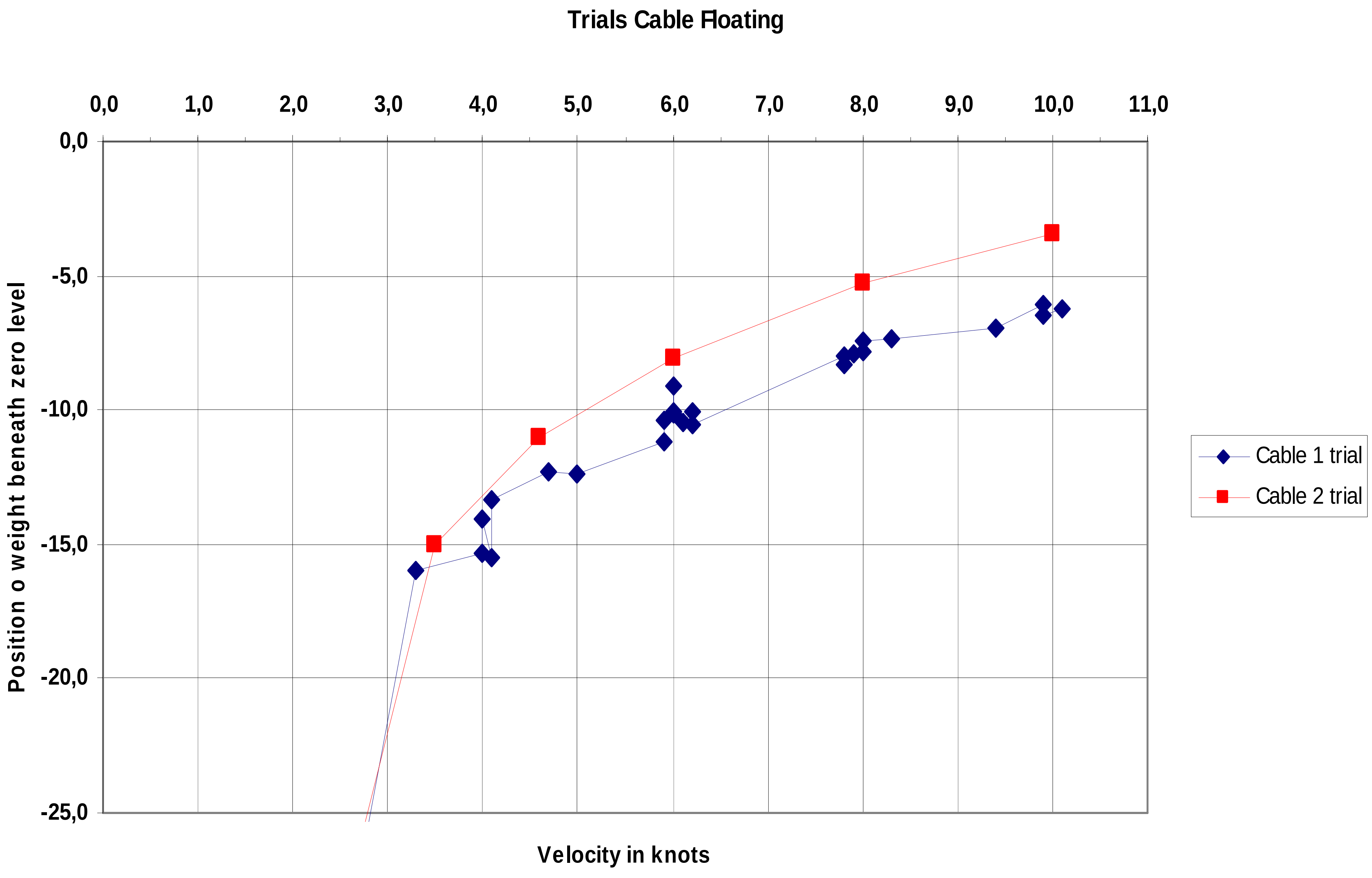
V i
d
F
H i
V
α
q.l
l
k.V 2
H i-1
V i-1
THV Nautic
07/09/2009



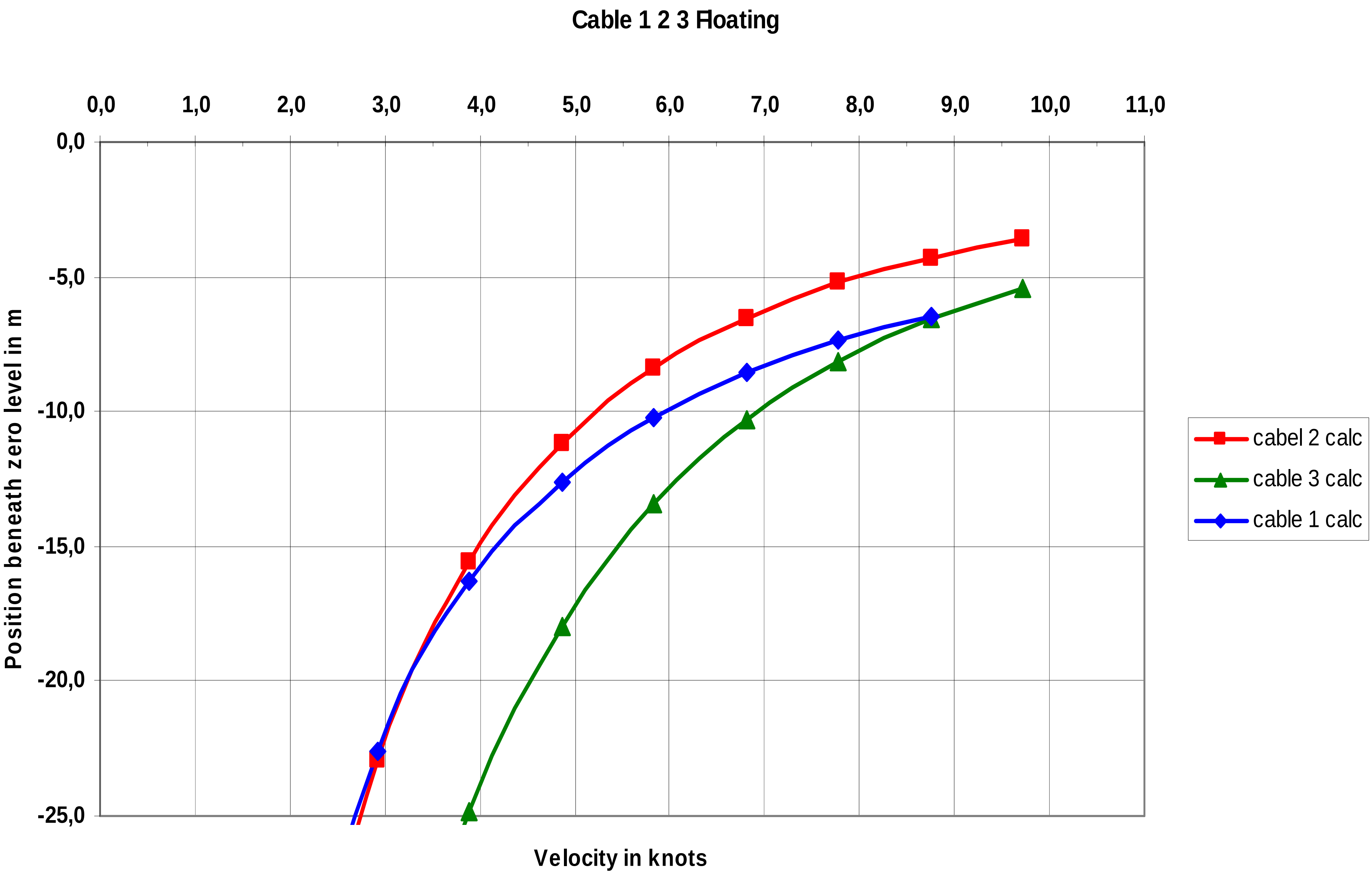
Cable 1 Floating
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position beneath zero level in m
Velocity in knots
H calc
H trial

