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MANOEUVRING WITH NEGATIVE UNDERKEEL CLEARANCE: 2ND FULL SCALE FIELD TEST IN THE PORT OF DELFZIJL

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SUMMARY

Wiertsema & Partners (Short: W&P) together with Flanders Hydraulics Research (short: FHR) investigated on behalf of Groningen Seaports (Short: GSP) the influence on the manoeuvrability of a vessel when sailing with a small and negative under keel clearance in the harbour of Delfzijl by performing a full scale field test. The full scale field test was performed in May 2015 during spring tide corresponding to a negative under keel clearance up to -5% UKC at low tide. Several trials were performed during the full scale field test in the harbour entrance channel with different under keel clearances and changing from going inbound to outbound. The paper gives a summary of the full scale field test, used measuring techniques for qualifying the mud layer, an overview of interactions between involved parties and the results.

NOMENCLATURE

cm	Centimetre
FHR	Flanders Hydraulic Research
GSP	Groningen Seaports
kHz	Kilohertz
kn	Knots (nautical speed)
KSN	Keep Sediments Navigable
N.A.P.	Normaal Amsterdams Peil (reference height)
m	Meter
Pa.s	Pascal second
UKC	Under Keel Clearance
W&P	Wiertsema & Partners
UKC210kHz	UKC with respect to 210kHz based on survey of 2nd of May 2015
UKC33kHz	UKC with respect to 33kHz based on survey of 2nd of May 2015

1 INTRODUCTION

The field test is part of the overall project ‘Sustainable Port Management’ for the port of Delfzijl.

One of the primary goals of the project Sustainable Port Management is to investigate whether it is possible to optimize the tidal window of the port without a significant increase of the maintenance dredging volumes. One of the realistic approaches to increase the tidal window of the port is to implement the Keep Sediments Navigable (short: KSN) method. This method has already been successfully applied in the port of Emden.

According to PIANC [1] the nautical depth can be defined as ‘the level where physical characteristics of the bottom reach a critical limit beyond which contact with a vessel’s keel causes either damage or unacceptable effects on controllability and manoeuvrability’. Accordingly, nautical depth can be defined as: the instantaneous and local vertical distance between the nautical bottom and the undisturbed free water surface.

The project ‘Sustainable Port Management’ for the ports of Delfzijl and Harlingen is conducted in four separate phases. The first three phases were executed from 2010 until 2013. In 2013 a full scale field test was executed consisting of a sailing trial with the vessel ‘CSL Rhine’ and dredging trials using the dredgers ‘Meerval’ and ‘Airset'. The dredger “Meerval” is also used in the port of Emden to implement the KSN method [2].

Based on the feasibility study in the first phase of the project it was concluded that, based on the mud conditions at that time, it was realistic to implement the KSN-methodology for both ports. To further test the feasibility of the KSN-methodology computer simulations were carried out during the second phase of the project. For these simulations, the lay-out of the port of Delfzijl including the mud and current conditions were implemented into a ship manoeuvring simulator using the expertise and facilities of FHR in Antwerp and Ghent University (Maritime Technology Division).

The influence of sailing at very low and even negative Under Keel Clearance (short: UKC) with respect to the mud layer on the inbound and outbound sailing to/from the port of Delfzijl were investigated in a full mission bridge simulator. During these tests the thickness of the mud layer and the mud density were varied systematically. In order to perform simulations as realistic as possible local pilots, experienced with the port of Delfzijl, did participate in the study. The investigations carried out during the second phase of the project confirmed that it was realistic to implement the KSN-methodology for the port of Delfzijl.

The third phase of the project was a full scale field test. The test was executed in the port of Delfzijl. The first full scale field trial with the CSL Rhine was carried out successfully and provided sufficient reference data for further field trials. The data gathered was sufficient to make recommendations for the next field trial to determine the nautical depth under present dredging practices.

The results of the simulation studies and the field trial were presented to an international audience on the occasion of the 33th PIANC Congress in San Francisco (USA) [3]. Referring to comprehensive model test studies performed at FHR [5], the major impact of the presence of fluid mud in situations with a relatively high UKC (10% - 20%) with respect to the mud-water interface on the manoeuvrability and propulsion of the vessel is due to the hindered flow towards the propeller and rudder. An important phenomenon in this respect is the internal wave which is generated by a sailing vessel in the mud-water interface in case of sediments with weak rheology , which appears to affect the ship's behaviour particularly in a speed range which corresponds to the speed applied in the entrance channel. Especially in case of rather thick mud layers, these phenomena appear to smoothen if the mud layer is penetrated by the ship's keel, which gives reason to a significant potential reduction of the UKC with respect to the mud-water interface.

Based on the results of the earlier simulation study and the field trial with the CSL Rhine it was thought acceptable to start with the second full scale field test.

