4th MASHCON, Hamburg - Uliczka et al. (eds) - © 2016 Bundesanstalt für Wasserbau ISBN 978-3-939230-38-0 (Online)
DOI: 10.18451/978-3-939230-38-0_8

THE DEFINITION OF THE NAUTICAL BOTTOM IN MUDDY NAVIGATIONAL AREAS

M Druyts, MDCE bvba, Belgium
P Brabers, Demco nv, Belgium

SUMMARY

When salt water meets fresh water, flocculation occurs and sedimentation starts. During the settling process, estuarine mud particles constantly reduce the mutual distance until, at a specific moment - van der Waals forces and electrostatic forces - the particles form network structures. The nature of the mixture changes from fluid mud to a gel like substance. This phenomenon generates in estuarine mud layers a physical two component structure: one component of low viscosity (fluid mud), and of high viscosity (solid mud). The interface between the two is characterized by a drastic change of the rheological parameters: a rheological transition. During trials with TSHD 'Vlaanderen XVIII' in Zeebrugge, the vessel, navigating with zero under keel clearance relative to this interface, was completely out of control. The rheological transition is, according to the PIANC definition, the Nautical Bottom in muddy navigational areas. Several sounding instruments are capable of measuring the rheological transition level.

1 INTRODUCTION

Since the SHZ 'Vlaanderen XVIII' trials and the publications of Prof. Toorman and Dr. Wurpts, no new trials and/or investigations, relating to the Nautical Bottom concept in muddy navigational areas, were reported. This paper is an attempt to put or to keep the subject on the agenda by focusing on the fact that the Nautical Bottom and the rheological transition are identical in muddy areas.

Without measuring the rheological transition, the safety of a vessel, maneuvering in a muddy navigational area, cannot be estimated or confirmed.

The concept of 'mud', as used in this context, refers to estuarine mud, a concentration in water of mainly cohesive sediment, some organic matter and a smaller fraction of coarser, non-cohesive sediment (silt and sand) [1].

Influenced by tide and increasing width of the river, mud settles on the seabed or the riverbed in ports and fairways.

The behaviour of ships in muddy navigation areas, especially with reduced under keel clearances, changes substantially. Guillaume Delefortrie in his doctoral thesis [2] has thoroughly researched this influence on the behaviour of a 6000 TEU and a 8000 TEU container carrier.

He reports however a major unsolved problem: what exactly is the Nautical Depth in muddy navigation areas, and how can it be measured directly and continuously: "*Finally the search for better survey techniques in muddy navigation areas should not be closed. It would be very useful if the rheological characteristics of the mud layer, and particularly the rheological transition, could be measured in a continuous way, as both echo sounding results and density values are only a surrogate to indicate the position of the rheological transition. [2, p. 12.6]"*

The significance of this quote with regard to the definition of the Nautical Bottom in muddy navigational areas, is highlighted by reading it next to the PIANC definition of Nautical Bottom: *"The Nautical Bottom is the level where the physical contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability"* [3]

Is the rheological transition in mud to be regarded and defined as the equivalent Nautical Depth?

There is no doubt that this is the case. In what follows, arguments are developed and illustrated. Furthermore, and most importantly, the existing (recently developed) survey techniques to measure this rheological transition already are operational and will be discussed.

2 THE GEL POINT

2.1 IN THE LABORATORY

The settling process of estuarine mud passes through different phases. E.A. Toorman [1] researches the process and carries out settling experiments: in Fig. 1 the water – mud interface relative height position is represented against the settling time in days. The experiment starts with a homogenized water mud column. Phases 1 and 2 are fluid, the phase 3 is not fluid.

In this phase 3, the cohesive sediment particles, under the influence of van der Waals forces and electrostatic forces, have formed a network structure: the gel point has been reached: see Figure 1.

