MARITIME SOLUTIONS FOR A CHANGING WORLD

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TERRA ET AQUA

TOP ENGINEER
Breaking the glass ceiling at the Panama Canal

PLUME PREDICTOR
Accurate surface plume generation is vital to environmental impact assessments

MUD CONSOLIDATOR

FIELD PERFORMANCE VS. LAB ANALYSIS OF PROCESSES CONSOLIDATING SOFT MUD

HIGHLIGHT

FIELD PERFORMANCE VS. LAB ANALYSIS OF PROCESSES CONSOLIDATING SOFT MUD

A main cause for settlement and an increase in shear strength is self-weight consolidation. This plays a role in the creation of land using mud, the ripening of mud layers and, also, in the storage of contaminated mud and slurries in ponds. There is significant compaction due to self-weight consolidation at lower stresses which gives the need for special laboratory tests and accurate modeling.

A tool has been developed to include several gas production scenarios with gas dissolution, a choice of boundary conditions and a simple creep model. Hydraulic consolidation tests were conducted where the mud sample was left to consolidate and stiffen for some days. Next it was loaded gently by applying a hydraulic gradient across the mud sample. Settlement and pore pressures at short distances across the sample were monitored. In this previous research, the experimental conditions were chosen carefully, resembling the field situation, as effects of thixotropy and creep were expected.

This article discusses evidence of time dependent processes affecting self-weight consolidation, such as gas production, thixotropy, creep and flow rate dependent effects. These processes result, among others, in non-unique effective stress-void ratio and permeability-void ratio relations. The initial (pre-loading) conditions and the type of loading should be realistic, similar to the field condition. In addition, significant gas production can occur and this retards the consolidation process and the final degree of densification. A team of authors from Deltares and Boskalis discuss their findings on page 37.

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CONTENTS

SAND IS A RESOURCE IN SHORTAGE. IS MUD A VIABLE ALTERNATIVE?

Frank Verhoeven
President, IADC

Sand is the second-most consumed material after water and is a key material used to build cities. Whether it is used for beach replenishments and reclamations to construct land or as part of the mixture to make concrete and glass for materials to construct buildings and infrastructure, sand is vital in our built environment. And growing urban populations have driven development of the built environment.

While deserts may seem like endless sources of sand, the granules of desert sand are eroded by air and are too smooth to be suitable for the afore-mentioned activities. In contrast, water-eroded sand, with angular faces that interlock, is the coveted and necessary version of the resource. But taking the suitable sand from rivers, lakes and coastal areas for use in other places can lead to problems with local habitats as well as erosion from the site of extraction.

Other than sand, what material can be used to ensure that infrastructure development continues sustainably?

Fine sediments dredged to maintain ports are traditionally removed from project sites. In the Port of Harlingen alone, 1.3 million cubic metres of material are dredged annually to ensure its navigability. The Mud Motor project emerged from EcoShape's Building with Nature initiative to see if this dredged material – ubiquitous in ports around the world – could be transformed into a resource, creating and extending salt marshes which would benefit the ecology while further protecting the coast. All without the need for sand.

Research and reported results help increase the understanding of the behaviour of mud in projects, increasing the industry's familiarity with mud as an alternative material to sand. This issue features three articles about mud and sediment-related topics including: predicting surface turbidity plume generation near a Trailing Suction Hopper Dredger, monitoring of settling and consolidation of mud after water injection dredging, and last but certainly not least, the consolidation of soft mud in field performance related to lab experiments, modelling, and analysis of time dependent processes affecting consolidation.

For this issue, the editor interviewed Ilya Espino de Marotta who was appointed to the role of the Panama Canal's Deputy Administrator at the start of 2020. No stranger to shattering glass ceilings, Ilya is the first woman to be interviewed for *Terra et Aqua*, and she gives insights into her career as she navigates the industry towards gender equality.

Research and reported results help increase the understanding of the behaviour of mud in projects, increasing the industry's familiarity with mud as an alternative material to sand.

CAN SURFACE TURBIDITY

PLUME GENERATION NEAR A TRAILER BE PREDICTED?

Photo © Van Oord

An important environmental impact of dredging can be caused by turbidity plumes generated during dredging.

A surface plume from overflow can stay suspended for long periods and distances. This can result in negative environmental impact through increased turbidity and sedimentation. Therefore, the question of surface plume generation is important for a proper dredging environmental impact assessment which is neither too optimistic nor too conservative.

Introduction

For dredging projects, often the environmental impact needs to be assessed by model studies beforehand and monitored during execution of the work (Aarninkhof et al., 2018). An important environmental impact of dredging can be caused by turbidity plumes generated during dredging. Increased turbidity can impact ecological sensitive areas by reduced light penetration, reduced visibility, clogging and burial. When dredging with a Trailing Suction Hopper Dredger (TSHD) the main source for a turbidity plume is the overflow (Bray, 2008). The overflow is a vertical shaft ending at the keel through which excess sea water from the hopper is released. This excess water can contain fine sediment fractions which did not have sufficient time to settle in the hopper. Under the keel of the vessel the turbid water from the overflow will mix with the ambient water flowing past the keel in such manner forming a turbulent plume (see Figure 1). This overflow plume can stay near the bed like a density current and settle quickly, but it is also possible that part of the plume will mix severely and form a surface plume. The difference between these two regimes is clearly visible on a dredging project, (see Figure 2). A surface plume can stay suspended for longer periods and in this time the ambient (tidal) currents can transport the turbidity plume towards ecologically sensitive areas. For a proper assessment of the environmental impact it is required to know whether a surface plume will occur or not. This depends on the mixing of the overflow plume under the keel of the TSHD. This close to dredging equipment it is very hard to carry out reliable measurements, but with increasing computing power it has become feasible to use Computational Fluid Dynamics (CFD) to find out what is happening under the keel of a TSHD. This article presents some remarkable results from a validated CFD model incorporating all important processes.

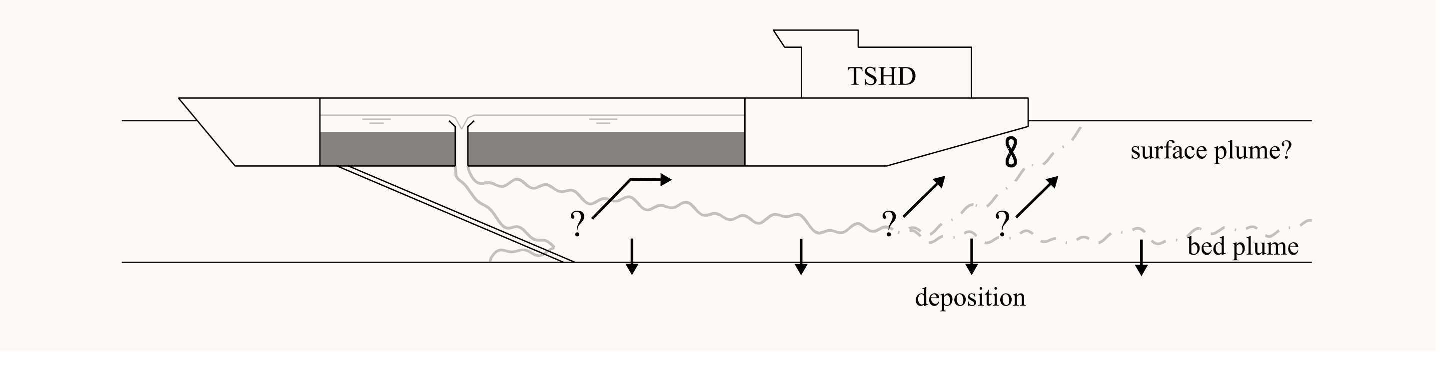


FIGURE 1

Schematic overview of the generation of an overflow plume under the keel of a TSHD.

FIGURE 2

Dredging example with overflow without surface plume (A) and with surface plume from overflow (B). Photo © H. Elbers, Fotovlieger.nl

Near field – far field

Close to a dredging vessel the behaviour of the dredging plume is governed by: interaction between plume, flow past the hull and propellers of the vessel; by the significant density difference between the plume and the ambient water; and by air bubbles entrained in the overflow. This zone where all these influences are important is called the near field. Further away from a dredging vessel the density difference is not significant anymore, air bubbles have disappeared and there is no interaction between the plume and the vessel. In this zone, called the far field, a dredging plume is turned into a passive plume being transported by ambient (tidal) currents and sediment settling velocity. Far field mixing of a dredging plume can be simulated by well-known large scale hydrodynamic and sediment flow models like Delft3d, FINEL, MIKE, or TELEMAC. Far field models cover the area of dozens of kilometres round a dredging work, often complete estuaries or coastal seas. The specific near field processes cannot be simulated by a far field model due to lack of grid resolution and lack of representation of all important near field physical processes. For accurate simulation of the near field a specific detailed near field model is required with sufficient resolution and incorporating all important physical processes. The plume results from near field then can be applied as source term in a far field model. See Becker et al. (2015) and Aarninkhof et al. (2018) for more information to go from the in-situ sediment to be dredged to the determination of a sound source flux in a far field model. The near field CFD model of present article can be used to determine the initial mixing in the near field, vertical and horizontal distribution of the overflow plume at the end of near field. Coarser sediment particles tend to settle already in the near field and will never reach far field and the near field CFD model can give information on what particle sizes and what amount of sediment will deposit in the near field.

Far field models cover the area of dozens of kilometres round a dredging work, often complete estuaries or coastal seas.

Near field dredging plume

The plume flowing out of the overflow mixes with the ambient water flowing past the keel. The overflow mixture flows with 0.5-5 m/s vertically downward in the overflow shaft and typically contains 25-250 kg/m³ of mud and fine sand (mixture density 1040-1200 kg/m³) with maxima of even 500 kg/m³ (mixture density 1330 kg/m³) which have been measured at the end of the overflowing phase when the hopper is nearly full (Nichols et al., 1990, Whiteside et al., 1995, Spearman, 2011, De Wit, 2014b). The time evolution, amount and composition of sediment flowing out of the overflow (overflow losses) depends on processes inside the hopper which have been simulated in detail by Van Rhee (2002), Saremi (2014), and due to recent advancements also the CFD model presented in this paper can simulate hopper sedimentation accurately in 3D (De Wit, 2019). Hence, the overflow losses can either be estimated, simulated by simplified hopper sedimentation models or determined in more detail by process based models. But knowing the overflow losses is not sufficient to determine far field source terms of a TSHD in environmental impact assessments, because also the near field processes have influence. Dependent on the velocity ratio between the flow velocity in the overflow and the effective flow velocity of the moving TSHD and the densimetric Froude (or Richardson) number of the overflow mixture, the plume follows a certain path. If the plume stays close enough to the TSHD keel, the expanding flow at the aft of the TSHD hull and propellers can lift the plume upward and increase mixing.

Air bubbles in the overflow plume can give the plume a higher path caused by a reduced mixture density and sediment particles from the plume can follow the rising air bubbles towards the surface. Air can be entrained in the overflow when the excess water from the hopper drops into the pipe in a free falling manner. When the inflow into the overflow is gentle, the amount of entrained air is less or even absent. An environmental valve can be applied in order to force a gentle inflow into the overflow in order to reduce air entrainment, see Decrop (2015) and Saremi (2014) for how

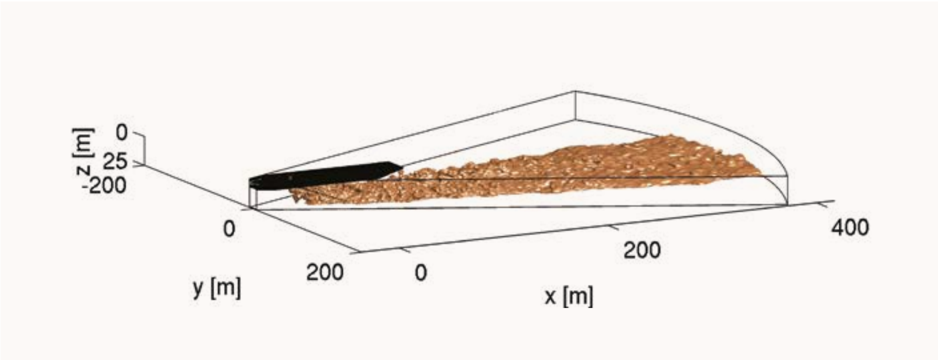


FIGURE 3

Near field CFD model area with TSHD hull and 3D contour of the overflow dredge plume.

efficient an environmental valve can be and for dredge plume simulations in the near field round a TSHD.

In this work results from a dedicated TSHD near field CFD model (De Wit, 2015) are presented which has been developed during an Ecoshape Building with Nature PhD project at the section of dredging engineering of TU Delft. In this model the influence of TSHD hull, propellers, entrained air bubbles in the overflow, multiple sediment fractions, density differences are represented accurately. It solves the Navier Stokes equation including variable density. The Large Eddy Simulation approach is used to account for the influence of turbulence by simulating the larger turbulent eddies directly on the grid. This requires very fine grids. The CFD model in this study employs grids of 10-30 million cells to cover the near field zone up to 350 metres with a resolution up to decimetres. Figure 3 shows a typical near field CFD model area with a TSHD and overflow dredging plume. The model has been validated by laboratory plume results (De Wit, 2014a) and field measurements of TSHD dredging plumes (De Wit, 2014b). The CFD model has also been used to assess the effectiveness of silt screens (Radermacher, 2013).

Results

The influence of the effective flow velocity, depth and amount of entrained air on the overflow plume mixing and generation of a surface plume is shown by comparing different runs with the CFD model. The base case consists of a 150-metre-long jumbo TSHD with a draught of 8 metres in a depth of 25 metres dredging with 0.75 m/s against an ambient current of 0.75 m/s leading to an effective flow velocity of 1.5 m/s. The round overflow pipe has a diameter of 2.25 metres and the overflow discharge is 7 m^3/s with a mixture density of 1200 kg/m^3. In the base case there is no air entrainment in the overflow. Starting from the base case other runs are defined with a different depth, effective flow velocity or amount of air entrainment. In each run only one parameter has been changed compared to the base case in order to assess only the influence of the condition under consideration.

Influence of effective flow velocity TSHD on surface plume generation

The magnitude of the effective flow is an important factor whether a surface plume will be generated or not. When dredging at a slow speed in stagnant water or when dredging with the current, the effective flow velocity remains low and the overflow plume descends towards the seabed quickly with hardly any surface plume being generated (see Figure 4A). With a strong effective flow, e.g. when dredging at high speed against an ambient current, a big surface plume with sediment concentrations of more than 100 mg/l is generated because the overflow plume gets into the influence zone of the propellers and expanding flow past the aft of the TSHD hull (see Figure 4C). These results are obtained without air entrainment, so purely the higher effective flow velocity is responsible for the

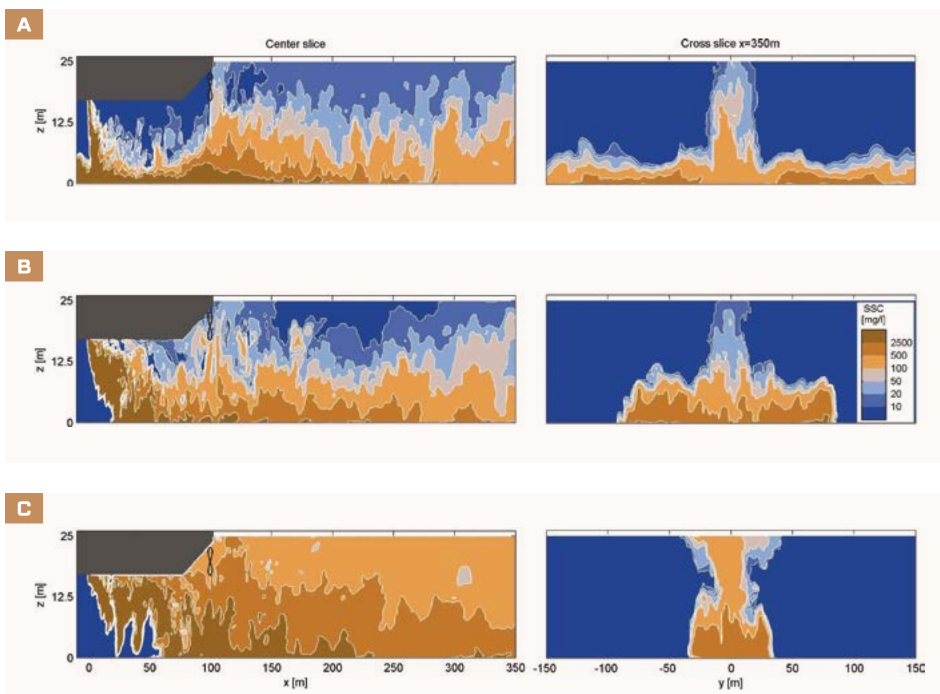


FIGURE 4

Influence of u_{ef} = trailing speed + ambient velocity: (A) u_{ef}=0.5 m/s; (B) u_{ef}=1.5 m/s; (C) u_{ef}=3 m/s on cross view plume.

The magnitude of the effective flow is an important factor whether a surface plume will be generated or not.

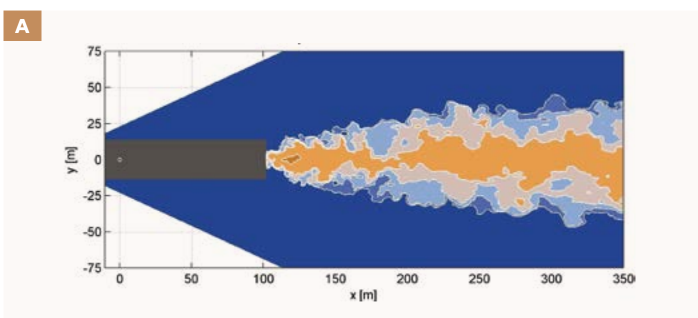
generation of a surface plume in this case. When dredging at an intermediate effective flow velocity (Figure 4B), no surface plume is generated. The top view in Figure 5 shows a surface plume growing to a width of 75 metres at x=350 metres for the case of a strong effective flow, and hardly any visible surface plume with low or intermediate effective flow velocity.

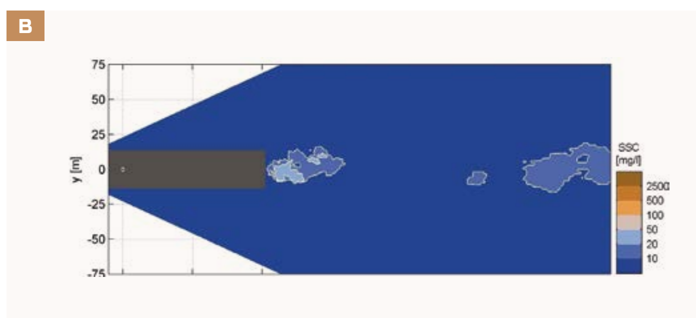
Influence of depth on surface plume generation

The depth is also an important factor for the generation of a surface plume. Figure 6 shows the cross view overflow plume results for three different depths: a normal deep water case of 25 metres, a shallow case of 12 metres and an intermediate case of 17 metres deep. When dredging in deep water of 25 metres no surface plume is generated, at intermediate depth of 17 metres a significant surface plume with sediment concentrations of more than 100 mg/l is generated and at a shallow depth of 12 metres, the overflow plume is fully mixed over the water column with concentrations of more than 500 mg/l to be found near bed and at the free surface. The lower keel clearance for dredging at shallower depth leaves the plume in the influence zone of the propellers of the TSHD and expanding flow past the aft of the TSHD hull which then generates a surface plume. Again these surface plumes are generated without air entrainment; it is purely the small keel clearance which is responsible for the surface plume being generated. Figure 7A shows a surface plume growing in width from equal to the TSHD width right behind the dredger to about 100 metres wide at x=350m for the 17 metres depth and 12 metres depth cases and no surface plume for the 25 metre case.

