# MANOEUVRABILITY IN PROXIMITY OF NAUTICAL BOTTOM IN THE HARBOUR OF DELFZIJL

**by**

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## ABSTRACT

The presence of a mud layer in the port of Delfzijl in the Netherlands implicates a major restriction to the nautical accessibility of the port. At present the maximum drafts for shipping traffic to Delfzijl are limited by a minimum under keel clearance with respect to the top of the mud layer. By order of Groningen Seaports and Wiertsema & Partners, Flanders Hydraulics Research investigated the influence of sailing at very low and even negative under keel clearances (UKC) with respect to the top of the mud layer on the inbound and outbound route to and from the port of Delfzijl, by means of a simulation study on a full mission bridge simulator. During this study, the mud layer characteristics (thickness, density and viscosity) were varied systematically. In order to perform the simulations as realistically as possible, local port pilots experienced with the port of Delfzijl participated in the study.

The simulations were carried out with a 1700 TEU vessel for which the mathematical manoeuvring models had been derived from a comprehensive captive model test program (cooperation FHR and Ghent University, 2001-2004). During this experimental program the ship behaviour above and in contact with several mud layers had been investigated.

The simulator study revealed the possibility to work with a nautical bottom which is at a lower level than the top of the mud layer. This opens up the possibility for the port of Delfzijl to receive vessels with a larger draft in the future without the requirement of extra dredging efforts. In order to validate the conclusions from the simulator study, full scale testing of ship manoeuvring was performed on a general cargo vessel sailing outbound from the harbour of Delfzijl. These full scale measurements reveal the influence of a mud layer on the manoeuvring characteristics of the vessel.

The paper gives a detailed introduction to the examined problem, a summary of the model test setup, simulator study and full scale testing.

**Keywords: Ports and Maritime Navigation, Nautical Bottom, Deep-draft Navigation and Waterways, Delfzijl.**

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# 1. INTRODUCTION

### Case study

The case study concerned the nautical accessibility of the Dutch harbour of Delfzijl. The harbour is located in the north of the Netherlands close to the eastern German border, and bordering on an important marine nature reserve and World Heritage area, the Wadden Sea. In the frame of the efforts of the harbour authority, Groningen Seaports (GSP), to optimise harbour maintenance, one of the issues to be covered is to determine and validate the definition of an optimal nautical depth.

### Delfzijl bottom profile

The harbour of Delfzijl is connected to the river Ems by the ‘Zeehavenkanaal’ (see Figure 1). The Zeehavenkanaal is oriented parallel to the shore and has a length of 5.5 km. The tidal range in the Zeehavenkanaal is approximately 3m.

Over a period of approximately one year Wiertsema and Partners (W&P) carried out measurements in the Zeehavenkanaal on a regular basis. The measurements consisted of surveys (parametric echo sounder with dual frequency single beam (210 kHz and 33 kHz)) and vertical profiling (Multisampler for turbidity, DRDP[5] for density and dynamic penetrometer measurements).

In Figure 2 the echo profile of the Zeehavenkanaal is shown. The dark blue line clearly shows the top of the mud layer in the harbour entrance. Near the entrance (4200 m to 4800 m) a mud trap is located. Between the harbour breakwaters (5500 m) a sand bar is present after which the bottom layer descends into the deeper entrance channel to the river Ems.

After geo statistical analysing over 1000 samples collected from the Zeehavenkanaal by means of both regular (grain size distribution, water content, organic content, density and specific weight) and rheological laboratory tests, W&P concluded that the mud layer in the harbour of Delfzijl can be considered as fluid mud. Furthermore W&P stated that the present characteristics of the material are suitable for a ‘Keep Sludge Navigable’ maintenance dredging approach and that the characteristics of the fluid mud layer had not changed significantly during the investigation period (Kamphuis J. and Meinsma R. (2013)).

Field measurements in the port of Delfzijl revealed that the 210 kHz reflection corresponds to water densities less than 1.1 ton/m$^3$ and that the 33 kHz reflection corresponds to densities more than 1.2 ton/m$^3$ and mostly in the range of 1.19 ton/m$^3$ and 1.2 ton/m$^3$. Kamphuis, J. and Meinsma, R. (2013) show the relationship between density and viscosity for field measurements in the Zeehavenkanaal which indicates that for densities smaller than 1.19 ton/m$^3$ the viscosity is smaller than 0.13 Pa s.

[5] DRDP: Dredging Residuals Density Profiler

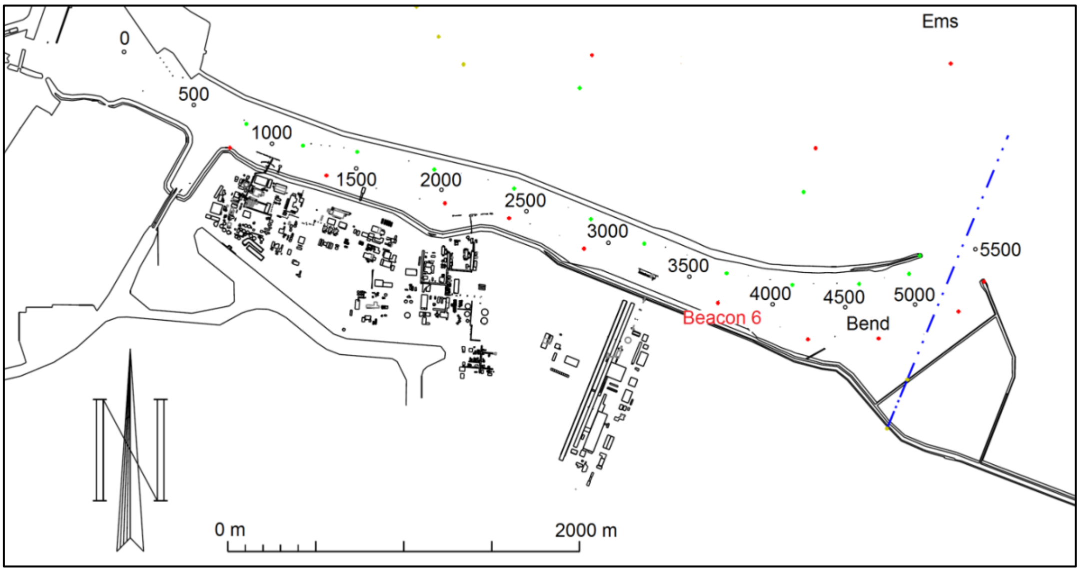


**Figure 1: The Zeehavenkanaal connecting the harbour of Delfzijl to the river Ems, marked by red and green navigation buoys (source: simulator database FHR)**

