Provide end users with the most accurate nautical depth measurement by using the combination of echo sounders and density measurement equipment

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ABSTRACT

Harbours and their access channels need to be dredged to the nautical depth to ensure safe vessel passage. When fluid mud is present, a critical density value is determined to establish this depth, which is area specific. Another consideration for establishing the level of safe vessel passage is yield stress. The yield stress indicates the level in the fluid where solidification of the mud occurs. Traditional survey techniques are not capable of detecting multiple density levels or yield stress. To optimize dredging operations and continuous harbour management one could benefit of using an ultra-high resolution sub-bottom profiler in combination with in-situ density and yield stress measurements. The geophysical software package SILAS will link both type of measurements and can in real-time determine density levels which spatially cover the entire harbour or access channel, therefore excluding interpolation in the process. The SILAS software enables all users to manage the nautical depth, while batch processing and data cross-referencing acquired using different sources can improve the overall data quality as well as provide the user with a more detailed understanding of sub-bottom features, such as cables and pipelines. Recent studies show that the SILAS system can detect various types of sub-bottom objects not only limited to cables and pipelines, but also individual boulders. These objects can be detected with a success rate of 75% and over on objects and cables with a diameter of 25 cm or higher.

1. INTRODUCTION

A global trend of increased harbour traffic can be partially attributed to the economic growth arising after the recovery from the setback of the 2008 crisis, resulting in an increase in cargo traffic of shipping vessels with more draught making use of the harbour on a daily basis. For instance, significant growth can be seen in ports like: Mombasa (Kenya), Cochin (India), Tianjin (China), Rotterdam (Netherlands), not to mention port facilities on the North American east coast (New York, Savannah, Jacksonville, Miami), the latter being due to the recent opening of the Panama Canal expansion in June 2016 introducing Post-Panamax vessels from Asia.

To ensure safe passage of these vessels, harbours and their access channels need to be dredged to the nautical depth. This depth is established by defining a critical density value which is related to a particular yield stress value. Both depth and the relationship between density and yield stress is area specific and does not remain constant during the year, especially in high-tidal or even monsoon environments. The presence of fluid mud will cause fluctuations and might even give a false value for the defined bottom depth in the first place. Correct harbour management implies continuous monitoring of the fluid mud and its physical properties.

In this paper the nautical depth principle will be explained. Accurate prediction of the nautical depth saves time and operating costs. The preferred working methods include in-situ density measurements and the relationship between density and yield stress will show that there is an even better understanding of the nautical depth today. Improved acquisition methods are introduced as well as real-time density calculations and batch processing, the latter acting as quality assurance. Integrating all this in one geophysical software package has many benefits. The discussed software package SILAS is not only suited for nautical depth assessment, but mainly for processing and managing of sub-bottom seismic data, including detection of cables, pipelines and boulders.

2. NAUTICAL DEPTH

2.1 General Principle

Navigational channels and harbours are often covered with a fluid mud layer, which is characterized by a low density and weak shear stress (Delefortrie et. al., 2004). When this water-mud interface is considered as the actual bottom the navigation depth will frequently be much shallower than the one required. In these conditions it is better to define a nautical depth 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" (PIANC, 1997).

This depth is usually defined by a physical level of a certain density within the fluid mud layer (Van Craenenbroeck et. al., 1998). As the physical characteristics of mud vary, the critical density used to determine the nautical depth is site specific. For instance muds from Guyana, Southern America show a very low yield stress at densities as high as 1.5 ton/m3, while North European harbours show a significant yield stress increase at density levels varying between 1.15 and 1.25 ton/m3 (Fontein, Werner, Van Der Wal, 2006). Therefore the decision to pass through a particular mud should not be based on its density alone, but by yield stress values as well, as will be explained later in this paper. Due to influences of nature, the actual nautical depth will vary over time as well and a proper monitoring system is required.

Traditional survey techniques are not capable of detecting multiple density levels or yield stress and will only acquire the top of the fluid mud layer. An ultra-high-resolution sub-bottom profiler in combination with in-situ density and yield stress measurements will be able to capture the full profile and detect all required density levels. The recommended operating principle is discussed below.

