The Rheocable Method:

Determining Nautical Depth in the Presence of Fluid Mud.

Marc Druyts[1], Peteralv Brabres[2] and Jason Errey[3]

The nautical depth is defined as the transition zone between the fluid and solid mud layers that to date, has been defined by techniques such as a dual frequency echo sounders, density meters, prick probes, laboratory analysis or techniques combining the above methods. It is recognised that all current methods and techniques either fail to accurately map the transition zone or fail to do it quickly enough to practically assist surveyors or dredge operators. As a result harbor managers are having to dredge significantly deeper than is required in order to ensure safe navigation for ships. The Rheocable is a new system for quickly and accurately determining the nautical depth (bottom) in an environment characterised by a fluid mud layer overlying solid mud. The capabilities and reliability of the system were proven during a pilot program undertaken jointly between the Belgian Port Authority and IWT (Instituut voor Wetenschappelijk en Technologisch Onderzoek, Belgium).

1. INTRODUCTION

The behaviour of ships sailing and manoeuvring above a fluid mud layer with restricted keel clearance or even negative keel clearance has been a worldwide concern for captains, pilots and harbour managers (The Pilot 2008). The true nautical depth (nautical depth) is defined as *"...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"* (Clandillon-Baker 2008, Delefortrie, G.; Vantorre, M. (2005)a, PIANC 1997). In muddy environments, nautical depth is defined here as the discontinuity in the vertical viscosity profile below which, given sufficient contact between a ships keel and the solid mud, ships may become dangerously un-controllable.

The actual depth of this discontinuity is very difficult to determine using classical acoustical methods (dual frequency echo sounders) and density measurements (density probes) (Clandillon-Baker 2008, Claeys 2008, Claeys 2006, Delefortrie, G. and Vantorre, M. 2005a. The failure of these methods is due primarily to the vertical discontinuity, or the horizon between the fluid / solid mud interface, representing a change in viscosity rather than a change in density. Though this rheological property of the discontinuity has been recognised, until now, a practical, accurate and reproducible method for mapping the horizon outside of the laboratory has not been available.

In recognition of the variable (and questionable) results obtained from dual frequency echo sounders in mud environments (Malherbe *et al* 1986), and that

---

1 Marc Druyts, MDCE bvba, mdce1@pandora.be, +32-478-518642

2 Peteralv Brabers, Demco NV, pb.demco@telenet.be, +32-495-251761

3 Jason Errey, OEMG Global, jasonerrey@oemg-global.com, +61-423-112-472

ships can safely navigate through liquid mud without compromising vessel manoeuvrability, significant research has been undertaken to relate nautical depth to mud density. As a general rule 1200kg/m^3 is accepted as the approximate density of mud that supposedly delineates nautical depth in the port of Zeebrugge (Delefortrie, G. and Vantorre, M. 2005b). However, as rheological characteristics and density relationships of mud will vary from port to port (Fontine *et al* 2006), appropriate mud density criterion must be determined for each port to define the approximate nautical depth. The result is that harbour managers must either dredge so that the top of the fluid mud or a prescribed density of mud is at the required nautical depth. However, both solutions fail to optimise dredging and the latter additionally increases the uncertainty that nautical depth has been achieved (Claeys 2008).

This paper describes the Rheocable method, a new method to determine nautical depth based upon pressure measurements carried out at the vertical discontinuity of the viscosity profile and the results obtained during the development and subsequent pilot program undertaken at the port of Zeebrugge by THV Nautic on behalf of the Belgian port authorities (Afdeling Maritieme Toegang, Belgium) and subsidised by IWT (Instituut voor Wetenschappelijk en Technologisch Onderzoek, Belgium). The pilot program included a comparison of methods including the DensiTune® and a dual frequency echo sounder.

2. PROJECT SETTING

The port of Zeebrugge lies on the North Sea approximately 16 kilometres north of Brugge in northwest Belgium (Figure 1). The use of the area as a port has its origins in the 7th century AD, however the modern port of Zeebrugge was opened in 1907. After being destroyed and rebuild after WW1 and WW2, the port has undergone continual expansion and improvements. In 1968 the first super tanker was accepted and in 1985 construction of the new outer harbour was completed. By 2007, the port handled over 42 million tons of cargo and over 650,000 passengers.

Figure 1, Location of Zeebrugge Port. Note significant sediment movement around the outer port.

Siltation at the port has been a constant problem since at least the 1930s (Bastin and Malherbe 1983). Indeed the expansion of the outer harbour served to exasperate the beach erosion in the area (Malherbe) with significant rehabilitation of the surrounding beaches and groins being required (Figure 1). The morphology of the local coast is characterised by large sand banks alternating with shoals and tidal flats. The physical processes are largely controlled by bidiurnal tides with a small asymmetry which range between 3.5 to 5m and can generate near shore currents of up to 1.5 knots. Net long shore drift is driven by the northerly Gulf Stream current in a north easterly direction along the Belgium coast. The effect of long shore drift and the resultant siltation within the port are clearly seen in Figure 1.

