MARITIME SOLUTIONS FOR A CHANGING WORLD

#153 - WINTER 2018

TERRA ET AQUA

SPILLAGE ESTIMATOR

MODELLING A ROTATING CUTTER HEAD'S SPILLAGE

GRASS-ROOTS SAFETY
Keeping safety as a top priority to weed out potential risks

SUSTAINABLE DREDGING
Building value-added marine infrastructure with proven processes

HIGHLIGHT

SPILLAGE ESTIMATOR

MODELLING A ROTATING CUTTER HEAD'S SPILLAGE

Depending on its size and installed power, a Cutter Suction Dredger (CSD) is capable of cutting silts, clays and fractured or solid rocks. Due to their high precision, CSDs can be utilised for a variety of tasks including navigational channel deepening, port construction and pipeline trenching among others. But despite being considered relatively efficient, CSDs can spill significantly and from simultaneous sources.

A team of authors from Delft University of Technology and Great Lakes Dredge & Dock classifies the concurrent sources of CSD spillage as well as identify model parameters to estimate sand spillage within a 5 percentage point bandwidth of the experimental data. A dimensionless velocity ratio proposed by Steinbusch et al. (1999) and Dekker et al. (2003) is adapted as a governing number for model calibration, and experimental data for sand from Miltenburg (1983) and rock from Den Burger (2003) is used.

The result is a analytical model for a priori computation of spillage due to high rotational velocity-induced flow.
Read more on page 22.

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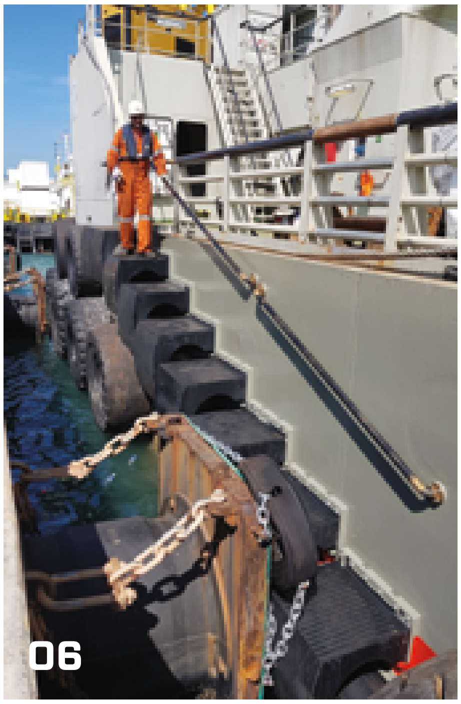


SAFETY

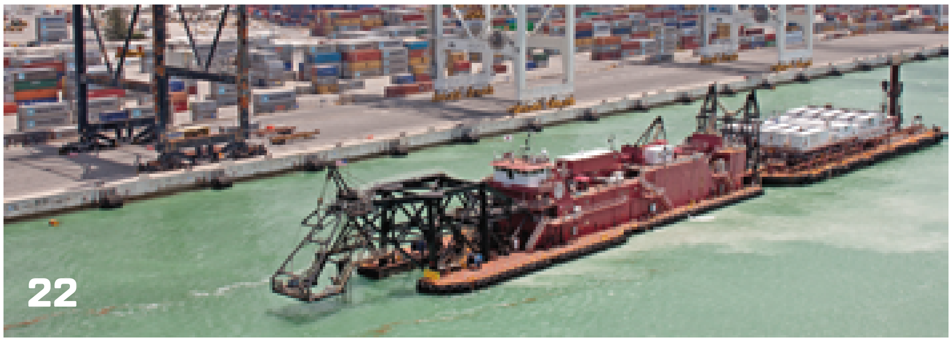
What happens when individuals step up safety during dredging activities?

By viewing routine processes and situations through a continuous lens of safety, individuals can help make operational processes on water or land safer. Eight solutions nominated for IADC's Safety Award demonstrate the benefit of this approach.

EQUIPMENT

Are the days of the double-walled pump housing numbered?

For several decades, the preferred solution for isolating dredging pumps within a vessel has been double-walled pump housing. To bypass this housing type's intrinsic problems, Damen formulated an alternative.



TECHNICAL

Can a preliminary model describe CSD spillage due to centrifugal advection?

Depending on its size and installed power, a Cutter Suction Dredger is capable of cutting a wide range of soil types. Although precise and relatively efficient, a CSD can spill significantly. The authors propose a preliminary model which describes spillage due to centrifugal advection.

EVENTS

Network to exchange knowledge

Battelle's conference on contaminated sediment settles in New Orleans and WODCON XXII brings the global dredging industry to Shanghai.

BOOK REVIEW

Dredging for Sustainable Infrastructure

CEDA and IADC's recently-launched publication promotes value-added projects by conveying an understanding of natural and socio-economic systems, and proactive stakeholder engagement.

WHAT IS NEEDED TO MAKE MARINE INFRASTRUCTURE SUSTAINABLE?

Frank Verhoeven
President, IADC

It takes a commitment from many key players to make sustainable marine infrastructure a reality. If clients, contractors and stakeholders make choices which support this commitment, then water infrastructure can be sustainable.

There are many decisions to be made during a marine infrastructure project, and each one leads the project down a different path. And not all paths lead the project to a sustainable destination.

There has been a gap in literature surrounding sustainability in water infrastructure. Published in 2008, the *Environmental Aspects of Dredging* is outdated. Ten years' worth of innovations have been put into use across the industry, with monitoring and data collection along the way to support their success. This data has expanded the industry's knowledge exponentially. Without a centralised interpretation, the data is useless in shaping future decisions.