2.2 Recommended Operating Principle

Traditional survey techniques consist of using a Singlebeam or Multibeam echosounder with a relative high frequency which is unable to penetrate to the bottom of the fluid mud layer. Figure 1 displays the clear difference in penetration between traditional Multibeam surveys (black and green lines) and the preferred use of a high-resolution sub-bottom profiler (blue and red lines). In the morning the top of the fluid mud layer is marked by the blue line, while the base is marked by the red line, according to the sub-bottom profiler. The Multibeam echosounder measures only the top (black line), but is inconsistent and penetration of top of the fluid mud is too high. On the other hand it is unable to penetrate towards the bottom of the fluid mud layer. In the afternoon the top of the fluid mud is marked by the blue circles, while the base is marked by the red circles, according to the sub-bottom profiler. The red circles align with the red line, showing consistency over time in measurements of the bottom of the fluid mud with this technique. The green line represents the Multibeam echosounder measurements in the afternoon. At this time the Multibeam has too little penetration to detect even the top of the fluid mud. The difference between both Multibeam surveys – morning (black line) and afternoon (green line) - shows that this traditional survey can give variable outcomes in one day only and should not be considered reliable. The way forward is to use a combination of a high-resolution sub-bottom profiler and an in-situ density profiler which is able to measure both density and yield stress. The recommended system setup is described in Figure 2.

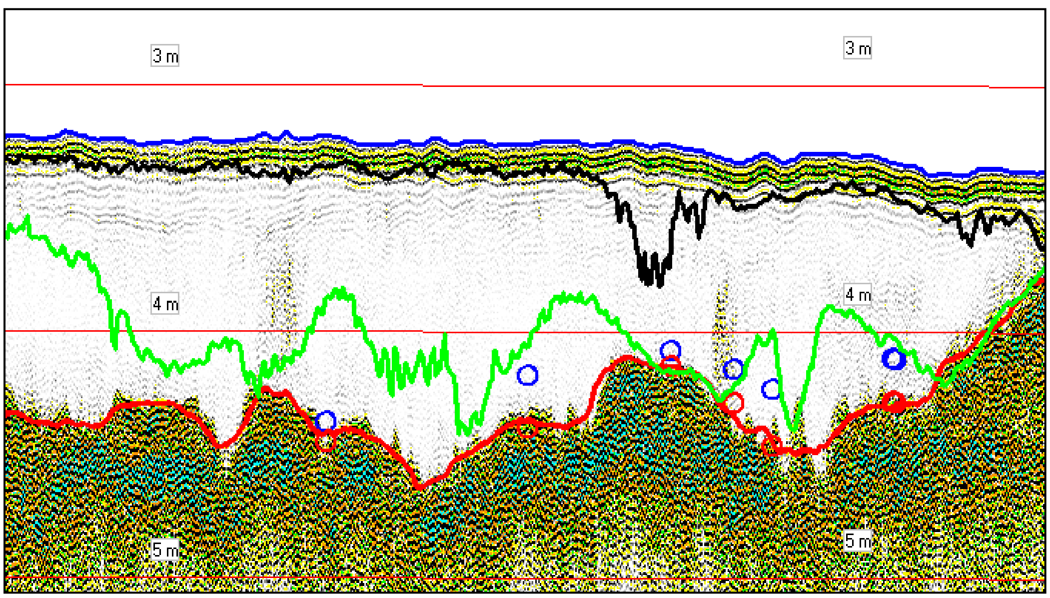


Figure 1. Example of a seismic recording including two depth levels determined by traditional Multibeam surveys. The black line is acquired in the morning, while the green line is acquired in the afternoon. The top of the fluid mud is marked by the blue line in the morning and by blue circles in the afternoon, while the nautical depth (1200 g./L.) is consistent during the day (red line and circles). The latter is acquired with a high-resolution sub-bottom profiler.