As a result constant maintenance dredging is required to maintain the required depth. However, in the case of the port of Zeebrugge, a significant portion of the dredged material is fluidised mud that does not pose a hazard to navigation. The solid mud underlying the fluid mud does pose a significant hazard to navigation, however, up to now, there has been no fast and reliable survey technique to map the rheological transition zone between the fluid and solid mud

2.1. The Rheological Transition Zone Within Zeebrugge Port

The physical reality of the rheological transition between the fluid mud layer and the underlying solid mud, in the port of Zeebrugge, is clearly measurable in the pipes of the dredger during dredging works. When dredging with the suction head in the fluid mud layer, the mixture velocity in the dredge pipes is approximately 4 to 5 m/s with the density of the fluid being between 1150 and 1250 kg/m^3. Upon increasing the suction depth to below a certain level, the mixture velocity dramatically drops to between 1.0 and 1.5 m/s, with the density remaining approximately the same, or only slightly increasing. This change is explained by sudden increases in viscosity values when passing through the rheological transition zone. This very abrupt change occurs with only a slight increase in the depth of the suction head, suggesting the existence of a very abrupt transition or discontinuity.

Indeed, the existence of this rheological transition zone within the port has been confirmed by a rheological analysis of the mud (sub 63µm sediment fraction) undertaken by Haecon NV in 1988 and 1999. During the study (Haecon 1999) a number of rheological profiles were measured throughout the port (Figure 2), illustrating the existence of an important discontinuity between 12.5 to 13.5m below the port datum. The results of laboratory analysis (Haecon 1988) to determine the rheological characteristics (comprising an analysis of the behaviour of the mud in transient conditions and in laminar flow to determine shear rates, shear stress and viscosity (Schramm 2000)) of mud samples collected during the study with varying sand content (Figure 3), clearly shows the relation between viscosity and density depending on the sand content in the mud samples. In this figure, the initial rigidity of the mud is represented along the y axis and the density along the x axis. It can be seen that with increasing sand content (lower mud content) the rheological transition (RG) is found at increased density values.

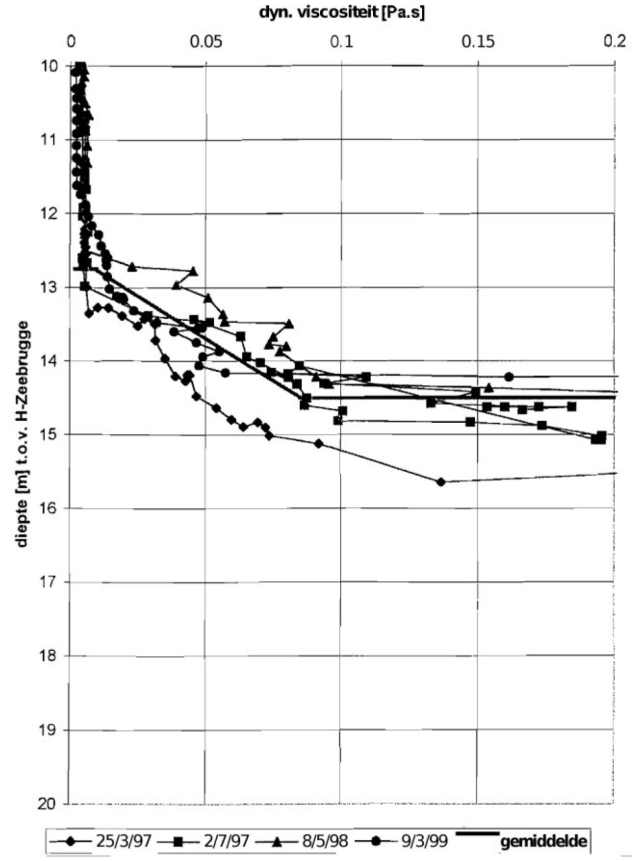

Figure 2, Rheological profiles undertaken in the Port of Zeebrugge between 1997 and 1999 showing dynamic viscosity (x axis) against depth (y axis). The transition zone is clearly evident between 12.5 and 13.5m below datum (Haecon 1999).

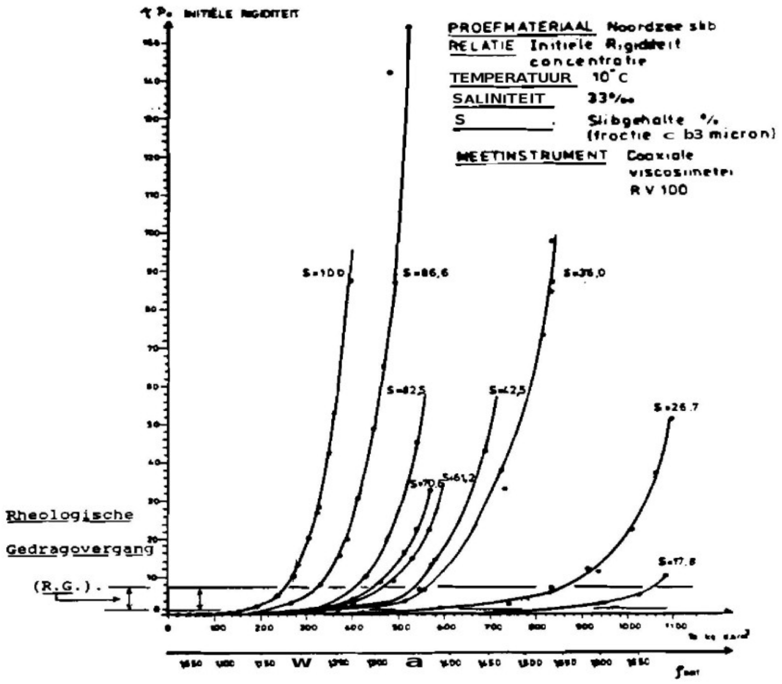

Figure 3, Rheological analysis showing the relationship between initial rigidity (y axis) and density (x-axis) as a function of mud content (S) (Haecon 1988).