Influence of entrained air on surface plume generation

The different overflow plumes resulting from three different amounts of air entrainment in the overflow shaft are shown in Figure 8. Without air entrainment in the overflow, for example by using an environmental valve, no surface plume is present for this set of conditions (see Figure 8A). Strong air entrainment can occur in the overflow when the water drops meters deep into the overflow and 12% air entrainment (in volume) is possible (De Wit, 2015). With 12% air entrained in the overflow shaft a large surface plume is generated with concentrations of more than 100 mg/l (see Figure 8C). The air decreases the overflow mixture density which leads to a higher plume path and when the air bubbles rise towards the free surface they lift water with sediment particles towards the free





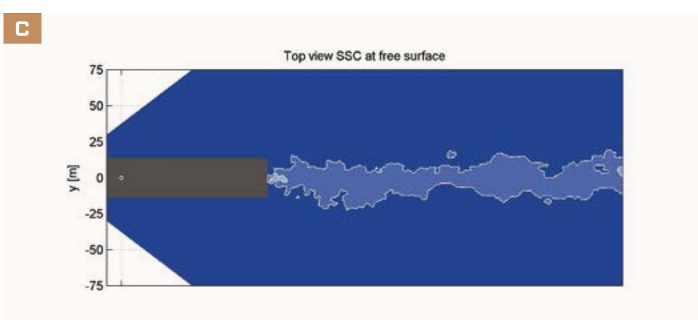


FIGURE 5

Influence of u_{ef} = trailing speed + ambient velocity:
(A) u_{ef}=0.5 m/s; (B) u_{ef}=1.5 m/s; (C) u_{ef}=3 m/s on top view plume.

The depth is also an important factor for the generation of a surface plume.

surface. With an intermediate amount of air in the overflow shaft (4% in volume) a small surface plume is generated with about 20 mg/l, see Figure 8B. With much air the surface plume in the top view in Figure 9 is 50-100 metres wide and with some air the width is limited to 50 metres, without air there is hardly any plume visible at the free surface. So air entrainment can be responsible for the generation of a significant surface plume from overflow, even with a large depth of 25 metres and an intermediate effective flow velocity of 1.5 m/s.

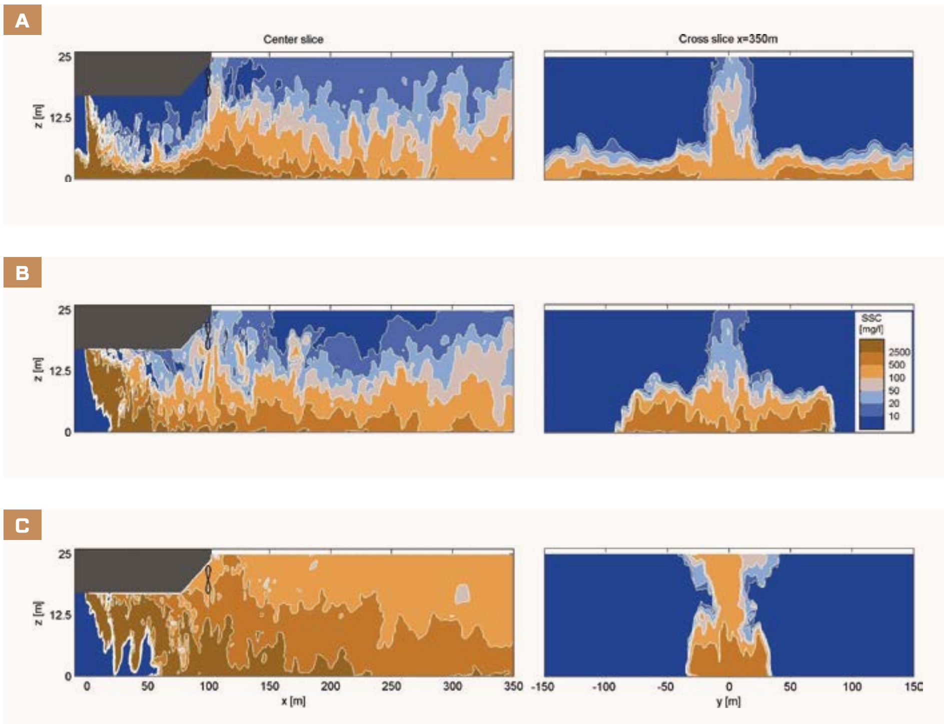


FIGURE 6

Influence of depth: (A) d=25m; (B) d=17m; (C) d=12m on cross view plume.

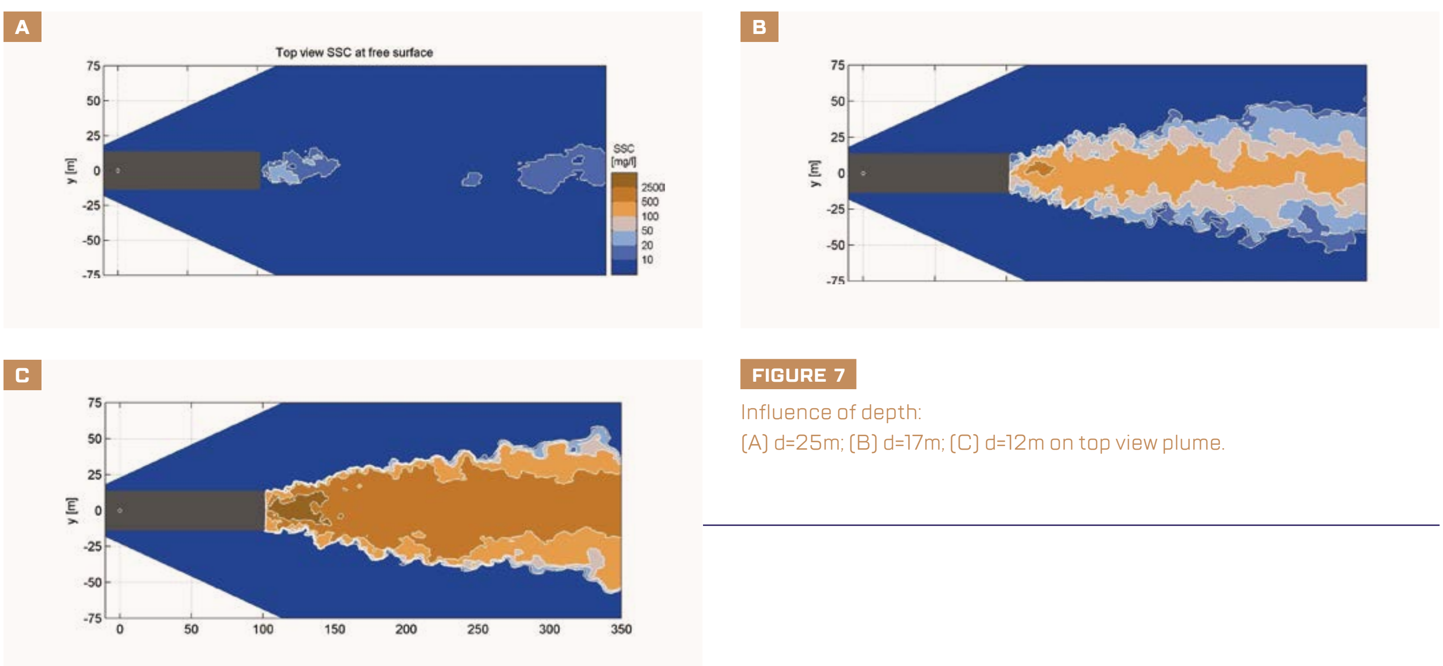


FIGURE 7

Influence of depth:
(A) d=25m; (B) d=17m; (C) d=12m on top view plume.

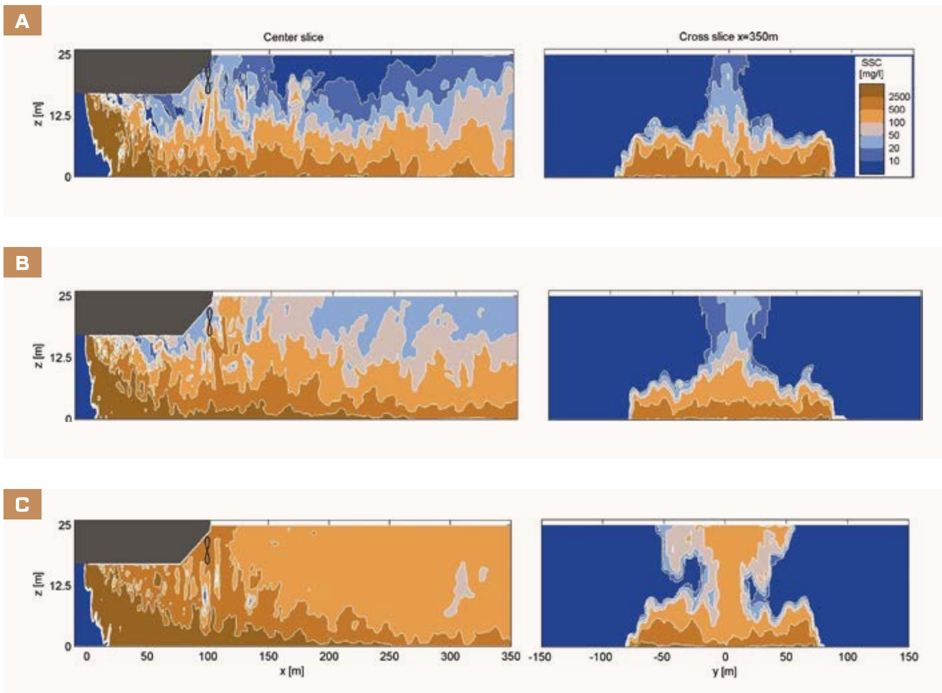


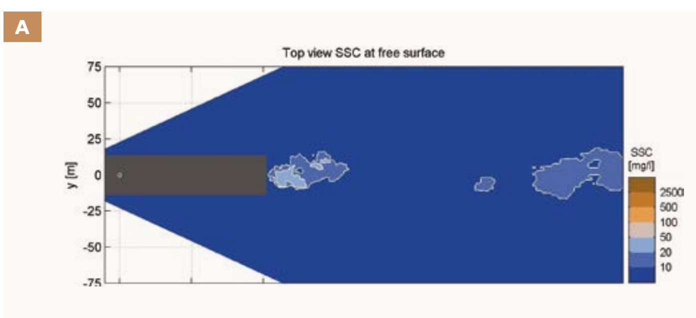
FIGURE 8

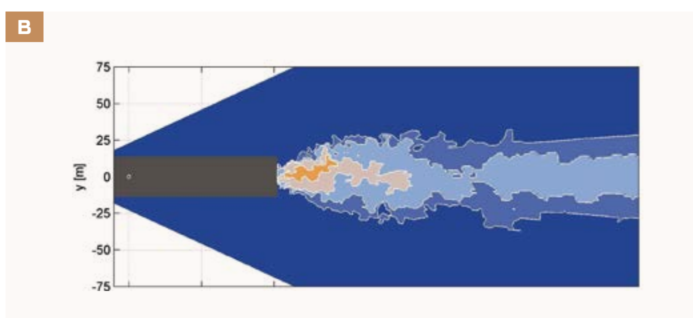
Influence of entrained air in overflow:
(A) no air; (B) some air (4% volume); (C) much air (12% volume) on cross view plume.

Translation to practice

The CFD results have made it clear that effective flow velocity, depth and amount of entrained air in the overflow are important factors for the question whether a surface plume is generated or not. The potential environmental impact depends on the answer to this question: a surface plume gives increased turbidity high in the water column which can have adverse effects on flora and fauna and a surface plume can stay suspended for longer periods thus being able to have influence on sensitive areas at larger distances from the dredging site. Therefore, when one wants to assess the environmental impact from overflow dredging plumes, then it is wise to conduct CFD simulations for some characteristic conditions of that specific project in order to see how the plume is mixing and whether a surface plume can be expected. Given the recent increase in computer power this does not have to take much time or money.

A typical CFD simulation as presented in this article takes about a day or two on a cluster computer. In past years several detailed sediment plume mixing simulations have been carried out with this CFD model in the preparation for actual dredging projects. Especially in non-standard situations like sediment released at very deep water, next to a platform or a trench, CFD has proven





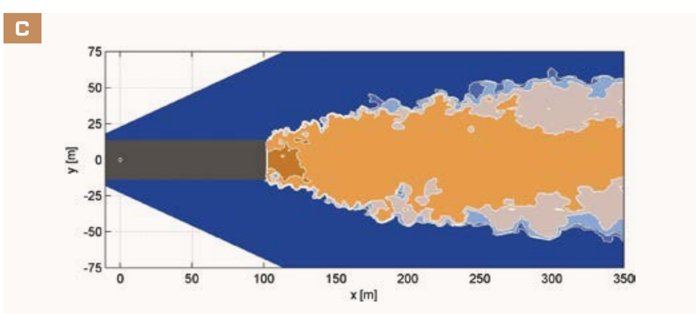


FIGURE 9

Influence of entrained air in overflow:
(A) no air; (B) some air (4% volume); (C) much air (12% volume) on top view plume.

to provide valuable insight in expected (surface) plume behaviour and the influence of operational changes on this.

However, in practice it is not always feasible to conduct heavy CFD simulations for a project at hand. Therefore, a large parameter study of 136 CFD runs for a wide range of possible conditions can be found in De Wit (2014c) and a translation of the results into mathematical formula is given. These mathematical formulas provide a prediction of the vertical distribution of the plume and how much of each sediment fraction within the plume has deposited after some minutes mixing in the near field. They give a reasonable result within a second on a laptop instead of days of calculation time on a cluster computer for a more accurate CFD run. This makes them very suitable for (extensive) parameter studies covering all possible conditions and also for live forecasting simulations.

The influence of other factors than effective flow velocity, depth and entrained air on the near field overflow plume mixing and surface plume generation can be found in De Wit (2014a) and De Wit (2014c). These other factors include: the overflow mixture density; what happens when a TSHD sails at an angle with the current; what is the influence of having the overflow in the front or back of the vessel; a pulsing flow in the overflow. A complete recipe to go from the in-situ sediment characteristics via dredging method to the determination of a sound source flux in a far field model is given in Becker et al. (2015) and Aarninkhof et al. (2018). The results from the CFD model presented in this article or from the predictive mathematical formula in De Wit (2014c) can be used to determine the amount of deposition of the coarser fractions from an overflow plume in the near field and the (vertical) distribution and remaining particle size composition of the overflow plume at the end of near field which is input in this recipe.

Monitoring of turbidity levels round a dredging site or near an environmental sensitive area might be needed during the execution of a dredging project (CEDA, 2015a). Through adaptive management strategy dredging can be adjusted in order to assure that the impact remains within acceptable limits (CEDA, 2015b). Detailed plume modelling might be helpful to optimise the dredging project beforehand and thus minimise the need for adaptation while executing the project and it can be used to place the monitoring stations at the best possible vertical and horizontal positions.

Conclusions

Whether a surface plume near a TSHD will occur can be predicted by process-based detailed CFD simulations of the near field zone. CFD results presented in this paper lead to the following main conclusions:

- **Quick descent overflow dredging plume towards seabed for base case**
  Without entrained air bubbles e.g. because of the use of an environmental valve, with a large depth and with a small effective flow velocity an overflow dredging plume descends quickly to the seabed under the keel of the TSHD without generation of a surface plume. In dredging practice this is often the case and it is caused by the significant excess density of the slurry flowing out of the overflow and the initial downward velocity.
- **Generation surface plume with large effective flow velocity**
  A large effective flow velocity can cause the generation of a large surface plume, even without entrained air bubbles. The reason for generation of a surface plume lies in the fact that a large effective flow velocity makes that the plume cannot descend enough to get out of the influence zone of the TSHD propellers and expanding flow past the aft of the TSHD hull.
- **Generation surface plume with small depth**
  Also a small depth can cause the generation of a large surface plume, even without entrained air bubbles. A small depth makes that the plume cannot descend enough to get out of the influence zone of the TSHD propellers and expanding flow past the aft of the TSHD hull; this leads to the generation of a surface plume.
- **Generation surface plume with entrained air**
  Entrained air can generate a significant surface plume as well, even with a large depth and small effective flow velocity. The reason now lies in the reduced mixture density caused by the entrained air and by sediment particles being brought to the free surface by the rising air bubbles.

The numerical results and photos in the paper show that significant surface plumes of >100 mg/l over areas of hundreds of meters from the dredger can occur behind a TSHD in ordinary dredging operations, but under slightly different conditions they are absent. Whether a surface plume is generated or not has big implications on the assessment of environmental impact of a TSHD. Increased turbidity high in the water column can have adverse effects on flora and fauna and a surface plume can stay suspended for long periods thus being able to have influence on sensitive areas away from the dredging site.

The presented CFD model can be applied to investigate surface plume generation under the conditions of a specific dredging project and characteristic plume results for a range of relevant conditions have been presented. For cases that CFD simulations require too much effort, predictive mathematical formulas are available which can predict the vertical distribution and amount of deposition of the coarser fractions of the overflow plume at the end of near field within a second on a laptop. The insight from this article can be used for a better assessment of the environmental impact of dredging projects and help with setting up appropriate monitoring campaigns and adaptive management strategies.

When dredging with a TSHD, the main source for a turbidity plume is the overflow which is a vertical shaft ending at the keel through which excess sea water from the hopper is released.

Summary

A surface plume from overflow can stay suspended for long periods and distances potentially resulting in negative environmental impact through increased turbidity and sedimentation. Surface plume generation is an important factor for a proper dredging environmental impact assessment which is accurate.

When dredging with a TSHD, the main source for a turbidity plume is the overflow which is a vertical shaft ending at the keel through which excess sea water from the hopper is released. This excess water can contain fine sediment fractions which did not have sufficient time to settle in the hopper. Increased turbidity can impact ecological sensitive areas by reduced light penetration, reduced visibility, clogging and burial. For dredging projects, often the environmental impact needs to be assessed by model studies beforehand and monitored during execution of the work.

Generation of a surface turbidity plume from the overflow of a TSHD is investigated by a process-based, detailed Computational Fluid Dynamics model. The influence of effective flow velocity (sum of dredging speed and ambient current), depth, and entrained air bubbles in the overflow pipe is visualised with appealing results. A selection of results from a validated CFD model incorporating all important processes is presented.

Lynyrd de Wit
Lynyrd is a dredge plume expert. He has been involved in projects regarding TSHD/WID/MFE/offshore mining plumes, outfall mixing, salt intrusion from a sea lock, land reclamation Khalifa Port, hopper/caisson sedimentation, siltation in harbor basins and approach channels. The combination of developing and applying models and monitoring in the field makes him aware of limitations of numerical models, but also of their possibilities. Between 2008 and 2014 he finished a PhD study on near-field mixing of overflow TSHD dredge plumes.