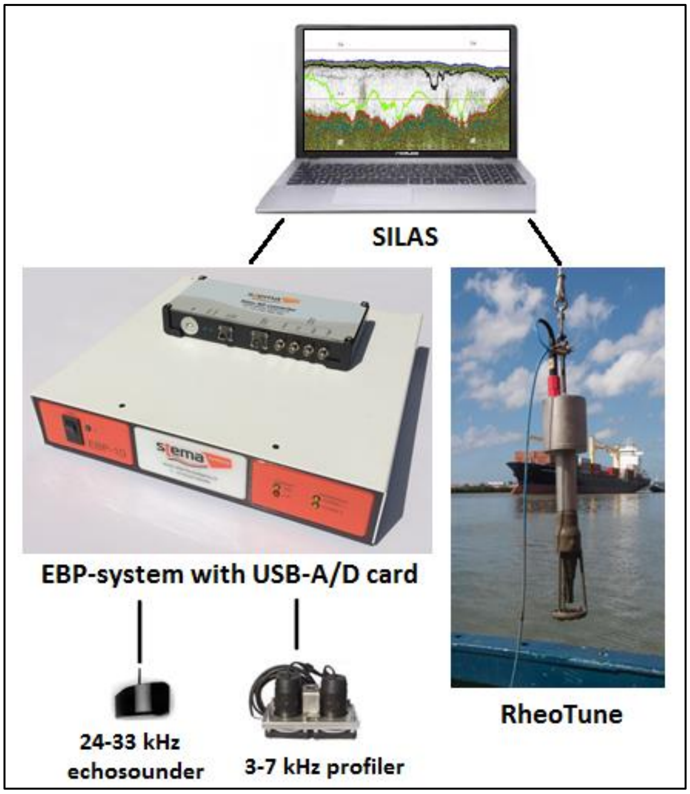


Figure 2. Recommended system setup for determination of nautical depth and sub-bottom features. The SILAS software (top) can integrate both profiler data, acquired with an echosounder or low frequent profiler set (bottom left), with an in-situ density and yield stress measurement. The latter is recorded with a RheoTune (right-hand side). To optimize the quality of the data output of the profiler a low frequency transceiver with an USB Analogue to Digital converter is preferred (left hand-side).

The ultra-high resolution geophysical software package SILAS (Fig. 2 top) can link profiler data (Fig. 2 bottom left) with in-situ density and yield stress measurements recorded by the RheoTune (Fig. 2 right-hand side). It is able to determine density levels which spatially cover the entire harbour or access channel and can detect density gradients as small as 0.4 g./L. per cm in fluid sediment of low yield stress (< 5 Pa) (Werner, 2012). The spatial coverage of the profiler data will result in the necessity of less point-measurements while SILAS will provide continuous information on lines in-between these points. This conclusion is confirmed in a validation study in the Netherlands by Deltares (Kruiver, Diafera, Vermaas, 2013). Interpolation in between point-measurements is not required anymore as the profiler data spatially covers the area and therefore continuous harbour management becomes more easy. Interpolation based on only in-situ measurements involves risk, as the fluid mud does not behave linearly.

Prior to the use of the above mentioned methodology nuclear density probes were used for the in-situ measurements (Van Craenenbroeck et. al., 1998), but nowadays they are largely replaced by tuning fork systems, like the RheoTune (Fontein, Werner, Van Der Wal, 2006). This probe is more environmentally friendly and handling is easy due to the ergonomic design of the system. Besides that, it is capable of measuring rheological parameters like yield stress, simultaneously with density resulting in a much more detailed analysis. Operation of the RheoTune (Fig. 2 right-hand side) is based on the vibrating element principle which is used in processing industry and widely accepted as one of the most accurate methods to measure continuous real time density, concentration and dynamic viscosity. As will be explained below, the rheology of the mud provides a better justification of the chosen nautical depth than density alone.

2.3 Rheology For Nautical Depth Assessment

The density of fluid mud can be defined by the amount of sediment particles within the fluid. Unfortunately this density does not provide you with information required to determine if a layer is still safely penetrable by a ship's keel, as it will not give enough knowledge about the strength of the mud. Rheology of the mud and especially yield stress does this, to a very accurate degree. Yield stress is the rheological property defined as the stress at which the mud begins to deform plastically. It can be considered as the initial stiffness of the mud (Fontein, Werner, Van Der Wal, 2006). Mud has different properties than sand. Shear strength of a mud is derived from cohesion between particles (cementation between sand grains and electrostatic attraction between clay particles), and frictional resistance between particles. Hence, the ratio between sand grains and clay particles is important, which is not uniquely related to density.