A major conclusion of these studies was that density measurements are not suitable to define the rheological transition level.

3. CURRENT SETTING

There are no current methods to map the rheological transition zone out side of laboratory analysis, however several methods are currently being used to approximate the nautical depth in the presence of fluid mud, including:

- Dual frequency echo sounders;
- The NaviTracker®;
- Prick probes; and
- Hybrid methods.

These methods are briefly discussed in turn here, along with problems associated with each method.

3.1. Dual Frequency Echo Sounder

One of the most common methods currently used to approximate nautical depth is a dual frequency echo sounder operating at frequencies between approximately 33 kHz and 210 kHz. It is generally accepted that the 210 kHz signal reflects primarily off the top of the fluid mud layer (Delefortrie, G. and Vantorre, M. 2005b) and thus provides a reliable indicator of the water / fluid mud boundary. The lower frequency 33 kHz signal does penetrate the fluid mud layer, however the results tend to be unstable and unreliable as the signal reflects, apparently randomly, from different reflectors within the mud and indeed behaves differently depending on the rheological characteristics of the mud present. In Zeebrugge the 33 kHz depth usually is situated below the true nautical depth.

3.2. NaviTracker®

The NaviTracker® is a device developed since 1987 by Baggerwerken Decloedt NV, capable of measuring density values within the fluid mud layer. Based on these density measurements the height of the nautical depth in various ports has been defined in ports in Europe and around the world with examples provided in Table 1.

Table 1, Permissible mud densities that supposedly defines nautical depths within European ports.

Port	Mud density at nautical depth (kg/m^3)
Zeebrugge:	1200
Rotterdam:	1200
Nantes,Saint-Nazaire, Bordeaux:	1200
Germany:	1180 – 1250

The NaviTracker®, however, is not capable of determining the level of the solid mud underlying the fluid mud layer. The probe would be damaged or lost if it were to penetrate the solid mud layer. Also, as discussed, density measurements are not always appropriate for determining the nautical depth within a fluid mud / solid mud regime as in many situations the rheological discontinuity does not coincide with a density discontinuity.

3.3. Prick probes

These probes are lowered through the fluid mud layer while simultaneously measuring density or viscosity values. As discussed density profiles cannot determine the true nautical depth (rheological transition level) but only vertical density variations.

Viscosity profiles as measured, for example, using the RheoTune® can be considered more appropriate and accurate in defining the true nautical depth as compared to density profiles. However, as viscosity probe measurements tend to be time consuming and cumbersome, they are less suited for routine survey campaigns in ports.

3.4. Hybrid methods

Methods have been developed that utilise both prick probe measurements and acoustic signals. The aim is to determine the rheological transition level by using prick probe results as a calibration for the acoustic measurements after advanced processing. Examples of such hybrid methods are provided by Stema BV (Silas® software and DensiTune® probe) and Norbert Greiser (Admodus – survey system). However hybrid methods have yet to prove themselves successful in the determination of the nautical depth in the presence of fluid mud.

4. THE RHEOCABLE METHOD

A reliable, reproducible and quick method to determine the nautical depth as defined by the rheological transition level should be based upon the rheological properties (viscosity) of the mud rather than density. For routine applications the method additionally needs to be applicable in a continuous manner at normal survey speeds (3 to 5 knots).

4.1. The Nautic Sounding Array

The rheocable method utilises the Nautic Sounding Array as a key component of data acquisition (Figure 4). Simply, a sensor package is dragged behind the survey vessel at the end of an umbilical (data) cable. The sensor package comprises a pressure gauge and weights. The pressure sensor is placed in a sealed pressure pod with 2 circulation tubes reaching above the fluid mud layer to ensure the correct translation of pressure measurements into water depths based on the known density of seawater. The water density is continuously measured at several levels along the umbilical cable using CTD (Conductivity, Temperature and Depth) probes (during post processing, pressure is further compensated for atmospheric pressure). Following the sensor package is a short resistivity cable. The resistivity cable is used to verify that the sensor package is travelling on the fluid / solid mud interface and not floating above it.

