Nautical Bottom

Rheological Behaviour Transition

Presentation of Rheocable sounding

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About the authors

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Later, from 1991 through 2001, he led the dredging operations on the Belgian coast in the function of Executive Director of the TV (temporary company) Noordzee & Kust. This TV is still performing dredging operations on the Belgian coast to this day.

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They founded THV Nautic as a partnership, to give a home to their combined activities related to sounding the Nautical Bottom.
Abstract

In 1986 and 1989, life-size tests, performed with the TSHD (trailing suction hopper dredger) ‘Vlaanderen 18’, have shown that the Nautical Bottom, as defined by the PIANC, conforms to the Rheological Behaviour Transition in the mud.

It is common knowledge that the acoustic sounding methods – usually using the 210 kHz and 33 kHz signals – are unable to detect the Nautical Bottom.

Other sounding methods use mud density or additionally viscosity to define the Nautical Bottom. Both of these parameters are, however, problematic for this purpose.

The proposed new contact methods are based on the fact that any object that is dragged along in an environment consisting of a top layer with low viscosity and a bottom layer with high viscosity, will inevitably position itself on the border of these two layers.

The sufficient and necessary prerequisite for this is that the dragging speed falls between a certain minimum and maximum speed, the so-called speed window. The depth of the cable contacting the consolidating mud will then equal the Rheological Behaviour Transition, i.e. the Nautical Bottom.

If the high-viscosity mud displays high resistivity and the liquid mud a low resistivity, this property can be used to confirm the Nautical Depth sounding and to record and monitor it unequivocally.

In October 2008, test soundings were performed in Zeebrugge. These have shown that the new method is not only practically executable, but also gives extremely interesting results. The results have been validated by the experts of the Vlaamse Hydrografie.

The tests were performed with support and co-operation of the Vlaamse Hydrografie, Afdeling Maritieme Dienstverlening en Kust, and IWT, the Institute for the Promotion of Innovation by Science and Technology in Flanders.
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1. The concerned parties

The entire story starts with this image: Figure 2.

The soundings using 210 kHz and 33 kHz can, but not necessarily have to be, significantly different.

Where they agree, there is no issue. Where they differ, there is an issue, because which of the two depths should then be given to the captain of a ship if he asks how much water there is? He wants to be able to ferry his boat safely. Where between these two values is the 'Nautical Bottom'?

Two important parties already make themselves known here:

- Captains, pilots, ship-owners: they expect safety and economical operations (not using too many towboats, not waiting for favourable tides, ...)

- Harbour authorities, hydrographical survey vessel services: they decide what the definition and therefore depth is of the 'nautical bottom'. They serve the same interests and responsibilities: safety and economy.

Then, there is a third concerned party:

- The dredgers.

  Depending on the definition of the Nautical Bottom, they will have to dredge more or less, with either more or less productivity and efficiency. They need to make sure the construction depth is available at all times.

Our new sounding method fits in a development where these three parties – the Management, the pilots and the dredgers – play an important part, ever since the seventies.
2. Development history

2.1 Zeebrugge

It is also a story about Zeebrugge: Figure 3.

In Zeebrugge, these three concerned parties have worked together since 1980 – the start of the expansion of the Zeebrugge harbour – in a quasi-continuous way to try and get this problem under control. This continues to this day.

Both in the field of the daily tasks of soundings, dredging programmes, co-ordination and meetings, and in the field of research.

Zeebrugge has been confronted in a very early stage with the issue of deep-lying ships (tankers up to the seventies, 55' ships since 1986) and the presence of mud.

The sounding in Figure 2 has been run along the beacon line from the outside to the inside, and clearly shows the erosion well in front of the entrance, the (sand) bank, and the start of the mud area in the CDNB.

At first – in the seventies – it was attempted to secure the location of the sounding 210 kHz by using large TSHD’s (trailing suction hopper dredgers) to dredge up large amounts of mud: see, for example, TSHD ‘Vlaanderen 18’, Figure 4.