The sudden presence of a higher yield stress in (part of) the mud gives a more precise identification of the level in the fluid where solidification of the mud occurs. The latter causing the safe passage of vessels not to be guaranteed anymore. The in-situ tuning fork system RheoTune can detect differences in yield stress with an accuracy of 1 Pa. This device determines a direct relation between density and yield stress in a specific mud and/or area at a particular point in time. Unfortunately this relationship is not stable over time, hence a direct in-situ measurement of the rheological characteristics remains required (Fontein, Werner, Van Der Wal, 2006).

2.4 Case Example: Acoustic Density Mapping

An example of a seismic recording including an in-situ density and yield stress measurement is displayed below (Figure 3 left-hand side). These measurements were performed near the Calcasieu Lake, Louisiana. The seismic recording was acquired with a 24 kHz profiler. The vertical profiles represent density (blue) and yield stress (red) measured by the RheoTune. These profiles are used to calibrate the seismic section and establish the calculation of the density levels within (horizontal blue, green and orange lines). The density levels computed are 1030 g./L. (blue), 1160 g./L. (green) and 1200 g./L. (orange). The SILAS software will calculate the density profile through the rest of the section so only a few point measurements are necessary to cover a large area (Kruiver, Diafera, Vermaas, 2013).

In Figure 3 on the right-hand side the density and yield stress profiles of the in-situ measurement are enlarged. The vertical blue line displays the density, while the vertical red line indicates the yield stress. The density increases quite linearly with depth, while the yield strength remains stable up to the 1200 g./L. density level (orange) and then suddenly increases rapidly from 15 Pa to around 50 Pa. This increase in yield stress is a better indication for the cohesion of the mud and the possibility of a vessel passing through as explained previously. This yield stress level can be related to a specific area, provided the material composition remains unchanged.