A formal update on the subject of sustainability was long overdue, until now.

IADC and the Central Dredging Association (CEDA) asked highly specialised professionals to dig into their wealth of accumulated knowledge and combine it into a single publication in the form of a guidebook. Guided by the comprehensive volume, users will be able to realise sustainable infrastructure through the latest methods and supporting data.

After six years of labour, *Dredging for Sustainable Infrastructure* has been officially launched at its dedicated conference in Amsterdam. The inaugural copy has been conferred to Dr Hartwig Kremer, head of the GEMS Water Unit in the Science Division of the United Nations Environment Programme. Now it is finally time for you to obtain your copy.

We hope *Dredging for Sustainable Infrastructure* becomes your path to a sustainable future. Read a review of the book in the following pages.

This issue also sheds light on the safety innovations nominated for the Safety Award 2018 – including the winning innovation – as well as an optimised alternative to double-walled pump housing and a preliminary model of soil spillage from Cutter Suction Dredgers.

Guided by the comprehensive volume, users will be able to realise sustainable infrastructure through the latest methods and supporting data.

WHAT HAPPENS WHEN INDIVIDUALS STEP UP SAFETY DURING DREDGING ACTIVITIES?

When individual employees, teams and companies view everyday processes and situations through a continuous lens of safety, they can each contribute to making all aspects of operational processes, whether on water or land, safer.

> **The IADC's members are committed to safeguarding their employees, continuously improving to guarantee a safe and healthy work environment.**

Affirming the importance of safety

Dredging activities can be risky operations with hidden dangers amongst heavy machinery. In response, the dredging industry proactively maintains a high level of safety standards.

IADC is committed to promoting safety in the industry. A representative of contractors in the dredging industry, the global organisation encourages its own members as well as non-members participating in the global dredging industry to establish common standards and a high level of conduct in their worldwide operations. The IADC's members are committed to safeguarding their employees, continuously improving to guarantee a safe and healthy work environment and reducing the number of industry accidents and incidents to zero.

Recognising advancers of safety

The IADC conceived its Safety Award to encourage the development of safety skills on the job and reward individuals and companies demonstrating diligence in safety awareness in the performance of their profession. The award is a recognition of the exceptional safety performance demonstrated by a particular project, product, ship, team or employees.

Eight solutions were nominated for IADC's Safety Award 2018 and each one aims to improve routine processes and situations encountered in the dredging industry.

Square tyres as fenders by Boskalis

Slips, trips and falls are considered to be the number one safety risk throughout the sector. An internal innovation event at Boskalis identified a situation on vessels to be unsafe and a solution has been conceived and implemented.

FIGURE 1

Boskalis' Magnor backhoe dredger is currently equipped with square tyre fenders and tyres are being produced for six other backhoe staircases.

Regularly round tyres are placed to form a fender which is intended to protect the equipment. These fenders can form a risk during crew transfers. Therefore in an effort to support the crew and make the transfer safer, squared tyres have been installed in place of conventional round tyres. Complete with an anti-slip surface, they can be installed on all sizes of barges or multi-cats.

Cost effective, the solution is also a sustainable one since it is easy to apply and limited resources are needed for maintenance. As it is a general application, the solution can easily be used across the maritime industry, in a context even broader than dredging.

Boskalis' Magnor backhoe dredger is currently equipped with square tyre fenders and tyres are being produced for six other backhoe staircases (see Figure 1). Two sizes are currently available and further development is being done to make it fit for purpose for different equipment.

Vessel-to-vessel transfer is the most critical operation for surveyors.

Wireless Broadband Mesh by Jan De Nul Group

Vessel-to-vessel transfer is the most critical operation for surveyors. When a vessel's survey computers needed to be updated, surveyors were required to board the vessels at sea, which is a hazardous and time-consuming activity. At Jan De Nul Group, a wireless broadband mesh was implemented on a project to reduce vessel-to-vessel transfers of surveyors.

After implementation on several projects, the system revealed to be more efficient than initially foreseen. Not only had the vessel-to-vessel transfer of surveyors been reduced drastically (see Figure 2), the survey updates could also occur faster and without delays, resulting in more operational efficiency. A part of improving efficiency also resulted in reduction of (fuel) cost and eventually lowering the environmental impact. The system is a plug-and-play outdoor Wireless broadband modem that can be easily interfaced with the vessels ICT infrastructure. Once the system is installed on a vessel for survey purposes, it can be used for a multitude of purposes as all other departments can use it for their own needs. ICT can control and update its network infrastructure, important operational information can be exchanged smoother with the vessels and so on.

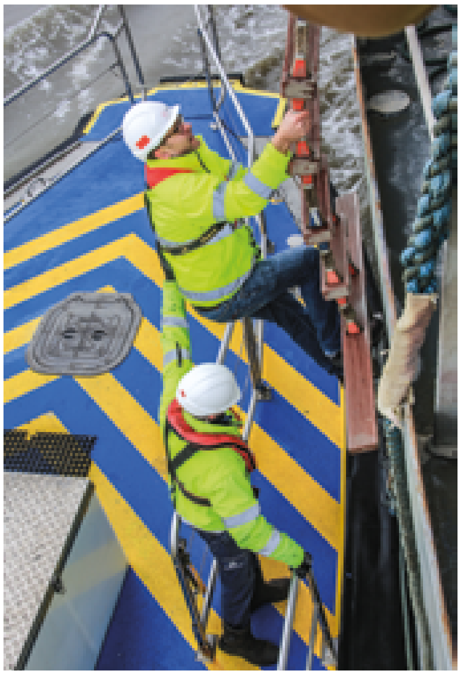


FIGURE 2

Wireless broadband mesh reduced the need for vessel-to-vessel transfers of surveyors, increasing both safety and efficiency.