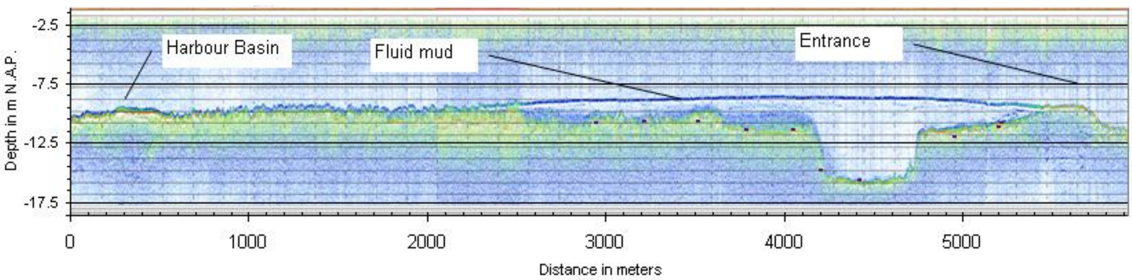


**Figure 2: Parametric echo profile 'Zeehavenkanaal' showing the fluid mud body (Kamphuis, J. et al (2013))**

## 2. SHIP MANOEUVRING IN MUDDY NAVIGATION AREAS

### Nautical bottom approach

In navigational channels covered by fluid mud suspensions, the bottom level and, therefore the depth are not clearly defined. In those cases it is not clear which minimum UKC should be selected, as contact between the ship's keel and mud would not cause any damage but on the other hand a ship's behaviour can change significantly due to the presence of a mud layer (Vantorre, M. (2001)).

Instead of using terms as 'bottom' and 'depth', in muddy navigation areas it is more appropriate to introduce the concepts 'nautical bottom' and 'nautical depth'. A universally accepted definition of 'nautical bottom' has been formulated by a joint PIANC-IAPH working group (PIANC-IAPH-IMPA-IALA (1997)) and was recently confirmed by PIANC (2014) :

> *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.*

### Behaviour of ships in muddy areas

Vantorre, M. (2001) gives an overview of the behaviour of ships in muddy areas based on model testing (at FHR) and full scale measurements (in the port of Zeebrugge) performed in the 1980s and 1990s. This publication states that even if no contact occurs with the nautical bottom a ship's behaviour may be affected by the presence of a mud layer, as a result of two kind of phenomena:

- the rheological properties of the mud, which is particularly of importance if contact occurs between the mud layer and the ship's keel;
- the presence of a two layer system, so that undulations are not only generated in the air-water interface, but also in the water-mud interface. This effect also may affect ship behaviour if no contact occurs.

Vantorre, M. (2001) states that the effect of fluid mud layers with low viscosity on a ship's behaviour mainly depends on the deformation of the interface caused by the pressure field around the moving hull.

These vertical interface motions are influenced by the ship's forward speed:

- At very low speed, the water-mud interface remains undisturbed (1$^{st}$ speed range).
- At intermediate speed an interface sinkage is observed under the ship's bow, which at a certain section changes into an elevation. This internal hydraulic jump is perpendicular to the ship's longitudinal axis and moves towards the stern with increasing speed (2$^{nd}$ speed range).
- At higher speed, the jump occurs behind the stern (3$^{rd}$ speed range).

In Figure 3 the interface motions corresponding to the 2$^{nd}$ and 3$^{rd}$ speed range or shown.

In the second speed range a given propeller rpm results in an significantly lower speed compared to a solid bottom situation, while in the third speed range, the effect of the muddy bottom is practically nil. These observations were related to obstruction of the flow to the propeller due to contact between the ships keel and the risen interface in the second speed range. The same phenomenon results in a reversed effect of the rudder at small rudder angles.

Delefortrie et al. (2010) states that for a vessel navigating at positive UKC with respect to the water-mud interface the rising of the interface will be higher when the density and viscosity of the mud layer are closer to water and that an important rising of thin mud layers only occurs for viscosities lower than a critical value located between 0.12 and 0.18 Pa s.

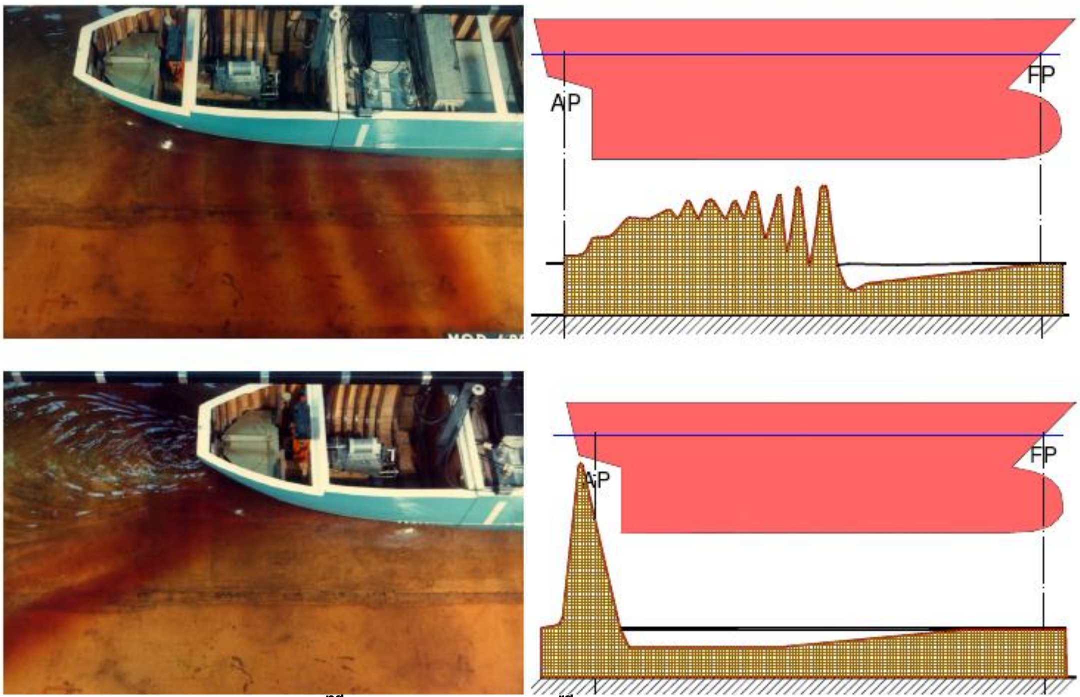


**Figure 3: Interface motions (a) 2nd speed range; (b) 3rd speed range (model test) (Vantorre, M. (2001))**

**Experimental research at FHR**

The behaviour of deep-drafted vessels in muddy navigation areas has been investigated comprehensively at Flanders Hydraulics Research (FHR) by means of self-propelled and captive model tests with models of a suction hopper dredger (1986-1989) and container carriers (2002-2004).

The model tests carried out at FHR in 1986-1989 with a self-propelled model of a suction hopper dredger (see Table 1) in a restricted channel with a bottom covered with a mud-simulating material (trichlorethane + petrol) of low viscosity showed a clear relationship between the ship's speed and the undulation pattern in the interface (Vantorre, M. (1990)) and did lead to the assessment of the behaviour of ships in muddy areas presented in Vantorre M. (2001) and summarized above.

While the tests in the 1980s were carried out in a preliminary experimental setup, the model tests carried out in 2002-2004 at FHR were executed in the towing tank for manoeuvres in shallow water (cooperation Ghent University and Flanders Hydraulics Research) (Delefortrie G. (2007)). Mud layers were simulated by means of a mixture of different types of chlorinated paraffins with petrol in order to control both density and viscosity of the mud layer. Most of the tests were carried out with a 1/75 scale model of a container carrier (see Table 1).