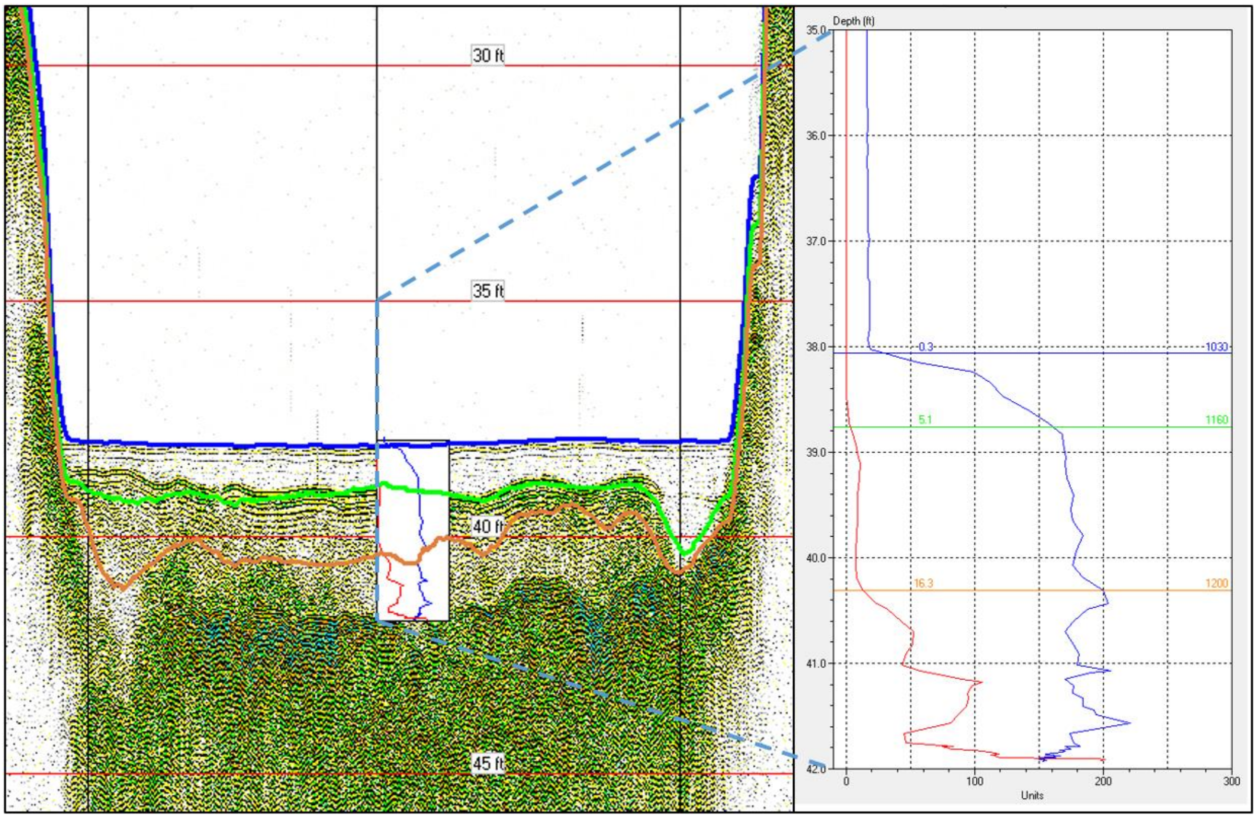


Figure 3. Example of a seismic SILAS recording (left) including an in-situ density and yield stress measurement (right) near the Calcasieu Lake, Louisiana. The vertical profiles represent density (blue) and yield stress (red) measured by the RheoTune. The density levels computed are 1030 g./L. (horizontal blue), 1160 g./L. (green) and 1200 g./L. (orange). Corresponding yield stress values are 0.3 Pa (blue) 5.1 Pa (green) and 16.3 Pa (orange). A strong increase in density is visible near the water-mud contact (1030 g./L.) where after the increase is less explicit. The first strong increase in yield stress (15-50 Pa) is visible near the 1200 g./L. density level, indicating a sudden increase in cohesion of the mud (De Boer, 2016).

3. IMPROVED ACQUISITION METHODS

3.1 Real-time Acoustic Density Mapping And Volume Calculation

The above recommended operating system has been used in multiple projects and can be enhanced with improved acquisition methods and equipment like the ultra-fast USB AD Converter, which results in a higher resolution (Werner, 2016). This USB AD converter (Fig. 2 left-hand side) is a piece of hardware which is easy to deploy and can be interfaced with an echosounder, profiler, non-linear parametric source, boomer and sparker system. It can be used to convert the full signal for both low and high frequency single beams.

Real-time heave correction, as well as real-time density calculations, have been improved significantly. If a position and heave input is available, SILAS has the ability to provide a real-time output of the required density levels after a calibration survey has been executed. In this case it is possible to perform surveys with real-time acoustic density mapping (Fontein & Byrd, 2007). This would enable a post dredging survey (if required) at an accelerated pace.

3.2 Quality Assurance

An automated batch processing module has been created for easy and faster initial processing of the data. This batch processing involves ringing reduction, heave correction, first order filtering and auto-tracing of the seabed. Ringing reduction can be necessary to reduce noise that appears at constant time interval after shot transmission. All processing steps are optional in the batch processing module and can be corrected afterwards if required.

The module can easily be added to the acquisition setup. The benefit of which would be to assure the quality of the data saving a significant amount of time, enabling to identify errors or highlight opportunities during acquisition, instead of afterwards. For instance, basic processing of profiler data is required during a nautical depth survey when determining the exact locations for in-situ density and yield stress measurements. The batch processing module can perform this step fully automated, resulting in significant less down-time of the vessel. A further example of the ultra-high resolution applications of batch processing is that it helps to detect pipelines which are not clearly visible during acquisition. In this case one knows the survey is performed at the right spot while you are still on site. More details will be described in the next chapter.

4. INTEGRATION OF GEOPHYSICAL DATA

4.1 Import And Export Capacity Of SILAS

The ultra-high resolution geophysical software package SILAS has been cited earlier in this paper. Beside hydrographical applications, the SILAS package disposes of many geophysical processing options. One of the main benefits of this system is recording of the full seismic signal which can be used for multiple geophysical solutions, making the application thereof more polyvalent. Hydrographical data like Multibeam, Side Scan Sonar and geological maps can be integrated into the required deliverable as well. Cross-referencing data acquired via different sources can assure the overall data quality.