The ICT department has implemented the system by request of the survey department for its own use. Other departments or operations that see the benefit in this system can study the possibilities and perform trials on the projects where the system is already implemented. By making the system universal, it will facilitate the implementation of project-specific requirements.

The system enables faster communication overall which will lead to more efficient operations, enabling the Project Management Team to get feedback faster. In addition to interconnecting vessels and being a back-up for communication system failure, the system provides faster survey updates, security updates and software patches on board of vessels with the possibility for remote troubleshooting and problem-solving. So far, the wireless broadband mesh has decreased fuel consumption and transport cost from the transfers, and increased operational time in terms of efficiency and productivity through less survey delays for operations and avoiding operational standby.

Wireless Broadband Mesh has an initial installation cost, and fine-tuning is necessary, but the benefits transcend the initial cost by far. Further experience and development is necessary in order to continue improving the system.

Mooring ropes handles by DEME

Mooring activities are one of the activities in our sector that are considered as a high risk task. One of our employees came up with the idea of 'mooring rope handles' to make the handling of mooring ropes easier and safer.

The handles – attached to the mooring eye – are keeping the hands of the crew member out of the 'risk zone' during (un)mooring activity (see Figure 3A). These handles are inexpensive and easy to apply to existing ropes.

The use of those handles reduces the risks of injuring fingers or hands between the bollards and ropes activity (see Figure 3B).

Mooring handles could also be a solution for a more extensive group of users outside the

FIGURE 3

Handles attached to a mooring rope intend to keep crew members' hands away from the risk zone during mooring activities [A] and also eliminate the need to place hands in between the mooring rope and bollard [B]. Under the umbrella of DEME's C.H.I.L.D.5 campaign, posters were hung in headquarters to increase handrail usage and proved to be highly successful [C].

dredging industry. The idea should become a new safety standard within the industry. We challenge the suppliers to provide ropes with pre-attached handles.

Safe on stairs – Use handrails by DEME

Incident trend analysis indicated some recurring incidents, with personal injury, related to the use of staircases on board of vessels. Also at the offices, staircase incidents occurred with serious consequences. The root causes of these incidents brought up the behavioral aspects and the fact that the handrails of the staircase at DEME's main personnel entrance in Zwijndrecht (Belgium), were not up to standard.

The question is: how can we persuade our personnel to give a good example and use these handrails? The opportunity was taken to experiment with technical changes of the handrails and testing the results of the changes at the same time. The results were measured by short and simple samples during the week.

- The first technical change was the replacement of the original steel handrails by more comfortable, wooden alternatives. This resulted in an immediate usage increase of 20%.
- Since employees could walk in the middle of the stairway, without a handrail within reach, the next technical change was the installation of two additional handrails. This led to an extra improvement of almost 30%.
- After an unexpected decline in use, a simple poster campaign (see Figure 3C) was launched to introduce the public to the desired target.

FIGURE 4

Van Oord developed its automated debris removal system in-house.

The use of handrails increased up to 75% in less than a few weeks' time. Since the start of the campaign, there have been no stair-related incidents at head office.

This type of campaign can be extended to any other site or ship. Before starting a motivational campaign, however, it is necessary to check the design of the staircases and find a technical solution to accommodate safer staircase use. Technical solutions can be

- anti-slip treads,
- improved handrails,
- adequate lighting
- and reduced staircase angle where possible.

Building on the principles of DEME group's C.H.I.L.D.5 campaign, the focus on preventing staircase incidents has resulted in significant behavioral changes. It evocated better housekeeping, better maintenance and safer design (up to the safety standards) of infrastructure. At the same time the awareness of the risk of carrying heavy loads (on stairs) and ergonomics popped up spontaneously.

Debris Removal Platform by Van Oord

During dredging, debris can fill the trailing draghead of trailing suction hopper dredgers. When the suction pipe is recovered on board, debris that was stuck in the draghead will fall onto the deck. To safely be able to remove this debris, Van Oord developed an automated debris removal system to reduce the risk of personal injury (see Figure 4).

There are infinite situations which can be considered risks to safety in dredging projects.

Van Oord changed the existing technique from the manual removal of debris to an automated system, reducing the risk of personal injury from manual handling and eliminating slips and trips. A debris removal platform for its fleet of Trailing Suction Hopper Dredgers (TSHDs) has been developed, letting crew safely and easily remove debris from the deck without the use of a broom or shovel. With a hydraulic drive bulldozer blade, the debris removal platform pushes the debris over the side of a vessel. Crew can stand-up straight next to the platform as the blade pushes the debris. The debris removal platform has several safety benefits including the elimination of manual handling, use of sustainable and safe material, covered rotating parts, safety railing, no lifting and rigging operation.

Critical Operations 'Lock Out, Tag Out' by Jan De Nul Group

There are infinite situations which can be considered risks to safety in dredging projects. That's why Jan De Nul introduced a critical operations campaign to increase awareness around the most serious risks which have historically resulted in the worst incidents. These are identified as working at height, lifting operations, tasks requiring lock out and tag out, site traffic, defining no-go areas, marine navigational awareness and marine transfer of personnel.

Specifically, the critical operation 'Lock Out, Tag Out' (LOTO) contributes to safety in the sector as it is a control measure present industry-wide. Jan De Nul's critical operation LOTO campaign was approached from an operational point of view. The campaign aimed to be interesting to crew normally involved in LOTO operations and for this reason, the people involved in LOTO are presenting it in the video.