For each combination of mud type, layer thickness and under keel clearance, a captive test program was carried out covering a range of speeds between 2 knots astern and 10 knots ahead, combined with a range of rpm and rudder angle combinations. For each bottom condition and under keel clearance a standard test program of 224 runs was carried out.

| Reference | Vantorre M. (1990) | Delefortrie G. (2007) | CSL Rhine |
|---|---|---|---|
| Testing period | 1986-1989 | 2002-2004 | April 30th, 2013 |
| Experimental setup | self-propelled model | Captive model in towing tank | in situ |
| Density [kg/m³] | 1110 to 1225 | 1100 to 1260 | - |
| Viscosity [Pa s] | 0.002 | 0.03 to 0.46 | - |
| Layer thickness [m] | 0.64 to 1.4 | 0.75 to 3.0 | 1.3 to 7 |
| UKCs with respect to water-mud interface | -10% to 20% | -12% to 21% | +15% to 20% |
| ship model discussed in this paper | suction hopper dredger | 6000 TEU container vessel | general cargo |
| $L_{PP}$ [m] | 115.5 | 289.8 | 111.3 |
| B [m] | 23.0 | 40.25 | 20.5 |
| T [m] | 8.0 | 13.5 | 8.64 |
| $C_B$ | 0.85 | 0.60 | 0.69 |
| Scale factor | 1/40 | 1/75 | 1/1 |

**Table 1: Main characteristics of models used for experimental research in muddy areas at FHR, compared with the ship used for the full scale measurements**

### Mathematical manoeuvring model

Based on the results of the captive model tests on the 6000 TEU container carrier, a mathematical manoeuvring model for simulation purposes has been developed for each bottom condition and under keel clearance (Delefortrie et al. (2005)). A mathematical manoeuvring model consists of a set of equations expressing the longitudinal and lateral force components and the yawing moment as a function of the ship's horizontal motion and control parameters (rudder and propeller action).

The mathematical manoeuvring models were implemented in the full mission bridge manoeuvring simulators of FHR and were applied to determine the operational limits for the navigation in the muddy areas in the port of Zeebrugge (Belgium) by means of real-time simulations performed by Flemish coastal pilots (Delefortrie et al. (2007)).

## 3. SIMULATION STUDY DELFZIJL

In summer 2011 Flanders Hydraulics Research was asked to investigate the influence of sailing at very low and even negative UKCs with respect to the mud-water interface on the inbound and outbound route to the port of Delfzijl. In addition the mud layer characteristics (thickness, density and viscosity) were varied systematically. In order to perform the simulations as realistic as possible, local port pilots experienced with the port of Delfzijl performed the real-time simulations on the full mission bridge manoeuvring simulator of FHR (see Figure 4). A total of six simulation days were organized during which 91 simulations were performed.

Simulations were carried out with a 1700 TEU vessel (180 m x 24 m x 8.1 m) for which the mathematical manoeuvring models were scaled from the 6000 TEU model (see Table 1). The passage through the Zeehavenkanaal was assisted by one tug boat fore and one tug boat aft. Both tugs were ASD tractors with a bollard pull of 30 ton.

The simulations were performed at relevant tidal conditions and the corresponding tidal current profiles derived from current measurements between the breakwaters of the 'Zeehavenkanaal' and the river Ems.

In order to optimally assess the effect of different mud characteristics all simulations were performed at a moderate wind condition corresponding to a wind direction South-West and a wind force 3 Beaufort.

**Figure 4: Impression of simulation study for the Zeehavenkanaal at Delfzijl**

### Mud layer characteristics

Based on the bottom conditions tested in the towing tank and field measurements in Delfzijl (see Figure 5) the combinations of mud characteristics and layer thickness as presented in Table 2 were assessed during the simulation study. The simulations were performed at UKCs with respect to the solid bottom between 10% and 32% if no mud layer was present and at 10% and 15% in case of a mud layer. Four types of mud were studied with densities from 1.11 ton/m³ up to 1.21 ton/m³ and viscosities from 0.03 Pa s up to 0.19 Pa s and with a layer thickness of 0.9 m or 1.8 m. These combinations led to UKCs with respect to the water-mud interface equal to +3.9%, -1.1%, -7.2% and -12.2%. The heaviest type of mud was only tested at the smallest penetration of the mud (UKC -1.1%). During the simulations the mud layer characteristics in the Zeehavenkanaal were assumed to be constant between beacon 6 and the breakwaters (see Figure 1).

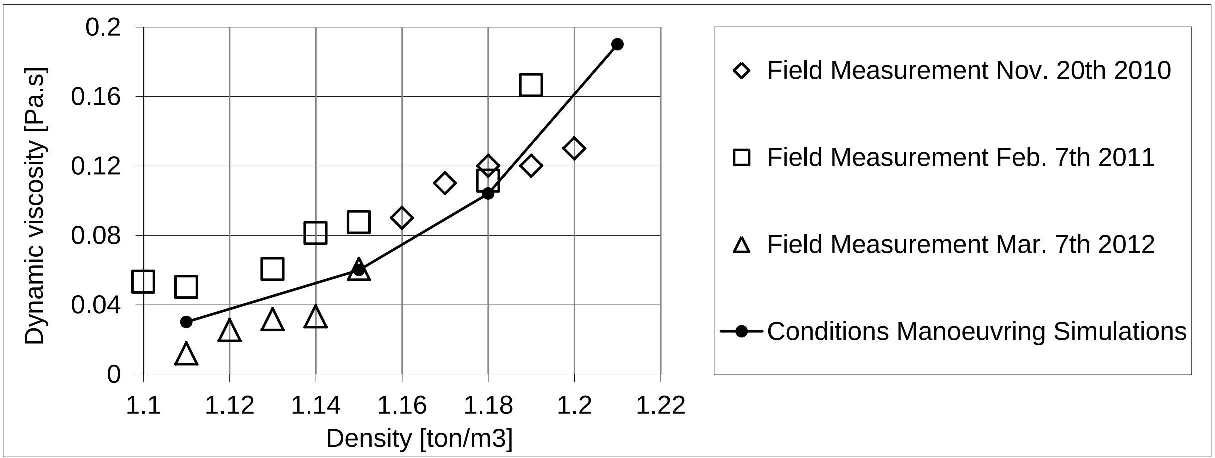


**Figure 5: Density-viscosity relation for field measurements in the Zeehavenkanaal (Kamphuis, J. and Meinsma, R. (2013)) and assessed by means of manoeuvring simulations**