Bram Bliek
Bram (1955) is the General Manager at Svašek Hydraulics since 1984. He joined the company in 1977 upon completion of his MSc. work at Delft University of Technology. He is a recognized expert in coastal engineering and hydraulic modelling. His expertise is based on a sound and practical understanding of the physical processes in surface waters and includes themes like tidal and river currents, wind wave and swell characteristics, seabed morphology, hydraulic structures and their environmental impacts, and the interactions between all of this.

Cees van Rhee
Since 1985, Cees has been engaged with research for the dredging industry. The first five years were at WL|Delft Hydraulics (presently Deltares) and then at Van Oord, a dredging contractor where he was employed at the various departments and projects, from 1990 to 2011. At the end of 2002, the author obtained his PhD degree. Since October 2007, he is professor Dredging Engineering at Delft University of Technology. His main scientific achievements are modelling of highly concentrated sediment water flows and high velocity erosion of granular sediments.

REFERENCES

Aarninkhof, S., Laboyrie, P., Koningsveld, M. van (2018).
Dredging for sustainable infrastructure, CEDA/IADC publication, ISBN: 9789090313184

Becker J., Eekelen E. Van, Wiechen J. Van, Lange W. De, Damsma T., Smolders T., and Koningsveld M. van (2015).
Estimating source terms for far field dredge plume modelling, *Journal of Environmental Management*, 149, DOI http://dx.doi.org/10.1016/j.jenvman.2014.10.022

Bray R. (Ed.) (2008).
Environmental aspects of dredging. Taylor & Francis / Balkema.

CEDA (2015a).
Environmental Monitoring Procedures. Information paper. [Online] Available from: http://www.dredging.org/media/ ceda/org/documents/resources/cedaonline/2015-02-ceda_informationpaper-environmental_monitoring_procedures.pdf

CEDA (2015b).
Integrating Adaptive Environmental Management into Dredging Projects. Position paper. [Online] Available from: http://www.dredging.org/media/ceda/org/documents/resources/ cedaonline/2015-01-ceda_positionpaper-integrating_adaptive_ environmental_management_into_dredging_projects.pdf.

Decrop, B. (2015).
Numerical and experimental modelling of near field overflow dredging plumes, PhD. thesis, Ghent University, KU Leuven.

Nichols M., Diaz R., Schaffner L. (1990).
Effects of hopper dredging and sediment dispersion, chesapeake bay. *Environ. Geol. Water Sci.* 15 (1), 31–43.

Radermacher, M., F. van der Goot, D. Rijks, L. de Wit (2013).
The art of screening: effectiveness of silt screens, Terra et Aqua issue 132

Rhee, C. van (2002).
On the sedimentation process in a Trailing Suction Hopper Dredger. Ph.D. thesis, TU Delft.

Saremi S. (2014).
Density driven currents and deposition of fine materials, Ph.D. thesis, Technical University of Denmark.

Spearman J., De Heer A., Aarninkhof S., Van Koningsveld M. (2011).
Validation of the TASS system for predicting the environmental effects of trailing suction hopper dredgers. *Terra et Aqua* (125).

Whiteside P., Ooms K., Postma G. (1995).
Generation and decay of sediment plumes from sand dredging overflow. *In: Proceedings of the 14th World Dredging Congress*, pp. 877–892.

Wit, L. de, A.M. Talmon and C. van Rhee (2014a).
Influence of important near field processes on the source term of suspended sediments from a dredging plume caused by a Trailing Suction Hopper Dredger: the effect of dredging speed, propeller, overflow location and pulsing, *Environmental Fluid Mechanics*. DOI: http://dx.doi.org/10.1007/s10652-014-9357-0

Wit, L. de, A.M. Talmon and C. van Rhee, (2014b).
3D CFD simulations of trailing suction hopper dredger plume mixing: comparison with field measurements, *Marine Pollution Bulletin*, DOI http://dx.doi.org/10.1016/j.marpolbul.2014.08.042

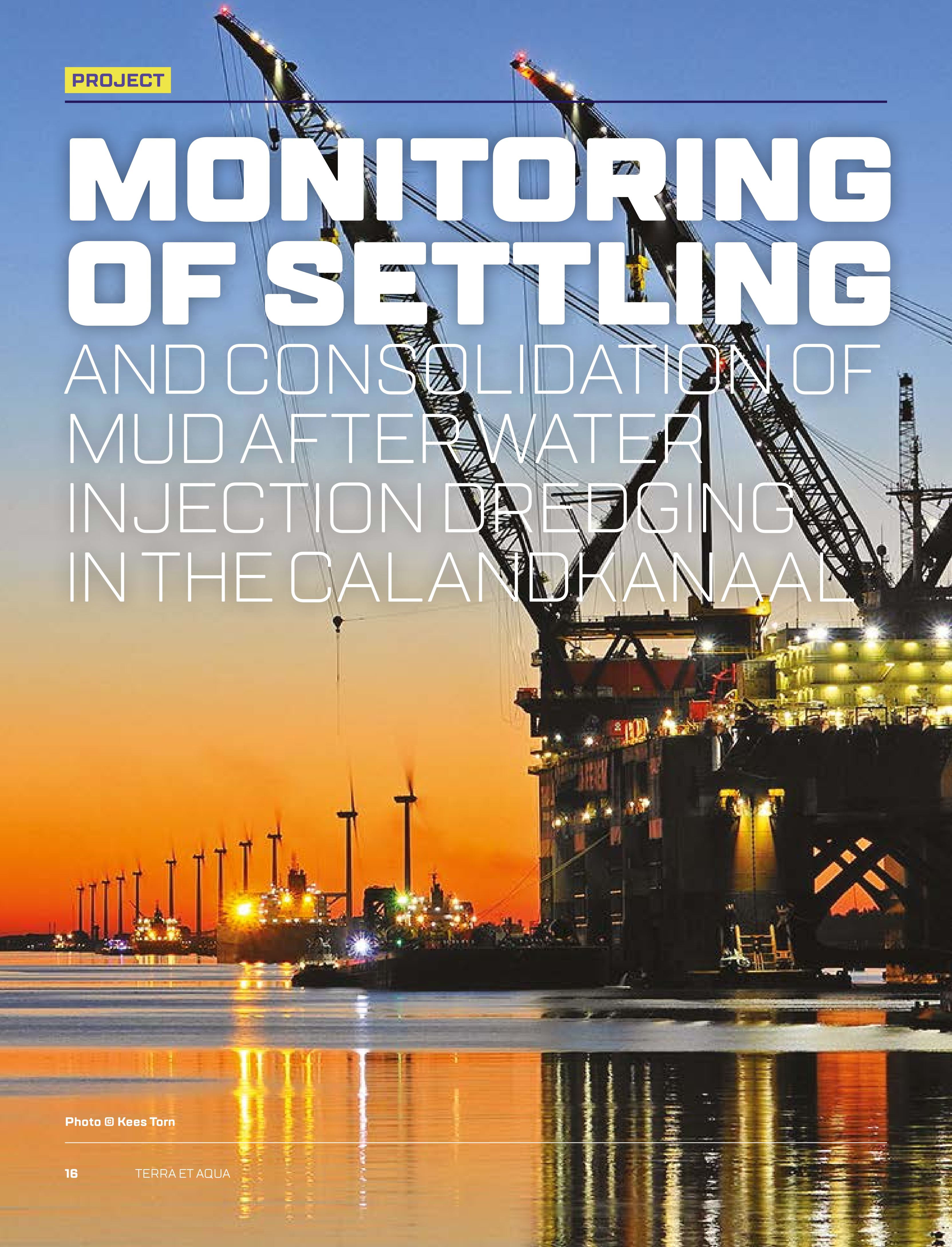
Wit, L. de, A.M. Talmon and C. van Rhee (2014c).
3D CFD simulations of trailing suction hopper dredger plume mixing: a parameter study of near field conditions influencing the suspended sediment source flux, *Marine Pollution Bulletin*, DOI http://dx.doi.org/10.1016/j.marpolbul.2014.08.043

Wit, L. de (2015).
3D CFD modelling of overflow dredging plumes, Ph.D. thesis, Delft University of Technology.

Wit, L. de (2019).
3D CFD modelling of hopper sedimentation, *Proceedings of CEDA Dredging Days 2019*, Rotterdam, the Netherlands

MONITORING OF SETTLING

AND CONSOLIDATION OF MUD AFTER WATER INJECTION DREDGING IN THE CALANDKANAAL



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In order to keep ports and waterways at Port of Rotterdam accessible, more than 11 million m^3 of deposited sediment were dredged in 2017.

As regular maintenance and relocation of sediment deposits are highly expensive, Port authorities seek more efficient solutions for reducing the costs and CO2 emissions of maintenance dredging. One solution, water injection dredging (WID), is carried out for maintaining the sediment deposits which predominantly consist of clay and silt. WID has been proven to be a cheaper solution by leaving the sediment in place, eliminating substantial costs for relocation of the dredged sediment.

Introduction

Navigation in ports and waterways must be safeguarded by maintenance dredging, which removes sediments deposited by tide, river flows and currents. The volumes of dredged sediment have been substantially increased in the Port of Rotterdam (PoR) over the last five years (see Figure 1). In order to keep ports and waterways accessible, more than 11 million m^3 of deposited sediment were dredged in 2017. The dredged volumes are almost doubled in comparison with the volumes dredged in 2011. The sediment depositions in these areas consist mainly of fine cohesive minerals forming mud layers, which are periodically dredged by a Trailer Suction Hopper Dredger (TSHD). As maintenance dredging and consequent relocation of mud can be highly expensive, port authorities seek for tailor-made solutions that can help to reduce the maintenance costs as well as CO2 emissions and at the same time guarantee safe navigation in the port.

There are various measures that can potentially help to reduce maintenance costs and CO2 emissions. For instance, revising the intervention protocols can bring additional short- and long-term benefits. In the long-term instead of removing sediment, its presence may be accepted since ships are – under certain conditions – able to sail through fluid mud. Local sediment conditioning may be required to avoid that mud layers become consolidated to allow sailing through them.

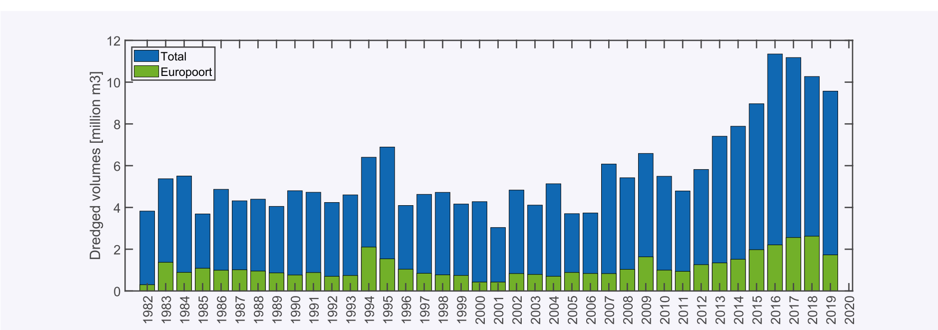

FIGURE 1

Dredged sediment volumes at the Port of Rotterdam from 1982 till 2020 (adapted from Kirichek et al., 2018a).

A conventional way for estimating the navigability in ports and waterways with fluid mud layers is done through the calculation of the nautical depth. This approach ensures that vessels can safely navigate through areas, where thick layers of fluid mud are detected. For practical reasons, a critical density (1200 kg/m^3) is typically used for estimating the nautical depth within PIANC's nautical bottom approach (PIANC, 2014). However, it has long been recognised, that a practical definition of the nautical depth should be based on considerations not only of density but should also include the so-called rheological properties of the water-sediment mixture (Wurpts and Torn, 2005, Kirichek et al., 2018b). Currently, a rheological parameter (100 Pa yield stress) serves as a criterium for estimating the nautical depth in the Port of Emden.

Optimising current maintenance strategies can substantially reduce the costs and CO2 emissions. Water injection dredging (WID) can be efficiently applied for fluidising and transporting the sediment within the port area. By applying WID, it is proposed to keep port

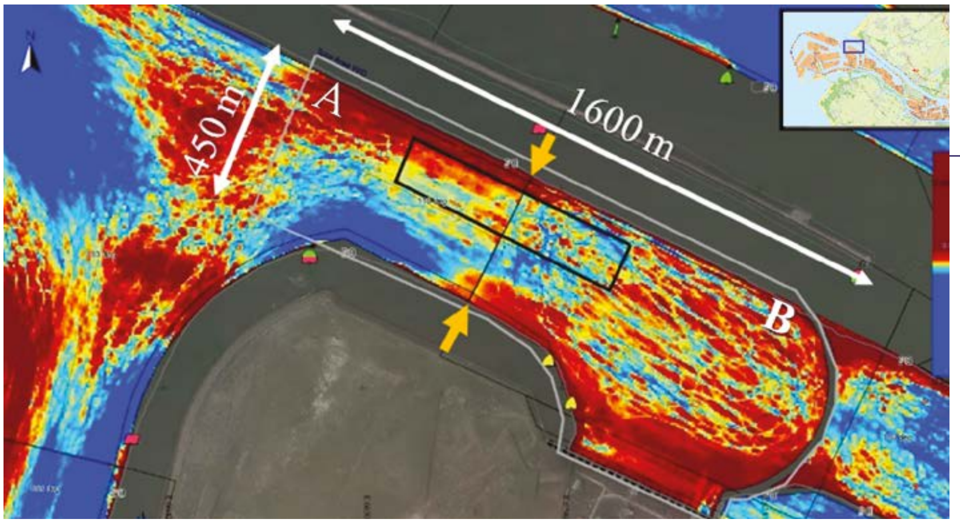

FIGURE 2

Location of the sediment trap in the Calandkanaal. Black rectangle shows the location of the sediment trap. Orange arrows indicate a boundary between Rijkswaterstaat's (A) and the PoR's (B) maintenance areas within the WID pilot location (gray contour). Based on the measured and simulated data, the western part of Europoort was chosen for the WID pilot.

locations, which are not easily accessible by TSHD, at required nautical depth. Fluidising the sediment by water injection creates homogeneous fluid mud layers of a substantial thickness (up to 2 m). These fluid mud layers have a weak shear strength (yield stress), therefore they can be easily transported as gravity currents by natural forces and/or by WID.

This paper presents the results of testing WID at the Calandkanaal. The efficiency of WID was compared to TSHD maintenance in the Calandkanaal. Available historical dredged volumes and CO2 emissions from the fuel consumption data from the last two years were analysed in order to assess the cost and CO2 efficiency of WID and TSHD for maintenance in the area of the investigation.

Descriptions of the pilot

Location

Several conditions had to be considered before location of the WID pilot was finally chosen. First, there should be enough sediment to fluidise and transport in the area. This sediment should be cohesive by its nature so that WID fluidising processes result in formation of fluid mud layers, which can be transported to the sediment trap. Second, the sediment trap should be located further away from the berths to avoid any ship-induced entrainment that can affect settling processes in the sediment trap. Third, the hydrodynamic conditions are expected to be favorable for trapping the sediment, therefore preliminary hydrodynamic modelling was done in order to find a right location for the sediment trap.

Sediment trap and WID actions

Figure 2 shows the location, where the sediment trap was designed and WID was carried out. The sediment trap was made by a TSHD on the northern bank in the Calandkanaal. The dimensions of the trap are 600 m over 120 m. The over depth of the sediment trap varies from 1 m to 1.3 m.

WID was conducted for fluidising the deposited sediment in the area of the sediment trap over the length of 1600 m, so that the fluidised mud layers would flow into the sediment trap. The WID area is shown by the grey line in Figure 2.

Monitoring plan and attributes

The main objectives of monitoring surveys were to capture settling and consolidation behaviour of mud after WID and to compare yield stress (100 Pa) and density (1200 kg/m^3) levels for applying the nautical depth in the area of the investigation. In addition, sediment dynamics during WID (see Figure 3) was recorded.

The monitoring plan is given in Table 1. WID was performed during day 1. A preliminary survey was conducted before WID. The measurements from this survey were used as a reference. The monitoring campaign was carried out every Wednesday on a weekly basis starting from day 1 until day 84 with occasional surveys afterwards.

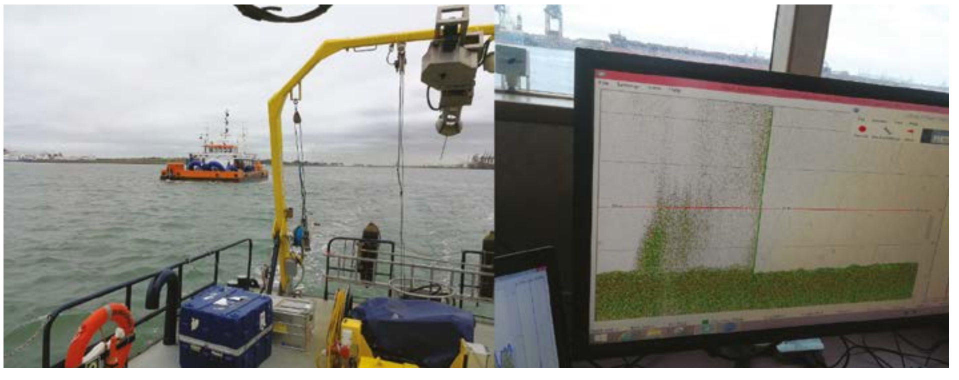

FIGURE 3

Monitoring during WID actions.

TABLE 1

Monitoring plan for the pilot.

	Week number	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5
	Day	**0**	**1**	**7**	**14**	**21**	**28**	**35**	**42**	**49**	**56**	**63**	**70**	**77**	**84**	**91**	**98**
I.	Multibeam		WID														
	SILAS		WID														
II.	DensX		WID														
	Rheotune		WID														
	Gaviprobe		WID														
III.	Frahmlot		WID														
	Slib Sampler		WID														
	MARS Haake		WID														

Table 2 provides the list of monitoring attributes which were used during the monitoring campaign. The monitoring attributes can be divided into three groups:

1. Acoustic/seismic tools;
2. Penetrometers;
3. Laboratory analysis.

There are two tools in Group I. These tools provide a 2D and 3D high resolution bathymetry and shallow subsurface profiles. Teledyne RESON SeaBat 7101 multibeam echo-sounder with Septentrio Asterx-U VRS GNSS positioning, Ixblue Hydrins motion sensor and Stema SILAS system are mounted on the survey vessel that was used for monitoring (see Figure 3). These two systems are used by the PoR surveyors for day-to-day surveys. The high-frequency multibeam echo-sounder is used for mapping the water-sediment level (200 kHz) and low-frequency (38kHz) SILAS system is employed in the port areas with mud layers, where the density-based (1200 kg/m^3) nautical bottom approach is applied for mapping the nautical guaranteed depth (NGD) on the nautical charts (Kirichek et al., 2018b).

The monitoring campaign was carried out every Wednesday on a weekly basis starting from day 1 until day 84 with occasional surveys afterwards.

TABLE 2

Monitoring tools used in the pilot.