While the technique of doing LOTO is not new, the way it is communicated to the dredging projects and vessels is. The engine room departments of all vessels wrote vessel-specific LOTO manuals detailing which isolations are required for the different jobs on board.

A usual day on board of a dredging vessel was filmed, documenting the actual crew which successfully applied isolation according to the LOTO standard. The movie followed Jan De Nul's Imagine, Think, Act (ITA) framework: imagine what should and should not happen, think of a plan and communicate with the team, and act by leading the plan. The movie was then sent to all dredging projects and vessels, and was shared on the ITA website (https://ita.jandenul.com) and Jan De Nul's social media accounts. Constant reminders were issued in the form of posters (see Figure 5) and the backgrounds of all of JDN's computer login screens. Elaborate training packages were also sent to all projects and vessels to increase knowledge of the LOTO procedure.

Through advance preparation of ship-specific LOTO manuals to describe which operations require which LOTO, and then through sharing of this material, awareness and safety can be increased. The risk of working on equipment is a common issue therefore applying this approach can benefit the industry.

FIGURE 5

A campaign for the critical operation 'Lock Out, Tag Out' (LOTO) included constant reminders in the form of posters.

DynaCover by Damen Dredging Equipment

Dredge pumps experience extreme forces during operation, requiring a robust piece of equipment to combat them. Failure of this connection can impact a project's efficiency

FIGURE 6

An easily-applied outer cover of Nomex protects the DynaCover from welding sparks and dirt.

FIGURE 7

Jan De Nul Group's movie *We Are ITA* is part of Imagine Think Act, a company-wide programme which aims to change culture from an operational perspective.

or in the worst case, crew. The advent of the double-walled pump improved safety and reliability, marking a major step forward compared to the formerly prevalent sheet steel pump casings. The wear-resistant casted pump casing was covered by a sheet metal outer casing which prevented the spilling of mixture while the inner pump house could be used until it disintegrated.

An alternative by Damen Dredging Equipment, the DynaCover, was fabricated and tested at full-scale. Holes were made in the inlet pipe, so when the pump was filled up, water flooded between the inner pump casing and the DynaCover. By doing so, the inner and outer pressure of the pump casing is the same, preventing the inner casing from collapsing.

The DynaCover is made from Dyneema, a material used for products such as cut-resistant gloves. With fibers produced from a polyethylene with a very high molecular weight, the material is lightweight, strong, durable and resistant against UV light, oil and sea water. An easily-applied outer cover of Nomex – a flame-resistant material worn by firefighters and racing drivers – protects the DynaCover from welding sparks and dirt (see Figure 6).

We Are ITA by Jan De Nul Group

During the course of a project, attention and priorities can shift, but one thing is certain: safety results from successful projects and vice versa. Jan De Nul Group acknowledges that proper preparation and keeping control makes all the difference in ensuring a successful project. That's why the company conceived 'Imagine Think Act' (ITA) which has a dedicated website (https://ita.jandenul.com/), a *We Are ITA* movie (see Figure 7) and regular newsletter messages to employees.

A company-wide programme, ITA's strategy is to approach culture from an operational point of view and not as a safety culture. The system is self-sustaining as long as company leadership give attention to ITA as it is about how leadership is realised, risks are handled and mistakes are responded to. ITA should become part of the language that all levels speak, and through this language a culture is formed, especially since direction and support comes from the top of the company. To put theory into practice, a challenge was introduced to vessels and projects worldwide, and teams challenged each other to show ITA on their vessel/project.

Some of the ingredients of ITA are a leadership expectations matrix, a process to provide feedback on risk management and level of operational control (Field Risk Talk (FRT)), a focus on critical operations, combined with a Stop and Rethink attitude when something doesn't go according to plan, and a culture model to grow more operational control.

> **A company-wide programme, ITA's strategy is to approach culture from an operational point of view and not as a safety culture.**

CAN A PLATFORM REDUCE RISK

OF PERSONAL INJURY DURING DEBRIS REMOVAL?

To safely remove debris that will fall onto the deck after recovering the draghead of a trailing suction hopper dredger, Van Oord has developed an automated debris removal system. IADC rewarded Van Oord's innovation with the IADC Safety Award 2018 during its Annual General Meeting in Budapest, Hungary.

> **During dredging, debris can fill the trailing draghead of a trailing suction hopper dredger.**

'Learning from the past and incorporating practical experience from the field is an important part of the research into possible improvements,' proud award-winner Coen van den Berg hits off. He is a Project Engineer currently working on Van Oord's new trailing suction hopper dredger Vox Amalia. 'For every new design, we take a critical look at how we can improve safety and functionality,' he continues. At the start of the project, the team received the request to see if they could improve the way of removing debris from underneath the draghead.

In-house development

Improving the working environment is important to Van Oord. That is why its fleet is continuously being updated to the highest standards in close cooperation with specialists within Van Oord, such as those who are heavily involved in the building process. These professionals are always looking for new ways to innovate. That is why, during the design phase of new trailing suction hopper dredgers Vox Amalia and Vox Alexia, the design team focused on making these brand-new vessels even more safe and energy efficient.

The inspiration

During dredging, debris can fill the trailing draghead of a trailing suction hopper dredger. When the suction pipe is brought back on board, debris that was trapped in the draghead will then fall onto the deck. This debris can range from large boulders to sticky clay and needs to be removed from the vessel. On large trailing suction hopper dredgers, this is traditionally done with a tilting platform (see Figure 1). A simple platform with hinges on the hull side and lifting pad eyes on the other end. By lifting one end with the crane or draghead, the accumulated debris can be transported overboard.