| Density mud | Dynamic viscosity | UKC solid bottom | UKC mud water interface | Depth to solid bottom | Thickness mud layer |
|---|---|---|---|---|---|
| [ton/m³] | [Pa.s] | [%] | [%] | [m] | [m] |
| - | - | 10 | | 8.91 | 0.00 |
| - | - | 15 | | 9.32 | 0.00 |
| - | - | 26 | | 10.21 | 0.00 |
| - | - | 32 | | 10.69 | 0.00 |
| 1.11 | 0.03 | 10 | -1.1 | 8.91 | 0.90 |
| 1.15 | 0.06 | 10 | -1.1 | 8.91 | 0.90 |
| 1.18 | 0.1 | 10 | -1.1 | 8.91 | 0.90 |
| 1.21 | 0.19 | 10 | -1.1 | 8.91 | 0.90 |
| 1.11 | 0.03 | 15 | -7.2 | 9.32 | 1.80 |
| 1.15 | 0.06 | 15 | -7.2 | 9.32 | 1.80 |
| 1.18 | 0.1 | 15 | -7.2 | 9.32 | 1.80 |
| 1.11 | 0.03 | 10 | -12.2 | 8.91 | 1.80 |
| 1.15 | 0.06 | 10 | -12.2 | 8.91 | 1.80 |
| 1.18 | 0.1 | 10 | -12.2 | 8.91 | 1.80 |
| 1.11 | 0.03 | 15 | 3.9 | 9.32 | 0.90 |
| 1.15 | 0.06 | 15 | 3.9 | 9.32 | 0.90 |
| 1.18 | 0.1 | 15 | 3.9 | 9.32 | 0.90 |

**Table 2: Bottom conditions simulated for the Zeehavenkanaal at Delfzijl**

## Results

The application of rudder, rpm and tugboats fore and aft was analysed for different manoeuvres during inbound and outbound simulations. It was noticed that the application of the tug boat aft during the bend in the Zeehavenkanaal (see Figure 1) was a good indication for the difficulty of the manoeuvre. The application of the aft tug boats in the bend in the Zeehavenkanaal is summarized in Figure 6 for inbound simulations and in Figure 7 for outbound simulations.

The simulations revealed that both for inbound and outbound simulations a mud layer with density up to 1.11 ton/m³ and viscosity up to 0.03 Pa.s did not significantly influence the manoeuvres. Even at high penetration (-12.2 %) of the mud-water interface the pilots considered the manoeuvre to be acceptable.

For UKCs of 15% with respect to the solid bottom all simulations were acceptable at all mud characteristics tested. Nevertheless the pilots mentioned that the simulations performed at small positive UKC with respect to the water-mud interface (+3.9%) gave rise to a less controllable ship than when simulating at an UKC equal to -7.2%.

For UKCs of 10% with respect to the solid bottom a mud layer with density 1.15 ton/m³ and higher required an adapted control strategy in order to perform acceptable manoeuvres. This led to a more intensive application of aft tugboat at UKCs with respect to the water-mud interface of -1.1% and -12.2% in inbound simulations and at -1.1% for outbound simulations. For outbound simulations at UKC -12.2% the application of the aft tug boat in the bend was rather moderate. At high penetrations of the mud layer the lateral force exerted by the propeller increases significantly. For a right handed propeller this results in a yawing moment towards port when using the propeller ahead. This effect was favourable for an outbound manoeuvre when the vessel had to perform a bend to port, which led to a reduction of the required assistance by the aft tugboat (see Figure 7). For an inbound manoeuvre, on the other hand, the increased propeller effect was unfavourable resulting in a more important application of the aft tug boat at higher mud densities.

For small penetrations of the mud (-1.1%) combined with UKC 10% with respect to the solid bottom, no influence of the mud characteristics was noticed in the range 1.15 ton/m³ to 1.18 ton/m³.

## Conclusions

For all simulations performed in the Zeehavenkanaal at Delfzijl the pilots succeeded to perform the manoeuvre in an acceptable way. It was concluded that manoeuvres in the Zeehavenkanaal in Delfzijl, with vessels sailing at small negative UKCs with respect to the top of a fluid mud layer were acceptable on the condition that the pilots are experienced with the local situation and well aware of the effects of a mud-water interface on the manoeuvring behaviour of the vessel.

The pilots noticed that the behaviour of the vessel in the simulator at UKCs with respect to the mud layer between +3.9% and -12.2% did differ from the behaviour they experience in Delfzijl at UKCs with respect to the mud layer between +10% and 20%. Especially an important speed reduction experienced in situ was not predicted by the simulation models.

In order to validate the results of the simulation study it was proposed to perform a survey on a deep drafted outbound vessel at a minimum keel clearance of 15% with respect to the 33 kHz survey and on condition that the density of the mud was not greater than 1.11 ton/m³.

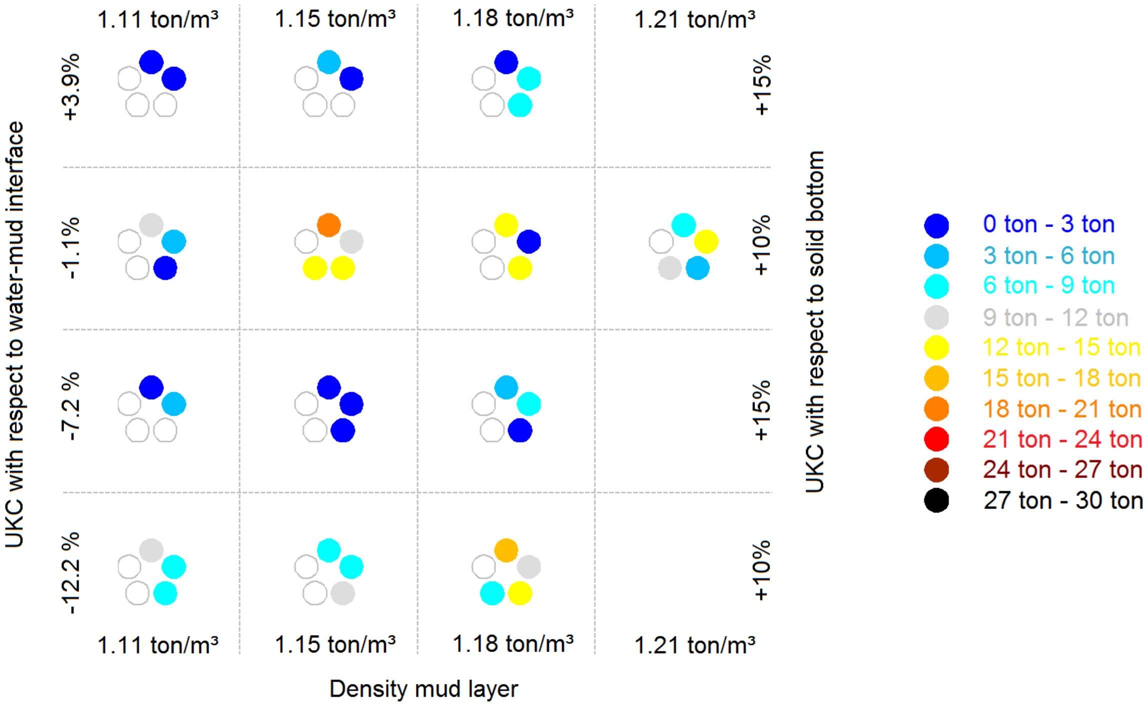


**Figure 6: Average thrust applied by aft tug boat in the bend of the Zeehavenkanaal during inbound simulations. Each coloured symbol represents one simulation run.**