Tool	Output	Unit
Multibeam	Water-mud level	m
SILAS	100 Pa and 1200 kg/m^3 levels	m
Graviprobe	Undrained shear strength	Pa
Rheotune	Density, Bingham stress vertical profiles	Pa, kg/m^3
DensX	Density vertical profile	kg/m^3
Frahmlot	Mud samples	-
Slibsampler with Anton Paar	Density vertical profile	kg/m^3
MARS Haake Rheometer	Yield stress	Pa

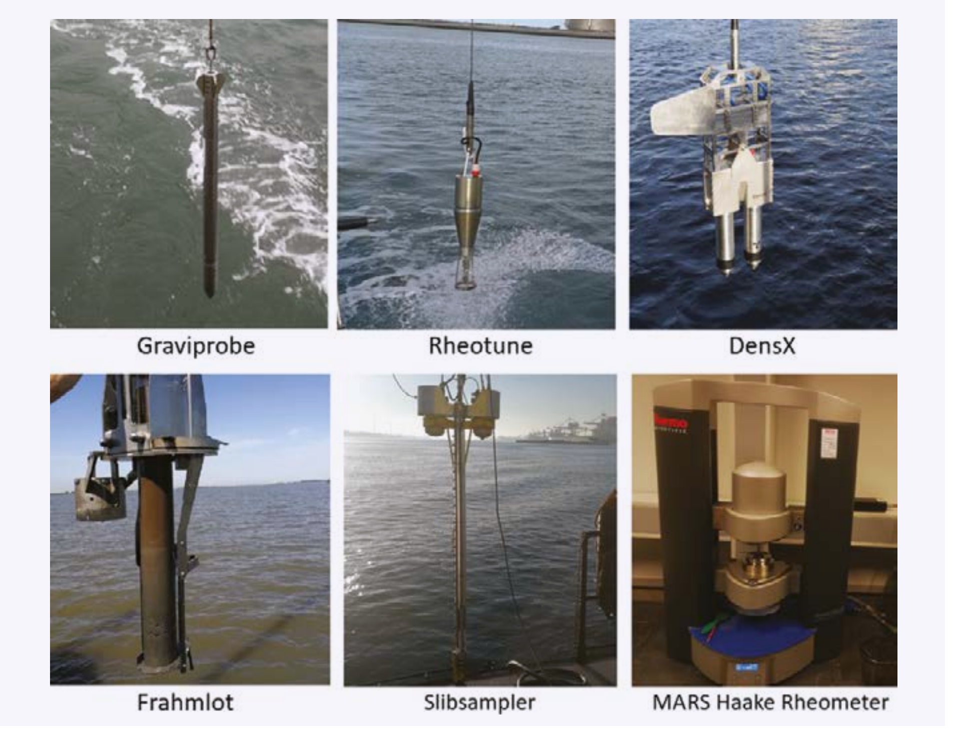

FIGURE 4

Vertical profilers and the rheometer that were used for characterising the mud layers.

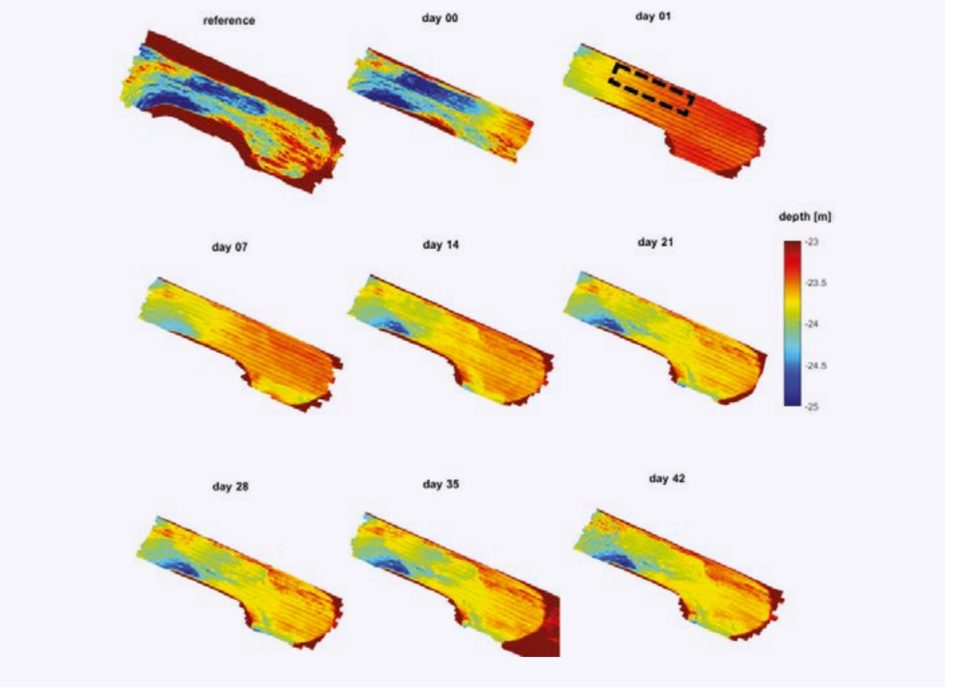

FIGURE 5

Development of bathymetry (water-mud level) before (reference) and after (day 01-day 42) WID. Black rectangle on 'day01' shows the location of the sediment trap.

Group II consists of three penetrometers, that measure physical parameters in the water-mud column. These tools are shown in Figure 4. DensX provides the vertical profile of density. The measurements of this device are based on X-ray scattering. At this moment, DensX measurements are used by Rijkswaterstaat and the PoR to measure densities of mud for SILAS calibration process, that allows applying 1200 kg/m^3 level for the nautical depth. Rheotune provides Bingham yield stress and density vertical profiles in water-mud columns. This tool correlates the amplitudes, that are triggered by mechanical vibrations at resonance frequencies, to either density or Bingham yield stress datasets, which are collected on various mud samples of different physical properties in laboratory. Graviprobe provides the vertical profile of the undrained shear strength, which is determined from the measured acceleration/deceleration of the instrument, that is acquired during a free-fall of Graviprobe.

Laboratory analysis was conducted by using the equipment in Group III. Initially, the sediment samples were collected using Slibsampler or Frahmlot. The former collects sediment core samples by using cylindrical tube with openings on the lateral side. The openings can be used for collecting a fluid mud samples from the core, that can be analysed directly on-board using Anton Paar density meter. The latter has a cylinder, that is connected to Frahmlot, and enables to collect soft sediment core samples up to 1 m in length and 0.1 m in diameter. The collected core is then subsampled and transported to a laboratory for further characterisation. The density and yield stresses of collected samples were measured in the laboratory. Anton Paar density meter was used for estimating the density of samples. As for rheology, MARS Haake Rheometer was utilised for analysing the yield stresses of mud samples. Newly developed time-efficient protocols (Shakeel et al., 2019) were applied for measuring the yield stresses.

Results and discussion

The monitoring results showed that state-of-the-art monitoring and surveying methods can provide us with useful information on development of mud layers due to WID and subsequent settling and consolidation processes. The monitoring tools from Group I gave a high-resolution spatial image during and after WID. Figure 5 shows the bathymetry before (reference, day 00) and after (day 01–day 42) WID. The indicated depth corresponds to the depth of water-mud interface. By comparing the measurements that were recorded before and after WID actions (day 00 and day 01, respectively), it was concluded that about 2 m of fluid mud was collected by the sediment trap. Further analysis showed that the mud layer settled in the sediment trap. This conclusion was justified by the fact that the contours of the sediment trap became more pronounced on the data acquired on day 42 comparing to the measurements collected on day 7. One might argue that the sediment didn't settle but eroded, however the sediment depositions around the sediment trap (see day 42) suggested that the settling process indeed took place at the sediment trap.

Figure 6 shows seismic profiles produced by the SILAS system. Typically, the processed data was used for correlating the density to seismic measurements in order to obtain density-based nautical bottom levels. Vertical blue and red lines are the Bingham yield stress and the density profiles that were measured by Rheotune. The change in seismic amplitudes (from light green to dark green) showed that there was no density gradient indication on the seismic data of the top sediment layer (Day 7, depth above 24.5m), suggesting that the top mud layer was homogeneous which is expected from fresh fluid mud layer.

The horizontal red line shows 1200 kg/m^3 levels, which were obtained by correlating the vertical density profiles given by Rheotune to seismic data acquired by SILAS system. The 1200 kg/m^3 level was in a proximity to a sharp color gradient (Day 7, depth of 25m), which could serve as an indication of the fluid mud – natural bed interface. However, a good correlation was only observed for a fresh fluid mud layer that was produced by WID (Day 7). Subsequent data (Day 21 and Day 42) showed a poor correlation between the 1200 kg/m^3 level and the sharp color gradient because of consolidation of fluidised mud.

Figure 7 shows the spatial variation of 1200 kg/m^3 levels during and after WID. The colour map corresponds to the depth, where sediment has a density of 1200 kg/m^3. The observation suggested that the fluidised sediment consolidated in the sediment trap

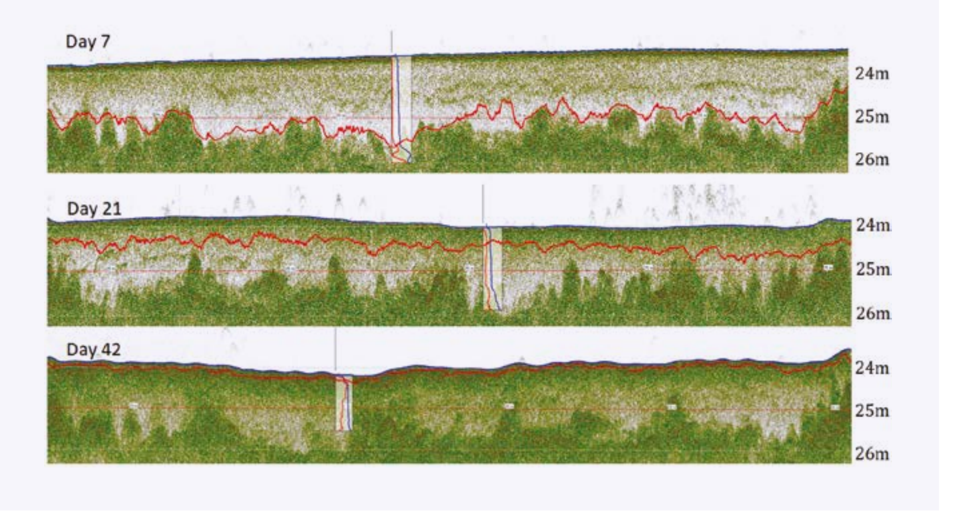

FIGURE 6

Vertical seismic profiles measured after WID at the Calandkanaal. Red line shows the 1200 kg/m^3 level.

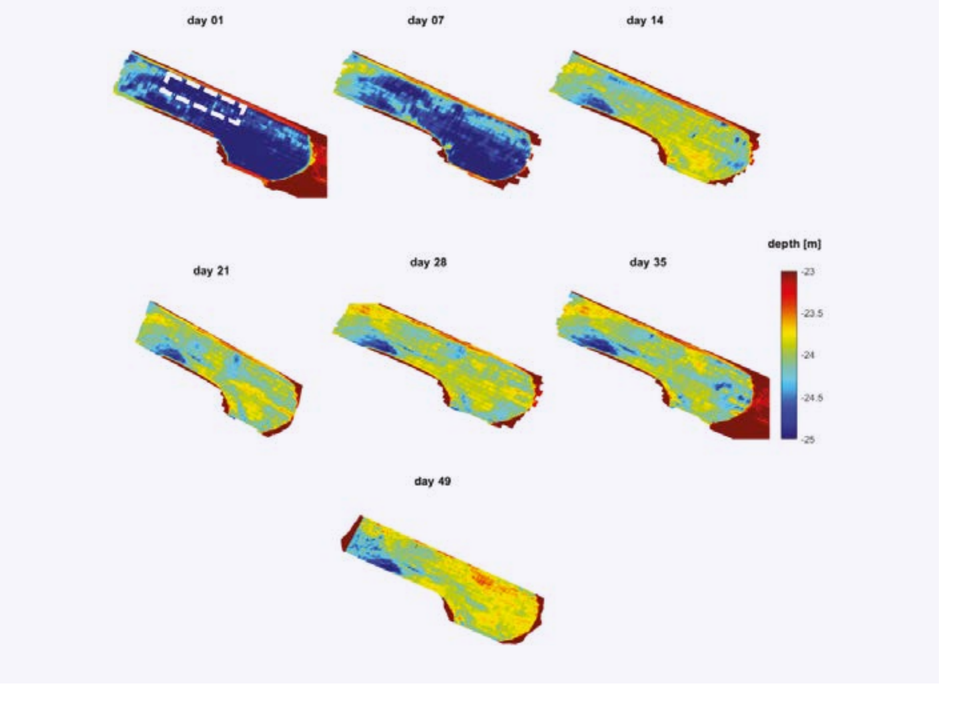

FIGURE 7

Development of 1200 kg/m^3 level after WID (day 01–day 49) at the Calandkanaal. White rectangle on 'day 01' shows the location of the sediment trap.

and in the surrounded area. However, the sediment did not consolidate at the South-West area, because this area was eroded due to hydrodynamic conditions. The eroded area was also clearly observed in the bathymetry data (see Figure 5).

The water-mud and 1200 kg/m³ levels over the cross-section (see Figure 2) of the Calandkanaal are shown in Figure 8. The development of 1200 kg/m³ level showed that mud layers in the sediment trap reached 1200 kg/m3 densities in 2-6 weeks suggesting that the over depth of the sediment trap can be used by arriving vessels for up to 6 weeks after WID if the density-based nautical bottom approach is applied.

The development of density and yield stress profiles measured by Rheotune in the sediment trap are shown in Figure 9. The measurements were conducted before (day 00) and after WID (day 01 – day 91). Day 00 shows the reference. Clearly, there was no fluid mud layers on the reference profiles (day 00). The measurements that were carried out right after WID (day 1) showed that the WID produced a fluid mud layer of about 2 m height. This fluid mud layer had a weak strength (the Bingham yield stress was less than 10 Pa) and the density was less than 1200 kg/m³.

Two weeks after WID (day 14), the density of mud reached 1200 kg/m³ at the bottom of the layer due to consolidation process. The Bingham yield stress of the settled layer was less than 60 Pa, suggesting that mud still had a weak strength.

Six weeks after WID (day 42), the density level reached 1200 kg/m³, but the Bingham yield stress level of the layer was less than 100 Pa. Laboratory analysis showed that collected mud hadn't reached its consolidated phase and might be in a transition from fluid to consolidated phase. In addition, laboratory measurements showed a good correlation between laboratory and Rheotune's measured densities and Bingham yield stresses (Kirichek et al, 2020).

The density measurements conducted almost two months after WID (day 77), showed that mud had densities closer to 1300 kg/m³ and the Bingham yield stresses of about 100 Pa.

DensX and Graviprobe measurements were used to confirm respectively the density and shear strength development of mud layer in the sediment trap. Figure 10 shows density and undrained shear strength profiles measured by DensX and Graviprobe before (day 01) and after WID (day 01 – day 98).

The DensX density profiles (Figure 10A) were in an acceptable agreement with the Rheotune density profiles (Figure 9A) in the density range of 1000-1250 kg/m³. For the densities above 1250 kg/m³, Reotune's profiles had more noise in the dataset.

The development of shear strength measurements provided by Graviprobe was consistent with the ones of Rheotune. From the Graviprobe measurements in the sediment

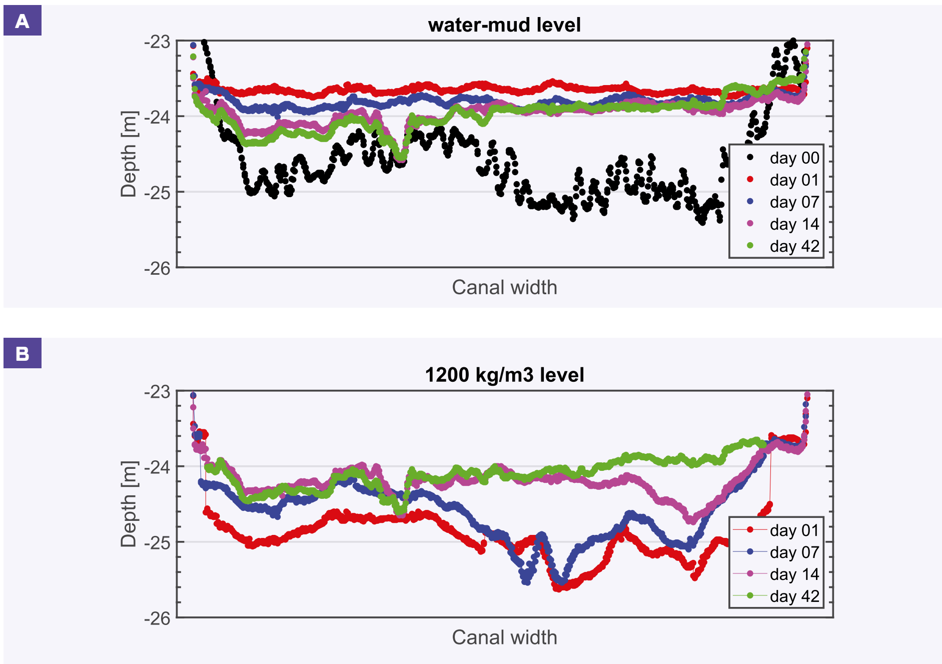

FIGURE 8

Development of water-mud level (A) and of 1200 kg/m³ level (B) in time over the cross-section of the Calandkanaal (shown by orange arrows in Figure 2).

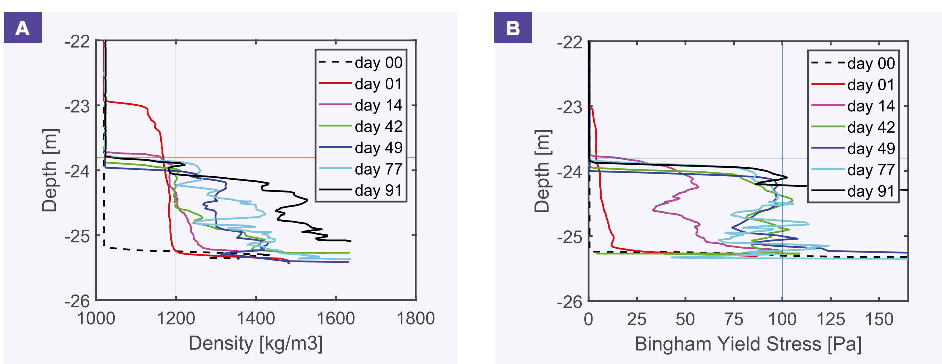

FIGURE 9

Density (A) and Bingham Yield Stress (B) profiles measured by Rheotune before (day 00) and after WID (day 01 – day 91) at the Calandkanaal.

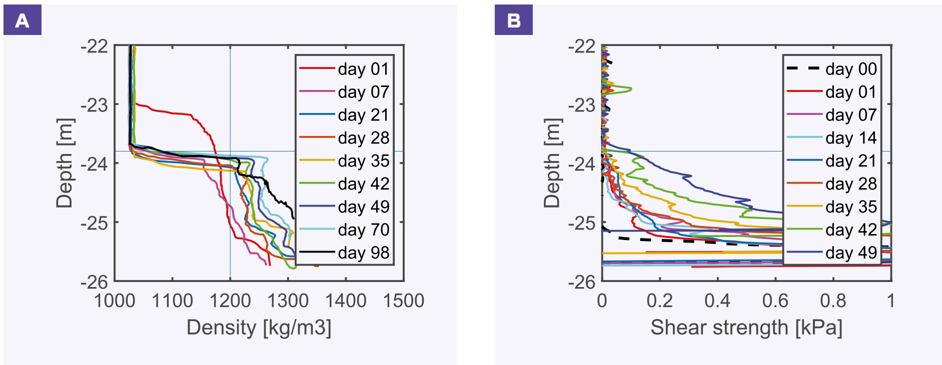

FIGURE 10

Density and undrained shear strength profiles measured by DensX and Graviprobe before (day 00) and after WID (day 01 – day 98) at the Calandkanaal.