Up to 1994, this ship has been the largest of its kind in the global dredging fleet. The proportion between loading capacity and hopper volume was 1.44, which is very low, to be able to dredge large volumes of low density mud.

In 1980, people realised that this is not a solution to the problem: The 210 kHz level could hardly be controlled. For example, after periods of stormy weather, the soundings would shallow out by 2 metres or more.

When constructing the harbour, it was also noted that the soundings with 33 kHz were much more stable: this way it was possible to monitor the dredging progress, which had proven to be impossible with soundings using 210 kHz. Indeed, the 33 kHz soundings were deeper, sometimes several metres deeper, and could the risk be taken in that case that this sounding really was the solid bottom, considered the nautical bottom?
2.2 Two types of mud

Observations while dredging also taught us that there are two types of mud: Figure 5

- mud with a density of 1.15, that was (easily) dredged with a mix speed of 4 to 5 m/s
  
  This mud clearly originated in the upper layers of the mud field, and was practically labelled 'black water'. The suspicion existed that this was navigable.

- mud with the same density or slightly higher, that was dredged (with difficulty) with a mix speed of only 1 to 2 m/s.
  
  This mud originated from the lower layers of the mud field, and was clearly not navigable, or only with extreme difficulty.

Something was going on with the mud's viscosity, and the suspicion was raised that the density also played a part here.

A nice illustration of this are the density and mix speed histograms that were created using recorded dredging parameters in a certain zone of the Outport of Zeebrugge, over a period of two weeks in 1997.

While the density provides an unambiguous profile of the 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 and a consolidating state at the same density.

(On top of that, something else was going on: this mud often contained gas pockets, making it even harder to dredge.

It is no coincidence that around this time - 1980/1985 - the degassing installation was invented to make the dredging process run continuously and in a stable way.)

It was decided at that time to develop and execute a research programme to chart these problems.

This programme contained several different parts:
2.3 *Viscosity and density: measurements*

The Navitracker was developed: Figure 8. This allowed to chart any desired density horizon in a mud layer, albeit only in the liquid portion.

It was also possible to measure vertical density profiles by using the Navitracker as a local probe.

At a later point in time, specific local probes were built: Figure 9.

This is the period 1985 - 1990.

In 1987 already, a local probe was built by the company Haecon (later absorbed by the Soresma group) that allowed measuring of viscosity profiles: Figure 10.

A great many measurements were performed in that period of time, but always with the same result:

- the viscosity profiles all had one common feature: at a certain depth, the viscosity - which factually is the initial rigidity - suddenly jumps to much higher values: Figures 11 and 12.

  This confirmed the observation while dredging that there are two kinds of mud, and led to the conclusion that liquid mud becomes a 'gel' at a certain density: it gains structure, the grains start touching each other and grain tension is introduced.

  This transition is called the 'Rheological Behaviour Transition' of the mud, and the suspicion was raised that this could be the actual Nautical Bottom.

- A second observation was that this Rheological Behaviour Transition was not linked to a fixed density.

  Laboratory tests found that the viscosity of the mud and the density at which the Rheological Behaviour Transition occurs, depend very strongly on the sand content of the mud. The more sand is mixed into the mud, the higher the density at which the Rheological Behaviour Transition occurs: Figure 13.
2.4 Life-size measurements

To test the hypothesis that the Rheological Behaviour transition actually is the Nautical Bottom, and to determine whether the presence of a liquid mud layer influences a ship's behaviour, it was decided to perform a life-size experiment.

Test trips were organised with the TSHD 'Vlaanderen 18' in the harbour of Zeebrugge: a manoeuvre was repeated several times with different keel clearances. This is the period 1985 - 1990.

For example, using a turning manoeuvre with a stationary ship - only using the bow thruster - it turned out to take three times as much time to make a 360° turn when there was no room below the keel with the 210 kHz horizon, compared to the same manoeuvre in deep water.

It was also found that the liquid mud is definitely navigable.

One test is especially important.

At a certain point in time, the ship was ferried with the keel at the depth of the Rheological Behaviour Transition, this is with the keel touching the solid mud. Several pilots were aboard, the harbour master of Zeebrugge, representatives of the Board....