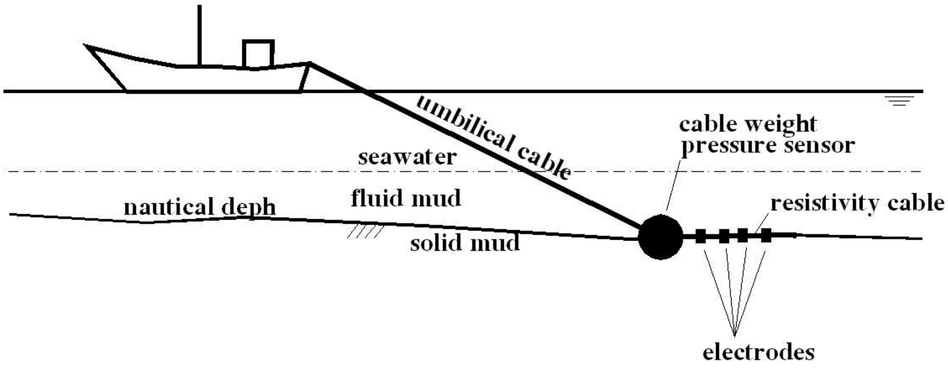

Figure 4, The Nautic Sounding Array of the Rheocable method.

The key to the Rheocable method is the real time verification that the sensor package is travelling along the rheological interface. Verification is achieved by monitoring real time resistivity values returned to the topside via the umbilical. If the cable is located on the solid mud layer relatively high resistivity values are measured. However, should the cable be floating within or above the solid/fluid mud interface, lower resistivity values are observed, corresponding to fluid mud and/or seawater. The vessel speed is adjusted to allow for the maximum survey speed without the cable floating. The high viscosity of the solid mud keeps the moving sensor package on the top the solid mud layer. Resistivity readings are gathered every 2 seconds and therefore the vertical position of the sensor package is continually monitored and vessel speeds can quickly be adjusted if the system starts to float.

5. RESULTS

In October 2008 the port of Zeebrugge was surveyed using the Rheocable method with the Nautic Sounding Array described above. In addition, 207 density logs were undertaken along with a survey utilising a dual frequency echo sounder at 33 and 210 kHz in order to provide a comparison of methods and validate the Rheocable method. The Rheocable survey was undertaken at an average speed of three knots. At speeds greater than this, the sensor package was seen to float off the solid mud horizon as noted by a significant drop in the resistivity values (to approximately 0.26 Ohmm) fed back to the acquisition computer. During the course of the survey and in post processing, key parameters of the port were determined (Table 2).

Table 2, Key resistivity indicators determined during the survey and in post processing.

Medium	Resistivity (Ohmm)
Seawater	0.26
Fluid mud	0.26 – 0.32
Solid mud	>0.32

The above observations are illustrated by comparing the raw unedited nautical depth results (Figure 5) with the resistivity monitoring results (Figure 6). The shallow anomalies of Figure 5 correspond very well with the low resistivity anomalies of Figure 6. This proves the resistivity results to be a good indicator to verify if the pressure sensor is on the solid/fluid mud interface.