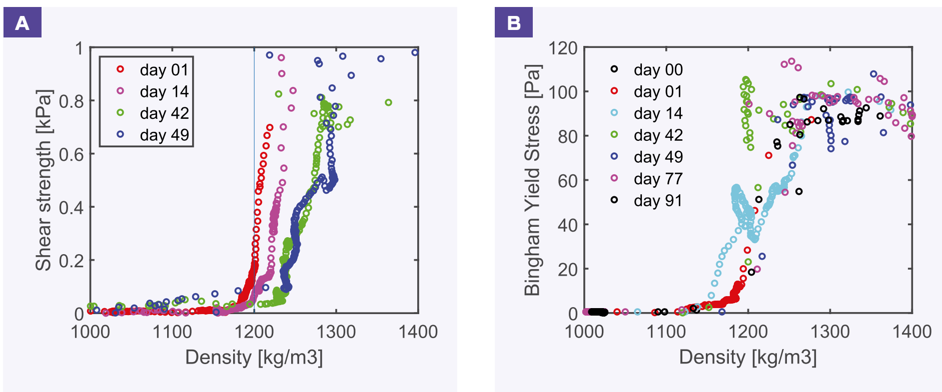

FIGURE 11

Density – yield stress/shear strength relationship measured (A) by DensX and Graviprobe, and (B) by Rheotune.

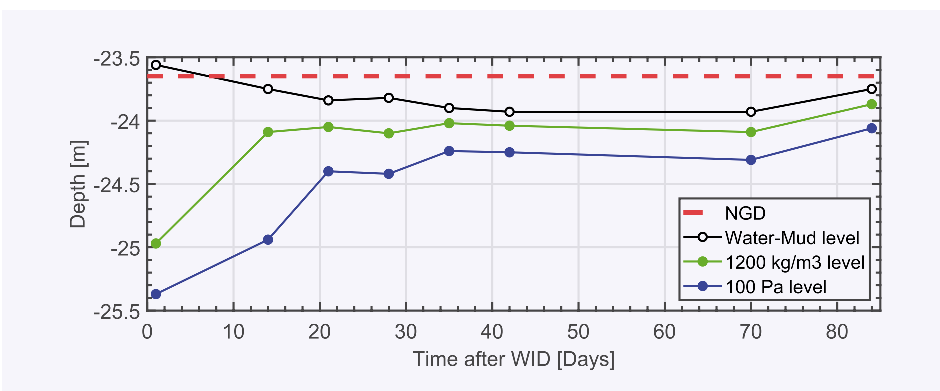

FIGURE 12

Development of measured water-mud level (black circles), 1200 kg/m³ level (green circles) and 100 Pa level (blue circles) after WID at the Calandkanaal. Red dashed line shows the Nautical Guaranteed Depth at the area of the investigation.

trap, it was concluded that the sediment gained 0.2 kPa undrained shear strength in two months (day 49). This is in line with the Rheotune measurements of the Bingham yield stress profiles shown in Figure 9.

Figure 11 shows a non-linear relationship between density and strength, that was measured by Rheotune (see Figure 11A) and by DensX and Graviprobe (see Figure 11B). This figure demonstrates, that the density of mud does not provide any information about the strength because the strength of mud is time-dependent. The density-strength relationship that was measured by DensX and Graviprobe had less scatter of the data than the one measured by Rheotune (see Figure 11B), especially at densities above 1200 kg/m³. This was most probably because DensX and Graviprobe
can penetrate mud with densities above 1200 kg/m³ easier than Rheotune.

In-situ strength and density profiles can be useful for improving maintenance strategies in ports in waterways. For instance, the measurements collected after WID can potentially be combined with consolidation modeling (Kirichek et al, 2020). Using density and strength profiles as input parameters for numerical models can provide a valuable tool for estimating a time line for the next maintenance cycle. Furthermore, knowledge of the density of deposited sediments can help to determining the volumes that should be dredged by WID or TSHD. Finally, the density and strength measurements can be used for estimating the navigable depth. Figure 12 shows the comparison of a regular bathymetry-based criterium for navigation to the yield stress and density based nautical depths, which correspond to 100 Pa and 1200 kg/m3 levels, respectively. Applying the nautical bottom approach in the area of the investigation resulted in additional 2 m and 1.5 m of nautical depth right after WID (day 1) in case of applying 100 Pa and 1200 kg/m3 criteria, respectively. As mud settled, the density of mud built up faster than the yield stress, therefore the 1200 kg/m³ level was always higher than the 100 Pa level. Furthermore, the 1200 kg/m3 level reached the equilibrium in 2 weeks after WID, but it took about 5 weeks for reaching a constant depth over time for the 100 Pa level. After 1 month, the difference between 1200 kg/m3 and 100 Pa levels were about 20-30 cm in favor of

An initial impression of the efficiency of the WID pilot at the Calandkanaal was analysed by comparing the historical data on dredged volumes of dry matter at the area of the investigation.

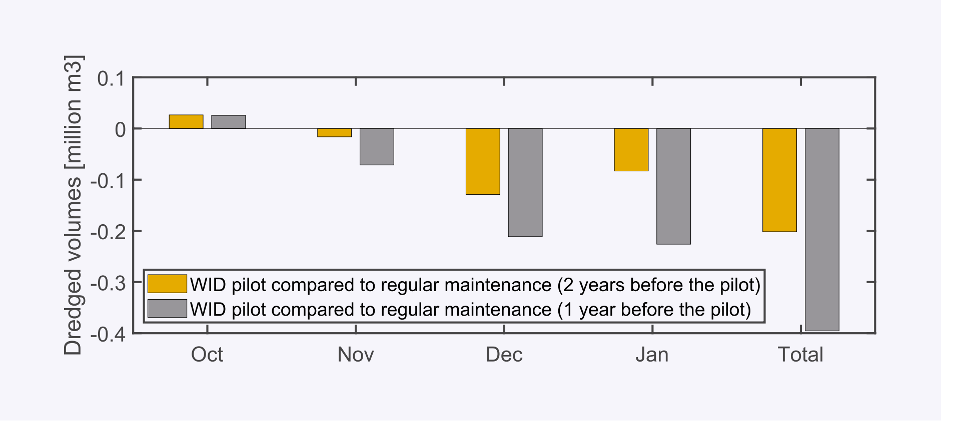

FIGURE 13

Difference of the dredged volumes during the WID pilot (Oct 2018 – Jan 2019) and the volumes that were dredged at the same area one year before the WID pilot (Oct 2017 – Jan 2018) is shown in grey bars. Difference of the dredged volumes during the WID pilot (Oct 2018 – Jan 2019) and the volumes that were dredged two years before the pilot (Oct 2016 – Jan 2017) is shown in orange bars.

yield stress based nautical depth. Finally, the regular maintenance was conducted in the area almost in 3 months after WID, which is a positive outcome because normally the area of the investigation is maintained every month by a regular maintenance.

Initial impression of cost implications of CO2 emissions

An initial impression of the efficiency of the WID pilot at the Calandkanaal was analysed by comparing the historical data on dredged volumes of dry matter at the area of the investigation. For this analysis, the dredged volumes data from the PoR's maintenance area (see Figure 2) was used. The comparison is done for the period of the WID pilot (Oct 2018 – Jan 2019), one year (Oct 2017 – Jan 2018) and two years (Oct 2016 – Jan 2017) before the WID pilot. The data on the dredged volumes for earlier periods is not considered in the analysis because of infrastructural changes in the vicinity of the WID pilot area.

Figure 13 shows the differences of the dredged volumes that were obtained by subtracting the volumes that were dredged one year ago and two years ago from the dredged volumes during the WID pilot.

In general, the dredged volumes for the first month (October) were higher for the WID pilot because of additional dredging actions needed for making a sediment trap. After the first month, the volumes dredged during the WID pilot were much lower because regular maintenance was not needed after WID. By analysing the total difference of the dredged volumes, it could be concluded that the WID pilot was able to keep sediment in place and to prevent dredging of about 200,000–400,000 m³ in the area of the investigation in the Calandkanaal. However, more detailed study has to be conducted in order to refine the outcome of the pilot. For instance, more knowledge on the sediment balance will help to analyse the impact of the WID pilot on the sedimentation in other areas of the port.

The CO2 emissions estimates from the fuel consumption of dredging vessels for the period of the WID pilot (October 2018–

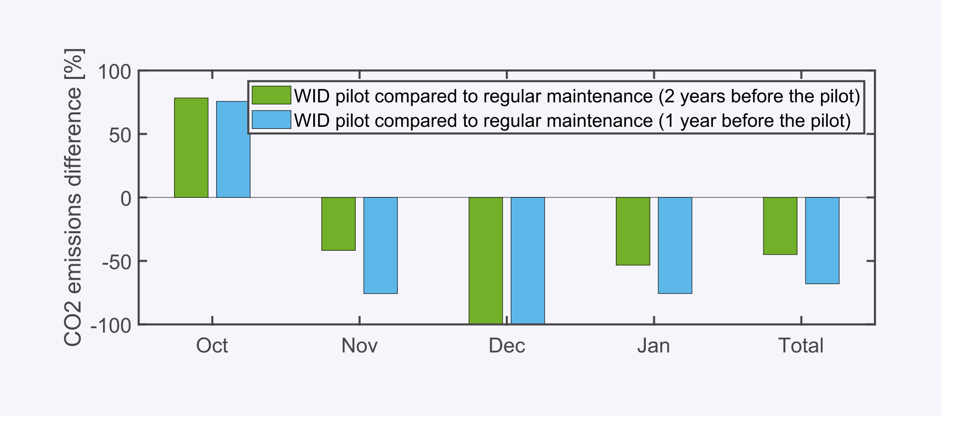

FIGURE 14

Difference of the CO2 emissions from the fuel consumption of dredging vessels during the WID pilot (October 2018–January 2019) and the CO2 emissions at the same area one year before the pilot (October 2017–January 2018) is shown in blue bars. Difference of the CO2 emissions during the WID pilot and the CO2 emissions two years before the WID pilot (October 2016–January 2017) is shown in green bars.

January 2019) were compared to the CO_2 emissions at the same area one year ago (October 2017–January 2018) and two years ago (October 2016–January 2017). The CO_2 emissions were determined from the data of dredged volumes, dredging cycles, durations and fuel type consumed by WID and TSHD vessels. Figure 14 shows the results of the comparison. The CO_2 emissions during the first month (October) of the WID pilot were about 75% higher than the CO_2 emissions one and two years ago because more dredged volumes were needed for making a sediment trap and additional CO_2 emissions from the WID vessel. However, the subsequent emissions for the period of the WID pilot were much lower than those of one and two years ago. For instance, in December the CO_2 emissions during the WID pilot were 100% lower than those of one year and two year ago because no maintenance was needed during the WID pilot during this month. For the total duration of the pilot, the WID pilot was more CO_2 efficient than the regular maintenance helping to reduce the CO_2 emissions by 45-65%.

Conclusions

The effect of WID in the Calandkanaal was monitored for three months by means of measuring the development of density and strength (yield stress) during settling and consolidation of fluidised mud layer. It was concluded that in-situ data can be useful for estimating settling and consolidation time of mud after WID. Furthermore, measured yield stress and density profiles were used for PIANC's nautical bottom applications, where 1200 kg/m^3 and 100 Pa levels were adapted for estimating the nautical depth.

Utilising the nautical bottom approach brought an additional 2 m and 1.5 m of nautical depth right after WID in case of applying 100 Pa and 1200 kg/m^3 criteria, respectively. The 1200 kg/m^3 level was always higher and built up faster than the 100 Pa level. The regular maintenance was conducted almost in 3 months after WID implying a successful outcome of the WID pilot since the area of the investigation is normally maintained every month by a TSHD.

The efficiency of the WID pilot was compared to the regular maintenance in the area of the investigation in the Calandkanaal. An initial impression of cost implications obtained from the analysis of historical dredged volumes showed that during the WID pilot dredged volumed decreased by 200,000-400,000 m^3 comparing to the volumes dredged 2 and 1 years before the WID pilot at the same location and the same time of year. However, an additional analysis on the sediment balance should be carried out in order to refine the outcome of the WID pilot in the Calandkanaal and to study the impact of the WID pilot on the other areas of the port.

The CO_2 emissions from the fuel consumption of dredging vessels were determined for the period of the WID pilot and for the regular TSHD maintenance conducted one and two years before the WID pilot at the same area and the same time of year. The CO_2 emissions were estimated from the data on dredged volumes, dredging cycles, durations and fuel type consumed by WID and TSHD vessels. It was determined that the WID pilot was more CO_2 efficient than the regular maintenance helping to reduce the CO_2 emissions by 45-65% during the total duration of the pilot.

Based on the results of the WID pilot, it was concluded that new CO_2 and cost efficient port maintenance strategy is feasible in the ports and waterways with mud layers.

Summary

Regular maintenance and relocation of sediment deposits are highly expensive causing Port authorities to seek more efficient solutions for reducing the costs and CO_2 emissions of maintenance dredging. Water injection dredging (WID) is a solution utilised for maintaining the sediment deposits which predominantly consist of clay and silt, and is proven to be cheaper than hopper dredging by leaving the sediment in place. This eliminates substantial costs for relocation of the dredged sediment.

At the end of 2018, the utility of WID was investigated in the Calandkanaal at Europoort in Rotterdam. As a first step, the sediment trap was made in the Calandkanaal. Next, the WID was carried out for fluidising the sediment in close vicinity of the sediment trap and transporting the fluidised mud layer into the sediment trap.

The effect of WID was monitored by means of multibeam and SILAS system, that measured water-mud interface and fluidised mud layer thickness, respectively. After WID, the WID area was regularly surveyed for three months. Shear strength, yield stress and density of mud were measured in order to monitor settling and consolidation of fluidised mud layer. Furthermore, measured yield stress and density profiles were analysed as criteria for PIANC's nautical bottom applications, where 1200 kg/m^3 and 100 Pa limits have been applied for estimating the nautical depth.

The efficiency of WID was compared to regular maintenance in the Calandkanaal. Based on the analysis of historical dredged volumes and CO_2 emissions from the fuel consumption data, it was concluded that WID is a more cost and CO_2 efficient maintenance method than the regular maintenance in the area of the investigation.

REFERENCES

Kirichek, A., Rutgers, R., Wensveen, M. & van Hassent, A. (2018a).
Sediment management in the Port of Rotterdam, Book of Abstracts, 10. Rostocker Baggergutseminar.

Kirichek A., Chassagne C., Winterwerp H. & Vellinga, T. (2018b).
How navigable a fluid mud layers? Terra et Aqua, 151, 6-18.

Kirichek, A., Shakeel, A. & Chassagne, C. (2020).
Using in situ density and strength measurements for sediment maintenance in ports and waterways. J. Soils Sediments, 20, 2546–2552.

PIANC (2014).
Harbour Approach Channels – Design Guidelines, Report 121, PIANC, Brussels.

Shakeel A., Kirichek A. & Chassagne C. (2019).
Rheological analysis of mud from Port of Hamburg, Germany. Journal of Soils and Sediment, 1-10.

Wurpts R. & Torn P. (2005).
15 Years' Experience with Fluid Mud: Definition of the Nautical Bottom with Rheological Parameters. Terra et Aqua, 99, 22-32.

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PANAMA CANAL'S DEPUTY ADMINISTRATOR ILYA ESPINO DE MAROTTA

'GENDER EQUALITY IN DECISION-MAKING IS A **WIN-WIN FOR THE WORLD IN ANY INDUSTRY.'**

Armed with degrees in both Marine Engineering and Engineering Economics as well as 35 years – and counting – of experience at the Panama Canal Authority, Ilya Espino de Marotta has blasted through the glass ceiling wearing a pink hard hat. Amongst the diverse roles she has under her belt, ranging from Marine Engineer in the shipyard to Vice President for Transit Business, Ilya has notably led the Canal's expansion as head engineer and now oversees operations from the second highest position at the authority.

Photo © Ima Ortega

My original inspiration was Jacques Cousteau. He caught my imagination. I started scuba diving when I was 16 and I wanted to be a marine biologist.

Can you tell me about your academic and professional background and experience?

I am a marine engineer. I went to school at Texas A&M in Galveston. Since I knew I didn't want to ship out, I didn't take the license option to go to sea. I decided I would work in shipyards or ship design, and that's what I did.

Actually, my original passion and major was marine biology and I had won a scholarship to study that. But back in 1982 in Panama, marine biology was not a career that would take me where I wanted to go. That's when I switched to marine engineering. I just wanted to be by the water – that was my driving force. When I came back to Panama after graduation, I got a job at the Panama Canal in the shipyard, which was perfect as that's exactly what I had studied. I worked in the shipyard for about four and a half years.

Within the Canal, I have had many, many functions. I've worked here since 1985 and the Canal is big with about 10,000 employees. There was a small newspaper where you could apply for jobs within the authority to move around, so I applied for a job in the dredging division, and then worked there for about two years. Then I applied for a job as a mechanical engineer in the design office and I was there for four years. After that I became a valuation engineer in accounting, followed by a job as capital investment coordinator for the maritime operations department which was the biggest department at the time. After working there, I got a call in 2002 from the then deputy administrator – which is the role I have now – to participate in the development of a masterplan to create the expansion programme. That lasted till 2019, when I moved over to head the operations of the Panama Canal, which is the biggest vice presidency. I was the first woman to be Vice President for Engineering, the first woman to be Vice President for Operations and then, since January of this year, the first woman Deputy Administrator. In a nutshell that's my career. It's been pretty amazing.

During your remarkable career, who has inspired you?

My original inspiration was Jacques Cousteau. It was he that caught my imagination. I started scuba diving when I was 16 and told everyone I wanted to be a marine biologist. Realistically marine biology wasn't feasible then in Panama, but I found something that would keep me by the water. Besides Cousteau, my parents inspired me by their work ethic, their dedication and commitment.

Do you enjoy your new role as Deputy Administrator of the Panama Canal?

It's been challenging. I'm still wearing two hats. I'm still COO and running operations, and I'm doing the Deputy role as well. It's a lot of work but being Deputy gives me an overview of the entire institution. I support the Administrator, Ricaurte Vásquez Morales, so whatever he asks me to concentrate on, I do. But I get to participate more in strategy areas in addition to operations.

What are the challenges you are facing in your new role?

Actually, the biggest challenges I faced since January 2019 when I became COO had to do with constantly dealing with union issues. During the expansion programme, there were no labour unions working in engineering; the Vice-presidency charged with the execution of the Project. But as a COO of the

Meet Ilya Espino de Marotta

In May 1985, Ilya received a degree in Marine Engineering from Texas A&M in Galveston, Texas, USA. Since graduating, she has worked with the Panama Canal in diverse roles. Her 1 January 2020 commencement as Deputy Administrator crowns her more than 35 year career at the authority. Before her latest role, she fulfilled pivotal positions such as Executive Vice President for Engineering and Program Management which included heading the execution of the Panama Canal Expansion, and Executive Vice President for Transit Business where she was responsible for all maritime operations, emergency response, dredging operations, maintenance of Canal's infrastructures, floating and rolling equipment, customer affairs and marketing analysis.