The main aim of the field trials was verification of the simulator results by full scale field tests with an instrumented representative vessel with adjusted UKC conditions in agreement with the captain and the pilot. The tests were performed in the port of Delfzijl.

2 SECOND FULL SCALE FIELD TEST

2.1 FIELD TEST DESCRIPTION

The full scale field test was executed in the port of Delfzijl in the early morning from 05:38AM until 09:19AM on the 20th of May 2015. The dredger 'Geopotes 15' from Van Oord Nederland b.v. was used for the trial runs.

The second full scale field test consisted of four trial runs with the selected vessel. Each trial run was started at predefined tide levels in order to experience a wide range of UKC. These different departures are numbered, subsequently T0, T1, T3 and T4. Departure T0 is the reference measurement with an UKC_{Gross} >10% with respect to top fluid mud (210kHz). This condition corresponds to the actual accessibility regulation of the port. Departure T1 was executed before the low tide, T3 was executed at low tide and T4 after low tide.

During the departures, the vessel's behaviour (use of propeller, rudder, thruster and tugs including corresponding speeds and yaw velocities) was monitored and analysed in a similar manner as during the computer simulation runs (FHR) from the second phase of the project and the first full scale field test.

During the field trial an assisting tug from Wagenborg Shipping named the 'Waterstroom' was assisting the trials. The 'Waterstroom' has a maximum bollard pull of 60 ton. If necessary the tug would be attached to the aft of the vessel to mitigate any risk of an uncontrollable vessel.

Before the trials and after each run the in-situ density profiles of the fluid mud were measured at pre-defined locations with the support vessel 'Havenschap 1'. Multi beam surveys were performed from this before and after the field trial as well.

The planning for the field trial was based on the predicted astronomical tides supplied by the Dutch governmental organization Rijkswaterstaat.

2.2 TIME SCHEDULE

The different timings for the trial runs of the second full scale field test are presented in Table 1. Run T2 was scheduled in the first planning but during the kick-off meeting on 2015-05-19 this run was cancelled due to expected lack of time after run T1. Run T3 was scheduled at low tide and could therefore not be shifted.

Table 1. Time schedule trial runs

Run	Time	Trial run locations
T0	05:30AM – 06:15AM	B05 ➔ B17
T1	06:15AM – 07:00AM	B08 ← B17
T3	08:05AM – 08:30AM	B08 ➔ B17
T4	08:45AM – 09:25AM	B05 ← B17

2.3 LOCATION

The trial runs were executed in the area with a known amount of sediment (fluid and consolidated mud) which was from reference point B05 until B17 (Figure 2). This is a total length of approximately 3400 meters as can be seen in Figure 1.

Due to the low tide it was not possible to execute the trial runs over the total length of the entrance channel during all runs, as the normal applicable safety precaution in the port of Delfzijl of 10% UKC_{Gross} was maintained towards the hard soil (33kHz survey). This led to a shorter run for trial run T1 and T3 of around 2200 meters. In Figure 1 the track covered during the four trial runs is presented.

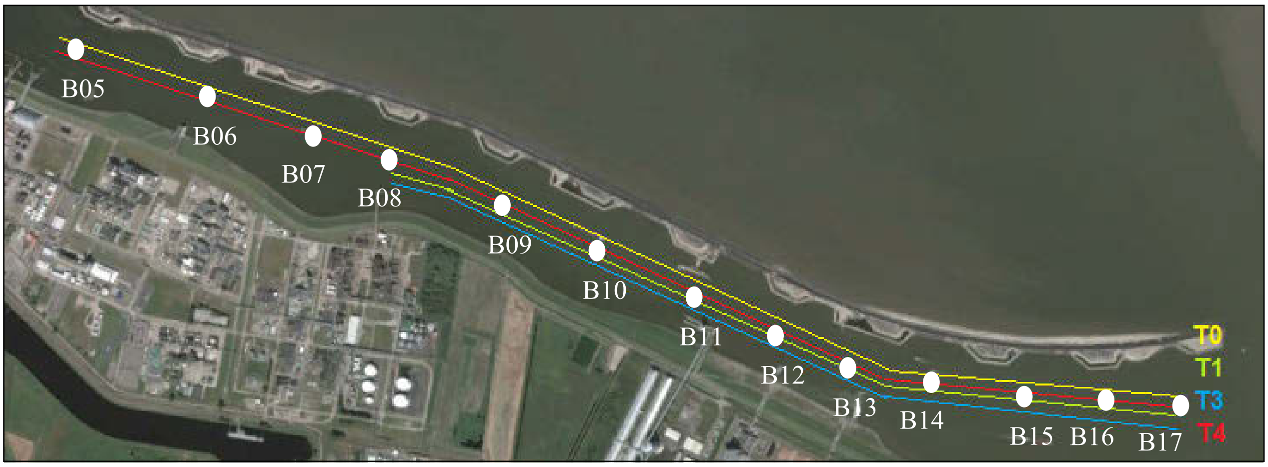

Figure 1. Location of the different trial runs (Source: Google Earth and W&P)