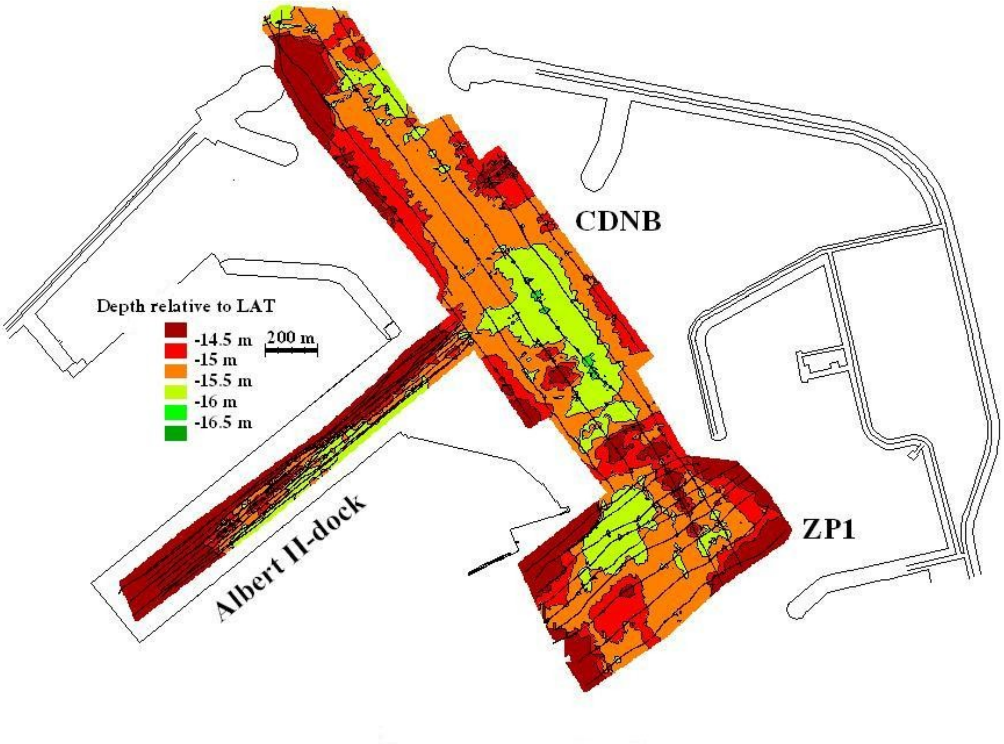

Figure 5, Unedited nautical depths as defined by the Nautic Sounding Array

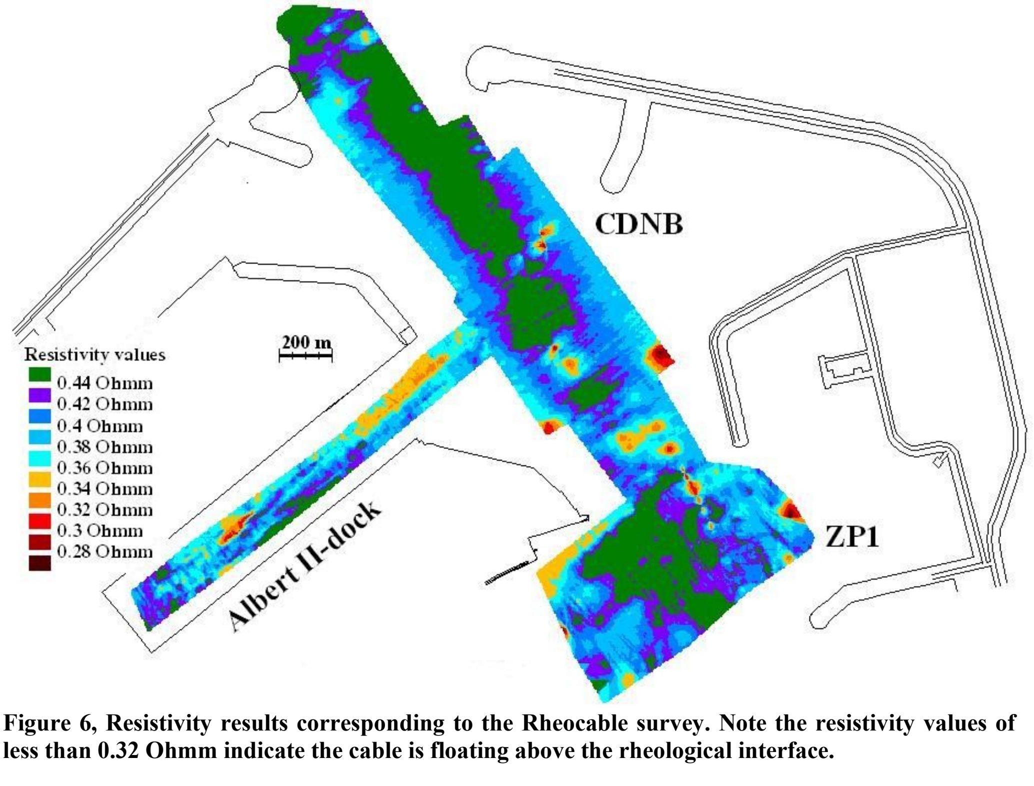

Figure 6, Resistivity results corresponding to the Rheocable survey. Note the resistivity values of less than 0.32 Ohmm indicate the cable is floating above the rheological interface.

The latter is further illustrated in Figure 7 showing the resistivity values measured over a limited period of time. The results are sorted from low to high values. This curve shows a distinct discontinuity with low values corresponding to 0.26 Ohmm seawater resistivity value measured with a cable floating above the solid/fluid mud interface and resistivity values above 0.32

Ohmm measured with the cable on the solid/fluid mud interface. Resistivity values between 0.26 and 0.32 Ohmm are rare or absent. Nautic depth determinations measured in combination with resistivity values greater than 0.32 Ohmm can thus be safely considered to represent data acquired with the pressure sensor on the solid/fluid mud interface.

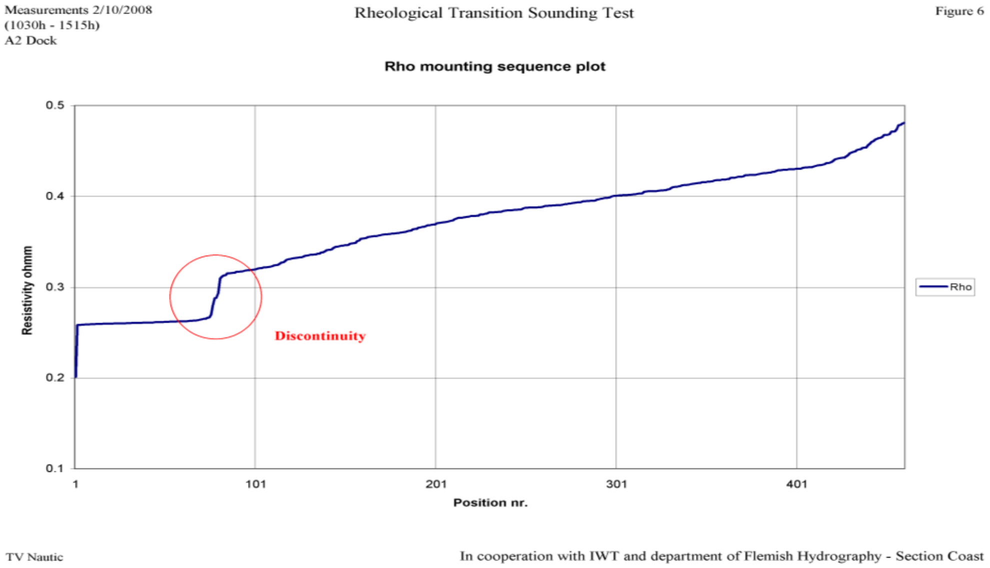

Figure 7, Sorted resistivity values indicating the interface at 0.32Ohmm

Based on the correlation with the resistivity results the erroneous nautical depth results associated with a pressure sensor floating above the solid/fluid mud interface can thus be removed unambiguously. The corrected results are shown in Figure 8.