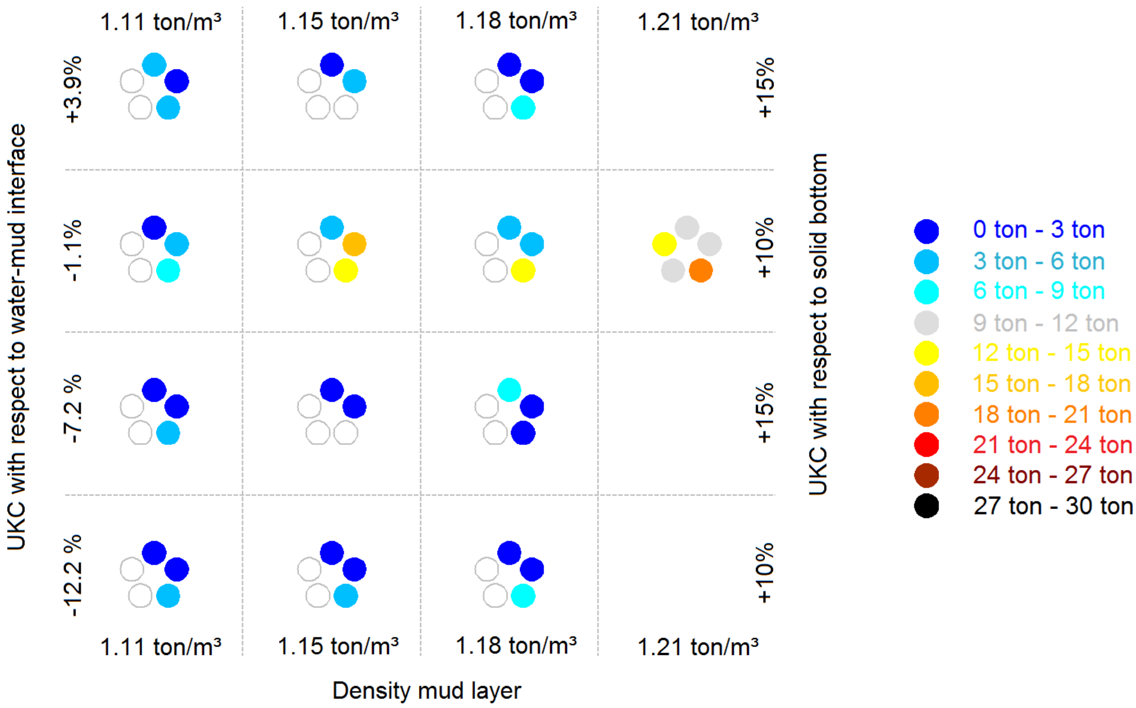


**Figure 7: Average thrust applied by aft tug boat in the bend of the Zeehavenkanaal during outbound simulations. Each coloured symbol represents one simulation run.**

## 4. FULL SCALE MEASUREMENTS

After the simulation study it was decided to perform a reference measurement corresponding to the actual regulations in the port of Delfzijl. The present regulations stipulate a minimum UKC with respect to the water-mud interface of 10%. For this purpose an outbound general cargo vessel was selected. The survey was performed at April 30th, 2013 on the CSL-Rhine (117.9 m x 20.5 m x 8.64 m) between the berth in the Zeehavenkanaal and the river Ems (see Figure 8). During the measurements the survey vessel 'Havenschap 1' performed a single beam survey at 33 kHz and 210 kHz.

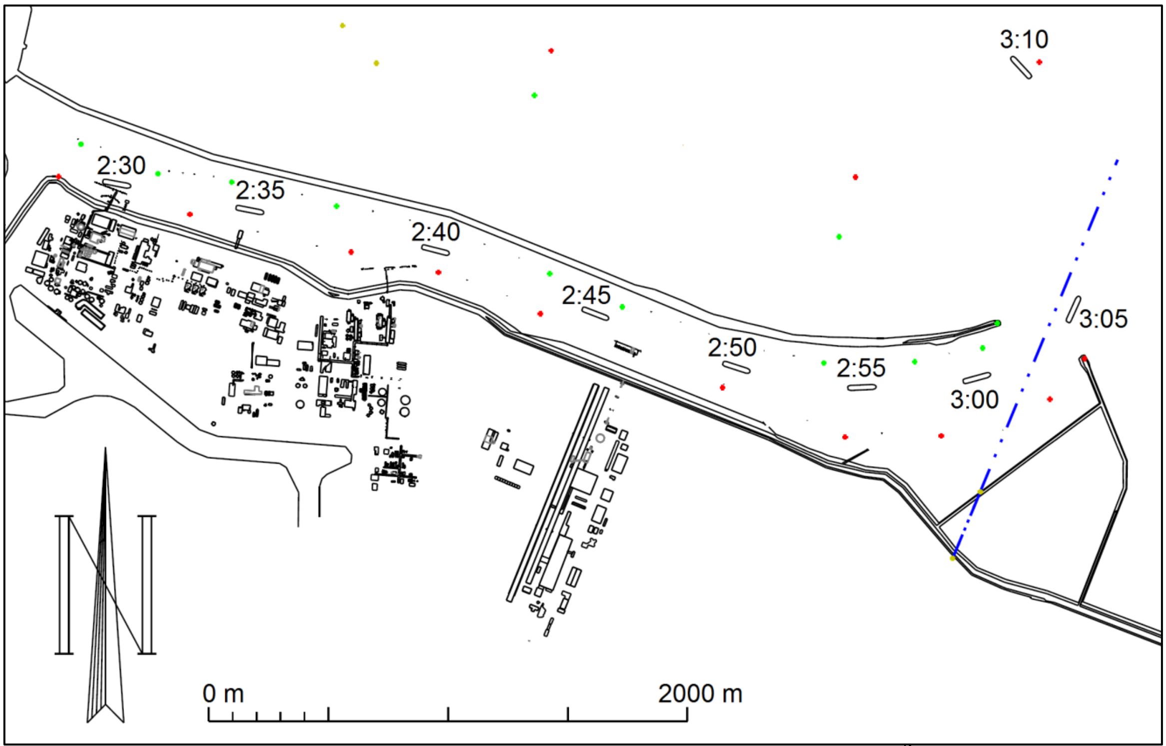


**Figure 8: Timeplot outbound manoeuvre CSL Rhine on April 30th, 2013**

### CSL Rhine

The general cargo vessel CSL Rhine transports salt from the port of Delfzijl to Scandinavia. The main dimensions of the vessel are shown in Table 1. The vessel is equipped with a controllable pitch propeller (CPP) and a Becker rudder. The bow thruster (560 kW) was not applied when sailing above the mud layer and no tug boats were present.


**Figure 9: CSL Rhine moored in the Zeehavenkanaal at Delfzijl**

**Measurements**

The measurement equipment consisted of a pair of RTK-GPS antennas mounted on a pre-calibrated inertial measurements unit (IMU). In this IMU the accelerations and orientations were measured in six degrees of freedom by means of accelerometers and gyroscopes. When fed with RTK-correction signals from reference stations, the measurement equipment has accuracies as indicated in Table 3. The actions of rudder and CPP were registered using video cameras and were post-processed to time series.