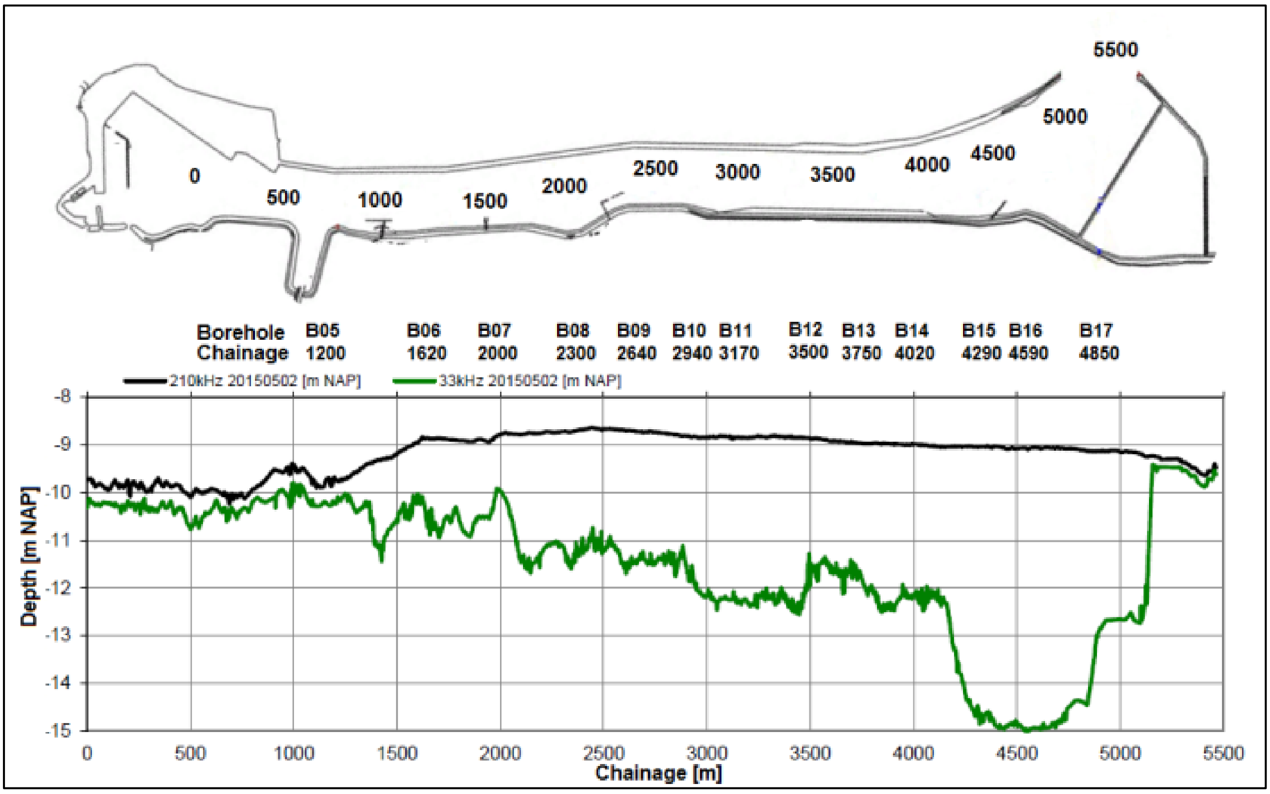

Figure 2. Location of the reference points on a longitudinal scale (source: FHR and W&P). The black line represents the 210 kHz reflection (top fluid mud), the green line in the bottom window represents the 33 kHz reflection (hard bottom).

2.4 VESSEL

During the simulation study a container carrying vessel was used.

For the second full scale field test it was preferred to monitor a vessel which has more or less equal dimensions as the vessel used for the simulation study. Although there is a difference between the vessels used in the simulation study and field test, the vessel used for the field test is representative for the port of Delfzijl. This is also confirmed by the pilot. All expected effects based on the simulation study were experienced during the field trial.

The second full scale field trial was executed with the 'Geopotes 15' from Van Oord Nederland. This vessel is a trailing suction hopper dredger and has the following main characteristics:

- Length	132 meter
- Width	23.6 meter
- Draft	7.4 meter (filled with water) 9.40 meter (dredging mark)
- Propellers	2

During the trials the vessel was partially loaded with sand in the hopper, to ensure no water would flow out of the hopper and consequently changing the draft of the vessel.

3 RESULTS MEASUREMENTS

3.1 IN-SITU MEASUREMENTS

3.1 (a) Survey

Bathymetric survey was performed by GSP with the support vessel ‘Havenschap 1’. The ‘hard’ soil can be surveyed with a 33kHz survey and the top of the fluid mud with a 210kHz survey. Several surveys were executed and presented in Table 2 and Figure 3.