And it turned out that the ship could no longer be controlled!

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 halted itself, 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 Bottom, as formulated by the International Navigation Association PIANC:

Quote:

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

Unquote

It very soon becomes clear that the Rheological Behaviour Transition is the Nautical Bottom.
The results of these life-size tests were also used to calibrate the laboratory tests that were to be performed afterwards in the Waterbouwkundig Laboratorium in Borgeresistivity ut near Antwerp. It should also be noted here that the academic world was also involved in this research.

### 2.5 Model experiments

These model experiments and their successors running to the present day, are a story all its own.

Right now, the WLB has access to a large towing tank in which thousands of towing tests over artificial mud have been performed and are still being performed.

The recorded results are converted to mathematical algorithms which are used in the two simulators present in the laboratory.

From the very start, pilots were consulted to compare the results with those from real life. They are also used now to train pilots, to evaluate the construction of new situations, and to practice certain manoeuvres: see, for example, entering and exiting the new Deurganckdok.

By now, pilots have gained great confidence in this way of working.

Since several months, a mud testing tank has also become operational, in which all kinds of measurements can be done in laboratory controlled conditions. E.g. a project is running right now comparing several different kinds of measuring methods.

In the meantime, the dredgers have not been sitting down either, and next to the already mentioned degassing installations, a new method was developed to measure weight of the dry mass (in tonnes) in the hopper directly: the Hopper Well Densimeter system. In addition, a dredging machine was also developed to dredge mud and systems to visualise information retrieved based on the dredging process parameters.
2.6 Nautical Bottom definition

To be able to sound the Rheological Behaviour Transition (= nautical bottom), one should therefore be able to chart the viscosity of the mud mass.

Apart from the fact that only local probes were available, viscosity is a very complex parameter when talking about mud, because of:

- the thixotropy: at a constant sliding tension, the viscosity of the mud changes over time.
- the viscosity also changes with the deformation speed: Bingham fluid, hysteresis effects...
- the mud's viscosity being very sensitive to the sand content of the mud
- the sand content in a harbour differs over time and per location

Because of the fact that the density in the liquid mud can be measured much more easy than its viscosity, density soundings are more commonly used than viscosity sounding to define the Nautical Bottom. However, one needs to record then which density is considered to be the nautical bottom.

In Zeebrugge, this was solved by gathering density and viscosity profiles at predetermined locations, properly spread out throughout the harbour, and recording the density position with regard to the Rheological Behaviour Transition.

It was found that the density at the Rheological Behaviour Transition was never less than 1.15: Figure 14 shows the histogram of the depth difference between the Rheological Behaviour transition and the 1.15 density horizon.

Hence the definition of the density horizon of 1.15 as the nautical bottom: with one or two exceptions, the 1.15 density horizon is always positioned higher than the Rheological Behaviour Transition and thus safe.

Using this method it is not illogical to find different values for this density horizon in different harbours: Figure 15.

Even though this method has led to satisfying results in Zeebrugge in terms of safety, some problems still occasionally occur regarding the manoeuvring behaviour of deep-lying ships, and it is suspected that there is considerable room to improve the efficiency of the dredging operations.

Our new sounding method has the pretence to directly measure the Rheological Behaviour Transition in a correct, accurate and unambiguous way, and thereby contribute to more security, safety, and more cost effective dredging.
3. Rheocable sounding

3.1 The measurement principle

The principle is very simple Figure 16.

We consider a low-viscosity medium - the liquid mud - and a high-viscosity medium - consolidating mud.

With consolidating mud, the 'gel' is meant that has been formed by exceeding the limit for the Rheological Behaviour Transition, and is further subject to the process of consolidation, and no longer to settling.

If one would drag a random object with the same speed, this object would take a low position in a low-viscosity medium - low resistance - and a high position in a high-viscosity medium - high resistance.

Assume now that, between both positions, a divider is installed: the Rheological Behaviour Transition. Above this divider, the mud is liquid, below it, the mud is consolidating. This is analogue to the real-life situation.