'There are two main operational downsides to this system,' Coen clarifies. 'You cannot use the tilting platform with the trailing pipe in its storage position, because it will be blocked by the draghead. The second issue arises from the use of the crane to move the tilting platform. In the past, we've experienced that the use of the crane while sailing offshore was not allowed by the client. This meant that we could not move the debris overboard as usual.' To find a suitable solution, which would improve operational efficiency, the engineering team joined forces with the vessel crew. They considered several concepts and carried out a short feasibility study. It was soon decided that the use of a dozer blade would provide the best solution.

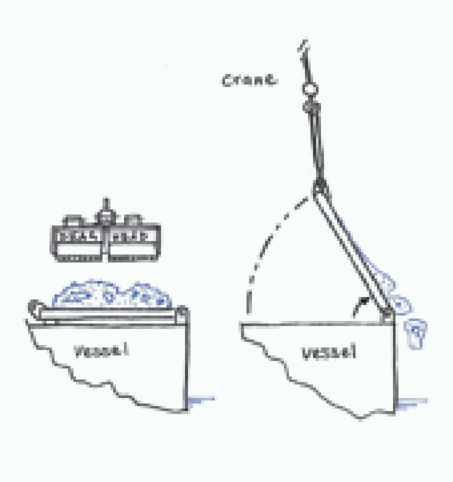


FIGURE 1

On large trailing suction hopper dredgers, a tilting platform is traditionally used to throw debris overboard.

During a ceremony at the Annual General Meeting in Budapest, Hungary, Van Oord's Debris Removal Platform was revealed as the Safety Award 2018 winner. IADC President Frank Verhoeven (left) conferred the award to Coen van den Berg (right) on behalf of Van Oord.

Do you know about a safety solution worthy of recognition? Then submit it for consideration for the Safety Award 2019! Find out how to submit nominations at www.iadc-dredging.com.

The mission

'Our mission? To create a safe, effective and fool-proof solution to move a dozer blade on deck,' Coen explains enthusiastically. 'It was great to work on the design and build of this Debris Removal Platform, as the dredging industry is normally quite traditional. Suction pipe equipment has largely remained unchanged for years. To innovate an established working method was a nice project for us. I was happy to experience that Van Oord gave us all the freedom to execute this in the best way possible.'

The challenge

Designing the ultimate solution was not a clear-cut process. The team faced various challenges. There is little height underneath the draghead and deck space is also limited. On top of this, the space underneath the draghead is one of the worst environments to place a machine, because of the seawater and debris falling from the draghead. The drive system therefore had to be robust and had to cope well with dirt. Because of the lack of space, the drive mechanism for the dozer blade was moved to the sides. A chain drive was chosen as it is robust and has a high dirt tolerance.

Safety was an integral component of the process. The requirement was that it has to be safe to operate the dozer. As work is carried out on the draghead on a regular basis, the platform also had to act as a stable and safe working platform for the crew. After several iterations in the design phase, the Debris Removal Platform was born.

The design

The Debris Removal Platform consists of a dozer blade that runs on rails with bogies (chassis carrying wheelsets) on either side of the platform. The rails are combined with a steel frame that keeps the working deck in place (see Figure 2). When the suction pipe is brought back on board, debris that was trapped in the draghead will fall onto this working deck. After the vessel crew has taken out materials such as plastic, scrap, car tyres, etc., the Debris Removal Platform – powered by a hydraulically-driven dozer blade – pushes the debris over the side of the vessel.

Drive mechanism

The blade moves with the help of a chain drive on either side with a standard steel chain running between them. The chain drives are both mounted on a single shaft, which is connected to an hydraulic motor with reduction gear. This means there is no need for hydraulic synchronous control. Hydraulic power comes from the main hydraulic system on board, but can also be delivered by a standalone power pack if the installation is retro fitted. The dozer blade is fixed to the chain. Once the motor starts running, the chain pulls the dozer blade forward. When the motor rotation direction is reversed, the blade will move backward. This system is simple, needs minimal control and is dirt resistant. The rotating parts are all covered with stainless steel plates and the chain is guided in Teflon blocks. The blade can be sea fastened with pins in the inboard position. The blade itself is fitted with wear resistant plates that can be replaced. In the component choice, Van Oord used standard parts for the wheels, bearing houses and couplings.

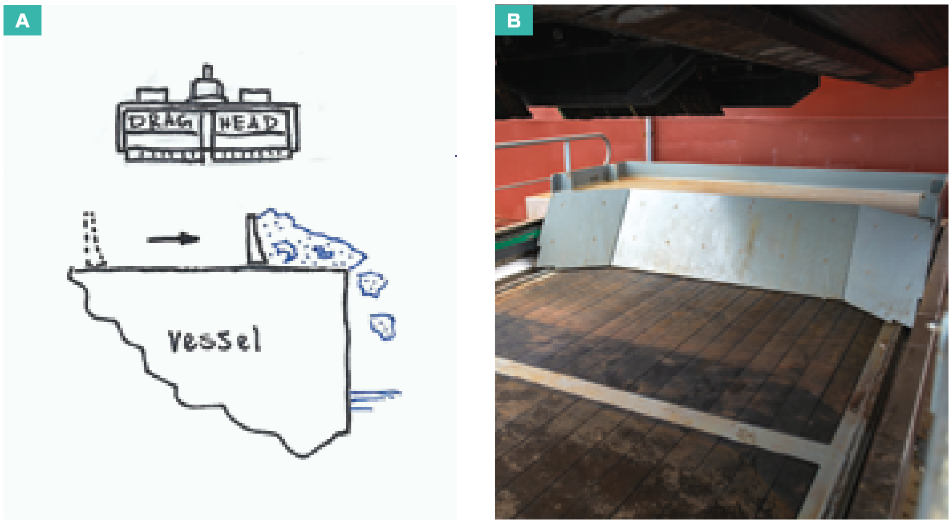


FIGURE 2

Debris falls onto a working deck consisting of a dozer blade which runs on rails with bogies [A]. A rail surrounds the working deck to keep it in place [B].