In 1996 she received a Masters in Economic Engineering from The Old Saint Mary University in Panama City, Republic of Panama. She also took courses in Managerial Development at the INCAE Business School in Managua, Nicaragua and the Kellogg School of Management at Northwestern University in Evanston, Illinois, USA.

She has been recognised widely for her achievements, including being named 'Outstanding Woman of the Year' by the Panamanian Association of Business Executives and added to Forbes Magazine of Mexico's list of the 50 most powerful women in Central America. Ilya is a judge for the Queen Elizabeth Prize for Engineering as well as a member of the Boards of Directors of the Ronald McDonald Charity Organization of Panama, the International Women's Forum, and Asociación Directoras de Panama, an association which aims to improve the effectiveness of Panama's boards of directors through the inclusion of women.

Canal, things were different, and I had a lot to learn. We have six different unions in the Panama Canal and I have to deal with all of them because they all under operations. This was a learning experience that expanded my knowledge and my horizons. As Deputy, I still have to maintain that part of my job because the deputy is the last administrative resort on union labour issues.

The other challenge has been managing the Canal during COVID-19. Our workforce went down to about 40% of its normal capacity at one point. After a while, we went up to 55% of the workforce in order to keep the Canal opened. But still 45% of people were on leave or working from home. In spite of a country-wide quarantine, we had to keep the operations running smoothly, maintaining shipping while half of the workforce was home.

With this smaller workforce, we had to create a special schedule. On March 24th, we implemented a 14 day cycle with people working 12 hour shifts, 7 days a week. Then they would go home and rest for seven days and we would bring in other employees. In this way, people were social distancing and if someone tested positive, we could isolate them and mitigate the spread. Most importantly, we had enough people working all the time so we didn't have to shut down operations.

On June 8th, we brought almost everybody back. And that too was a challenge. In a little over two weeks' time, we prepared all areas for people to return to the office – all of the distancing requirements, the signaling everywhere and the capacity of the rooms. Cleaning up the trucks, the cars, and the launches, all of that was a learning curve.

Now we are back to normal. Of the Canal's 9,600 employees, 1,200 remain at home. All the administrative employees that can actually do their work from home, we are keeping at home for now.

Is working from home likely to become a permanent change?

So far it's a temporary measure we are doing to ensure social distancing. Personally, I love working from home. I work longer hours and harder but I have more flexibility with my lunch time or if I need to work out in the morning. I think I actually put in more hours. For example, having to drive to work, that time you have gained. Having to get dressed up to go to work, that time is gained. You can be more casual. You eat healthier because you eat all your meals at home. Working at home has definite advantages.

How did you make decisions with stringent measures regarding health and safety so early, already in January, when the world was struggling to understand the scope of the problem?

In the beginning, we took drastic measures and went to the bare minimum of employees. We asked ourselves 'What was the critical number of people we *need* to *not* shut down?' We reduced our

‘I think I should wear a pink hard hat just to make a statement that I am a girl and I can do this job’.

workforce to 3,600 but soon we realised that that was a bit tight. Little by little we increased the number. For instance, you can stop maintenance for a while but not forever. We saw that we needed maintenance people to come in two days a week, every week. We shut down 100% of dredging, 100% of preventative maintenance and only had running maintenance. Each week we learned something new and adapted.

This process also gave us a good idea of things we could improve upon in the long term. At times, there was some idleness or not full workloads, but this gave us the opportunity to evaluate and better utilise resources, and refocus on some areas. It was a good learning experience to see how a company could run with 50% of its workforce.

What is the impact of COVID-19 on world trade from the Canal’s perspective?

We had multiple things going on at the same time so it’s difficult to differentiate what was the biggest impact. 2019 was one of the driest years in 70 years at the Panama Canal. Water levels were low. As a result, on 15 February, we implemented a new, freshwater charge for all vessels transiting in the Canal: a $10,000 flat rate for the biggest vessels with a length overall greater than 300 feet, $5,000 for the 200-300 foot range and $2,500 for the smaller vessels under 200 feet in length. In addition to that, there is an adjustable rate that is a percentage of how many tolls you pay according to the lake level. The idea was to restrict traffic a bit because we didn’t want to implement draught restrictions for our customers. We wanted the lake level at a good elevation to provide a competitive draught. In addition, there are the US-China conflicts. Add that to the freshwater fees raising our tolls, and COVID-19, and yes there has been a reduction in trade.

The impact to the Canal has occurred with a two or three month delay from when the pandemic hit. In March, there was maybe a 1% decrease in arrivals, 5% in April and then 14% in May, which is basically COVID-19 causing a drop in trade. At first, production stopped in certain areas of the world, and then consumers were buying less because the economies in the world were affected.

To what extent is the Cascade Effect affecting the Panama Canal?

Roll on/roll off is one of the main segments that’s been impacted. Of course we’ve had a dramatic number of cancellations in cruise vessels. Panama was just established as a home port so even though that doesn’t impact the Canal, it impacts the country.

Another impact was the drop in fuel prices which came in the middle of everything. When fuel costs are low, there are some sea routes that become more competitive than the Panama Canal. Add to that low charter rates and that affects us. As of now, however, fuel prices are coming back up. Container vessels are less loaded, coming with less containers than normal. The Cascade Effect has also meant less port calls in our ports. There are many blank sailings now – also an effect of the coronavirus – and less transits through the Canal because 72% of the ships that transit the Panama Canal do make port calls. If you have a drop in transit, then you have a drop in port calls.

Looking back to the Panama Canal Expansion, how did your role change throughout the course of the project?

From 2002 to 2006, we were a small team of four or five people working with 120 other professionals from the Canal. We were integrating everything – environmental, engineering and financial issues – into one single proposal, and developing a communication strategy. We needed this communication plan because to expand the Panama Canal with a third set of locks required a national referendum. We analyzed it for five years. We had contractors from the USA – Parsons Brinckerhoff – who helped us put the project together with 120 studies and $40 million that we managed as a team. In 2006, they created an office to implement the execution, create the organizational structure, and everything that had to be put into place if the referendum were positive.

Luckily, the referendum was positive and after that they created the position of Vice President of Engineering that was going to lead the project. I was the manager for resources and was in charge of safety, environment, historical documentation, budget, control, and legal. It was quite intense and that was my role from 2007 until 2012.

In February 2012, my boss got promoted to Administrator and I became the lead of the project. From February 2012 until June 2016, which was the inauguration of the new locks, I headed the project. All of the engineering of the Panama Canal was under the same Vice Presidency. Then from June 2016 until January 2019, I became head of engineering, which encompassed all of the engineering of the Panama Canal. During this time, we also had to build a bridge on the Atlantic side because there was no bridge. To cross from one side of the country to the other, you drove on top of the lock gates. In February 2019, I became Chief Operating Officer.

What was it like to work on such a massive project?

We were a little over 800 people working at the Canal on the expansion project and we had over 200 contractors from all over the

A Pink Hard Hat with a Message

When Ilya was tasked with leading the construction of the Panama Canal's third set of locks, she began wearing the standard white hard hat. Soon she realized that there were a few people that were not too comfortable with a woman leading the project. Ilya remarked to her husband 'I think I should wear a pink hard hat just to make a statement that I am a woman and I can do this job'. Beginning as a personal message, the item became very popular. Ilya explains: 'I didn't think of the ramifications wearing a pink hard hat would bring but I'm very glad I did it because it made a statement that women can do any kind of a job. The pink hard hat was a statement from me to the people around me that weren't confident that I could do the job. It said "Hey I'm a woman and I'm doing this job".'

world. I told people 'I'm here to make your life easy to do the big stuff'. I'm here to facilitate things, to make things happen, to resolve problems.

When you have a very good team working with you, you can do great things. Being the lead puts pressure on you. You need to make sure people are happy, engaged and committed. Of course it was stressful. My motto was 'never a dull moment'. There was always something to be resolved, every single day. I made sure I was always available to everybody, the contractors or the Panama Canal people to act as a liaison and make sure things ran as smoothly as possible. Communication was always primary. And it was the hardest part of the project, not the engineering.

We had over 80 nationalities working on the project. We had contractors that had never worked with the Canal before. We had contractors who were not very happy with each other. It was demanding but fun because you get to see this amazing project being built close up. I got to go to South Korea to see the valves fabrication, I went to Italy to see production of the rolling gates. It was a project built in Panama that came from all over the world. A team in the Netherlands designed the gates. The main designer of record was Montgomery Watson Hart from Chicago, Illinois, USA. The challenge was maintaining all the moving parts.

How did you orchestrate and maintain the communications between the international stakeholders?

I had regular meetings. I had a staff meeting every week with the full staff. I would make sure to go to the field a minimum two to three days a week. I always went to see the project. On the Atlantic side, once a week or every two weeks because it was a little farther out, and on the Pacific, a minimum of two to three days a week. Also I went to the different parts of the project because we had dredging parts, construction parts, and environmental parts. I went to reforestation projects, I went to the live animal rescues, I went to see the archeological findings, and I went to the construction. I participated in everything. If coronavirus had happened during the expansion, I don't think it would have been such an easy, smooth task at all. Being able to be out there was very critical for me.

What were the environmental goals of the project?

We had two things in our favour. The area where the project was, was all patrimony area of the Canal so we didn't have to buy land or expropriate land. A few areas had already been

We also did animal rescue for whichever animals were not inclined to leave the area on their own. We had the contractors relocate them to specific areas.

impacted in 1939 when the Americans tried to build a third set of locks at the Panama Canal. They abandoned it in 1942 because of World War II. As a result, a big portion of the project was done in areas that had already been impacted. Another area of the project was land where the US had had their military bases in Panama. It was a shooting range where there was unusable land which we cleared and could use. The deforestation taking place in all areas of the projects would be compensated for as we reforested twice as much land in national parks all over the country. Our environmental agency decided where reforestation should be done. It was a five-year project – one year for planting, four years for maintenance. For the communities that live around the area, it was a positive impact. They were hired to do those jobs giving them guaranteed employment for five years. Also they could use this knowledge of reforestation to do it elsewhere in the future. We also did animal rescue for whichever animals were not inclined to leave the area on their own. We had the contractors relocate them to specific places.

We also had an archeologist on call in case there were any findings. Many areas had never been excavated before and we had a contract with the Smithsonian Institute for research they wanted to do on paleontology. It was a five-year project, with a $1 million budget, and they had important findings. The environmental part was done very responsibly in preparation for the national referendum, and communication was key. We issued reports to Congress, to the cabinet, and to our lenders. We borrowed $2.3 billion of the $5.2 billion estimated on the project and we self-financed $2.9 billion. Reporting, standardized information and a programme management system to make sure the information was maintained the same way was crucial.

What other factors played a role in the project's preparations?

Since we had to go to a national referendum, we definitely had to take into account all the pros and the cons. We analysed the job generation. There were 41,000 jobs generated in the nine years. During execution of the works we had 14,000 people working at the same time. We also implemented a training programme with some national institutions on the skills that would be the most required for the project such as heavy equipment maintenance, heavy equipment operations, sophisticated welding, specific masonry and electrical. In this way people with the right trades could be put to work when the contractors arrived. This was necessary because Panamanian law requires that 90% of the unskilled workforce and 85% of the skilled work must be Panamanian. In this way we could guarantee that contractors would find qualified people in-country and hire people locally which would have a positive impact on the economy. We developed some training programmes with national entities and some companies like Caterpillar participated in the trainings too.

In addition, we established full offices with the Ministry of Labour and the Ministry of Immigration to make sure that contractors coming from abroad would have expedited processing of their work permits in Panama. We trained about 300 people in programme management within the Canal and we certified about 75 of them as programme managers. Even though some of these people were hired on a temporary basis, once the project was done, they could move into the economy better prepared to provide growth for the country.

What were the considerations in the Panama Canal project's design and construction to create sustainable infrastructure?

The first reason – the reason we needed to expand the Panama Canal – was because ships were getting much bigger and we were losing market share. To maintain the Canal as a sustainable, reliable route, we had to make bigger locks. However, because of the market demand, we couldn't make two lanes. The original Canal has two lanes so you could take one lane out to do maintenance while the other one is operating. Well in the new Canal, you only have one lane so you can never take it out for maintenance. We took measures that would allow us to operate the Canal while maintenance is going on, and one of those things were the gates. The original Canal has miter gates and you actually need to bring a floating crane on site to remove the gates to take them to a shipyard, and you need to shut the lane down for that process. Now, we have rolling gates that go into a recess and you block the recess with some stop logs so you actually do the maintenance on site. We have two gates everywhere so one gate can be in maintenance while the other is in operation.

The second thing is we don't have locomotives in the new locks. Locomotives require extensive maintenance. The structure would have to be much bigger and more expensive. We are operating with tug boats in the new locks.

The filling and emptying system on the original locks is through the bottom of the locks – through the floor. This gives a very symmetrical flow, but to do maintenance, you need to dry the chambers and empty the lanes. We cannot do that in the third set of locks so we did a lateral filling and emptying system that comes through the walls so you can actually block areas of the tunnels where the water runs to do maintenance. All we do is slow down the traffic but we don't stop it.

Also the locks were built to allow 55-foot draught vessels but our channels are not dredged to offer that. Right now we offer a maximum of a 50-foot draught on vessels. In the future we can expand to 55 feet by dredging all of our navigation channels. These are the main things we considered for the long term.

We also put water-saving basins in the new locks which we don't have in the original locks. This allows us to recycle 60% of the water of each transit to utilize it on the next one. So the new locks – even though they are much larger – use 7% less water than the existing locks and you can transit a ship with three times more cargo using less water.

The gates are fantastic, my favorite part of the project. How the gates were transported across the ocean by ship, how the gates for the Atlantic and Pacific sides are different sizes, how they were put in place, and how they were installed. It's just a completely amazing project.

How can the dredging industry inform clients best about the concept of Dredging for Sustainable Infrastructure?

Our main concern right now for sustainability and reliability of the canal is water projects. In the next couple of months we are putting out a tender to bid on water solutions to guarantee the right amount of water for the uninterrupted transit of the canal. This is because in the last five years, we have seen that rainfall has diminished and we are a freshwater canal. We rely 100% on rainfall. We have a certain capacity and most years we spill large amounts of water. Last year was an exception and we didn't spill any water because there was so little rainfall. If we can increase the reservoir capacity of the lake then we can store rain to prepare for scarcity. Gatun Lake also provides drinking water for 60% of the population of the country. This is definitely one of our main concerns and our main focus right now.

During the construction of the Panama Canal Expansion you were the 'face' of the project and you started wearing a pink hard hat. How did that start?

It was an unplanned thing. During my studies, there were two women in the faculty. When I worked in the shipyard, we were two women in the engineering division. I was pretty used to working around men. To me it's been clear that the higher up you go in management, the stranger it is for a woman to get a role. That's changing now but it certainly hasn't been the norm, especially in the construction or maritime fields. I found out about six months after I had been appointed to lead the project that there were people that didn't trust a woman heading the project. Or maybe they were not comfortable with women.

If you look at the first pictures, I'm wearing a white hard hat which is the standard. When I found out that people were making comments about a woman leading the project, I thought, 'I should wear a pink hard hat just to make a statement that I am a woman and I can do this job'. So that is how the pink hard hat came about. It was mainly a very personal message and feeling but the pink hard hat became very popular. I didn't think of the ramifications wearing a pink hard hat would bring, but I'm very glad it did because it made a statement that women can do any kind of a job.

What would it take for the maritime industry to achieve a more balanced gender equal workforce? What role does management play in this shift?

I've seen the shift from when I went to school. As I said, we were two women in the faculty of marine engineering. When I went back to my Alma Mater in November last year, there were many more women.

I think there are role models out there. I see more women in shipping. Even on board ships.

Even in the Panama Canal. Many years ago, being a line handler was a job just for men but no longer. Women are becoming line handlers. Women are becoming launch operators, tug boat captains and pilots. The more women you have, the more it will broaden. More women will see it and say 'hey I can do that too'. I think the maritime industry is an important and good field to be in. In dredging, I don't see many women at

An award dedicated bold, groundbreaking engineering innovation which is of global benefit to humanity, the Queen Elizabeth Engineering Prize gives £1 million to celebrate engineering's visionaries.

all. Not even in the dredging of the Panama Canal so that's an area where it could also be extrapolated to. It takes one or two, and then they become role models. In every industry, the more gender equality you have, the better because as I tell people, one gender is not better than the other. We are different and we complement each other. Decision-making becomes richer when you have different points of view. When you have more positions you make better decisions, absolutely. Gender equality in decision-making is a win-win for the world in any industry.

In the beginning I wasn't for quotas because I thought 'I've never been a quota and I made it where I made it'. All the jobs I moved into, I was the only woman. I was the only woman in the mechanical branch of the design section, I was the only woman in the shipyard.

This seemed normal. I thought nobody was interested and it was not an issue – until I had to buy my pink hard hat. That was the first time ever that it hit me that I thought 'oh wow, there is an issue'. And I think that t that's the point I thought 'there *should* be quotas'. If you don't present the opportunity, nobody will go for it. Having a quota doesn't mean I am going to put a woman in a job no matter what. Is she qualified? Does she have the competences? Having a quota doesn't mean just because you are female you get the job. It's gender with all of the right qualifications. You need opportunities and you need role models. You need both sides to make gender equality happen.

Quotas force management to look for qualified women. On a professional level, it's easier to achieve gender parity than in management positions. Changing management is harder, so you need to make it visible. In Panama, a law was approved that boards of directors of government entities and government-regulated entities need to have 30% women in their Board of Directors. The law stipulates this should be achieved in three years' time because, of course, you haven't had these women developed so you're not going to have an influx of women that are qualified. If you do it gradually over three years, eventually you will build that workforce and there will be an equal pool of women and men to choose from. It's going to take a while. But it's forcing companies to look for these women – and they are out there.

In what ways are you actively promoting the next generation of professionals to follow in your footsteps? I saw you are a judge for the Queen Elizabeth Prize for Engineering. How did that role come about?

I guess they saw my pink hard hat in London and they contacted me saying, 'We are looking for women role models for women to go into STEM. We want women to be involved with the prize'. I said 'sure I'll be happy to'. Of course anything to be able to make an impact and contribute to gender equality in the world, I'm there.

It's another learning experience. All the nominees have been men because as I said, it's going to take time to reach that critical mass of women to be able to be recognised as engineers, but there are some. We want to influence women to study engineering. And if you have a role model, people will be more keen and interested.

It's a relatively new prize, it only exists for three years. And so far, in all the teams, it's been only men winning. The prize is for an innovation that has been implemented, that

The Queen Elizabeth Engineering Prize

An award dedicated to bold, groundbreaking engineering innovation of global benefit to humanity, the Queen Elizabeth Engineering Prize gives £1 million to celebrate engineering's visionaries. The award recognises engineering as a diverse, multifaceted and continually evolving discipline. One which creates solutions to global challenges and improves billions of lives. Engineers have enabled us to work together across the planet, explore the smallest cells and the most distant stars, and navigate our way around the world.