Assuming the dragging speed lies between a minimum and maximum speed, inside a speed window, this object will inevitably position itself on the dividing line. The object will start 'surfing' on top of the consolidating mud.

Indeed, assume a high dragging speed where the object will be above the dividing line in the low-viscosity medium. When the speed drops, the position will lower. The moment it reaches the height of the dividing line - equal to the maximum speed of the previously mentioned speed window - its position will no longer be able to lower further, because that would put it in the consolidating mud and inevitably assume a position higher because of the higher viscosity and higher resistance.

This, in turn isn't possible, so the object will, with certainty, position itself on the border, at the Rheological Behaviour Transition.

It will now suffice to measure the depth of the object of choice, to determine the Rheological Behaviour transition and therefore the Nautical Depth.
3.2 Resistivity: the watchdog

The simplest object to drag would be a cable.

From long-time experience dragging cables on the seabed for the purpose of resistivity surveys, it is known that resistivity measurements can also be used as a watchdog, verifying whether the cable is touching the seabed or not.

The resistivity of consolidating mud is significantly higher than the resistivity of liquid mud or water. The resistivity measurement, even though largely simplified, may serve to ensure that the cable is touching the consolidating mud and will not (start to) float when the dragging speed is too high.

Therefore, the measuring arrangement for the Rheological Behaviour Transition will be as follows: Figure 17.

- An umbilical cable connects an on-board power source of the hydrographical survey vessel with electrodes that are built into the tip of the cable
- Two current electrodes and two potential electrodes are fitted
- A weight will make sure the tip of the cable, the resistivity part of the cable, remains on the ground. The depth gauge is located near this weight.

Every time the cable starts floating and separates from the consolidating mud, the resistivity will jump to a lower value, providing a perfect signal to potentially reject the measured depth values.
3.3 Practical implementation

The included Figures 19, 20, 22, 21, and 22 provide an indication how things are done in practice.

In principle, any vessel can be used - sometimes measurements are even taken with a rowing boat - but most obvious is the use of a 'normal' hydrographical survey vessel as platform.

For the test soundings performed at the start of October in 2008, in Zeebrugge, the hydrographical survey vessel Geosurveyor II of the company Geoxyz was used. You can see the cable lying on deck already.

Previously, the cable was built up onto the quay at the old fish mine in Zeebrugge. Rule of thumb is that the length of the cable is about 3 times the depth to be measured.

On board you can also see the DC generator and the required laptops (2 of them).

The last photograph gives an impression of the cable being operational during towing: everything is calm and no issues.
4. Rheocable test-sounding

4.1 Discontinuous resistivity

The experiment was performed in co-operation with the Dienst der Vlaamse Hydrografie and support of the IWT. Its initial goal was to determine the speed window discussed earlier by means of experimentation, and also to confirm the hypothesis of a discontinuous change in resistivity.

A suitable location in the Albert II dock in Zeebrugge was chosen: Figure 23.

The experiment consisted of sailing along a single line of direction at different speeds, to determine when the cable would start to float, and what effect this would have on the resistivity measured.

Graph 1 - Figure 24 - graphically plots the measured and registered resistivity values during the experiment in measured sequence (run sequence plot). A clear discontinuity is found in measured values of resistivity: see measurements between Nos. 240 and 305.

This discontinuity is clarified even more when we order the measured values for resistivity by value: see graph 2, Figure 25.

The graph shows a collection of measured values with low resistivities, a very limited transition area, and a collection of measured values with high resistivity.

The low resistivity values are around 0.256/0.260, and are equivalent to the resistivity of sea water.

The high resistivity values are measured when the cable touches mud of which the resistivity is clearly higher compared to the resistivity of sea water.

There is only a very limited area of transition between these low resistivity and high resistivity collections.

Therefore, by experiment, a very clear discontinuity is found in the resistivity values measured. It is also very much possible to order each individual measured value as being part of one of the three observed collections: low resistivity, high resistivity and transition.