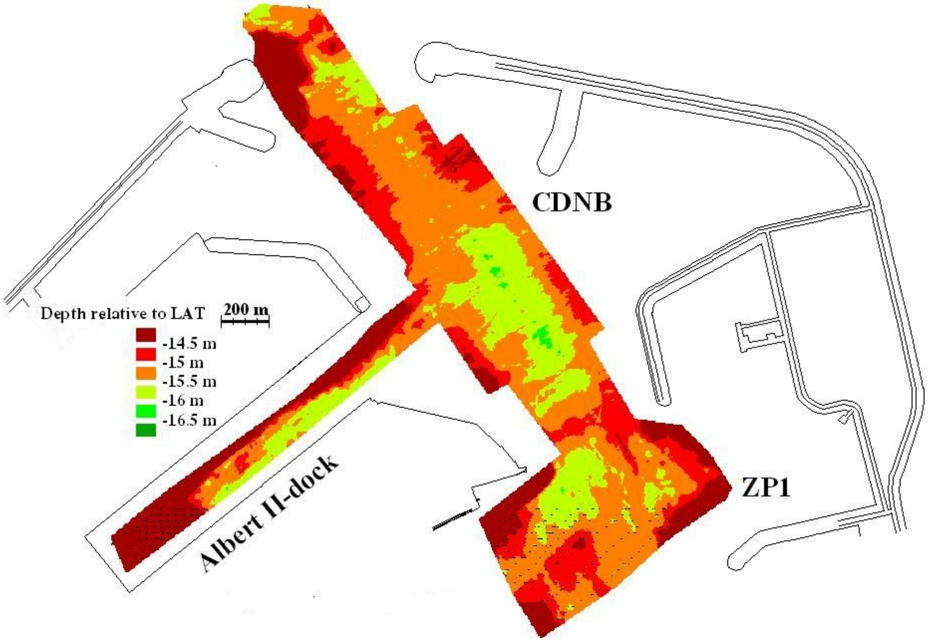

Figure 8, Corrected nautical depths as defined by the Nautic Sounding Array and corrected with resistivity measurements

5.1. Correlations with the Density Probe and 33 kHz Echo Sounder

A bathymetric maps utilising the 33kHz signal and the DensiTune results are provided in Figure 9 and Figure 10.