Table 2. Bathymetric surveys

Date in May 2015	Survey
2nd	Multibeam 33kHz and 210kHz
20th (1 hr. before T0)	Multibeam 210kHz
20th (2 hrs. after T4)	Multibeam 210kHz
22nd	Multibeam 210kHz

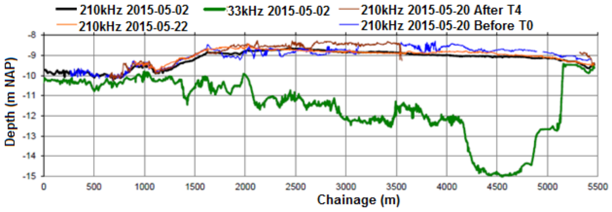

Figure 3. Longitudinal section and surveys executed in May 2015 (Source: FHR)

Figure 3 shows that the 210 kHz reflections on the day of the trials are at a higher position than the reflections measured on the 2nd and 22nd of May 2015. One possible explanation for the difference of the sediment thickness is the earlier passages of Geopotes 15. Since the differences in altitude can reach up to 0.7 m they have a significant impact on the UKC towards top sediment for a vessel with draft 7.4 m (see figure 4 for visualization). To illustrate the differences in UKC during the field test, the values of UKC_{Net} to the top of the sediment, were compared for a position halfway trial run T3, corresponding to different surveys carried out in May 2015:

- -4.6% based on survey 2nd of May 2015;
- -9.2% based on survey 20th of May 2015, prior to the test runs;
- -11.7% based on survey 20th of May 2015, after the test runs;
- -4.1% based on survey 22nd of May 2015.

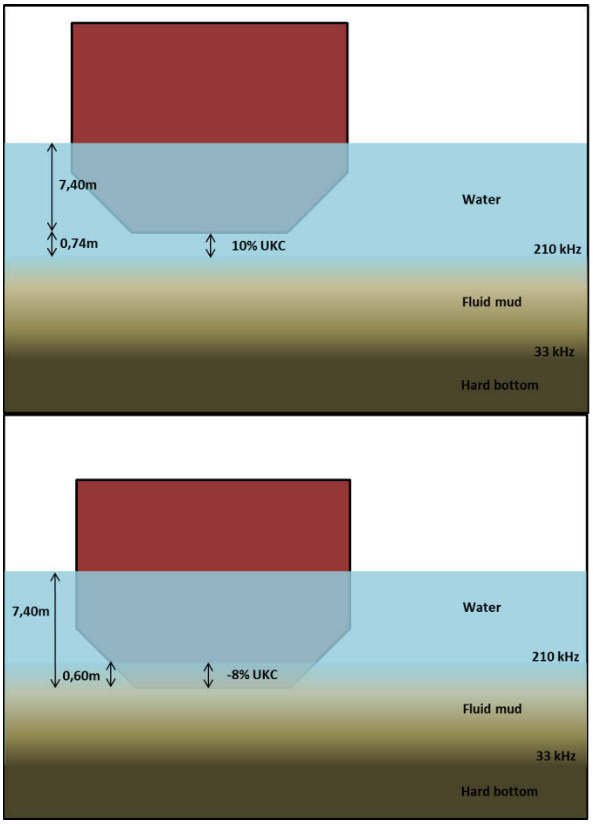

Figure 4. Schematic presentation of +10% UKC_{Gross} and -8% UKC_{Gross} conditions in respect to the 210 kHz reflection of the single beam measurements.

3.1 (b) Density profiles

The in-situ density profiles were measured on the 18th and 20th of May with the SoniDens. The SoniDens is an accurate piece of equipment for the measurement of the in-situ density of fluid mud (unconsolidated sediment).

3.1 (c) Sampling

On the 18th of May 2015 fluid mud samples were taken at 4 different locations with a Sludge Sampler (see figure 5).

The Sludge Sampler is a sampling tool for taking samples of the fluid mud layer which is present in the entrance channel of the Port of Delfzijl. The Sludge Sampler takes 11 samples over a height of 211cm. The samples were collected in jars with a volume of 720ml.

Figure 5. Taking fluid mud samples using the Sludge Sampler

3.1 (d) Water level

The water level during the trial runs at three different locations was measured with a Diver datalogger. The Diver datalogger measures the water pressure and temperature in time.

The Diver data loggers were situated along the entrance channel of the port of Delfzijl. During the tide the port is filled with seawater, which runs in and out via the entrance channel. Differences in water level height will occur due to the inflow and outflow of water in the entrance channel. Therefore three pressure sensors were installed along the route of the trial run to measure the exact water level.

Based on the measurements the uncertainty of the water level measurement was estimated at 8cm. This is an additional uncertainty of 1.1% in the determination of the UKC during the field runs.