Full transparency is therefore possible for the creation of maps: depths measured where the resistivity belongs to the low category or transition area are simply excluded.
4.2 Speed window

That there is a connection between resistivity and speed is shown when we compare graph 3 - Figure 26 - to graph 1.

Graph 3 displays the ground speed, also represented graphically in sequence of measurements.

The link between the measured values for resistivity and the speed is clear. Measurements between Nos. 240 and 305 are done with a (high) speed where the cable started to float, causing a sudden drop in resistivity.

The connection that is found here is that, if the cable starts to float at a certain speed, the resistivity drops to that of sea water with an extremely brief transition.

Therefore, the resistivity indeed, as presumed, monitors the state of the cable: dragging or floating.

At what speed does the cable start to float, then?

Initial calculations have shown that the speed window would be between 2 and 5 knots, and the question was clearly answered with the following experiment.

A high sailing speed, where the cable floats, was held at several levels for a brief moment, and at the same time, the cable's measurement point position was recorded.

The result of this exercise is recorded in graph 4, Figure 27.

The results achieved fit \( R^2 = 0.97 \) a squared function of the position, where the sailing speed is the independent variable.

From this graph, the speed at which the cable comes into contact with the bottom, when the speed drops, can be read as a function of the available depth.

Experience teaches us that the cable connecting to the consolidating mud, the dragging, occurs at a speed lower than that causing the cable to come free and starting to float.

Why this is the case is currently investigated through modelling and computer simulations.

Experiences gained from the test soundings taught us that a maximum speed of only 3.0 to 3.5 knots could be used when sounding in Zeebrugge, at construction depths of -15.5 m with tide differences of up to 4.5 m.
This speed was considered to be too slow. Calibration and refinement of the calculation model show that the speed can mainly be increased by choosing a cable with a smaller diameter. Such a cable is therefore frantically searched for.

To compare, graph no. 5 – Figure 28 - shows the same exercise as graph no. 4, but this time for the registered depths with high values for resistivity, meaning where the cable is in contact with the consolidating mud. The measurement point position is plotted against the towing speed.

There is obviously no connection anymore here: the measurement point's position is determined completely independently, by a different parameter than the speed, as opposed to graph no. 4.
4.3 Sounding maps – Difference maps

Following, a complete sounding was performed of the following zones in the harbour of Zeebrugge:

- Central Part of the New Outer Port (CDNB)
- The Albert 2 – dock (A2 – dok)
- The Zwaaiplaats 1 (ZP1)

The final result of the sounding and processing of the data is shown on sounding map no. 1, Edited Depth R.B.T. (Rheological Behaviour Transition): Figure 29.

It is shown that at the moment of sounding, the largest part of the zones CDNB and ZP1 have a Rheological Behaviour Transition shallower than the construction depth of -15.5m.

The sounding map displays normal internal logic, and the position of the R.B.T. test sounding compared to other soundings is as follows:

4.3.1 33 kHz

The acoustic sounding at a frequency of 33 kHz was done by the company Geoxyz, executed simultaneously with the R.B.T. test soundings and made available to us by the Management.

Sounding map no. 2, Difference in Depth R.B.T. - 33 kHz depth, shows the difference map Rheological Behaviour Transition - 33 kHz: Figure 30.

The Rheological Behaviour Transition is clearly shallower than the 33 kHz: more than half a metre shallower in the largest part of the zone, with peaks up to 1.5 m.

(Some locations register the Rheological Behaviour Transition to be deeper than the 33 kHz sounding.

For example at the NE corner of ZP1, it wasn't 100% sure that the cable was trailing in a straight line behind the hydrographical survey vessel: due to 180° turns of the barge at the end of the line of direction, and/or due to the presence of a steep bank. In both cases, a small diversion of the cable compared to the line of sailing results in a large difference in depth.

This phenomenon - cable diverted from the line of direction sailed - needs further investigation.)
4.3.2 210 kHz

The acoustic sounding at a frequency of 210 kHz was also done by the company Geoxyz, executed simultaneously with the R.B.T. test soundings and made available to us by the Management.