Geophysical solutions that can be provided by the software package include:

- Import of full in-situ density measurements (e.g. RheoTune) for calibration of density levels and real-time display in seismic sections (Figure 3)
- Import of boreholes and Cone Penetration Tests (CPT) including all additional data like grainsize, formation factor, porosity and shear strength
- Import and integrated processing of Ground Penetrating Radar (GPR)
- Import and export of several data formats including commonly used SEGy data
- Advanced filtering techniques like multiple reduction, deconvolution and frequency filtering
- Automated contact detection for sub-bottom cable, pipeline and boulder detection
- Import and integrated processing of magnetometer data
- Determination and validation of Sidescan and Multibeam contacts for cable, pipeline and boulder detection

4.2 Case Example: Sub-Bottom Cable And Pipeline Detection

To illustrate the polyvalence of the SILAS program the author would like to highlight a new application that will permit the reader to further gain insight into the quality that SILAS has to offer. The new application referred to is automated sub-bottom cable and pipeline detection. Figure 4 displays outcomes at different stages within the process of automatic detection. In the three seismic sections two hyperbola are clearly visible, which are the signatures of cable and pipelines. The double 1.5m pipelines are located at an average depth of 3m below the seabed. Raw data gathered during acquisition (Fig. 4A) can be batch processed during the survey, which is a very useful tool to highlight and identify the position of the cables or pipes (Fig. 4B). If the data would not be as clear as shown below (Fig. 4B), this step will assist the user to establish the correct area of survey.

The automated detection module is an advanced processing tool. This module uses an algorithm which can identify and rate the quality of hyperbolic structures (based on probability) within the data set. Figure 4C shows two contacts that were detected automatically, which are marked by purple and red triangles. The purple and red windows indicate the horizontal range where the algorithm was applied. A vertical range can be adjusted as well. This not only saves time but also increases overall quality as some hyperbolas - which are hard to identify by the human eye only - will be detected by the algorithm. Furthermore, the algorithm is constant in the way it calculates the top of each hyperbola, while human interpretation will vary over time and can change per individual.

The vertical depth display (Fig. 4D) shows all auto detected contacts of the pipeline on the left (marked by purple triangles). The grey line running through provides the user a first- second- or third-order polynomial estimation of the pipeline location. The small triangles facing down indicate the depth of the bottom as found directly above the contacts. Multibeam data can be imported in here as well to cross-reference data acquired via different sources.