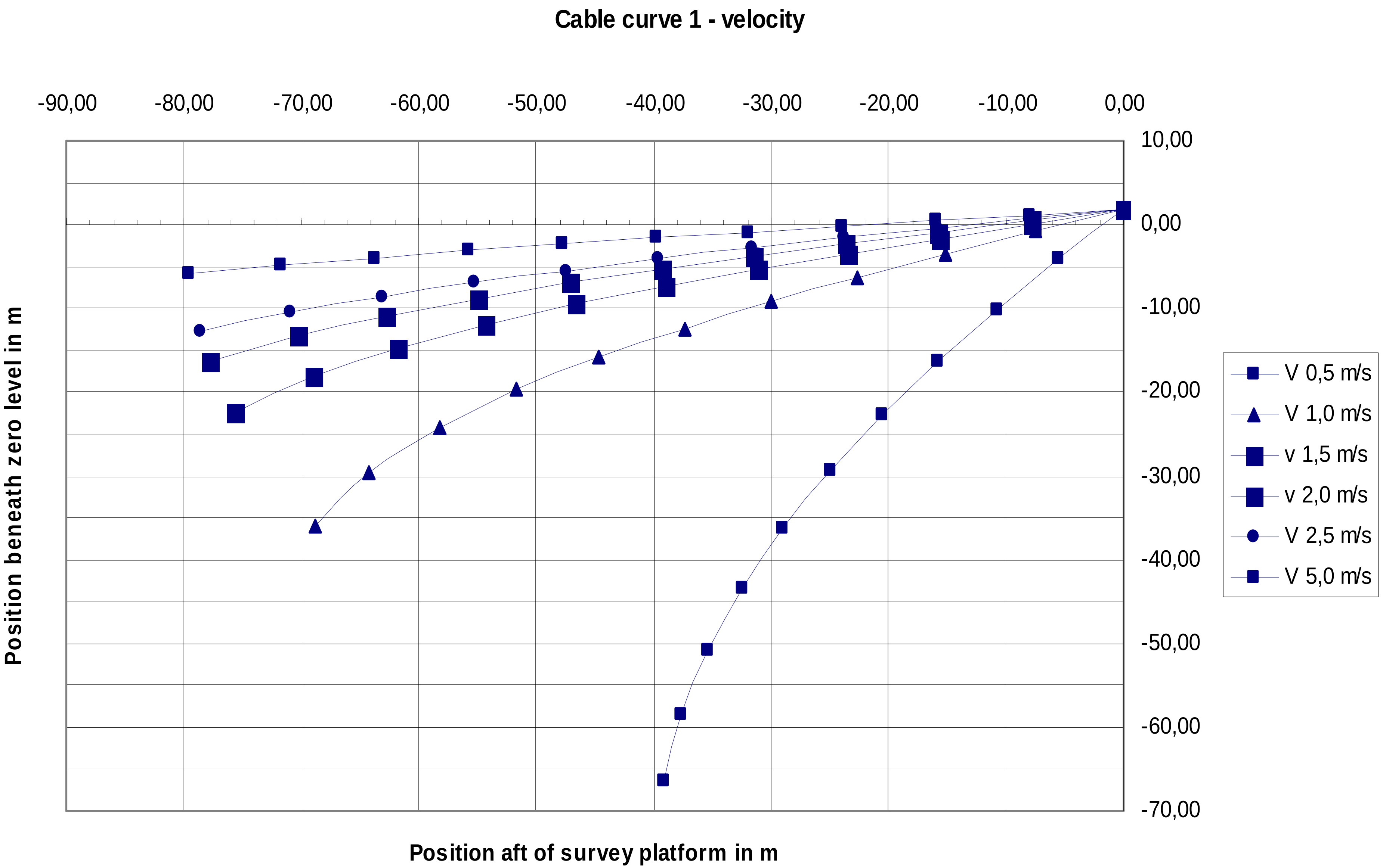


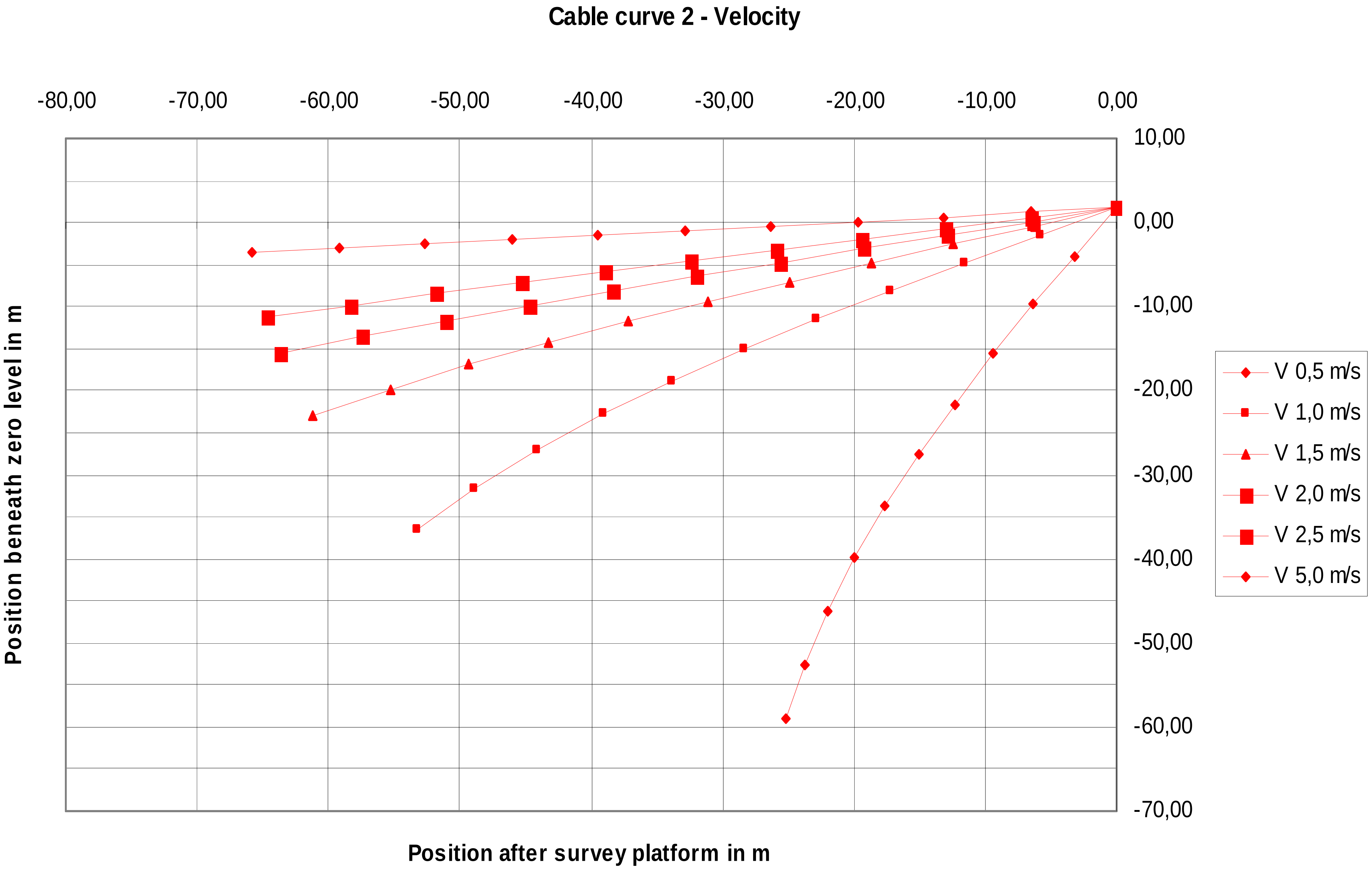
Cable 2 floating
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position benaeth zero level in m
23
Velocity in knots
H calc
H trial

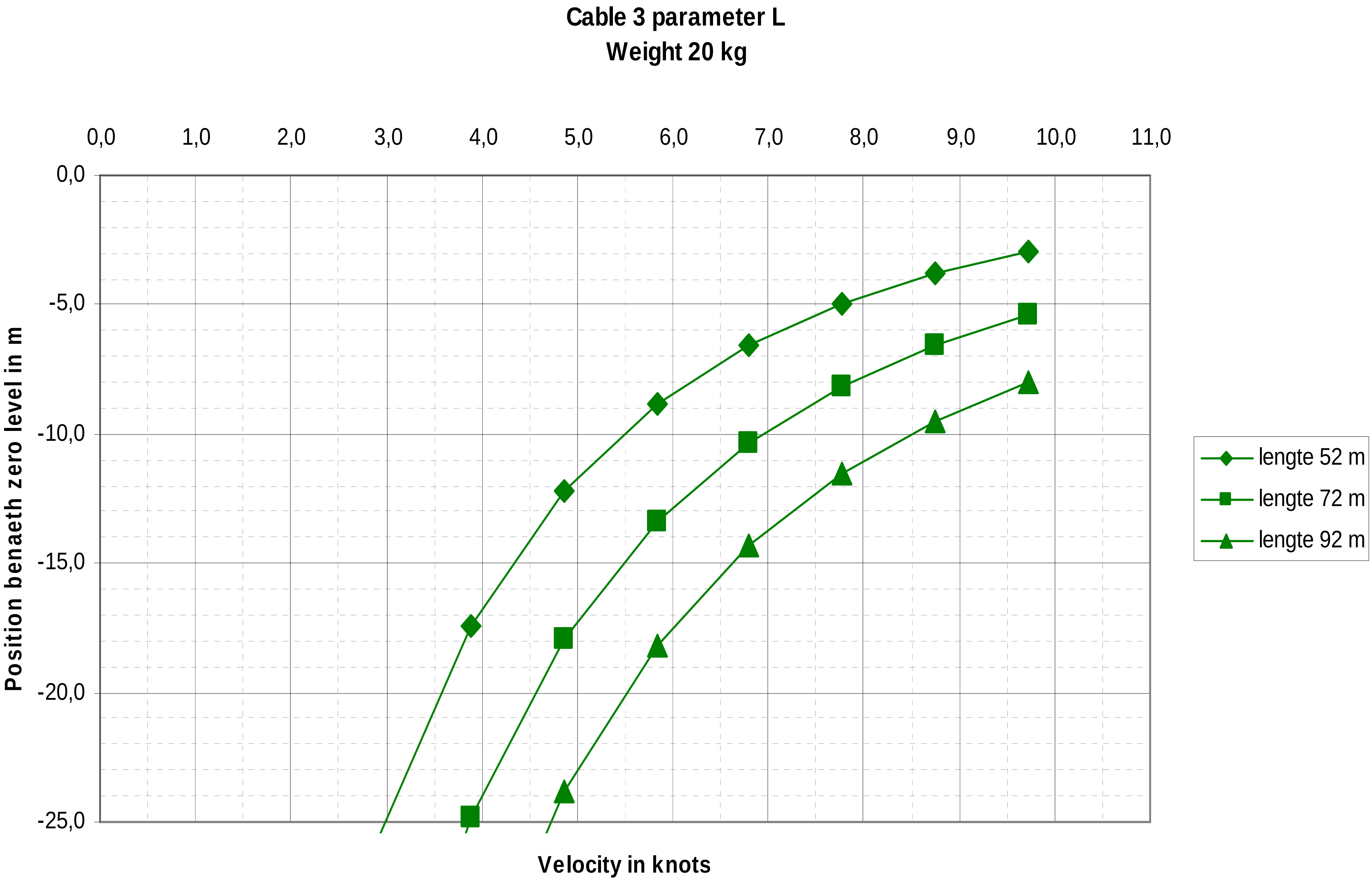


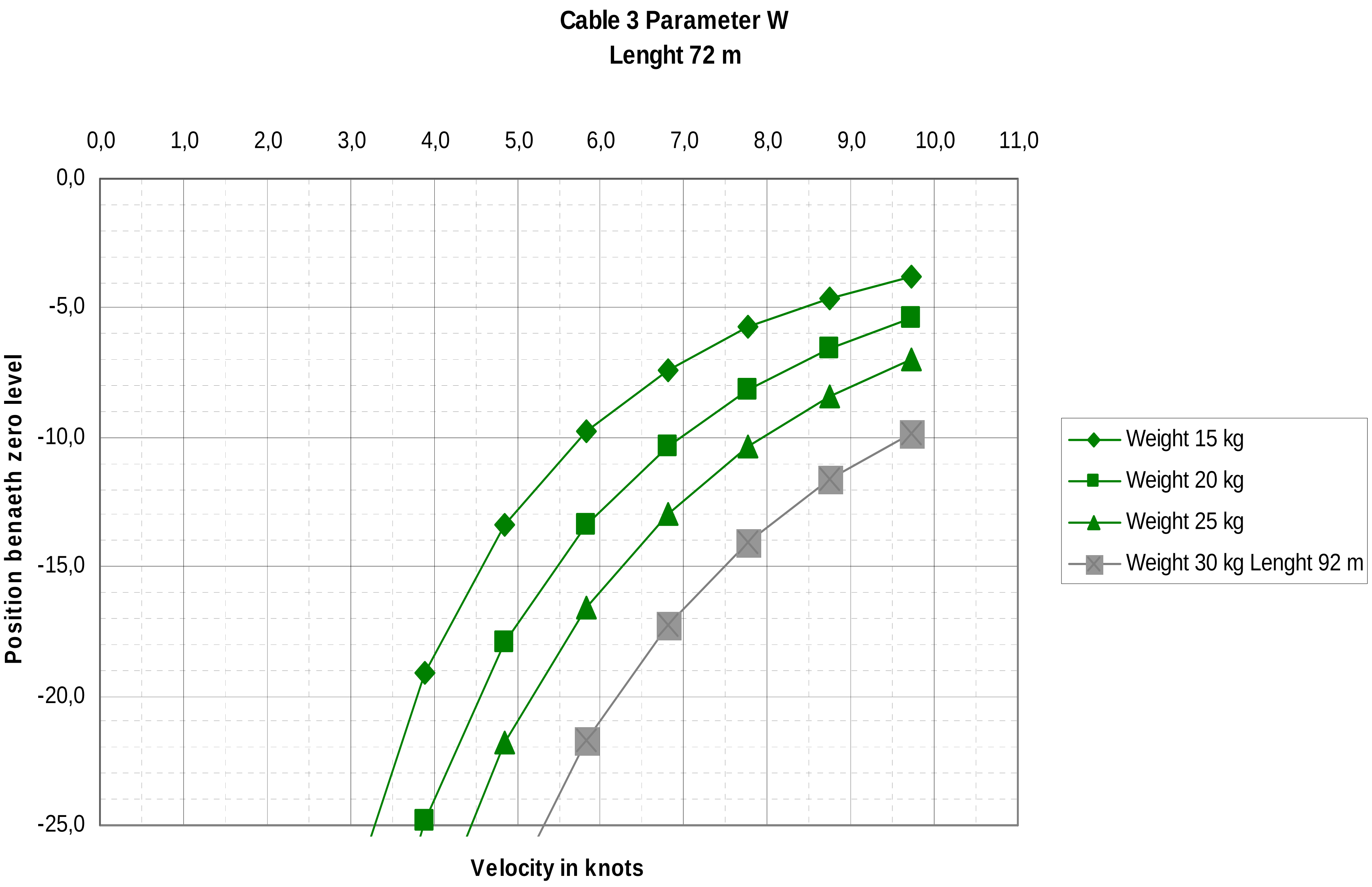