The vertical position of the keel with respect to the water surface (dynamic draught) was calculated by subtracting the vertical position of the keel referred to the NAP reference level from tide measurements at three locations in the Zeehavenkanaal. The initial draft at zero speed (8.64 m) was subtracted from the dynamic draft to calculate the sinkage of the ship.

The vertical positions of the water-mud interface and the solid bottom were derived from single beam surveys at 210 kHz and 33 kHz, respectively. Just before the outbound sailing of the CSL Rhine a single beam survey was performed. This survey was combined with a historical survey (December 3rd, 2011) in order to cover the complete trajectory (see Figure 10).

Based on Figure 10 the trajectory can be subdivided into three areas. From 02:30 to 02:40 the ship sailed above a thin mud and the UKC with respect to the water-mud interface was rather high (25% to 35%). At this stage the vessel was accelerated to a maximum speed. Between 02:40 and 03:04 an important mud layer was present as a result of a lower bottom and a higher water-mud interface. In this area the UKC with respect to the water-mud interface varied from 14% to 20% while the UKC with respect to the bottom (33 kHz) varied from 35% to 100%. The thickness of the mud layer varied between 1.3 m and more than 7 m (at the mud trap). When leaving the Zeehavenkanaal (from 03h04) the mud layer disappears.

| Parameter | Unit | Accuracy |
|---|---|---|
| Horizontal position | [m] | 0.010 |
| Vertical position | [m] | 0.015 |
| Roll angle | [°] | 0.06 |
| Trim angle | [°] | 0.01 |
| Heading | [°] | 0.05 |

**Table 3: Accuracy of measurement equipment applied**

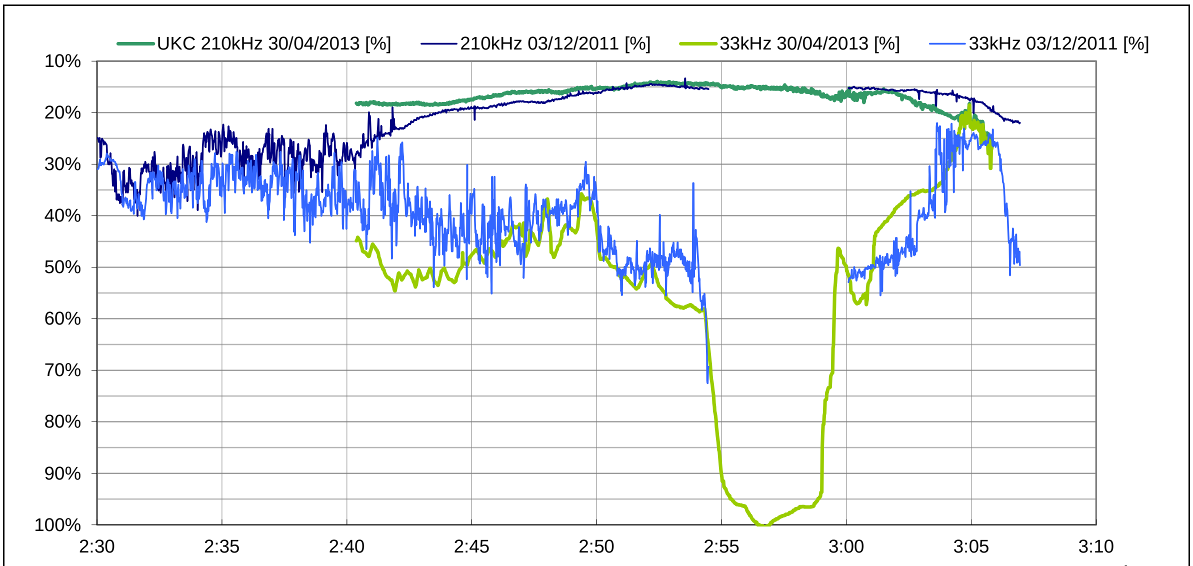


**Figure 10: Bottom profile at Zeehavenkanaal Delfzijl experienced by the CSL Rhine on April 30th, 2013**

**Analysis**

The time evolution of the most important ship parameters are presented in Figure 11. Figure 12 shows a trajectory plot of the manoeuvre in the bend of the Zeehavenkanaal.

*Acceleration at large UKC with respect to water-mud interface (02:30 to 02:37)*

From 02:30 to 02:37 the vessel was accelerated to 5.2 kn corresponding to a propeller pitch equal to 30%. In this area no influence of mud on the ship behaviour was noticed.

*Propulsion in proximity of mud layer (02:35 to 03:04)*

From 02:35 to 02:57 a straight trajectory was performed characterised by small rate of turns. Although the propeller pitch was not adapted, the ship speed gradually decreased from 5.2 kn to 2.98 kn at 02:55. The most important deceleration of the vessel occurred between 02:41 to 02:43 (5.05 kn to 4.46 kn). Figure 10 reveals that in this area the thickness of the mud layer increases and the UKC with respect to the water-mud interface decreases to about 19%. Between 02:43 and 02:54 the UKC with respect to the water-mud interface decreases gradually to 14% and the deceleration continues. As from 02:55 to 03:00 the UKC with respect to the water-mud interface increases to ca. 16% and the UKC with respect to the solid bottom significantly increased (mud trap); a small acceleration of the vessel was noticed (3.27 kn). This acceleration turned into a deceleration again when the UKC with respect to solid bottom decreased again to 50%. At 03:01 the propeller pitch was increased which makes further comparison between ship speed and mud characteristics more difficult. It can be concluded that there is a direct correlation between the UKC with respect to the water-mud interface, the UKC with respect to the solid bottom and the ship speed. The vessel is operating in the 2$^{nd}$ speed range and can be assumed to be partly in contact with the water-mud interface. As noticed in chapter 2 this situation might lead to an obstruction of water flow towards the propeller resulting in less efficiency.

*Manoeuvrability in proximity of mud layer (02:35 to 03:04)*

In order to perform a straight trajectory between 02:35 and 02:46 a rather important use of the rudder was required as can be noticed from Figure 11. Furthermore the sign of the average rudder angle did change at 02:43'30''. Before that time it seemed that rudder angles to starboard were required to perform a straight trajectory while after that time rudder angles to port were necessary. It can be noticed that the roll motion of the vessel is strongly related to the application of the rudder so that the change in sign of the rudder angles from 02:43'30'' also results in increasing negative roll angles. Figure 10 reveals that approximately at 02:43'30'' the UKC with respect to the water-mud interface has values smaller than approximately 18%. It can be concluded that also the manoeuvring behaviour is influenced by the mud layer at UKCs with respect to the water-mud interface smaller than 18%. Both the ship speed and the manoeuvring behaviour of the vessel are influenced by the rising of the water-mud interface between 02:43 and 02:53.