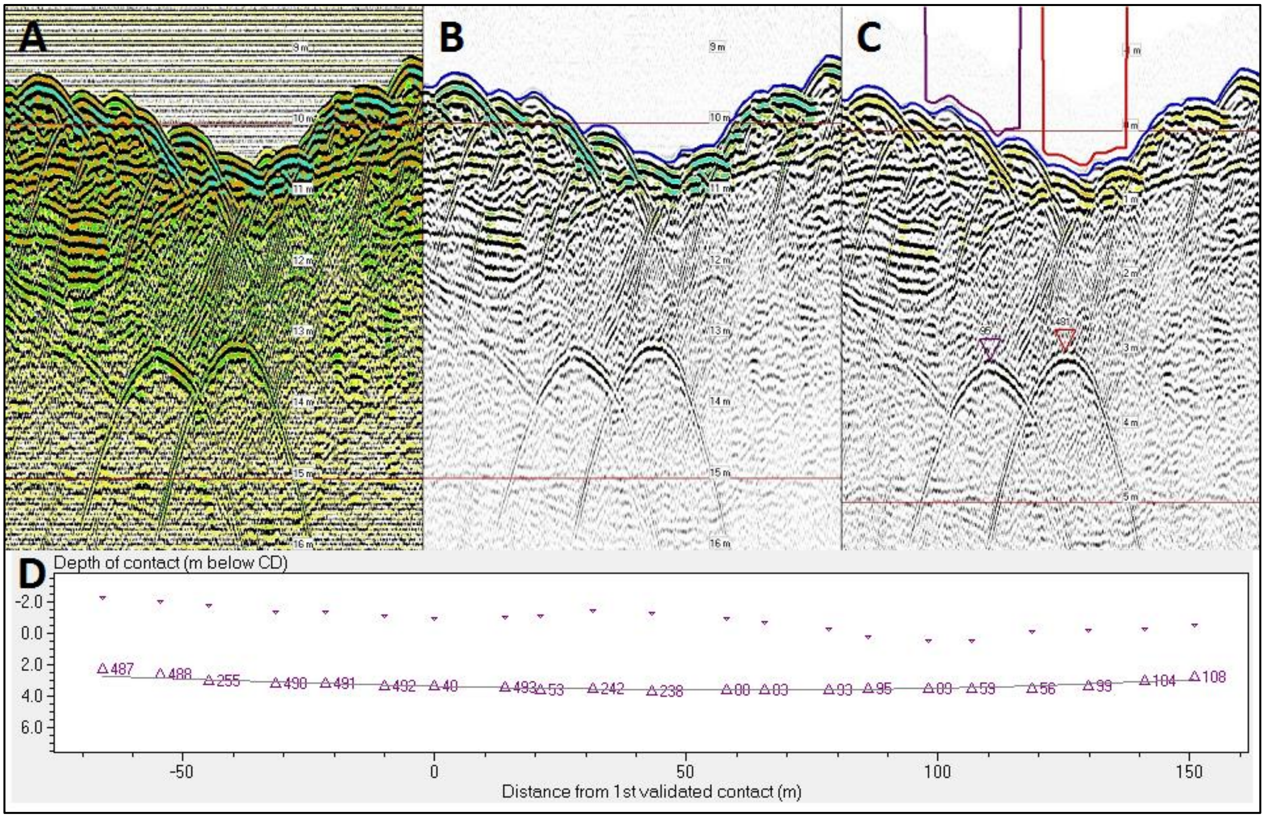


Figure 4. Example of automated contact detection proceedings displaying outcomes at different stages. Two 1.5m pipelines are visualized as hyperbola in the upper three seismic displays (A: raw data B: batch processed data C: processed data with automated contact detection applied). The vertical depth display (D) shows all auto detected contacts of the left-hand pipeline (purple) and the bottom depth as found directly above the contacts. The grey line running through is a third-order polynomial estimation of the pipeline location (De Boer, 2016).

Recent studies show that the SILAS system can detect various types of sub-bottom cables as well. These objects can be detected with a success rate of 75% and over, on cables with a diameter of 25 cm or higher. Results of one of these studies are shown in Table 1. In this study both export cables and infield cables were surveyed on 14 different locations with varying water depths (up to 35m). Depth of burial varied between 1,5m and 3m while diameter of cables varied between 11cm (infield cables) and 25cm (export cables). A clear difference in results is visible between the two type of cables. On export cables a hit rate of 77,2% has been acquired if we exclude the two areas where rock dumps or vast amount of boulders are present. If we consider a cable to be detected with confidence when at least a hit rate of 50% is acquired and these hits have a good dispersion in all lines surveyed we can increase this number to 100%. The results for infield cables are – as is to be expected – significantly lower.

Hit rates of detecting contacts per crossing	**Hit rate (%)**	**Remarks**
Average all export cables	77.2	Excluding rock dump & boulder areas
Average all infield cables	39.7	
Number of cables detected with confidence		**> 50% hit rate & good dispersion**
Export cables	100	Excluding rock dump & boulder areas
Infield cables	37.5	

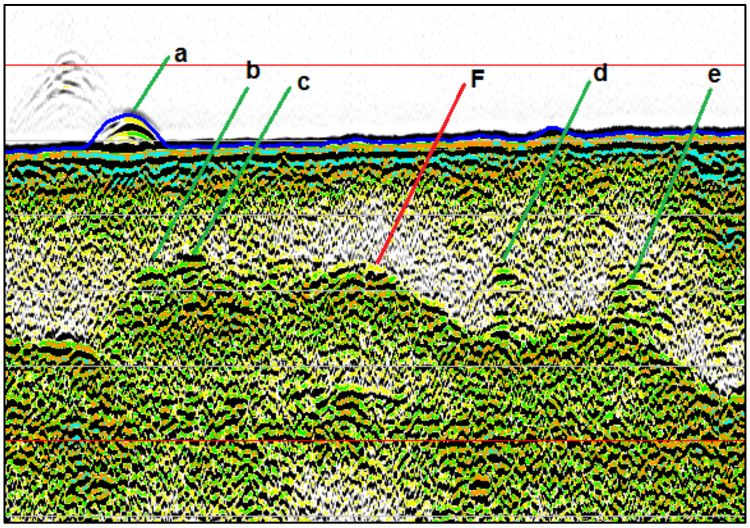
Table 1. Hit rates (%) per cable type (Silas Trials Cable Detection, 2016, *not published*).