KLP® working deck

A material with high impact resistance was required for the working deck, as large boulders can fall from the draghead. Moreover, as vessel crew often have to carry out maintenance activities underneath the draghead, the working deck needed to be safe and stable. The design team set out to find a better material than the standard hardwood and selected sustainable KLP® plastic material. This is made out of recycled bottle caps, crates and agricultural plastics, has a high impact resistance and provides more grip when wet.

Safe operation

The blade is operated from a local control cabinet next to the installation. When the operator starts the movement of the blade, an audible and visual alarm sounds to inform people around the platform that it is starting to move. Continuous actuation of the button is necessary for movement of the blade. If the operator takes his hand of the button, the blade will stop moving (dead man button).

Safety stops

A railing is installed around the platform. When the access gate is opened, the blade will automatically stop (interlock system). The blade also stops automatically on the maximum inboard and outboard positions by means of proximity switches. An additional mechanical end-stop in combination with hydraulic pressure valves serves as a backup end-stop. As a last option to stop the movement of the blade, the local control cabinet is fitted with an emergency stop.

Say yes to safety

The Debris Removal Platform will first be installed on trailing suction hopper dredger Vox Amalia, the latest addition to Van Oord's fleet. It will be installed on all other trailing suction hopper dredgers as well at a later date. 'With the installation of the Debris Removal Platform, we have improved the working circumstances around the draghead and are one step closer towards a zero-accident organisation,' concludes Ton van de Minkelis, Staff Director QHSE. 'By taking safety into consideration in the design phase, hazardous working conditions during operations can be eliminated or significantly reduced. This is the most effective way of risk control. Working together proactively on safety with all disciplines is very important. As a global player in the marine contracting sector, safety is our license to operate. Within our "Say YES to safety" programme, we encourage everyone to demonstrate safety leadership. Continuously improving our working environment by using our ingenuity is a natural part of that!'

Safety Benefits of Van Oord's Debris Removal Platform

Elimination of manual handling

No manual handling with brooms and shovels is required. No pulling or pushing has to be done in an uncomfortable or awkward position. There is limited height under a draghead, so crew are currently working in a location that is difficult to access. They also need to bend and push or pull at the same time. These two activities together create a high risk probability that a manual handling injury will result. This will all be eliminated by installing this platform. The person involved can stand up straight next to the platform and the blade pushes the debris instead of the person doing this manually.

Sustainable and safe material used

For the working deck, sustainable KLP® plastic material (recycled bottle caps, crates and agricultural plastics) is used. Besides providing a sustainable alternative to a wooden working deck, this material has a better impact resistance and provides more grip when wet. When working in an area with mud and water, the risk of slipping is high. By using this type of material, the probability of a person slipping or falling is low.

Rotating parts covered

All rotating parts are covered to prevent entanglement with clothing or hands, etc.