Sounding map no. 3. Difference in Depth R.B.T. - 210 kHz depth, shows the difference map Rheological Behaviour Transition - 210 kHz: Figure 31.

The difference is 1.5 m and more in practically every zone.

(Where the differences are small or even negative, the same remark is true as is made for the differences with 33 kHz, including the recommendation to further investigate this.)

4.3.3 Nautical Bottom

These days, for Zeebrugge, a density horizon of 1.2 is defined as the Nautical Bottom in muddy areas.

This horizon is determined by performing local probe measurements. (The Navitracker is less suited to perform these measurements, because it threatens to run aground in the consolidating mud).

These measurements are done in a number of specified locations of the harbour docks, and these locations are always the same and retained for each sounding.

Sounding map no. 4, Difference R.B.T. - Nautical Bottom shows this difference between the Rheological Behaviour Transition and the Nautical Bottom: Figure 32.

In the ZP1, the Nautical Bottom is unequivocally deeper than the Rheological Behaviour Transition: the difference, at first sight, is around 1 metre.

In the CDNB, the difference is less unequivocal. In the Eastern half, the Rheological Behaviour Transition leans towards being lower than the Nautical Bottom, in the Western half, the opposite is seen: there, the Nautical Bottom is below the Rheological Behaviour Transition.

This trend – the Nautical Bottom being lower than the Rheological Behaviour Transition – still seems to be predominant in the CDNB as well, at first sight.

The conclusion is that, in general, the Nautical Bottom is lower than the Rheological Behaviour Transition, and that the difference is larger in the ZP1 than in the CDNB.
If one charts the resistivity values - see Sounding map no. 5, Resistivity values, Figure 33 – you will notice grouping of the values: the resistivity values are also gathered in spots.

When this map is compared to Sounding map no. 1, Edited Depth R.B.T. a clear indication of a potential parallel between resistivity values and the depths sounded can be noticed.

High resistivity values equate to large depths for the R.B.T.

Assuming the top surface of the mud is about -13.50 m everywhere, a possible explanation for this phenomenon could be that the resistivity is also influenced by the thickness of the liquid mud layer. The thicker the liquid mud layer, the higher the measured resistivity.

Because, indeed, apart from the consolidating mud layer, the cable, at the dividing surface, is also exposed to the liquid mud layer above it.

This is a potential area of further investigation: will the thickness of the liquid mud layer be measurable through resistivity?
4.4 The statistical approach

Sounding maps are the first and most important form of results. However, a statistical approach certainly complements insights.

Indeed, all of the soundings discussed in this article generate large amounts of data, and it is then almost preset to also use the statistical method when analysing this data.

The (relative) frequency distributions and the cumulative frequency distributions allow us to compare the different soundings to each other.

4.4.1 ZP1

Graph 7 - Figure 34 - shows us the frequency distributions of some of the soundings in zone ZP1: the Rheological Behaviour Transition, the Nautical Bottom (density horizon 1.2) and the acoustic sounding done with 33 kHz.

The three distributions mainly look like the normal distribution model: bell curve shaped and symmetrically grouped around an average. Additionally, the spread of the distributions is comparable between them.

These distributions therefore give us a proper image of the sounding positions.

The average position is 15.50 m for the Rheological Behaviour Transition, 16.00 m for the Nautical Bottom and 16.50 m for the 33 kHz sounding.

To keep things clear, the sounding with 210 kHz was not included in graph 7. 90% of the recorded values are between 13.00 m and 14.00 m. The average depth for the sounding with 210 kHz is 13.50 m, three metres shallower than the 33 kHz sounding.

Diverting from the 'normal', the percentages of 8 to 17% are values shallower than 13.50 m.

As can be seen on the maps in question, the shallows are mainly found at the edges of the zone.

The cumulative frequency distributions - Figure 35 - mainly take the shape of classical S-curves, as seen in normal distributions: see graph 8. The deviation here is, of course, also found at shallower values.

These distributions provide an important additional piece of information.
According to the S-curve of the Nautical Bottom (density horizon 1.2), 44% of the recorded depths have a value of less than 15.50 m, and 56% of the depths meet the Nautical Bottom criterion.