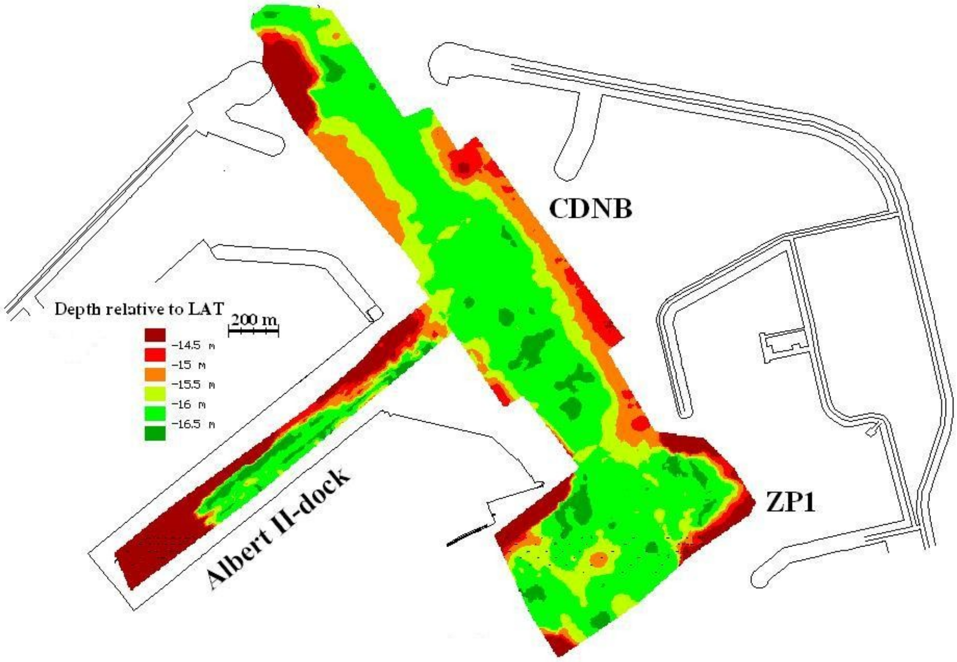

Figure 9, A Bathymetric map utilizing the 33kHz signal

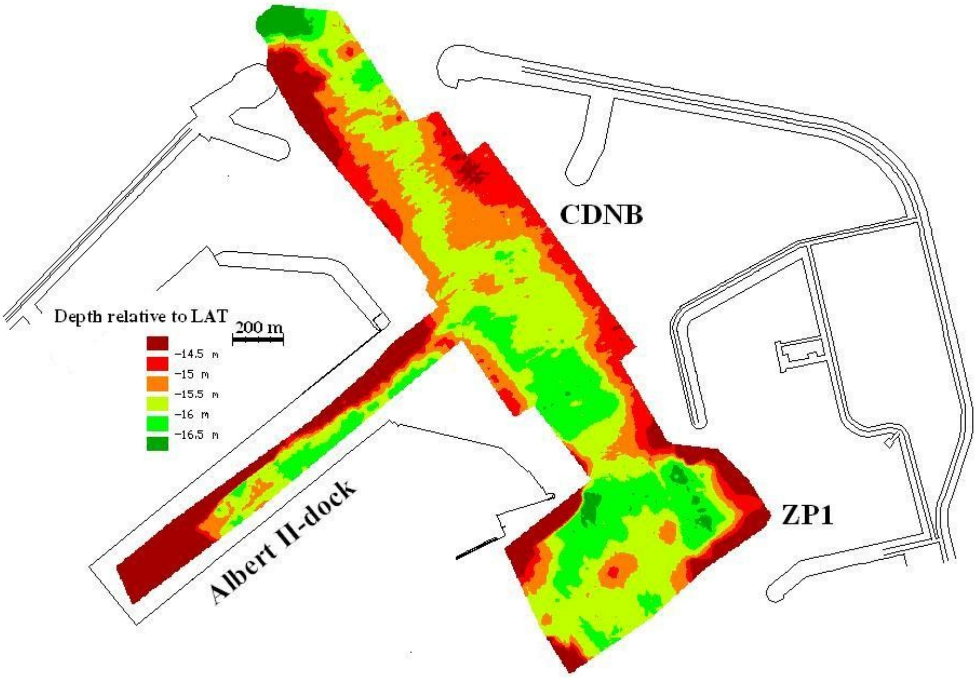

Figure 10, A Bathymetric map utilizing the results of the densiTune results. A density minimum of 1200kg/m^3 is used to define nautical depths

A statistical compilation of the acoustic data, the density results and the Rheocable results for 2 subareas of the port are shown in figures 10 (CDNB area) and 11 (ZP1 area). Each of these figures shows the statistical depth distributions for the 33 kHz results, the Rheocable results and the density results. 132 density logs were carried out in the CDNB area and 75 density logs in the ZP1 area.

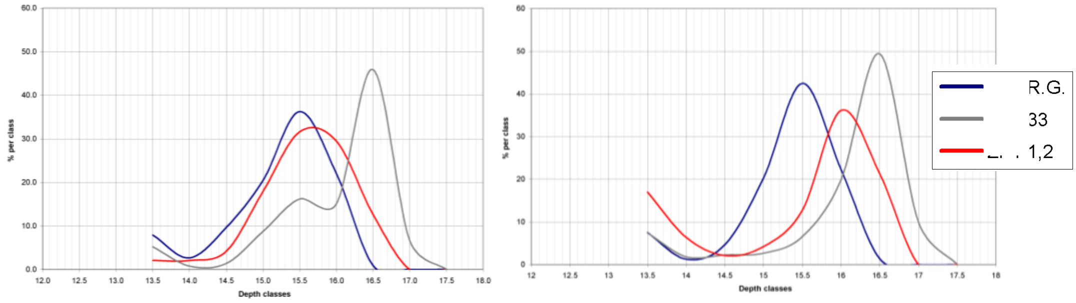

Figure 11, The nautical depth frequency distribution in the CDNB area (left) and the ZP1 area (right) for the Rheocable (R.G) the 33kHz signal and the density probe for the 1200kg/m3 depth criterion.

Both in the CDNB and the ZP1 areas the 33 kHz echo sounding results are about 1m below the true nautical depth as defined by the pressure measurements. The density pricks result in depths of about 0.5 m below the true nautical depth in the ZP1 area and only 0.15 m below the true nautical depth in the CDNB area. The latter difference between ZP1 and CDNB is likely due to a higher sand content in the mud in the CDNB area resulting in higher mud densities.

When the dual frequency echo sounder (210 and 33kHz) and Rheocable results are plotted on selected density logs (Figure 12), the limitations on the use of the density probe are clearly evident with the 1200kg/m^3 density criterion failing, in all cases, to define the nautical depth. From these density logs, the three main shortfalls of using density probes to approximate nautical depth are seen;

1. Density logs fail to reach the 1200kg/m^3 density criterion. This is evident in density logs CDNB52 and ZP1-12. Overall 4% of the density logs recorded in the CDNB area and 29% of those recorded in the ZP1 area exhibit this problem.

2. The density log cuts the 1200kg/m^3 criterion several times. This is evident in the CDNB125 log. Overall 10% of the density logs for the CNDB area exhibit this problem and there are none in the ZP1 area.

3. The 1200kg/m^3 density criterion is located on a discontinuity that is very marked, but not related to the nautical depth. In this case the discontinuity corresponds to the 33kHz reflector and is likely the original dredge level. Overall, 40% of the density logs in the CDNB area and 51% of those recorded in the ZP1 area exhibited this problem.