From 02:50 until leaving the Zeehavenkanaal at 03:04 rate of turns to port (altered with straight trajectories) were applied (see Figure 12). Table 4 summarizes the rate of turns reached at several UKCs and thicknesses of the mud layer. From 02:50 to 02:51 the vessel experienced an UKC with respect to the water-mud interface equal to 15%. In order to generate a rate of turn of 9.5 °/min a rudder angle of 23° was required. At 02:53 a UKC of 14% was experienced. At that time a rudder angle of 25° corresponded to a rate of turn 7.5°/min. At 02:58 the ship was sailing above the mud trap leading to a higher UKC with respect to the mud layer and a significant higher UKC with respect to the solid bottom leading to a rate of turn of 8°/min resulting from a rudder angle of 24°. The three cases do not reveal a direct relationship between the mud layer and the manoeuvrability as other phenomena also influence the manoeuvring behaviour (e.g. bank effects).

At 03:01 the propeller pitch was increased from 30% to 52%. In combination with a rudder angle of 35° to port this resulted in a rather small acceleration between 03:01 and 03:04 and initially in an increase of the rate of turn up to 14°/min (03:02) which decreased again to 4.5°/min (03:03). After this the mud layer disappeared and the rate of turn increased again to 20°/min (03:04). The deceleration of the rate of turn when leaving the Zeehavenkanaal was assumed to be a result of the tidal current on the river Ems.

| Time | 02:51 | 02:53 | 02:58 |
|---|---|---|---|
| Propeller Pitch [%] | 30 | 30 | 30 |
| Rudder angle [°] | 23 | 25 | 24 |
| UKC water-mud interface [%] | 15 | 14 | 16 |
| Thickness mud Layer [m] | 3 | 3 | 7 |
| ROT [°/min] | 9.5 | 7.5 | 8 |

**Table 4: Manoeuvring characteristics of CSL Rhine in proximity of mud layer**

## Conclusion

The survey on the CSL Rhine on April 30th, 2013 gives a good insight in the effects of the mud layer on the ship behaviour in the Zeehavenkanaal in Delfzijl in situations corresponding to the actual regulations (UKC with respect to the water-mud interface > 10%) and can be a reference measurement for other surveys with similar ships. Navigating at UKC between 14% and 19% with respect to a mud layer with a thickness of 1.7 to 7.2 m led to a significant influence of the ship's propulsion and manoeuvrability.

Taking into account the relatively limited propeller pitch applied during the outbound sailing of the CSL Rhine indicating the rather high reserves in controllability of the vessel a second survey at a lower positive UKC with respect to the water-mud interface was proposed. This second survey was not yet performed in March 2014.