The prize serves to encourage engineers to help extend the boundaries of what is possible across all disciplines and applications, while inspiring young minds to consider engineering as a career choice and to help to solve the challenges of the future. In 2019, the prize winners were Dr Bradford Parkinson, Hugo Fruehauf, Professor James Spilker, and Richard Schwartz for their work on the Global Positioning System (GPS) which has transformed navigation and precision timing and is essential for today's transportation services, smartphones, food production, banking and science.

https://qeprize.org

has made an impact in society, and is being utilised. Inventions like the internet. GPS is the most recent one. There was also a medical device that gives medication intravenously. All these recognised innovators have been given to men. I hope that soon we'll see women up there as the winners of the Queen Elizabeth Prize for Engineering.

How do you make time for all of these activities? Do you say yes to everything and welcome the opportunities?

Yes. My husband says 'Sometimes you have to say no'. Sometimes I do say no but I consider myself a mentor. Many people tell me 'Well you should pick what you say yes and no to.' But just because it's a small group of people or because it's students from a high school, how can I say no? On the contrary, those are the ones I should yes to because that's where you want to make a difference. More than any corporation that may invite you for something. Sometimes I do say no, many times because of conflicts. I don't know if I would keep my sanity without my secretary. I have three kids, they are all grown and working, thankfully, and my husband sometimes complains that I don't dedicate enough time to family but I try. And I try to keep time for myself. I do try to balance.

What has impacted your career?

Something that was critical in my personal life: In September 2010, my middle child had cancer and my husband as well, three months apart. We were in the middle of the Expansion project so I took a partial sabbatical year from work to go to the States and take care of my son and my husband. I would come back to the office one week a month for that year and my mother would fly to the States that week to watch over them. So that was a very critical year that made me a more empathic person because I saw a part of the world I've never been exposed to before.

You said empathy came out of that experience. How does empathy come into your daily life after that experience?

I've always been a very introverted person. With the Expansion project I had to become more of an extrovert in the sense that I had to give many presentations, I had to speak to the media. But I also had to care about people's lives. Not just the professional part of their lives, but caring about their personal needs. I had to have empathy. When I was out for a year I had an amazing team working for me, and they kept my work going. I came one week a month, and with the great people working with me, it was fantastic. The work got done. Shortly after that, I got promoted. I could not have done it without them. Through my own difficult experience, I became more empathetic and understanding of others.

When I was out for a year I had an amazing team working for me, and they kept my work going. I came one week a month, and with the great people working with me, it was fantastic.

Resumé

Jan 2020–Present
Deputy Administrator

Feb 2019–Present
Vice President for Transit Business (COO)

Sep 2012–Jan 2019
Executive Vice President Engineering and Program Management

Oct 2007–Sep 2012
Executive Manager Resources Management and Project Controls

Oct 2004–Apr 2007
Multidisciplinary Engineer – Office of Program Development

May 2002–Sep 2004
Engineer – Master Plan Coordinating Team Office of the Administrator

Feb 1998–Apr 2002
Multidisciplinary Engineer Capital Investment Coordinator Department of Maritime Operations

Jun 1994–Jan 1998
Valuation Engineer in Accounting Division

Apr 1991–May 1994
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Jan 1989–Mar 1991
General Engineer in Dredging Division

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Northwestern University's Kellogg School of Management Executive Development Program

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Universidad Santa Maria la Antigua Master's degree in Engineering Economics

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Slippery Rock University of Pennsylvania

SOFT MUD:

FIELD PERFORMANCE RELATED TO LAB EXPERIMENTS, MODELLING AND ANALYSIS OF TIME-DEPENDENT PROCESSES AFFECTING CONSOLIDATION

Introduction

Self-weight consolidation plays a major role in the creation of land using mud, the ripening of mud layers and, also, in the storage of contaminated mud and slurries in ponds. There is a significant compaction due to self-weight consolidation at lower stresses (0.1 to 10 kPa) which gives the need for special laboratory tests and accurate modeling. The self-weight consolidation theory according to Gibson was extended to other time dependent processes: Gas production has been included in this theory and in a numerical code (Wichman 1999a and 1999b) and this was validated in the laboratory and the field (Wichman et al. 2000). The user-friendly numerical tool FSCongas has been developed, including several gas production scenarios with gas dissolution, and a choice of boundary conditions. To this tool also a simple creep model has been added (Greeuw et al. 1999). In the hydraulic consolidation tests GASCON and HYDCON the loading condition in the Slufter disposal site – with up to 20 metres of mud at maximum effective stress of 10 kPa – has been successfully simulated (Wichman et al. 2000). In these tests the mud sample was left to consolidate and stiffen for some days, and next it was loaded gently by applying a hydraulic gradient across the mud sample. In the GASCON-tests, after the initial self- weight consolidation was finished, the hydraulic gradient was increased a several times. Settlement and pore pressures at short distances across the sample were monitored. The GASCON-cell allows for the monitoring of gas production and gas accumulation throughout the consolidation process, whereas the HYDCON-cell is suitable for saturated samples, only. In this previous research the experimental conditions were chosen carefully, resembling the field situation, as effects of thixotropy and creep were expected.

Recently, effects of thixotropy and creep were studied more closely by means of the Suction Induced Consolidation test (SIC). Some results are discussed in this article. Initial sample conditions, creep and thixotropy may significantly influence consolidation performance and containment structure stability in the short and long term. Permeability of the sample affects the consolidation speed. The response of the sample permeability to a varying imposed sucking flow rate was studied and compared to the field situation.

Recently, effects of thixotropy and creep were studied more closely by means of the Suction Induced Consolidation test (SIC).

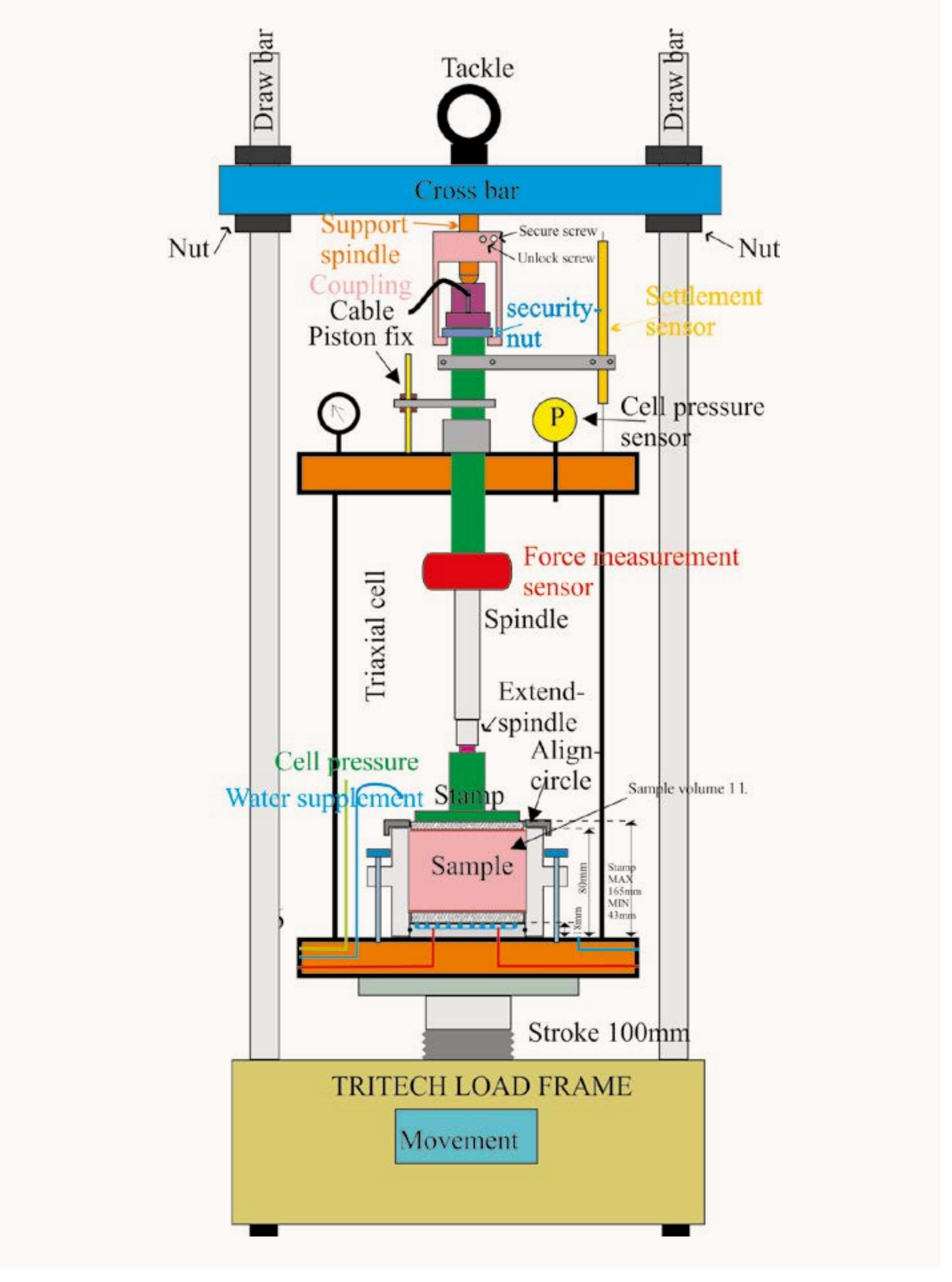

FIGURE 1

Part of the Suction Induced Consolidation (SID) set-up.

Time-dependent processes

Two processes were found to have a major effect at low stress levels, i.e. thixotropic stiffening and creep. Mitchell (Mitchell 2005) says: 'Thixotropy is defined as an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest and softens or liquefies upon remolding'. This effect is largest in a soil structure with high water content and active clay content, as the soil particles have more freedom to rearrange, react and form bonds. Sills (Sills 1995) has shown that creep can be a mayor effect at low effective stress levels, i.e. the volume effect induced by creep is one order of magnitude larger than at higher stress levels (say 50 kPa). Creep can be considered as a time dependent adjustment of soil structure at constant effective stress, which gives a reduction in pore volume and an increase in strength. In addition, in permeability testing care should be taken not to disturb the sensitive soil structure. Permeability values might depend on the imposed sucking flow speed, which is discussed in this article.

Experimental set-up

The experimental set-up of the SIC is shown in Figure 1. A sample of freshly mixed mud is placed in a ring in a triaxial cell, which is partly filled with water. The sample can be drained at both sides or at the upper side only. The latter was the case in the consolidation tests presented here. The sample is loaded by pressing the sample against a fixed stamp, by using the load control at the bottom of the triaxial cell. At the bottom of the sample a piston pump is attached that can be used to extract a chosen discharge from the sample. In this way the sample can be consolidated by sucking water from it, but this was not done so in our research. By sucking a small amount of pore water, a permeability test can be done. The load, displacement, differential pore water pressure across the sample and cell pressure (set to 3 Bar) are measured.

The test consists of a series of loading steps with a duration that is long enough for the excess pore pressures to dissipate to a large extend. This is defined as the end of consolidation. At that stage the settlements might still go on, mainly due to creep. At the end of each loading step, i.e. at the end of consolidation, typically after 1 to 3 days, the piston pump was used to determine the permeability of the sample. The pump sucks a chosen constant discharge from the sample, whereas the differential pore water pressure across the sample was measured in time. This was done until the pore pressures reached a steady state. The sucking lasted for about 1000 seconds. Imposed discharge and the resulting change in differential pore pressure were inserted into Darcy's law, to determine permeability. The imposed discharges were of the same order of magnitude as in the typical field situation (1 to 5 E-08 m/s, see Discussion).

Two SIC tests were performed on mud from the same supply bucket, using the same sequence of loadings. The initial density was 1316 kg/ m^3 as settled in the supply bucket. The initial sample height was 56 mm. In SIC1 the sample with the filter stone on top was left in the ring for 1 week before further loading, whereas the SIC2 sample was left there for 24 hours. The loading schemes for SIC1 and SIC2 are shown in Figure 2. The total duration of the stepwise

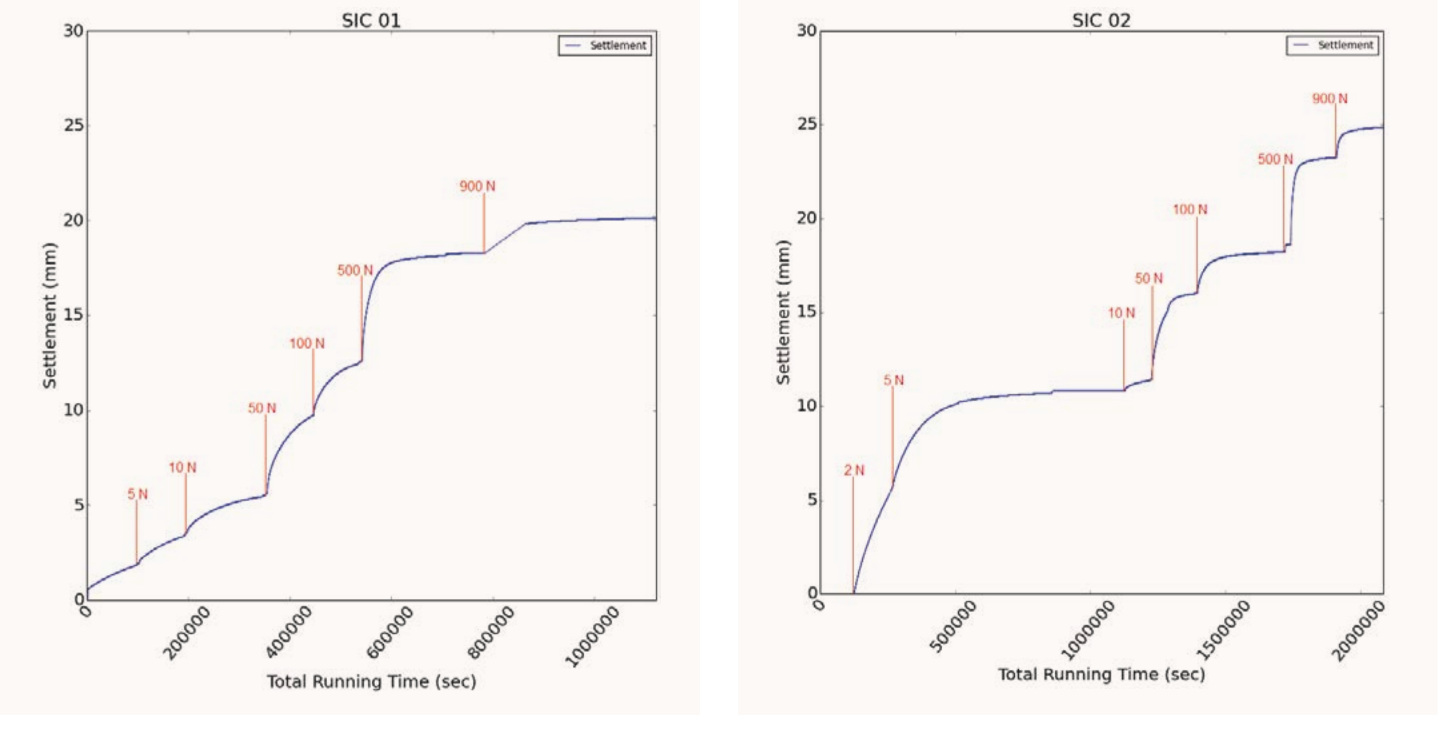

FIGURE 2

Settlement in time for the loading scheme in SIC1 and SIC2, starting from the first load at 2N.

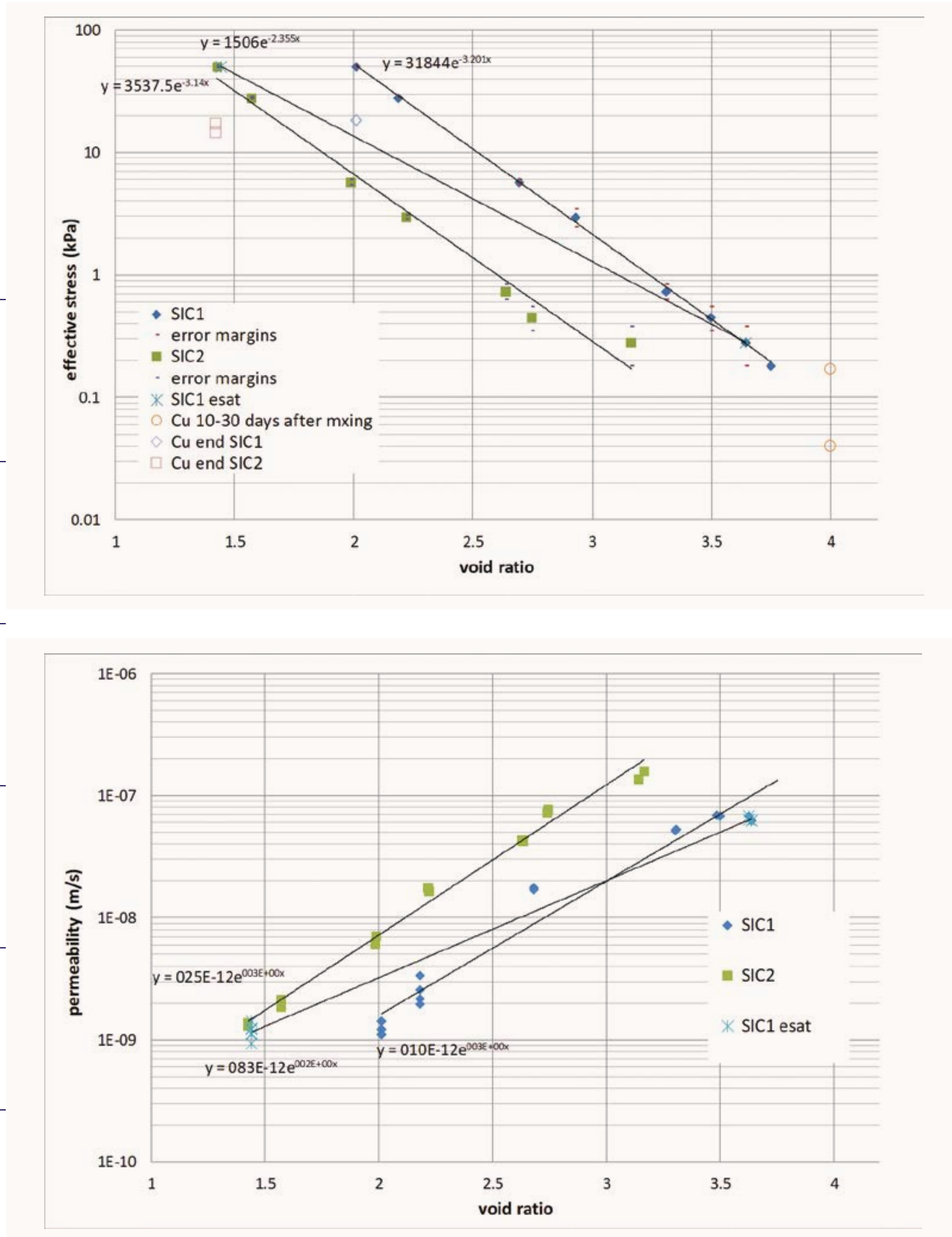

FIGURE 3

Effective stress and permeability results from SIC 1 and SIC2. Three type of regression lines have been added, see text.

loading in SIC1 was 1.1E06 sec and for SIC2 this was 2E06 sec. All loading steps lasted 1 to 3 days, except the step at 5N in SIC2 where a creep test was done at an effective stress of 0.45 kPa. After 1 to 3 days of consolidation the excess pore pressure had dissipated to a large extend. The residual pore pressure at the end of the respective loading steps was used as an error margin to the effective stress points.