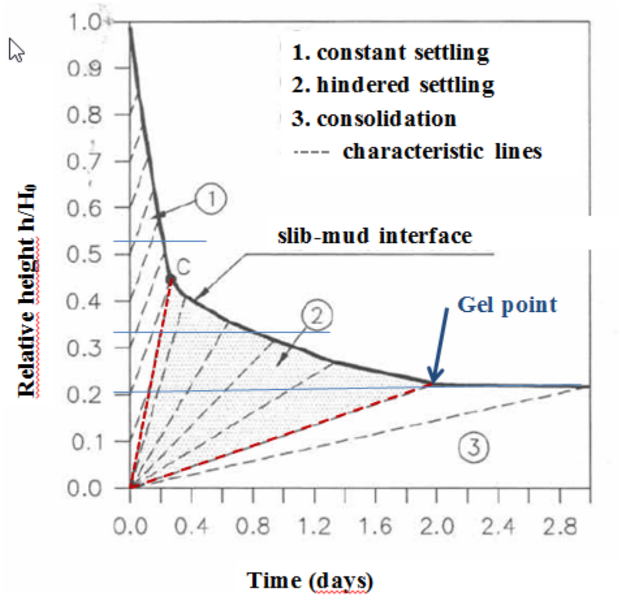

Figure 1. Settling curve (mud-water interface evolution) and characteristic (iso-density) lines. (adapted)

The 3rd phase is a soil marked by significant shear stress σ'[1] [4]. The gel point separates fluid mud from solid mud.

The same experiment, carried out with a constant feed of mud particles, would result in the situation as represented in Fig. 2. The gel point will slowly rise, but, unlike in the original experiment, all three phases would be present simultaneously and continuously.

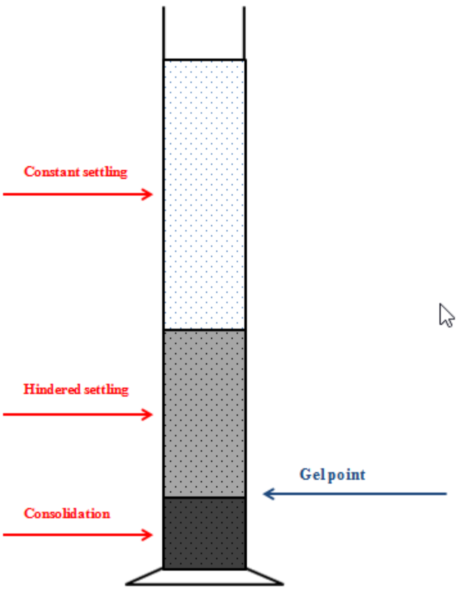

Figure 2. Profile generated during continuous/ cyclical feeding with mud particles as in estuaries.

In an estuarine mud layer, continuously or cyclically fed by settling mud particles, a gel point exists. It is situated at the interface of the fluid mud layer (hindered settling phase) and the consolidating mud layer.

2.2 IN SITU

In the presence of mud, the in situ depth measurements with dual frequency acoustic survey methods – Figure 3 Zeebrugges – reveal the first two phases as in Figure 2: constant settling phase (above the 210 kHz echo) and hindered settling phase (below the 210 kHz). The 33 kHz reflection generally is unstable and unreliable when fluid mud is involved: there apparently exists no clear reflector for the 33 kHz signal. In general, the transition level from the hindered settling phase to the consolidation phase is situated in between the 210 and 33 kHz reflections.

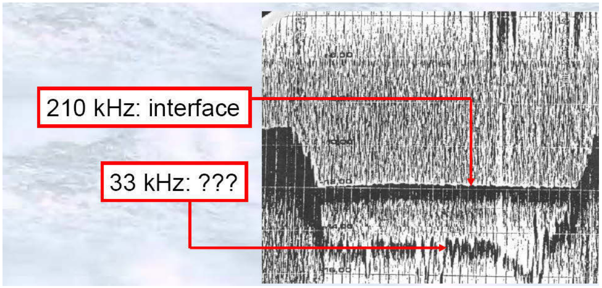

Figure 3. In situ profile (CDNB, Port of Zeebruges)

A following example is the Port of Emden: the blue line represents the water – fluid mud interface, generated by the 210 kHz echo, the red line the echo of the 15 kHz echo.

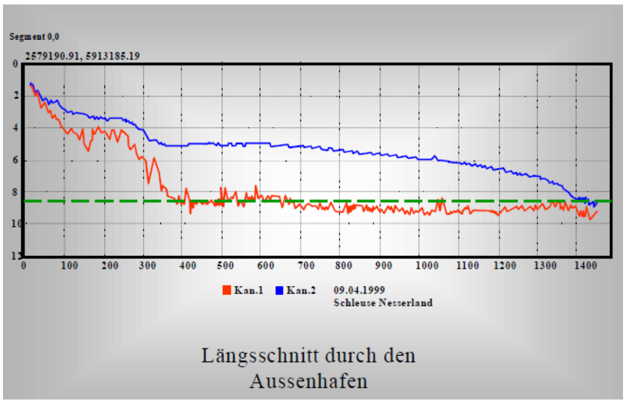

Figure 4. Longitudinal section outer port Emden [5]

It is a persistent and ongoing problem that the position of the 33 kHz echo in the mud, or of any low frequency, is not stable, but depends on echo sounder settings and on the surveyors' skill, both subjective parameters.