A cable or pipeline detection survey can be a vital tool in the dredgers arsenal when planning the upcoming works, given that it will utilize almost the same set up as the post-dredging SILAS density survey parameters.

4.3 Case Example: Sub-Bottom Boulder Detection

The pipeline and contact detection module of the SILAS processing program is also able to detect boulders (large stones > 25 cm diameter) or other small objects of similar diameter. These features can be recognized in seismic data by a hyperbola signature (Fig. 5) that can be detected in an automated manner, which saves significant processing time while improving quality and objectivity. The detection procedure consists of a calibration phase, automated detection phase and finally validation and export of detected contacts.

The contact detection is calibrated using available data, consisting of either seismic reflection data on the seabed and if possible also Sidescan data. During the calibration process the hyperbola detection parameters; such as semblance and power, of the signal in the hyperbola of a valid boulder detection in the seabed are determined, and compared with detection parameters of boulder contacts on the seabed (Fig. 5). The semblance is a value that describes how well the hyperbola is defined.



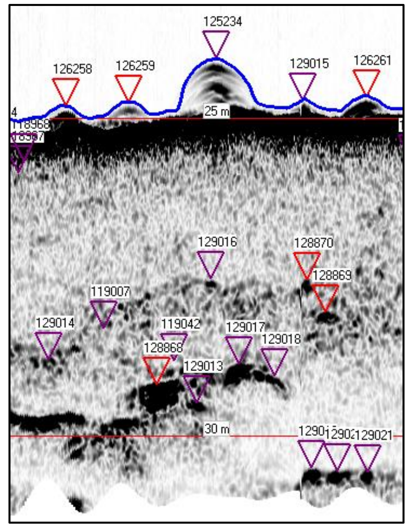


Fig. 5: Example of seismic boulder registration at seabed surface (a) and below seabed (b, c, d, e). All detections are visible as hyperbolas. Blue line: seabed. A deeper level is visible at the reflector below F. This layer consists of numerous cobbles and boulders.

Fig. 6: Example of validated boulder contacts in seismic power display (red and purple triangles). Individual boulders are clearly visible as high power reflections (black) with discrete boundaries.

During the automated contact detection all contacts are detected automatically using the power and semblance settings resulting from the calibration. During the validation stage the detected contacts are validated by the user who can apply different types of displays to validate the data: both the true amplitude (Fig. 5) as signal power display (Fig. 6). During the final export phase all contacts are exported to a format which includes contact number, x, y, z position, power and semblance.

5. CONCLUSION

To ensure safe vessel passage, harbours and their access channels need to be dredged to the nautical depth. This depth is established by defining a critical density value, which is area specific. Yield stress measurements can aid in establishing the critical density value as the sudden increase in yield stress gives a more precise identification of the level in the fluid where solidification of the mud occurs. Traditional survey techniques are not capable of detecting multiple density levels and will only acquire the top of the fluid mud layer. An ultra-high-resolution sub-bottom profiler in combination with in-situ density and yield stress measurements will be able to capture the full profile and detect all required density levels. The ultra-high resolution geophysical software package SILAS can link both types of measurements and is able to determine density levels which spatially cover the entire harbour or access channel. Therefore interpolation is not required anymore and continuous harbour management becomes more easy. The modular approach of the SILAS software enables customers with standard hydrographical skills to manage the nautical depth. Real-time density mapping, batch processing and data cross-referencing acquired via different sources can assure the overall data quality. Moreover the software package offers extensive geophysical modules for those who wish to use the package to integrate seismic data with geotechnical and geophysical data of various origin. Automated contact detection of cables, pipelines and boulders is an example of one of these modules.

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BIOGRAPHICAL NOTES

P.J. de Boer graduated in 2014 with a MSc in geophysics from the University of Utrecht. In the same year he joined Stema Systems as geophysical engineer. At present he is managing multiple geophysical projects including but not limited to the use of Silas and high-resolution sub-bottom profilers.

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