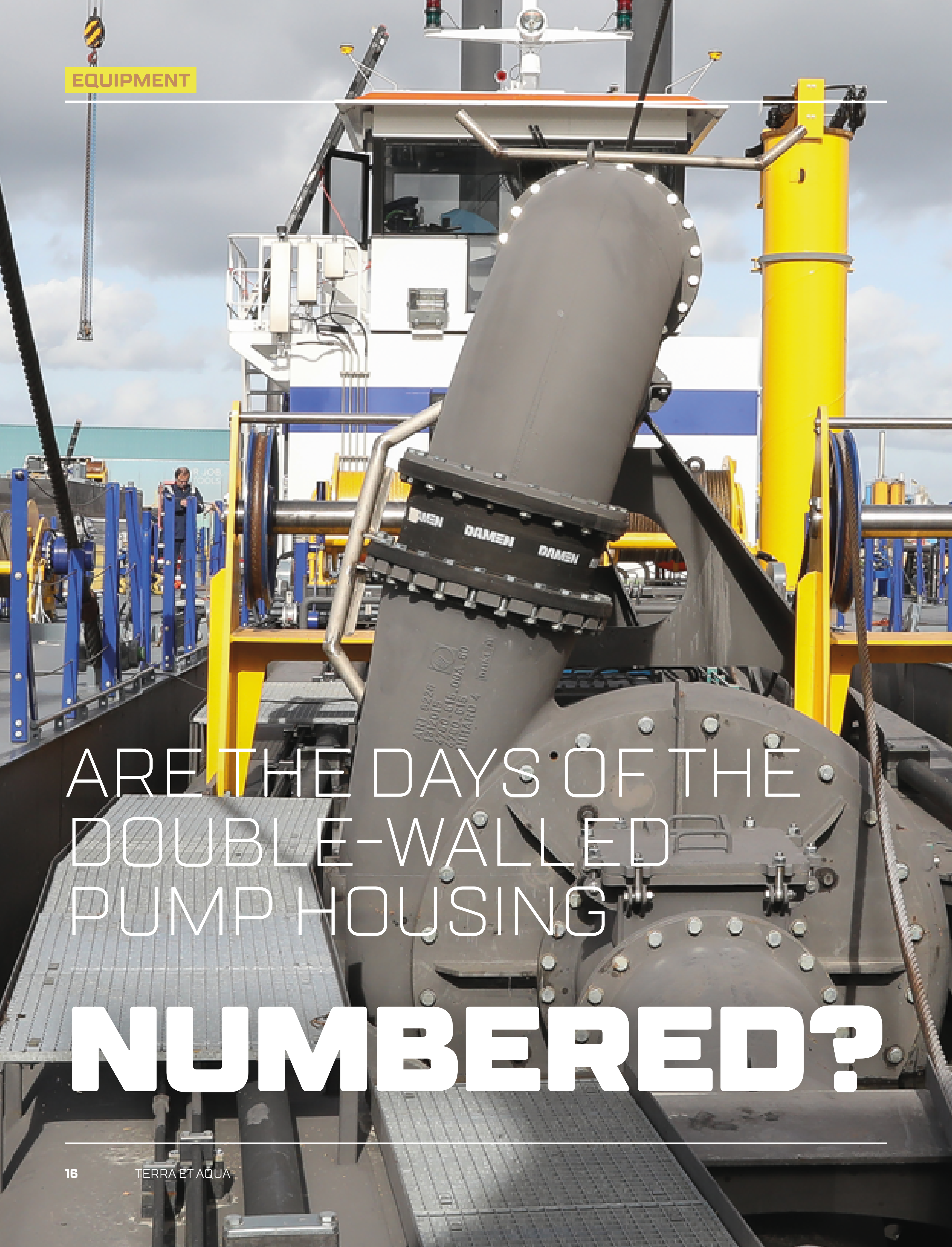
Safe railing

The unit has its own railing with self-closing doors, which are fitted with an interlock system, and movement stops when the doors are opened.

No lifting and rigging operation

Compared with existing tilting platforms, no lifting or rigging operations with a crane are required to move the platform so that the debris can be deposited overboard.

The Debris Removal Platform consists of a dozer blade that runs on rails with bogies (chassis carrying wheelsets) on either side of the platform.



ARE THE DAYS OF THE DOUBLE-WALLED PUMP HOUSING NUMBERED?

For several decades, the preferred solution for isolating dredging pumps within a vessel has been the double-walled pump housing. While an improvement in both safety and reliability compared to the previous use of single-walled pumps, it still has two significant problems: it requires the pump to be raised to accommodate the casing, which has a negative impact on pump efficiency, and it adds considerably more weight to the pump assembly.

> **A few tonnes less payload may sound insignificant, but over the course of year this adds up to a substantial loss of capacity.**

This extra weight reduces the additional payload that the dredger can take and over the years can represent a significant loss of capacity. To address this Damen has been conducting an extensive research project in partnership with its customers and materials specialists to develop a solution that can overcome these issues. The result is now available commercially and will no doubt surprise many as it is radically different to what has gone before.

A demand for greater efficiency

The double-walled pump housing was introduced in the early 1970s by De Groot Nijkerk (see Figure 1). The design is made up of an outer housing in fabricated structural steel fitted around the cast inner pump housing. The steel outer casing protects the external environment in the event that the cast inner housing, which ensures that the pump has sufficient wear resistance, fails. The double-walled pump housing was a great improvement, significantly increasing both the safety and durability of the dredge pump. With the double-walled pump housing in place the cast pump could safely be operated until it reached the end of its life and disintegrated.

However, the conventional double-walled pump house did come with a number of disadvantages. Firstly, all that steel is heavy,

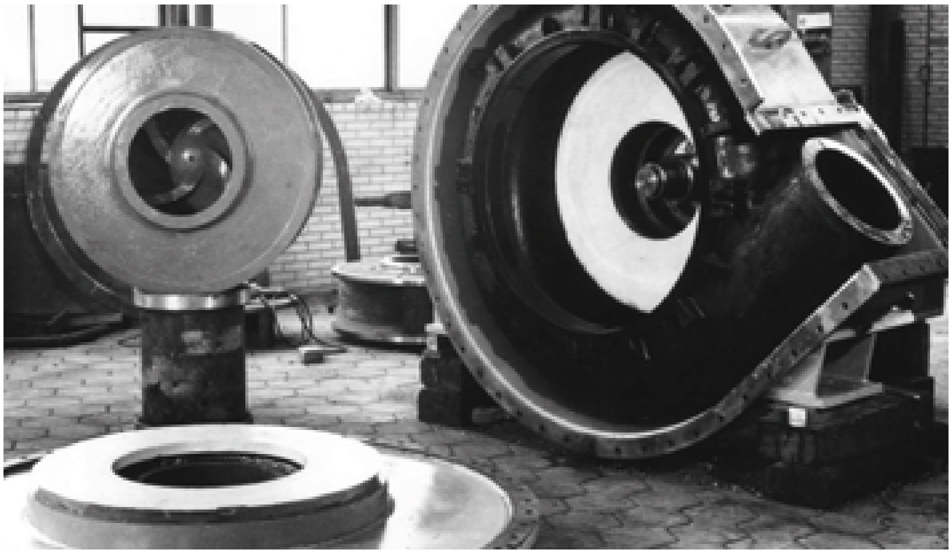


FIGURE 1

In the early 1970s, De Groot Nijkerk introduced double-walled pump housing.

and the extra weight comes with the cost of reducing the final payload that the trailing suction hopper dredger can carry before having to cease operations and move away to offload. A few tonnes less payload may sound insignificant, but over the course of year this adds up to a substantial loss of capacity. Also, with its double-wall housing, the pump requires more space, which is a particular issue with Cutter Suction Dredgers (CSDs), and results in the pump being raised to a greater height than would otherwise be the case. With the core of the pump now closer to the surface of the water the suction efficiency of the pump is reduced, negatively affecting the production rate of the dredger.