Trials Cable Floating
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position o weight beneath zero level
Velocity in knots
Cable 1 trial
Cable 2 trial


Cable 1 2 3 Floating
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position beneath zero level in m
Velocity in knots
cabel 2 calc
cable 3 calc
cable 1 calc

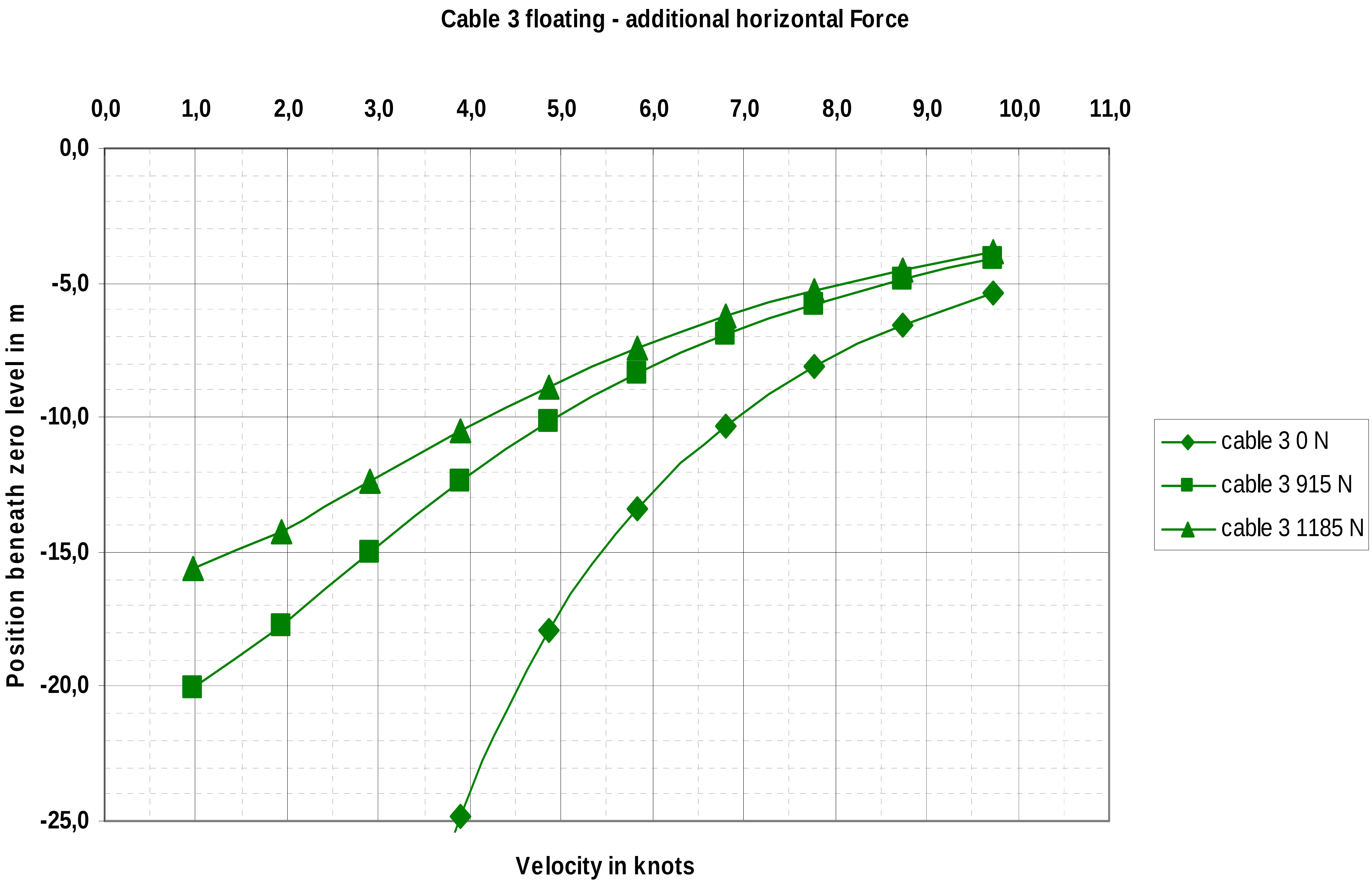

Cable curve 1 - velocity
-90,00
-80,00
-70,00
-60,00
-50,00
-40,00
-30,00
-20,00
-10,00
0,00
10,00
0,00
-10,00
-20,00
-30,00
-40,00
-50,00
-60,00
-70,00
Position beneath zero level in m
Position aft of survey platform in m
V 0,5 m/s
V 1,0 m/s
v 1,5 m/s
v 2,0 m/s
V 2,5 m/s
V 5,0 m/s


Cable curve 2 - Velocity
-80,00
-70,00
-60,00
-50,00
-40,00
-30,00
-20,00
-10,00
0,00
10,00
0,00
-10,00
-20,00
-30,00
-40,00
-50,00
-60,00
-70,00
Position beneath zero level in m
Position after survey platform in m
V 0,5 m/s
V 1,0 m/s
V 1,5 m/s
V 2,0 m/s
V 2,5 m/s
V 5,0 m/s


Cable 3 parameter L
Weight 20 kg
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position benaeth zero level in m
Velocity in knots
lengte 52 m
lengte 72 m
lengte 92 m



Cable 3 Parameter W
Lenght 72 m
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position benaeth zero level
Velocity in knots
Weight 15 kg
Weight 20 kg
Weight 25 kg
Weight 30 kg Lenght 92 m



Cable 3 floating - additional horizontal Force
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
Position beneath zero level in m
Velocity in knots
cable 3 0 N
cable 3 915 N
cable 3 1185 N