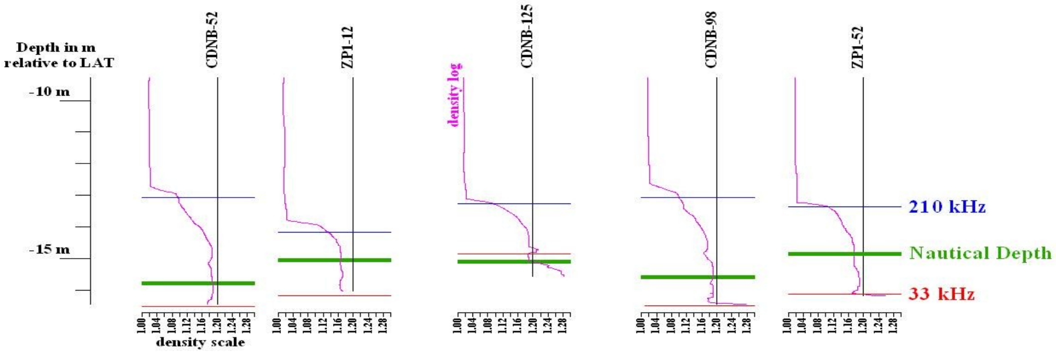

Figure 12, Typical density logs showing the echo sounder (210 and 33kHz) and rheocable (Nautical Depth) results demonstrating that neither density logs nor the 33kHz results are able to provide results suitable for optimizing dredging.

From the above error categories the density log results for the CNBD and ZP1 areas are summarised (Table 3). 54% of the density logs for the CNBD area and 80% of the logs for the ZP1 area provide either inconclusive or false indications of the nautical depth.

Table 3, The results of the density logs are broken down into three broad error categories, failure to reach the density criterion, crossing the density criterion at multiple depths and reaching the density criterion at the incorrect discontinuity. This results in the majority of the density probes providing an incorrect nautical depth.

Log type	**CDNB**	**ZP1**
Type 1	4%	29%
Type 2	10%	-
Type 3	40%	51%
Total:	**54%**	**80%**

6. CONCLUSIONS

The Nautical Depth method is shown to be a relevant and efficient method in determining the nautical depth as defined by the discontinuity in the vertical viscosity profile, separating fluid mud and solid mud. In Zeebrugge significant density discontinuities measured with the density probe seem to correspond to the original dredge level located at deeper levels below the true nautical depth. The result is that dredge campaigns have continually failed to be optimised and Harbour managers have specified dredge depths, in some areas, of almost one meter below nautical depths, and / or have had to needlessly request dredging of fluid mud that poses no risk to navigation. Regular surveys utilising the Rheocable will significantly reduce dredge costs and allow Harbour managers a clear idea of the behaviour of fluid mud as well as the accretion rates of solid mud within a harbour.

7. REFERENCES

Bastin A., Malherbe B (1983). Zeebrugge port extension sediment transport measurement on and off the Belgium coast by means of tracers. *Heacon NV, Gent Belgium*.

Claeys, S. (2006). Evaluation and combination of techniques used to determine the nautical bottom: a call for rheology based instruments, in: (2006). *Evolutions in hydrography, 6th - 9th November 2006, Provincial House Antwerp, Belgium: Proceedings of the 15th International Congress of the International Federation of Hydrographic Societies. Special Publication of the Hydrographic Society*, 55: pp. 141-144

Claeys, S (2008). Evaluation of nautical bottom detection techniques (2008). *Sea Tecnnology, Compass Publications, Arlington VA, USA*. July 2008.

Clandillon-Baker J (2008). Squat – Part 2 Mud Navigation and negative under keel clearance. *The Pilot, United Kingdom Maritime Pilots' Association*. April 2008 N0 293.

Delefortrie, G.; Vantorre, M. (2005)a. Modelling navigation in muddy areas, ***in***: (2005). *Hydronav'05 - Manoeuvring '05: Joint 16th International Conference on Hydrodynamics in Ship Design and 3rd International*

Symposium on Ship Manoeuvring, Ostróda, Poland, September 2005. pp. 49-58

Delefortrie, G.; Vantorre, M. (2005)b. Revision of the nautical bottom concept of Zeebrugge based on the maneuverability of deep-drafted container ships. *Proceedings of the CEDA Dredging Days* 2005

Haecon (1999). Optimization of the maintenance dredging works, Analysis of the mean rheological and density profiles. *Haecon NV Gent Belgium*.

Haecon (1988) Optimization of the dredging activities 1984 – 1988, evaluation of the results. *Haecon NV Gent Belgium*

Malherbe B, Knokke Heist, *Haecon NV, Gent Belgium*.

PIANC (1997) Approach channels – A guide for design, *Final report of the joint Working Group PIANC and IAPH, in cooperation with IMPA and IALA.* Supplement to PIANC Bulletin, No. 95, 108 pp.

Schramm (2000). A practical approach to rheology and rheometry (2nd edition). *Gebrueder HAAKE GmbH Karlsruhe, Federal Republic Germany*.