Furthermore and as a consequence, the physical reality connected to the level of the 33 kHz echo is confuse, unknown and unrelated to the position of the gel point.

On the other hand the fact itself that there exists a difference between the 210 kHz reflector and the 33 kHz reflector, measured at the same location, is always sufficient evidence for the presence of a fluid mud layer.

2.3 GEL POINT AND DENSITY

The gel point can be considered the equivalent for mud, as the temperature of 0° C is for water: above 0° C there is water, below 0° C there is ice and nothing in between.

All over the world at this moment, densities are being used to identify the gel point. This is basically incorrect. The density at the gel point is strongly influenced by the sand content. With each variation of the sand content corresponds a different density for the gel point. Since the sand content in any port or fairway varies continuously form location to location, density is to be ruled out as a parameter to measure the depth of the gel point.

3 THE RHEOLOGICAL TRANSITION

3.1 THE ‘FREEZING’ OF MUD

The physical reality of the concept ‘gel point’ at the interface between fluid mud and solid mud, may seem to be rather abstract, but can easily be visualized: see Fig. 5.

The photo is taken in the DEME harbour on the left bank of the river Scheldt. The harbour is exposed to the tide, which makes this photo possible: at low tide both the fluid mud and the consolidating mud are visible at the same moment.

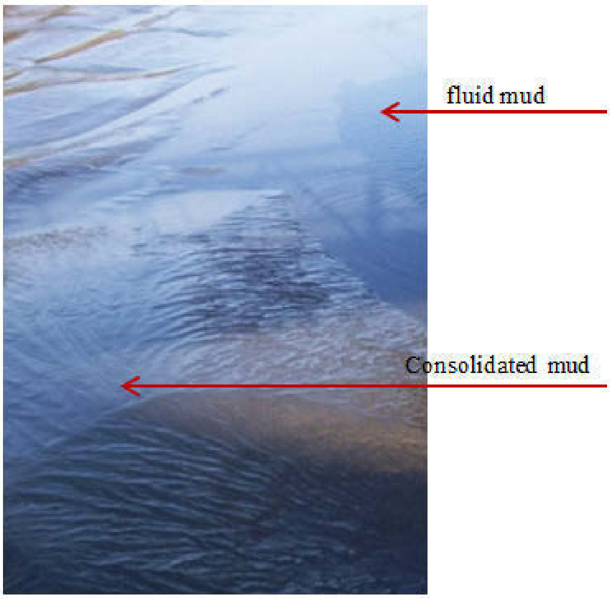

Figure 5. DEME harbour Antwerp, left bank river Scheldt

Visual observations confirm the presence of a fluid (smooth surface) and a soil (rough and undulating surface). There is no evidence of a third element, an eventual intermediate phase between them: the transition is abrupt and shows the physical reality of the gel point, which is the ‘freezing’ point of mud.

As a consequence, the gel point phenomenon generates a physical separation between two phases in the mud layer: the liquid state and the solid state, or a low viscosity phase and a high viscosity phase as reported by Kerckaert, Malherbe and Bastin already in 1985 [6]. Moreover, it was observed that in the transition between the two phases, the viscosity parameters do change drastically.

The conclusions at that time were based upon laboratory measurements – dynamic viscosity, initial rigidity or yield stress – of Zeebrugge mud. Although in situ measurements of viscosity are very difficult to achieve, later developments made it possible to measure yield stress depth profiles.

3.2 YIELD STRESS

The yield stress depth profile in fig. 6 [7] is a representative sample of – literally – hundreds of profiles measured in the Port of Zeebrugge.