3.1 (e) Wind

The average wind speed and direction was measured by Groningen Seaports with equipment installed permanently at the Diver 1 location in the entrance channel.

3.1 (f) Temperature air and water

The average air temperature was measured with a Baro Diver at diver 1 location in the entrance channel.

The water temperature was measured during the in-situ density profiles. The values are different per location and over depth. The average temperature for the brackish water in the port was between 8° and 12° Celsius.

3.1 (g) Maintenance dredging

The sediment in the entrance channel is conditioned by an air injection dredger called the ‘Airset’. The Airset technique is presently used in Delfzijl for maintenance dredging. The conditioning of the mud is done during the outgoing tide from chainage 4500m towards 5500m.

3.2 LABORATORY MEASUREMENTS

3.2 (a) Samples

The samples were tested for physical and rheological properties in the laboratory of W&P in Tolbert (NL). The laboratory results were checked by the sediment laboratory of FHR. Below paragraphs describe the different tests and results.

Important for navigability at minimal or negative UKC is the resistance of the ‘muddy sediment’ against the vessel’s movement. The resistance of ‘muddy’ sediment is generally shear stress dependent. Rheological properties to be tested regarding this resistance are the yield point and dynamic viscosity. The rheological properties differ over time and therefore tests were performed on samples after stirring and 2 days after stirring.

The rheological properties were determined with the Brookfield DV3T. The ratio of shear stress and shear rate of the dynamic viscosity and the yield stress is determined by applying the Bingham method [4] on the flow curve (shear rate against shear stress).

The wet and dry densities were determined for all fluid mud samples for which rheological tests were executed. The wet density was acquired by filling a ring with known volume (approximately 17 cm^3) with the fluid mud. The ring is weighted and the wet density is calculated. The dry density is acquired by drying this sample and weighing this again.

Average organic content of the fluid mud was 17.4% and average carbonate content was 9.15%.

4 RESULTS MONITORING VESSEL POSITIONS AND ORIENTATIONS

The vessel’s positions and orientations during the field test were measured and processed in time series for each trial run. The evolution of the manoeuvrability of the vessel is described with the interaction between the fluid mud layer and the propeller.

The following items were monitored during the field test:

- The position of the vessel in six degrees of freedom,
- Rudder angles,
- Propeller pitch,
- Draft,
- Vertical position.

4.2 MONITORING EQUIPMENT

4.2 (a) Vessel positions in 6 degrees of freedom

The measuring equipment consists of a F185 positioning system from Coda Octopus (developed on behalf of FHR) which is placed inside a rigid housing with a span width of 2 meter. The raw data as well as the processed position, speed, and acceleration data is transmitted via Wi-Fi to a laptop situated on the bridge.

4.2 (b) Rudder angles

The evolution of the rudder angles during the field test is monitored by means of photo-cameras (1Hz) which capture the rudder angle indicator on the bridge of the vessel.

4.2 (c) Propeller pitch

The Geopotes 15 is equipped with two CPP (controllable pitch propeller) propellers. With CPP propellers the propulsion is realized and controlled by a variance in pitch of the propeller blades. The evolution of the propeller pitch is acquired via the datalogger of the vessel.

4.2 (d) Draft

In the datalogger the draft of the vessel, hopper volume and vessel speed was logged.

This draft measurement is based on pressure measurements in the hull. In the event that the vessel achieves an important speed through the water, the pressure around the body is influenced by the flow along the hull, and the depth measurement is therefore unreliable. The depth measurement therefore only delivers reliable values with negligible speed of the vessel. The static draft (draft at cruising speed equal to zero) varied during the trial run. The reason for this is that the water volume in the hopper tanks leaked and was replenished in order to compensate so that the mass of the vessel (and hence the static draft) remained almost constant.

The periods during which trial runs were conducted (5h30 to 7h00 and 8h05 to 9h25) the drafts fore and aft deviate relatively little from 7.4 m (at around 10 centimetre). A deviation of 10 cm in static draft gives rise to a deviation in the UKC equal to 1.4%.

4.2 (e) Vertical position

The vertical position of the vessel is influenced by the vertical position of the reference point, the roll angle and trim angle. The static values of the roll angle (list) and trim angle were calculated as the average during the first part of the measurement when the vessel was not moving and did not use the propellers. The trim and roll angles varied little in this period.

Due to the variable static draft during the measurement campaign (due to a variable content of the hopper tanks) the squat of the vessel could not be accurately estimated.

Due to the uncertainty about the static drafts and water level measurements on one hand, and by the accurate determination of the vertical distance between the measuring point and vessel's keel on the other hand, the UKC is defined as the vertical distance between keel and bottom. This UKC corresponds to the so-called UKC_{Net}, while the UKC_{Gross} is reduced with the squat of the vessel. UKC_{Net} will have a lower value than UKC_{Gross} (defined based on static draft), see figure 6.