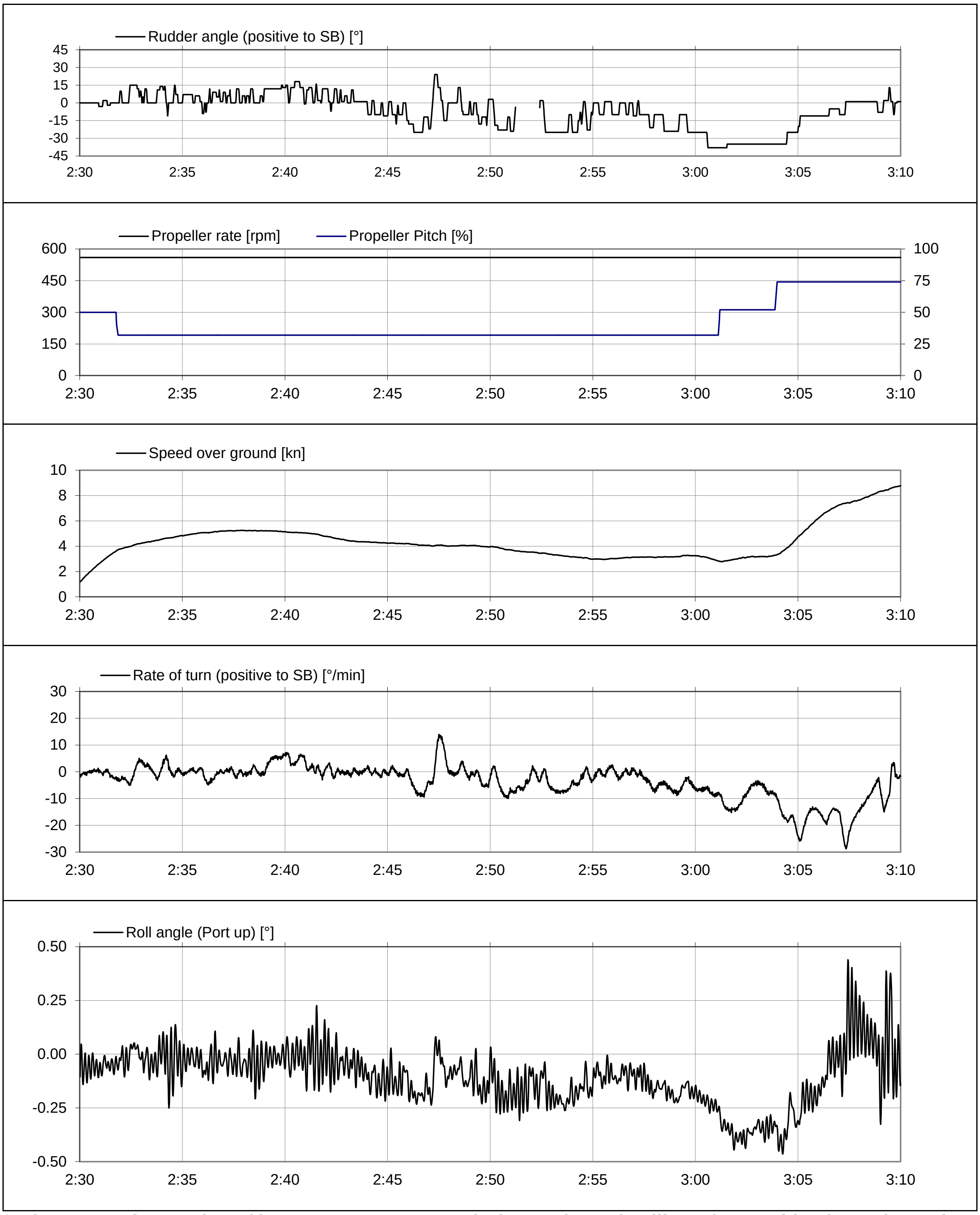


**Figure 11: Time series of important parameters during outbound sailing of CSL Rhine in Zeehavenkanaal Delfzijl.**

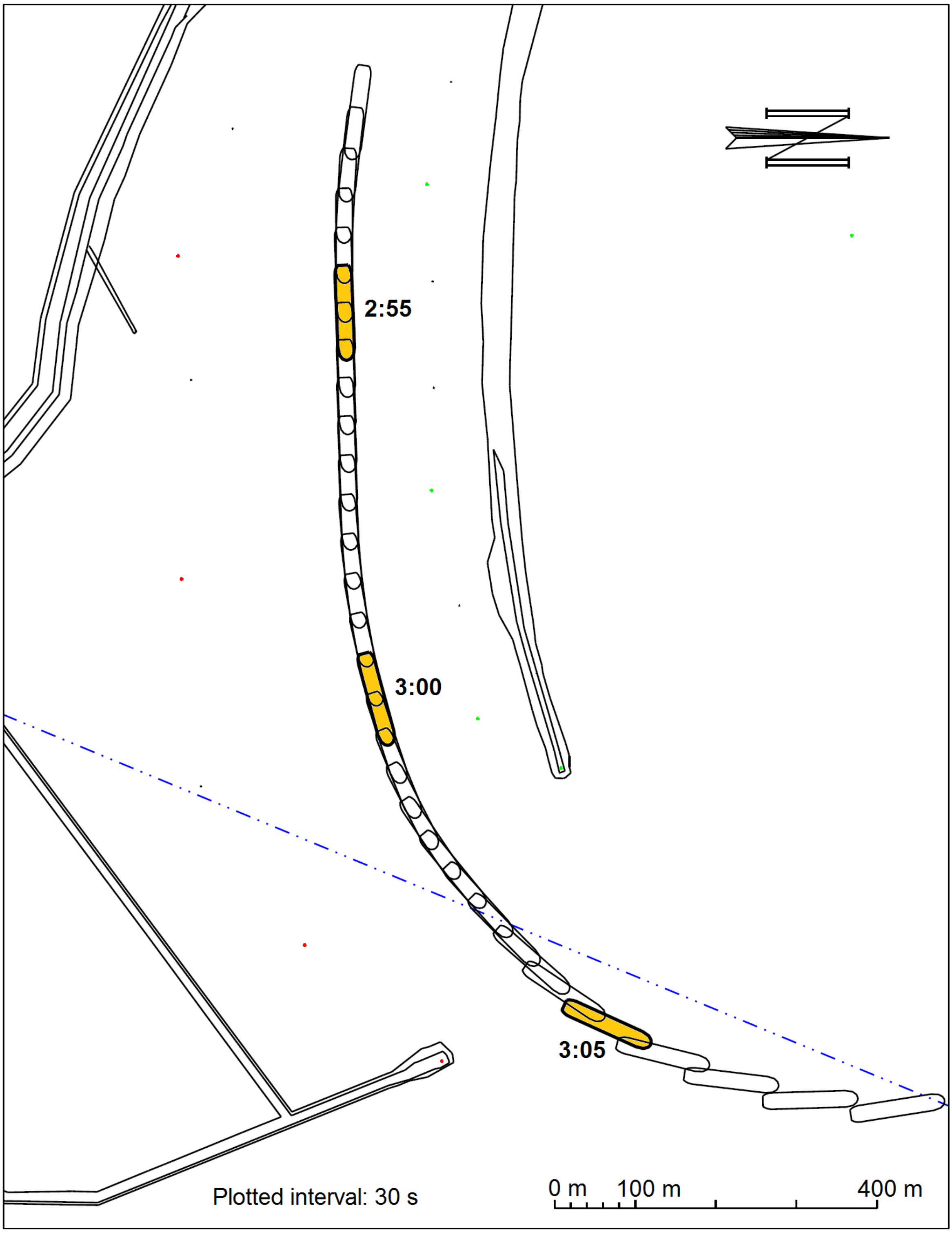


**Figure 12: Trajectory plot bend manoeuvre during outbound sailing of CSL Rhine in Zeehavenkanaal Delfzijl (02:52’30’’ to 03:07’00)**

## 5. CONCLUSION

The paper gives an overview on ship behaviour in muddy navigation areas applied to a case study in the port of Delfzijl.

A general description of the phenomena related to sailing in proximity of a water-mud layer is given together with an overview of the experimental research carried out by Flanders Hydraulics Research and Ghent University (Chapter 2).

The accessibility of the port of Delfzijl was studied by means of real time simulations on a 1700 TEU container vessel at positive (+3.9%) or negative (-1.1% to -12.2%) UKCs with respect to the water-mud interface and with different mud characteristics (Chapter 3). The simulation study revealed the feasibility of manoeuvring in the port at lower UKCs in case of fluid mud characteristics and showed an important influence of the UKC with respect to the solid bottom.

As the cases in the simulation study differed from the actual practice in Delfzijl (UKC interface larger than 10%) the local port pilots involved in the simulation study noticed a different manoeuvring behaviour on the simulator as in reality. In order to judge the effects of lower UKCs on the manoeuvring behaviour of the vessel it was agreed to perform in situ surveys at gradually decreasing UKCs. On April 30th, 2013 a reference measurement corresponding to the actual regulations in Delfzijl was performed on the CSL Rhine at approximately +15% UKC with respect to the water-mud layer (Chapter 4). The manoeuvring behaviour of the CSL Rhine did indeed differ from the behaviour of the 1700 TEU container vessel studied during the simulation study. This can be explained by the important differences in UKCs and ship characteristics. Nevertheless the ship behaviour measured on the CSL Rhine corresponds very well to the conclusions of the model testing (Chapter 2).

The relatively small propeller pitch applied during the outbound sailing of the CSL Rhine indicates the rather high reserves in controllability of the vessel. A second survey at a lower positive UKC with respect to the water-mud interface was judged acceptable but was not yet carried out in March 2014.

## 6. REFERENCES

Delefortrie, G.; Vantorre, M.; Eloot, K. (2005). Modelling navigation in muddy areas through captive model tests. Journal of Marine Science and Technology.

Delefortrie, G.; Vantorre, M.; Verzhbitskaya, E.; Seynaeve, K. (2007). Evaluation of safety of navigation in muddy areas through real-time manoeuvring simulations. Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 132, no. 2, p. 125-135, 2007.

Delefortrie, G.; Vantorre, M.; Eloot, K.; Verwilligen, J.; Lataire, E. (2010). Squat prediction in muddy navigation areas. Ocean Eng. 37(16): 1464-1476. In: Ocean Engineering. Pergamon: Elmsford. ISSN 0029-8018

Kamphuis, J.; Verwilligen, J.; Meinsma, R. (2013). Fluid mud and determining nautical depth. Hydro International January / February: 22-25. Geomares: Lemmer. ISSN 1385-4569

Kamphuis J.; Meinsma R. (2013). Succesfull Approach to 'Keep the Sediment Navigable' in Port of Delfzijl. World Dredging Congress and Exhibition, 3-7 June 2013, Brussels, Belgium (WODCON XX).

PIANC-IAPH-IMPA-IALA (1997). Approach Channels: A Guide for Design. PTC II-30. Final report of the joint Working Group. Supplement to PIANC Bulletin No. 95, 108pp.

PIANC (2014). Harbour approach channels design guidelines. PIANC Report No. 121, 311 pp.

Vantorre, M. (1990). Systematic experimental series with the self-propelled model of a trailing suction hopper dredger above a mixture of petrol and trichlorethane as a mud simulating material: experimental observations and theoretical interpretations. Ghent University / Flanders Hydraulics Research. Ghent / Antwerp. (in Dutch)

Vantorre, M. (2001). Nautical bottom approach: application to the access to the harbour of Zeebrugge. Hansa 138(6): 93-97. Hansa: Zentralorgan für Schiffahrt, Schiffbau, Hafen: Hamburg. ISSN 0017-7504