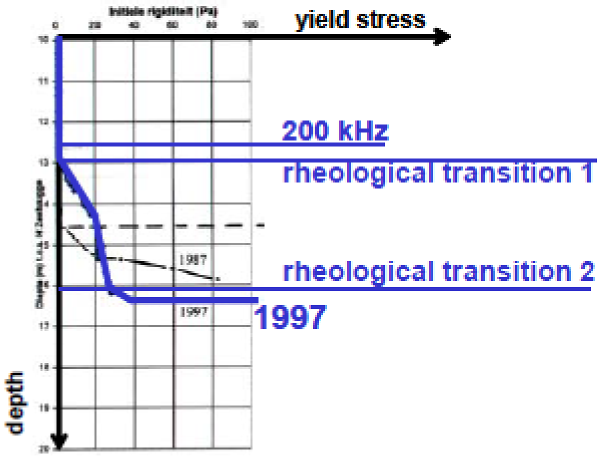

Figure 6. Yield stress depth profile, Zeebrugge [6]

Again, the profile reflects the situation as showed in Fig. 2 and Fig. 3: no yield stress in the constant settling phase (above the rheological transition 1, which is the earlier mentioned mud – water interface), low viscosity in the hindered settling phase (between the rheological transitions 1 and 2), high viscosity in the consolidation phase (below the rheological transition 2).

The yield stress depth profile reflects the three phase settling situation but, in contrast to the situation reflected by the acoustical survey methods, the gel point is accurately identifiable.

While just below the water-mud interface – the 1st transition –, the rheological properties of the mud are hardly different from those of water, it is undeniable that the 2nd transition is from a low viscosity area to a high viscosity area. The transition is also very drastic: the yield stress increases very quickly with the depth. This depth is the transition between fluid mud and solid or 'frozen' mud.

3.3 OTHER RHEOLOGICAL PARAMETERS

During individual trials of the Rheocable in the laboratory of Flanders Hydraulics Research at Antwerp, the relation shear stress – shear rate at different depths in the Sediment Test Tank (STT) was measured [8]. In Fig. 7, some of these relations have been visualized.

The STT was, among other things, used to test different survey methods in an environment of classic mud layers: see Fig. 2 and Fig. 3. Estuarine mud from the river Scheldt was used for these tests.

The drastic change (discontinuity) of the viscosity in the mud – in terms of dynamic and kinematic viscosity parameters - between the level of -85 cm and -95 cm is striking. The drastic change of the yield stress at shear rate 0 (1/s) between the same depth levels is also evident.

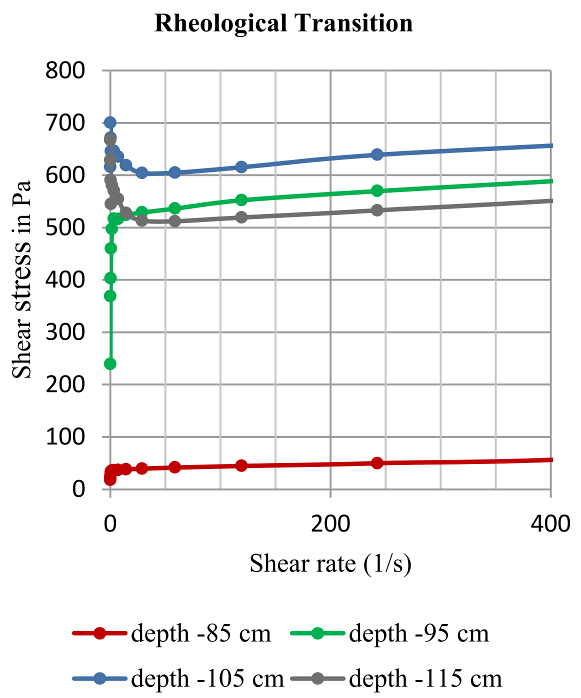

Figure 7. Shear stress/shear rate in the STT

This transition was not only observed in the laboratory, where the conditions for sample taking, for measurements and for observations are optimal. In situ measurements in many different locations, with different survey methods, have confirmed, directly or indirectly, the presence of this drastic change in the viscosity parameters, i.e. the presence of a true rheological transition.

All viscosity parameters do change drastically at the gel point level in the estuarine mud layers: this is called the rheological transition (and this transition occurs in all estuarine mud layers).

4 A SHIP'S BEHAVIOUR

4.1 IN A MUD-FREE ENVIRONMENT

A reduction in under keel clearance (squat), reduced effectiveness of the propeller(s) and the rudder, increasing stopping distances and stopping time, increasing diameter of turning circles: these are the shallow water effects related to the interaction between ship and seabed. [9]

With the exception of the squat, these effects are caused by the reduced effectiveness of the propeller(s): the flow of water to the propeller becomes severely hindered (throttled) with decreasing under keel clearance. As a consequence, rudder forces are equally reduced producing the effects as mentioned.