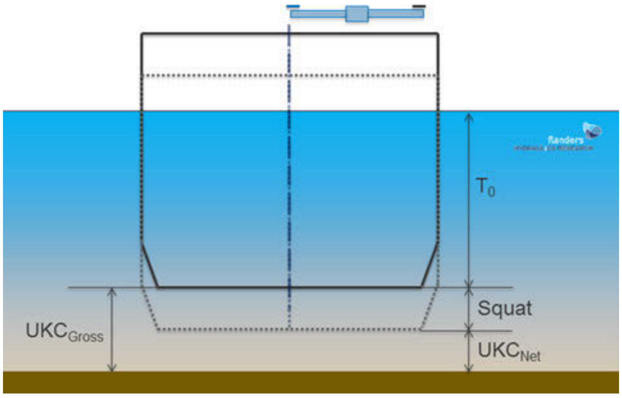

Figure 6. Definition of the UKC (Source: FHR).

5 ANALYSIS

5.1 MUD CHARACTERISTICS

5.1 (a) Physical properties

The average organic content of the fluid mud is 17.4%.

The average carbonate content is 9.1%.

The particle size distribution shows an average silt content of 34.7%.

5.1 (b) Rheological properties

The rheological properties of the fluid mud samples taken before the field test are compared to the previous investigations for this project and the ports of Emden, Rotterdam and Antwerp (Deurganck Dock).

The results of the rheological tests show the difference in characteristics directly after stirring and 2 days after stirring, see figure 7. As expected and found in previous investigations in Delfzijl the yield point was higher for the same density after 2 days. This is due to the thixotropic behaviour of the mud and its ability to regain strength after conditioning.

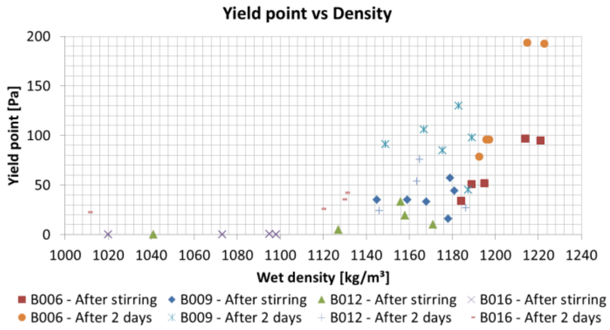

Figure 7. Yield point vs Density (Source: W&P).

Figure 7 shows a figure in which the yield point is presented against the measured density. The yield point increases with density for all samples taken over the length of the entrance channel.

The rheological properties can be positioned in between Rotterdam/Emden and Antwerp (Deurganck Dock). When the mud is conditioned (after stirring) it shows to be more fluid and tends towards behaviour similar to Emden port.

The wet density at the yield point threshold (defined in previous feasibility study at 100 Pa) is for the stirred mud around 1210 kg/m³ and for the unstirred mud after 2 days around 1150 kg/m³ based on the rheological tests performed over the length of the entrance channel.

The mud conditions used for the model tests (performed by FHR) during an earlier phase of the project are different from the conditions presented in this paper. The dynamic viscosity density combinations used during the model tests in Antwerp were as follows:

- Mud D, 1108 kg/m³, viscosity 0.03 Pa.s.
- Mud C, 1149 kg/m³, viscosity 0.06 Pa.s.
- Mud B, 1179 kg/m³, viscosity 0.10 Pa.s.
- Mud H, 1207 kg/m³, viscosity 0.19 Pa.s.

The dynamic viscosity of the samples taken during the field test are compared with the dynamic viscosities used with the model tests.

The dynamic viscosity results after stirring (conditioning) are closest to the model tests mud characteristics. The tests after 2 days give a higher result than after stirring for the same density.

During an earlier phase of the project the effect of temperature on the dynamic viscosity of the samples was investigated. Comparing these results with the current results, for the tests after stirring, it was concluded that the differences at the lower densities could not be explained by differences in temperature.

The dynamic viscosities at certain densities used for the model tests are lower than during the field tests. The effect on the ship's behaviour, however, is negligible because the viscosities are within the same range [6].

5.2 DENSITY PROFILES

The mud density profiles taken on the 18th of May before the trial runs were compared to the results of the samples taken with the Sludge Sampler. The densities determined in the laboratory are corresponding with the densities of the in-situ density profiles. No discrepancies were observed.

Based on the density profiles and 210kHz -33kHz survey data the test area is subdivided in three sections based on:

- Thickness of the mud layer;
- Intensity of maintenance dredging by the 'Airset'.