The S-curve of the Rheological Behaviour Transition, however, shows us much different values: 77% is too shallow, and only 23% is deep enough.

For the 33 kHz sounding, the values are: 21% too shallow, 79% deep enough.

This result underlines the importance of choosing the right criterion for the Nautical Bottom.

In addition, the frequency distributions resulting from the Rheological Behaviour Transition, are very similarly shaped to the frequency distributions of other soundings. The new sounding method, using resistivity measurements, therefore gives us as robust and reproducible results as classic sounding methods.

### 4.4.2 CDNB

Graph 9 shows us the same distributions as in zone ZP1, although with some differences: Figure 36.

Here, too, the bell-shaped curves can be observed of which the properties were already described in the previous paragraph 3.3.1.

Remark.

An interesting difference is observed in the 33 kHz sounding curve. Next to the main peak at 16.50 m depth, a second peak is found around a depth of 15.50 m.

There is no explanation for this phenomenon at this time. Maybe this indicates a localised problem somewhere in the CDNB - for example a location that still needs to be dredged - or maybe a mechanism in the digitalisation procedure may cause this.

The average position is 15.50 m for the Rheological Behaviour Transition, 15.65 m for the Nautical Bottom and 16.50 m for the 33 kHz sounding.

Here, too, the sounding with 210 kHz was not included in the graph: the average depth for this sounding is 13.1 m.

The cumulative frequency distributions are plotted in graph 10: Figure 37.

According to the S-curve of the Nautical Bottom (density horizon 1.2), 59% of the recorded depths have a value of less than 15.50 m, and 41% of the depths meet the Nautical Bottom criterion.
The S-curve of the Rheological Behaviour Transition also gives us diverting values, but the diversion is not as big as in ZP1: 78% is too shallow, and only 22% is deep enough.

For the 33 kHz sounding, the values are: 33% too shallow, 67% deep enough.

The same conclusions as for zone ZP1 can be drawn here: the importance of the criterion used, and the reproducibility of the new sounding method.
4.5 *Dredging strategy*

Implicitly, the discussion thus far also includes that the dredging strategy is dependent on the sounding method used to define the Nautical Bottom.

This can be illustrated explicitly.

If the Rheological Behaviour Transition is used as the definition for the Nautical Bottom, the situation is the same in both parts of the harbour - CDNB and ZP1: see Graph 11, *Figure 38*.

The dredging activities should be the same for both.

If the 33 kHz sounding is used as Nautical Bottom, then, like when using the Rheological Behaviour Transition, the situation is the same, with the remark that somewhere in the CDNB an area has insufficient depth: *Figure 39*.

If the local probes and 1.2 density are used as standard, a significant difference is found: the CDNB shows the Nautical Bottom to be about 0.4 m shallower than in the ZP1: *Figure 40*. Dredging would be done sooner in CDNB in that case than in the other zone, despite the fact that the situation is equal(ly bad) there.

There will be too much of a delay before dredging in ZP1 is done, meaning deep-lying ships may run into trouble there.
In closing

The method described and tested allows for distinguishing between liquid mud (good mud) and consolidating mud (bad mud) in a direct and transparent manner.

Liquid mud cannot be managed, constantly moves, but is no concern for the safety of ships because of navigability, provided the normal keel clearance is respected.

(Sailing through the mud is also not a problem: in Zeebrugge, this is also linked to the availability of the necessary tow boats and capacity in terms of 'bollard pull': for this, see Vantorre and Delefortrie.)

Liquid mud should therefore not be a point of attention for dredging activities.

Consolidating mud, however, should take the centre stage for dredging activities. The dividing surface between liquid and consolidating mud definitely is the Nautical Bottom as meant by de PIANC definition: consolidating mud needs to be dredged.

Using the right focus in terms of dredging activities - not dredging liquid mud, definitely dredging consolidating mud - dredging can be done much more purposeful, and ultimately more cost-effective, planned (therefore no less productive and profitable) with all the guarantees for safe and smooth sailing of deep-lying ships.