Ultimately, with the under keel clearance reduced to zero, the vessel, in contact with the hard surface (sand or rock) of the bottom, will be immobilized: the friction between the ship's keel and the bottom is overpowering.

In this case, the definition of the Nautical Bottom is not a problem, nor its detection by survey techniques.

4.2 IN THE PRESENCE OF MUD

4.2 (a) In the Laboratory

The behaviour of a ship in the presence of a fluid mud layer has been thoroughly researched by G. Delefortrie [2]. This work is based upon multiple captive manoeuvring tests in Flanders Hydraulics Research shallow water tank, with a model of a 6000 TEU container carrier, a 8000 TEU container carrier and a bulk carrier.

Figure 8 summarizes very well the influence of fluid mud on the ship's behaviour: on top of the effect caused by the interaction ship-hard bottom (see preceding paragraph 4.1), a ship's behaviour is additionally affected – slowed down – by the presence of a fluid mud layer in the speed range from 2 to 6 knots, a speed range very commonly applicable within harbours.

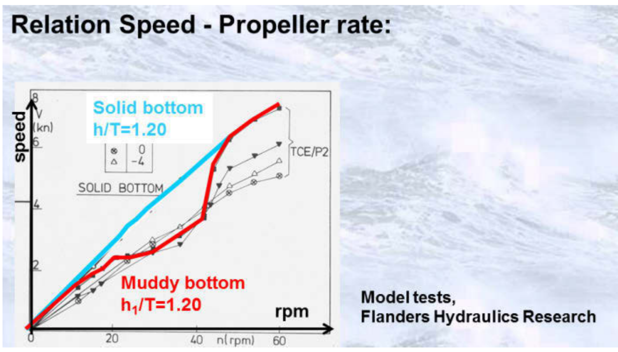

Figure 8. Influence of fluid mud layer [2]

The definition of the Nautical Bottom in the test towing tank is not a problem, nor it's detection: it is the bottom of the towing tank.

Supposing the rheological transition would be accepted – quod non at this moment – to coincide with the Nautical Bottom, would it be safe than to transfer the test results to the in situ reality, without additional correction factors with regard to this Nautical Bottom concept?

4.2 (b) In situ

In the test tank, exactly as in situ, there are two interfaces: the interface water – fluid mud equivalent – and the interface fluid mud equivalent – solid bottom.

This second interface in the test tank (fluid mud / solid bottom) is a very extreme transition and, although not a rheological one but a fluid/solid one, it is similar to the rheological transition in the in situ mud layers.

Furthermore, from the point of view of fluid mechanics, the high viscosity mud phase does resist flowing much more than the low viscosity phase, the propeller's efficiency degenerates accordingly and induces the same kind of effects as described in paragraph 4.1.: reduced effectiveness of the propeller(s) and the rudder, increasing stopping distances and stopping time, increasing diameter of turning.

The scale of these effects, however, may be somewhat less pronounced because the high viscosity mud does flow eventually while solid soil doesn't. Anyway, the laboratory test results can be expected to be on the safe side as compared to the real situation.

5 SHZ VLAANDEREN 18 TRIALS [10]

In the period 1986 – 1988, a series of trials were carried out with SHZ 'Vlaanderen 18'. These have been reported on many occasions and one particular trial is extremely relevant and has raised a lot of interest in the maritime community. Delefortrie [2] reports it as follows: *An occasional full scale trial that deserves to be mentioned is when the ship navigated at slow speed in contact with the probable rheological transition level, situated at a density of 1.20 ton/m³. The crew of the ship thought the vessel would decelerate quickly due to contact with the highly viscous mud layer, but the opposite occurred. The ship kept navigating at slow speed and not even the reversed propellers or bow thrusters were able to stop the vessel. A disaster could be avoided in extremis by decreasing the draught of the vessel.*

The vessel sailed with an under keel clearance of quasi zero, relative to the rheological transition level. Propeller and rudder effectiveness were reduced to zero, but the vessel didn't stop when in contact with the high viscosity mud.