In the creep test consolidation and creep was allowed during 7 days at a constant load of 5N and another 3 days at constant volume, the latter stage giving a decrease in effective stress of 0.1 kPa (2N decrease in load). The creep was found to be dominant in the last 6 days of loading. At the end of the SIC-tests the unloaded sample was tested to determine water content, bulk weight, gas content and undrained shear strength by means of a vane test. For further analysis, the peak shear strength was considered.

The tested mud has: 30% sand content, 18% < 2 μm (lutum content); 7% organic content, and the clay consists of mainly illite, kaolinite and montmorillonite with a specific mass of solids = 2580 kg/m³.

The undrained shear strength was expected to increase due to thixotropic stiffening, and this was verified by a sequence of vane tests. The undrained shear strength in time at zero load was measured with a vane in a separate bucket. As the sample height in the SIC is small and almost no water was expelled, the main cause of increase in strength during the waiting period before loading is thixotropic stiffening of the mixed sample.

Figure 3 gives the effective stress and permeability results at the respective loadings for SIC1 and SIC2. In SIC1 significant gas production occurred, which is visible from the difference in the (total) void ratio (that follows from the final sample height) and the void ratio e_{sat} of the fluid part that was determined from the water content after the tests were finished. This implies a final gas volume percentage of 19% (at 3 Bar cell pressure) for SIC1. In SIC2 hardly any gas production occurred (< 1% gas content). This might be due to the longer storage time (1 month longer) of the bucket of mud before mixing it for use, during which the gas production had slowed down already. Before loading with the first 2N load in SIC1, there was no evidence of gas that had been produced. Therefore, it is likely that the amount of gas in the sample is still limited at the loading step of 2 N and thus the resulting void ratio is close to the void ratio of the fluid part e_{sat}.

The error margins for effective stress indicated are obtained from the residual excess pore pressures at the end of the loading steps. This was sufficient for practical purposes, i.e. to determine the effective stress-void ratio regression relation. During the permeability test, the sucking was stopped after the steady state had been reached and, subsequently, the sample was left to equilibrate. In principle the final equilibrated differential pore pressure should be almost equal to the value just before the start of the sucking. The differences observed were taken as an error margin in the analysis of the permeability-void ratio regression relation, as these differences exceeded the measurement inaccuracy. Thus, the accuracy in permeability is better than 20%. In Figure 3, the permeability values that were derived from the change in pore pressure during the sucking are plotted.

In Figure 3, three type of least squares regression lines were added: first, a least square fit of the SIC1 results (including gas),

TABLE 1

Undrained shear strength after mixing of the mud used in the SIC-tests. The undrained strength was measured in a separate bucket.

Time after mixing (days)	0	10	30
Peak Cu (kPa)	0.01	0.04	0.17

The effect of sample stiffening can be described in terms of the time evolution of the undrained shear strength that can be determined with laboratory vane-tests.

secondly, a line that excludes the effect of gas by connecting the result from SIC1 at 2N (i.e. 0.3 kPa, where little gas had been produced yet) with the SIC1 result at 900 N (i.e. 50 kPa), using e_{sat} at 50 kPa and, finally, a least square fit of SIC2 results. The second regression line gives an idea of the effective stress and permeability relations as functions of e_{sat}. The measured undrained shear strength values of the mud after mixing are given in Table 1 and are also shown in Figure 3.

At the end of both SIC-tests the undrained shear strength has been measured at three spots in the consolidated sample. The minimum and maximum peak Cu-values for the consolidated sample are shown in Figure 3 with Cu = 18.4 to 18.8 kPa for SIC1 and Cu = 14.4 to 17.2 kPa for SIC2.
The permeability data show a range in permeability at the respective void ratios. The higher permeability values were determined from tests with a higher flow rate. For SIC1 the range in flow speed at 28 kPa (900 N, void ratio = 2.19) was a factor of 10, which gives a range in permeability values of factor of 2. This is caused by the fact that the excess pore pressure was not linearly proportional to the flow speed. For SIC2 the range in flow speed was less than a factor of 1.7, which gives only small range (max. factor 1.3) in permeability values at the respective loading steps. The volume change of the sample during all permeability tests was very small and it might partly be due to creep.

Discussion

The effect of sample stiffening can be described in terms of the time evolution of the undrained shear strength that can be determined with laboratory vane-tests. In addition, the effective stress can be related to the undrained shear strength.
(Merckelbach 2000) reports that for soft mud the undrained peak strength is of the same order of magnitude as the effective stress. In Figure 3, this insight can be used by extrapolating from the lowest stress level to the initial void ratio of 4, at which the effective stresses are 0.1 kPa for SIC1 (using the regression line with e_{sat}) and 0.01 kPa SIC2. When comparing these effective stress values with the undrained shear strength in Table 1, it follows that after 1 week of resting, the sample in SIC2 might had stiffened even more than it was the case in the bucket after 10 days.
The differences between SIC1 and SIC2 in effective stresses and related shear strength are possibly due to thixotropic stiffening. At a stress level of 50 kPa the peak shear strength is a fraction of 0.32 (SIC2) to 0.37 (SIC1) of the effective stress. This is normal for typical clay with a higher consistency.
The deviation between the three effective stress – void ratio and between the three permeability – void ratio relations (i.e. the

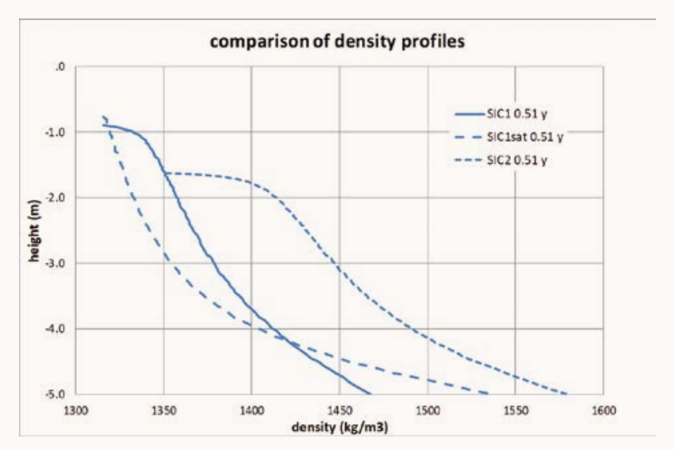

FIGURE 4

The results of some FSCongas model runs that are typical for large scale land reclamation.

regression lines) is caused by gas production, but also due to thixotropic stiffening of the sample before the first load was applied. From Figure 2 it is visible that the sample in SIC2 was much more compressible than that in SIC1, especially at the low loading levels up to 10 N (i.e. 0.74 kPa). It is also visible in Figure 3 that at 50 kPa the results from SIC1 in terms of e_{sat} and SIC2 (that had no gas) are very similar. This is more in-line with what would be expected for a typical clay with a higher consistency.

Creep also plays a role in stiffening of the sample, which is visible from Figure 2 by comparing the settlement in SIC2 at the 5 N step (i.e. at effective stress = 0.45 kPa), at which during 6 days', additional creep had been allowed to occur, and the 10 N step in which little settlement occurred as the sample had stiffened by then. For comparison: the difference in settlement between the 5 N and 10 N step in SIC1 is much less, so it is likely that stiffening due to the additional creep at 5N limited the settlement at 10 N. These effects are also visible in Figure 3 in which the effective stress points are less in line for SIC2 as compared to SIC1.

Finally, it was found that the permeability values from the SIC-test depend on the imposed flow speed, as the excess pore water pressures generated are less than linearly proportional to the applied sucking flow rate. The flow rate values used in the tests are in the same range as occurring in the field, the flow rates being larger at the start of consolidation. This flow-rate effect needs further study, considering the effective part of the sample porosity through which the water flows. If the effective part of the porosity is larger, less pore water is 'bounded' and immobile to the solids structure. The flow speed might affect the amount of water that is 'bounded' to the clay particles. The permeability tests in the SIC did probably not disturb the soil structure itself, as during the test the sample volume hardly changed.

Practical implication

The results of some FSCongas model runs that are typical for large scale land reclamation are shown in Figure 4. In these runs a layer of 5 metres of mud was deposited under water in 0.5-years' time with an initial density of 1316 kg/m³. In these model runs all three types of regression lines as shown in Figure 3 were used. The bottom of the layer was assumed to be drained. Figure 5 shows profiles in depth of density and effective stress for the 3 runs just after deposition (at 0.51 years).

In Figure 3, the regression lines from SIC1 contain two effects: a larger void ratio in time for the respective loadings due to gas production, and, at low stresses, a stiffening due to thixotropy. The retarding effect of the gas on self-weight consolidation can be explicitly added (Wichman 1999a and 199b), in case the gas production rate in the field is known. Prediction and quantification of this retarding effect requires further research.

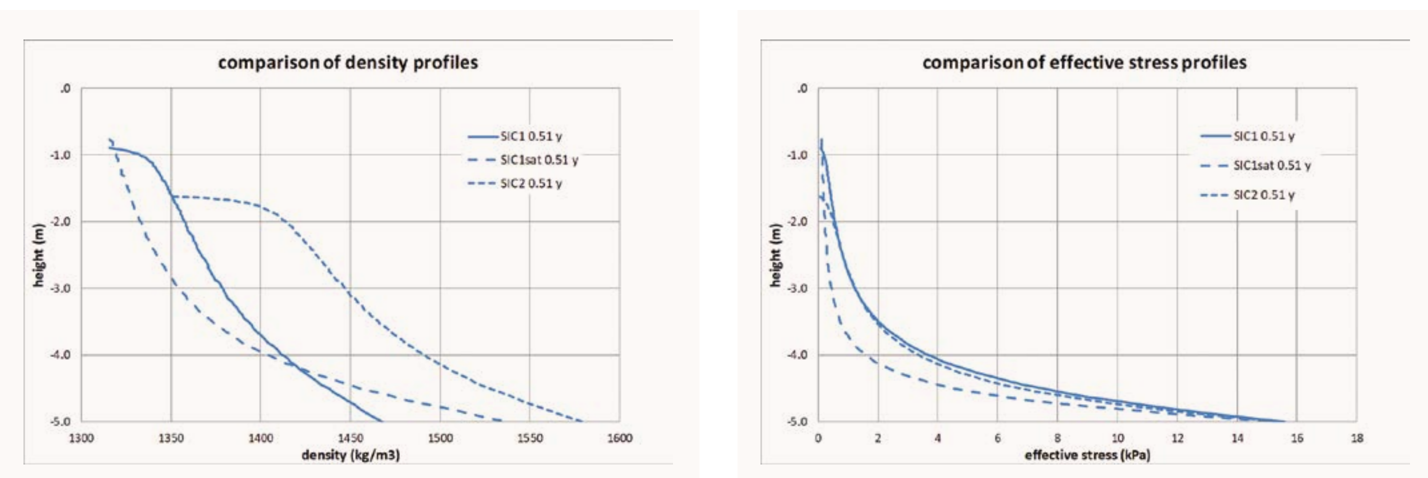

FIGURE 5

Profiles of density and effective stress in depth from the FSCongas runs using the SIC results.

Self-weight consolidation in layers of soft mud is considered as a main cause of settlement and increase in shear strength.

Summary

Self-weight consolidation in layers of soft mud is considered as a main cause of settlement and increase in shear strength. This plays a role in the creation of land using mud, the ripening of mud layers and, also, in the storage of contaminated mud and slurries in ponds. This article discusses evidence of time dependent processes affecting self-weight consolidation, such as gas production, thixotropy, creep and flow rate dependent effects. These processes result, among others, in non-unique effective stress-void ratio and permeability-void ratio relations. Suction Induced Consolidation (SIC) tests were performed to investigate the influence of the before-mentioned time-dependent effects.

Numerical simulations of a typical Dutch land reclamation project showed a significant effect on consolidation of the non-unique effective stress-void ratio and permeability-void ratio relations that were obtained from the SIC tests performed. Especially at lower stresses between 0.1 kPa and 10 kPa that are most relevant for land reclamation projects, the effects were found to be largest and they affect a mayor part of the settlement and resulting densification. It is concluded that, in combination with numerical modelling, the laboratory procedure to determine the consolidation parameters should be established such that significant time dependent processes -alike those acting on full scale- are part of the testing.

The initial (pre-loading) conditions and the type of loading should be realistic, i.e. similar to the field condition. In addition, significant gas production can occur and this retards the consolidation process and the final degree of densification.

The observed differences in effective stress and permeability relations are relevant for practice, i.e. the mud level in Figure 4 differs up to 1 m for the three options. It is visible that the settlement from the runs using the results from SIC1 and SIC2 occurred to a large extent during the deposition time of 0.5 years, whereas the SIC1sat run - using the estimated saturated effective stress and permeability lines – also shows a major settlement in the years after 0.5 years. For the SIC1 and SIC2 runs the consolidation seems to be finished after 3 years, whereas the run with SIC1sat takes 5 years.
From Figure 5 it follows that after 0.51 year the effective stresses for the runs using the SIC1 and SIC2 results are similar, whereas the SIC1sat run shows lower effective stresses inside the mud layer. In addition, the density profiles show more progress for the SIC1 and SIC2 runs than for the SIC1sat run, as, at that stage, more consolidation has taken place at smaller depth. This is typical for self-weight consolidation that starts at the bottom and gradually proceeds upward. For all runs at 0.51 years, the effective stresses are still below 10 kPa for the top 4.5 metres of mud.

Conclusions

Experiments in the SIC set-up turned out to be useful to investigate the effect of thixotropy and creep on the effective stress – void ratio and permeability – void ratio relations that were obtained from these tests. In the first SIC1 experiment gas production occurred, that was considered in determining the effective stress and permeability relations including the gas and without it. From two SIC-test results three types of regression lines were obtained that were used to model a typical land reclamation project. The practical implication of thixotropy and gas production is major, as the stress levels in the field are relatively low and the effect of gas, thixotropy and creep are largest at low stress. In addition, creep is much more significant for soft mud than for consolidated clay, as visible from the sequence in settlements from the SIC-tests reported. In general, the laboratory procedure to determine the effective stress and permeability relations should be established such that significant time dependent processes (as acting on full scale) are part of the testing. As consolidation in the field takes longer than in the laboratory, thixotropy in the field will increase the stiffness of the soil at low stress levels, which is demonstrated best by the results from SIC1 in comparison to test SIC2, where SIC 1 is considered to have a more realistic initial condition, i.e. a longer pre-loading resting period. In testing permeability, the flow rates need to be chosen realistically, i.e. as expected in the field situation, as they affect the permeability values at a given void ratio. Larger flow rates, that occur at the start of consolidation, tend to result in a relatively larger permeability.

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The tests as discussed in this article were executed at the request of and supervised by Royal Boskalis Westminster N.V. Results were applied as input for the design and engineering process for a large-scale reclamation project.

REFERENCES

Greeuw, G. and Best, H. (1999).
Manual FSCongas version 2.1; A program to simulate consolidation of gassy sludge. Deltares CO-378630/49.

Merckelbach L. (2000).
Consolidation and strength evolution of soft mud layers. PhD Thesis Delft University of Technology.

Mitchell, J.K. (2005).
Fundamentals of soil behavior. 3rd ed. Wiley, Hoboken.

Sills, G.C. (1995).
Keynote lecture: Time dependent processes in soil consolidation. Proceedings International Symposium on Compression and Consolidation of Clayey Soils Hiroshima. 59-74.

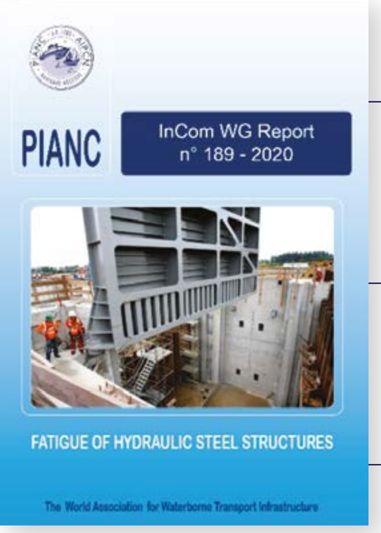
Wichman, B.G.H.M. (1999a).
Consolidation behaviour of gassy mud: theory and experimental validation. PhD Thesis Delft University of Technology.

Wichman, B.G.H.M. (1999b).
A finite strain theory for gassy sludge. Géotechnique 50 (1), 35-41.

Wichman, B.G.H.M., G.C. Sills and R. Gonzalez. (2000).
Experimental validation of a finite strain theory for gassy mud. Canadian Geotechnical Journal 37 (6), 1227-1240.

FATIGUE OF HYDRAULIC STEEL STRUCTURES

PIANC's latest report is the final product of InCom Working Group 189. It contains a detailed analysis of the current engineering practice and offers guidelines for a more uniform, systematic approach to fatigue-related issues. A summary of the appropriate design tools, analysis methods, technical codes, other guidelines and best practices are provided.



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The existing guidelines and norms that handle fatigue of structures in other fields have thoroughly been reviewed and recommended if and where appropriate. The matters that have been investigated include:

Nature of fatigue in hydraulic structures, significance and specific character of fatigue damage; Identification of fatigue loads, their sources, characters and correlations. Modeling these loads for analytical purposes; Requirements and boundary conditions of fatigue management, e.g. gate service life, permissible damage, accessibility for repair, conditions imposed by maintenance; Fatigue analysis methods and their assessment in view of hydraulic structures. This includes a study of literature and a critical discussion of the existing design codes; Relevant material aspects of fatigue, like fatigue behavior of various steel alloys, connectors, welding details etc; Detailing and construction of hydraulic gate components that are crucial in view of fatigue prevention; Monitoring, field inspections, assessment and maintenance of fatigue sensitive details; Available repair techniques of fatigue damage and other methods of service life extension; General conclusions and recommendations.

It gives examples of both correct and incorrect solutions, provides the discussion of crucial issues and presents the lessons learned from fatigue failures of hydraulic structures.

In response to the general guidelines of PIANC, the Working Group paid special attention to the following two groups of context issues: Relevance for the countries in transition and Issues overlapping the challenges of Climate Change.

As concerns the first point, the investigation field of the Working Group – fatigue of hydraulic steel structures – is relevant for any country that maintains waterborne infrastructure. This includes the Countries in Transition. Efforts have been made to receive contributions from these countries to the discussions and other activities of the Working Group.

As concerns the second point, there is no direct link between the fatigue of hydraulic structures and the issues brought upon by the climate change. Indirectly, there is a link because climate change has impact on the design loads of hydraulic structures, including fatigue loads. For fatigue, however, the most critical parameters of these loads are their variation frequency and amplitude. For some locks, increased water levels do have a significant effect on the amplitude of the fatigue load, however the correlation of these parameters with the climate change is not considered particularly strong according to the current views.

Nevertheless, there are scenarios that forecast not only a general increase of hydraulic loads as a result of climate change. They also predict the increased frequencies and amplitudes of these loads. The Working Group paid attention to such forecasts and included the relevant discussion and/or references in appropriate sections of the report.

It gives examples of both correct and incorrect solutions, provides the discussion of crucial issues and presents the lessons learned from fatigue failures of hydraulic structures. Apart from the design, the report also provides proper recommendations and best practices for the repair of different fatigue damages and for the management (particularly monitoring and assessment) of structures exposed to fatigue.

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