In all three sections (B05 until B07 and B08 until B14 and B15 until B17) of analysed density profiles a decrease in in-situ densities is observed below the top of the fluid mud layer (210 kHz) after trial runs T3 and T4, which could be explained due to the turbulence of the propeller which is in contact with the fluid mud layer. The influence by the propeller could reach several meters below the initial top of the fluid mud layer (210 kHz). The clear distinction of the top of the fluid mud layer is changed in an unclear density profile where the density gradually increases over depth.

In section 3 (B15 until B17) the fluid mud is conditioned by the 'Airset'. Lower initial densities were present, before trial runs took place, compared to the initial densities of section 1 (B05 until B07).

Section 2 has a clear difference between the initial densities and the densities after the trial runs. The dense fluid mud layer was clearly diluted and distributed over the depth.

The mud in section 1 was less than 1.8 meter thick and situated furthest away from the entrance of the channel. The initial profile shows a density which is clearly higher than the initial densities in section 2 and 3. The diluted fluid mud is seen at the same density as the other sections after trial runs T3 and T4.

The average density profiles between different measurements of section 2 are very clear (figure 8). The fluid mud is diluted roughly 3 times until around 2.5 meter below the 210kHz line. The arrows show the decrease in density below the 210kHz line and the increase in density above the 210kHz line.

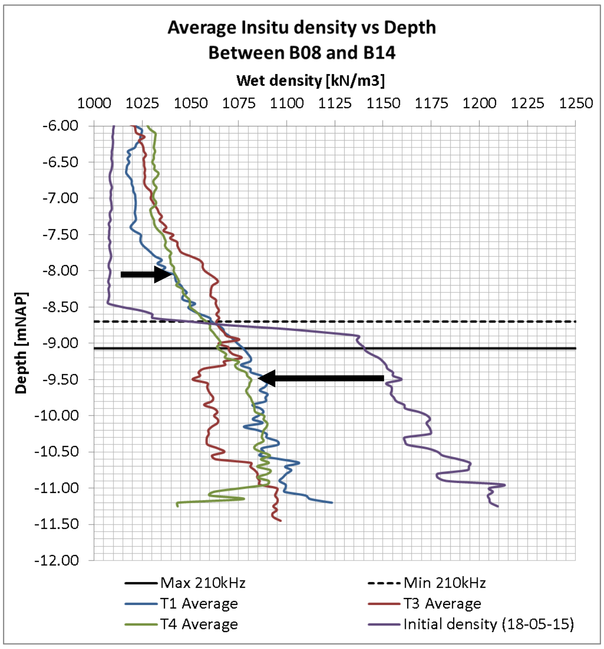

Figure 8. Average Insitu Density versus Depth for the area between B08 and B14.

5.3 MONITORING

The different runs during the field trial are analysed based on the vessel's manoeuvrability and presented in the following paragraphs. In this analysis the mud-water interface was assumed to correspond to the 210kHz survey performed on May 2nd. However, analysis of the density profiles (figure 8) revealed that as a result of consecutive distortions of the mud, the water-mud layer was not well defined during the full scale tests.

5.3 (a) Trial run T0

The results of the T0 run performed with the 'Geopotes 15' appear to be similar to those observed for the 'CSL Rhine' with respect to the evolution of the speed of the vessel. Regarding the manoeuvring behaviour it shows that the disturbance, caused by the sediment-run at UKC210kHz$_{Net}$ equal to approximately 14%, is less than it was on the 'CSL Rhine'. It can be stated that the 'Geopotes 15' is a suitable vessel to assess the impact of different soil conditions and under keel clearances on the vessel's behaviour.

The vessel's speed at a propeller pitch ratio equal to 41% was found to decrease from initial 5.5 kn (CPP at 40%) when the 'Geopotes 15' reached the sediment layer to 2.83 kn at the location of the sediment trap. The rudder angle required appeared to be limited to the execution of the manoeuvres above sediment. The largest rudder angles that had to be handled during the T0-run, can be ascribed to bank effects.

At the height of borehole location B10 a relatively large speed reduction occurred. The master and pilot also noticed vibrations in the vessel, although the strength of the vibrations was definitely not assessed as exceptional or alarming.

5.3 (b) Trial run T1

During sailing into the entrance channel a major rudder change and associated yaw movement must be realized when the vessel reaches the port mouth at relatively high speed. Trial run T1 shows that for UKC$_{Gross}$ in accordance with the current accessibility criteria (UKC210kHz$_{Gross}$ > 10%) there is a significant influence of the sediment on the vessel's behaviour. For example, when the vessel was located above the sediment layer, despite the combination of propeller pitch ratios 41% with maximum rudder angles, the initial yaw speed dropped completely resulted in. Also the vessel's speed showed a significant drop over a relative short distance from 5kn to 2.14kn. Limited temporary increases in propeller pitch (up to a maximum of 78%) was found necessary in order to go through a favourable route.

After the required course change was realized in the port mouth, T1 showed a straight trajectory accompanied by small rudder angles and low yaw velocities. During this process the vessel's speed showed a minimum at the same location as was the case in the trial T0 (at borehole location B15).