In comparison to the vessel's contact with the mud-free (sandy/rocky) bottom, the friction forces between the ship's keel and the high viscosity mud are too small to reduce the ship's speed immediately.

This situation is extremely critical: a vessel, without steering capacity, without propeller capacity, unstoppable, retaining its original speed from time of first contact with the high viscosity mud….The consequences could be very damaging, not only for the vessel itself, but also for nearby vessels, quay walls, sluices, bridges…*The Nautical Bottom is the level where the physical contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability* [3]

The situation described – a vessel navigating with zero under keel clearance relative to the rheological transition – fits perfectly the PIANC definition of the Nautical Bottom

6 SURVEYING THE NAUTICAL BOTTOM

Without the availability of operational survey techniques to measure the rheological transition, it would be useless to introduce the rheological transition as the Nautical Bottom in muddy navigational areas.

Above mentioned survey techniques, however, do exist, and are operational for some time now. Their specifications are public, but these are not the object of this paper: only a synopsis is provided.

The following instruments are perfectly capable to detect the rheological transition.

Remark: derived parameters such as density, viscosity and others are not taken into consideration by the authors, only the capability for locating the level of the rheological transition.

6.1 PRICK PROBES

6.1 (a) MIR – Jan De Nul Group

This instrument is a rebuilding of the Rheometer [11], introduced by Haecon nv in the eighties (the company is no longer active). It is a single point rheometric profiler, measuring the resistance encountered by a small propeller when lowered in the water and the mud layers.

6.1 (b) Graviprobe – dotOcean nv

This instrument is a free fall penetrometer, measuring the accelerations/deceleration when passing through the water and mud layers.

6.1 (c) Rheotune – Stema Systems BV

It uses the tuning fork response in the water and mud layers when lowered.

6.1 (d) Acceleroprobe - THV Nautic (prototype)

This probe uses the measurement of acceleration/ deceleration of a falling (streamlined) body in the water to detect the depth of the rheological transition. It is integrated in the Rheocable equipment

6.2 CONTINUOUS SURVEY METHODS

6.2 (a) Rheocable – THV Nautic

A heavy object is towed behind a survey vessel. If the vessel would stop the object would slowly sink into the solid mud. Within a given velocity window, usually between 1 to 5 knots, the high viscosity of the solid mud generates a tension in the towing cable pulling the object out of the solid mud, where it stays on the solid/fluid mud interface. A pressure sensor attached to the object measures the water depth. A resistivity cable trailing behind the object verifies if the cable is on the solid mud and not floating above it.

7 CONCLUSIONS

The following steps have led to the conclusion that the Nautical Bottom coincides with the rheological transition:

1. In an estuarine mud layer, continuously or cyclically fed by settling mud particles, a mud gel point always exists.

2. The gel point phenomenon generates a physical separation between two phases in the mud layer: the liquid state and the solid state, or a low viscosity phase and a high viscosity phase.

3. All viscosity parameters do change drastically at the gel point level in the estuarine mud layers: this is called the rheological transition.

4. This rheological transition is a physical reality in all estuarine mud layers.

5. A vessel navigating with zero under keel clearance relative to the rheological transition is out of control. Therefore - in accordance with the PIANC definition - the rheological transition is identical to the Nautical Bottom

6. Instruments, based on different techniques, are available and operational to measure the rheological transition.

Without the use of the under keel clearance to the rheological transition as a parameter, no exact estimation of a ship's safety, navigating in a muddy area, can be obtained. This involves important risks: the safety of the ship on one side, a (to) heavy maintenance dredging budget on the other side. In the present state of affairs, these risks are perfectly avoidable.

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9 AUTHORS' BIOGRAPHIES

Peteralv Brabers is since 1996, the managing director of Demco NV, a company performing marine geophysical surveys: Aquares and Rheocable. He holds a Ph. D. in mining engineering and was from 1981 to 1986 teaching and research assistant at the KUL-Leuven. His previous experience includes also project management and development of new geophysical techniques for Geosurvey NV, a Belgium based geophysical company.

Marcus Druyts is since 2001 managing director of MDCE bvba, a company involved in dredging consultancy, development of new sounding equipment – Rheocable – and tools for the dredging industry. He holds a M. Sc. Degree in naval architecture, Ghent University and has a career in the dredging industry: Baggerwerken Decloedt NV (Deme). From 1991 to 2001 he was operations manager for the capital and maintenance dredging activities on the Belgian Coast.