The continuous Rheocable measurements of the THV make such an approach an immediate option.
Rheokabel sounding presentation
Figures

THV Nautic
MDCE bvba – DEMCO nv
Pump - and resistance curves

\[ y = 92.975x \]

- Pump curve
- Fluid mud resistance curve
- Consolidated mud resistance curve
- Fluidization pressure
- Linear (fluidization pressure)
Mixture Density Histogram

**Histogram Densiteit**

Sleephopperzuiger 2000m³  weken 47-48 1997  8494 samples

Decloedt 1997 intern
Mixture Velocity Histogram

Histogram Mengselsnelheid

Sleephopperzuiger 2000m³ weken 47-48 1997 8494 samples

Decloedt 1997 intern
VISKOSITY PROFILES

Taken with the >NAUTISONDE<

Outer Harbour of Emden
Station 5
14.01.1999 and 26.02.1999
Relation

initial rigidity
density
sand content


Haecon 1985
NAUTICAL BOTTOM CONCEPT
SITUATION IN ZEEBRUGGE

selection of characteristic density

✧ Zeebrugge 1.15 t/m³

Rheological transition lower than 1.15 t/m³ horizon
Rheological transition higher than 1.15 t/m³ horizon

Nautical Bottom Workshop – Antwerp, 29 April 2005
**NAUTICAL BOTTOM CONCEPT**

**SITUATION IN ZEEBRUGGE**

<table>
<thead>
<tr>
<th>Location</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeebrugge</td>
<td>1.15 t/m³</td>
</tr>
<tr>
<td>Rotterdam</td>
<td>1.20 t/m³</td>
</tr>
<tr>
<td>Nantes St-Nazaire, Bordeaux</td>
<td>1.20 t/m³</td>
</tr>
<tr>
<td>Cayenne</td>
<td>1.27 t/m³</td>
</tr>
<tr>
<td>Germany</td>
<td>1.18-1.25 t/m³</td>
</tr>
</tbody>
</table>
Chart 1: Tracks 02/10/2008
Correlation towing speed – cable floating
Rheological Transition Sounding Test

Rho mounting sequence plot

Discontinuity

TV Nautic

In cooperation with IWT and department of Flemish Hydrografa - Section Coast
Rheological Transition Sounding Test

Cable trailing

$R^2 = 0.0504$

Depths

Polynoom (Depths)

TV Nautx

In cooperation with IWT and the department of Flemish Hydrography - Section Coast
Sounding map nr. 1: edited depth R.B.T.
Sounding map nr. 2. Difference R.B.T. - 33 kHz
Sounding map nr. 3. Difference R.B.T. – 210 kHz
Sounding map nr. 4. Difference R.B.T. – Nautical Bottom (density local probes)
Sounding map nr. 5. Resistivity values
Rheological Transition Sounding Test

Rheological Transition Depth, frequency distributions in ZP1 area

- ZP1 R.T.
- ZP1 33
- ZP1 1.2

TV Nautic

In cooperation with IWT and the department of Flemish Hydrography - section Coast
Rheological Transition Sounding Test

Rheological Transition Depth, cumulative distributions in ZP1 area

In cooperation with IWT and the department of Flemish Hydrography - Section Coast
Rheological Transition Sounding Test

Rheological Transition Depth, cumulative distributions in CDNB area

TV Nasac

In cooperation with IWT and the department of Flemish Hydrography - Section Coast
Rheological Transition Depths, frequency distributions

Depth classes

% of total
Rheological Transition Sounding Test

33 kHz frequency distributions

Graph 12

33 CDNB
33 ZF1

Depth classes

% of total

12.0 12.5 13.0 13.5 14.0 14.5 15.0 15.5 16.0 16.5 17.0 17.5 18.0

TV Nave in Cooperation with IWT and the department of Flemish Hydrography - Section Coast
Rheological Transition Sounding Test

Nautical Bottom (1,2 kg/m³) frequency distributions

Depth classes

% of total

1,2 CDNB
1,2 ZF1

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