The reduction of the sediment layer thickness and the reduction of UKC33kHz when sailing out from the sediment trap gave reason to a limited speed reduction. After this the ship speed stayed constant throughout seven minutes at approximately 2.3kn, although the UKC210kHz$_{Net}$ decreased from 11.3% to 7.2%. It was further noted that during the T0-trial run at the same straight trajectory the speed stagnated at 3.65kn and a UKC210kHz$_{Net}$ equal to 15%.
A further reduction of the UKC210kHz$_{Net}$ (from 7.2% to 5%) gave rise to an increase in vessel speed towards 2.87kn at the end of the trial run.

5.3 (c) Trial run T3

The trial run T3 performed with UKC210kHz$_{Net}$ ranging between -5% and +1% had a very good result. With the same propeller settings higher speeds could be achieved than in T0 and T1. This indicates an improved propeller efficiency with keel penetration compared to the case of UKC$_{Net}$ towards top sediment of more than +7%. The manoeuvrability of the vessel was found similar to the manoeuvrability during the T0 trial run.

Remarkable during trial run T3 was that the ship speed seemed to be mainly influenced by the thickness of the sediment layer where thicker mud layers, despite the higher UKC to solid soil that accompanied it, gave reason for lower ship speeds.

Both captain and pilot were positively surprised by the vessel's behaviour during the trial conducted at T3 with negative UKC_{Net}. Despite the realistic ship speed with moderate propeller use, the vessel showed good manoeuvrability and vessel's vibrations were limited.

5.3 (d) Trial run T4

Trial run T4 was accompanied by UKC_{Net} towards top sediment which reached small and alternating positive and negative values. At the start of the trial run an unfavourable manoeuvring behaviour seemed to occur above the sediment trap with $UKC210kHz_{Net}$ up to +3%. In the same area also the minimum ship speed in this field run occurred. During the further course of the trial run T4 the ship speed still showed different extremes which could always be related to bottom conditions.

Summarizing it could be stated that small negative $UKC210Khz_{Net}$ (in this trial to -2%) result in higher ship speeds and better manoeuvrability than small positive UKC_{Net} (in this trial run around +3%). Moreover the T4 trial run shows that with small positive UKC_{Net} with respect to the mud-water interface a larger thickness (in spite of the larger UKC with respect to the solid soil) corresponded to a less favourable manoeuvring behaviour.

6 CONCLUSIONS

Summarizing it can be stated that based on the trial runs an UKC_{Net} between 0% and roughly +14% (up to 20%) has a significant influence on the vessel's behaviour, see figure 9. It should be noted that the current minimum operational UKC_{Gross} of +10% is already in the unfavourable range. Based on the trial runs, no reduced manoeuvrability is expected for an UKC less than +10% to penetration in to the sediment up to an UKC of -5%.

From reference [6] it is known that the major impact of relatively high UKC (10% - 20%) on the manoeuvrability and propulsion of the vessel is due to the hindered flow to the propeller and rudder. Especially in cases where sediment layers are present with a weak rheology, a sailing vessel generates an internal wave at the interface of sediment and water. In a speed range of a vessel, corresponding to typical speeds in the entrance channel, a significant reduction of the clearance between the keel and the sediment water interface (see Figure 1) can be allowed without jeopardizing safe shipping. The field trials with the 'CSL Rhine' and the 'Geopotes 15' confirm these findings.

Although the full scale field tests reveal an important relation between the UKC with respect to the mud-water interface, the mud layer thickness and the ship behaviour on both manoeuvrability and ship speed (figure 9), it should be noticed that, as a result of consecutive disturbance of the mud layer, the mud-water interface was not clearly defined during the tests (figure 8). In order to validate the conclusions of the full scale field tests in case of an undisturbed mud layer, recommendation is made for a supplementary full scale test in this condition.

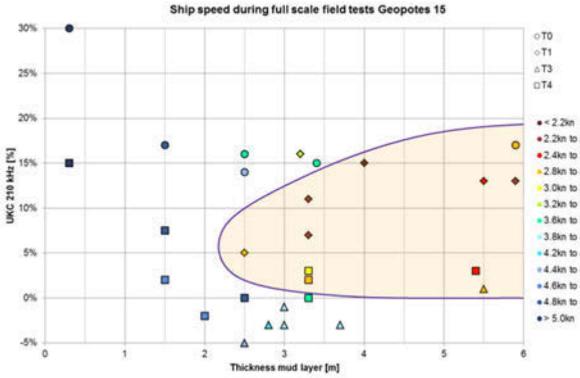

Figure 9. Summarizing graph of the evolution of the speed of the 'Geopotes 15' in function of the sediment layer thickness and the under keel clearance to the top of the fluid mud layer (source FHR).

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