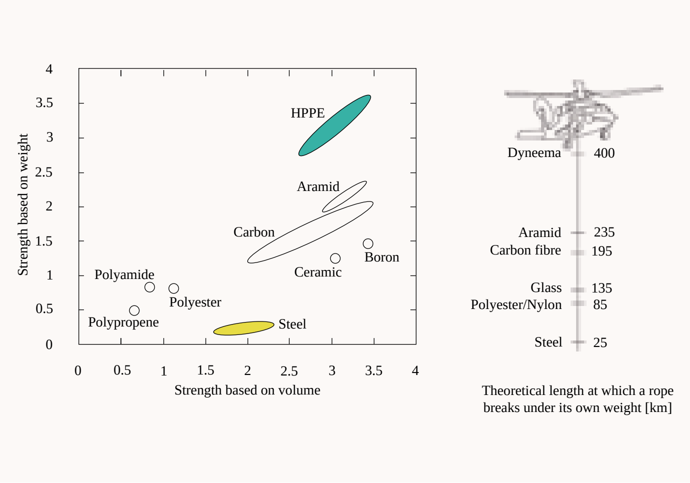


FIGURE 2

In the early 1970s, De Groot Nijkerk introduced double-walled pump housing.

A new approach

As the Damen team reviewed the issues arising from the standard steel double-walled pump housing, it was quickly realised that an effective solution would need a number of key attributes. It would need to be:

- Lightweight
- Easily accessible to allow the replacement of parts subject to wear
- Water tight up to 20 atmospheres
- Safe and reliable
- Hard wearing
- Easy to retrofit

To meet these requirements, the team launched an extensive research project in association with a number of industry and research partners.

The first stage was to determine the material to be used for the new casing. In particular, it had to be strong and durable, yet also lightweight. It also had to be resistant against seawater, sunlight (UV), chemicals and micro-organisms. Initial candidates were the textiles Twaron/Kevlar and Dyneema, both of which offered the necessary high-tensile strength. However Dyneema emerged the winner due

Why is the height difference between the waterline and the pump significant?

A pump doesn't really suck in the sense that it creates a partial vacuum into which water flows. It actually just moves water using an impeller. As the water moves, the pressure in the inlet pipe drops due to the resistance of the suction pipe. The pump itself also needs some pressure, plus a margin. The outside pressure (atmosphere and water above the pump) pushes on the water inside the suction pipe (which has a lower pressure). The maximum suction pressure is therefore limited. When a pump is positioned at the waterline, the maximum pressure available is only 1 bar (atmospheric pressure). For the pressure drop of the suction pipe in general only 0.6 bar is available. An additional metre of water increases this by 0.1 bar (17%), so even raising the pump by only 0.5m results in a loss of suction capability of almost 10%.

to its ability to meet all the other criteria (see Figure 2).

Dyneema is a UHMWPE (Ultra High Molecular weight Polyethylene) fibre that has a yield strength as high as 2.4 GPa (240 kg/mm^2 or 350,000 psi), making it comparable to high-strength steel. However it has a strength-to-weight ratio eight times that of high-strength steels. It was invented by Albert Pennings in 1963 but became commercially available in 1990.

Dyneema fibres also have a very high molecular weight which makes them lightweight, strong and durable, as well as resistant to ultraviolet light, oil and seawater. As a textile, Dyneema is also proven when it comes to high stress environments. Current uses include body armour, cut-resistant gloves and various aerospace applications. Calculations were performed to determine the number of layers that would be required to meet the pressure goal of 20 atmospheres.

With that decision made, the next step for the team was to create a textile casing with an opening through which technicians could gain access to the pump within for maintenance and the replacement of worn-out parts. The challenge here lay in the fact that the entire textile 'shell' had to be fabricated as a single piece to guarantee its strength. Zips and other fasteners would compromise the shell's integrity.

With the case clamped to the inner pump housing, folds in the shell of textile were introduced so that the opening could be enlarged. This in turn launched a search for a solution that would ensure that the line of connection to the pump would be watertight.

Making it 100% watertight

Ensuring that the entire housing was watertight was a consistent theme throughout the project. Dyneema itself is not completely waterproof. Over time water will make its ways through the weaving, however this was easily solved by incorporating a layer of plastic film between the layers of Dyneema that make up the overall fabric. The plastic film selected is very elastic and does not fail under high pressure. The fabric is produced to very tight tolerances, using a special drum developed for this process plus a special, heated press for gluing the layers together.

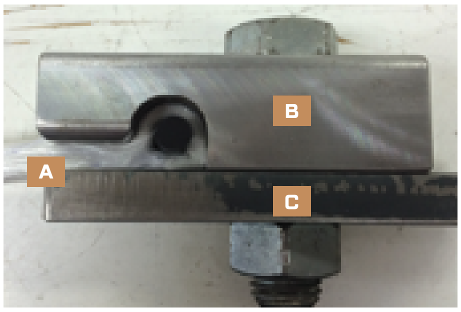


FIGURE 3

The connection to the pump is comprised of textile with a rim [A], the clamp [B] and the base plate inner pump casting [C].

The second challenge was to connect the textile to the steel of the pump in such a way that it is completely watertight and yet still easy to handle. The solution involved attaching a rim around the edge of the textile that could then be clamped to the pump's steelwork (see Figure 3). The design of the clamps was vital to the success to the Dynacover product and much effort went into their design and testing.

The key challenge was to reconcile the need for complete water resistance with that of the need for folds in the fabric that allow the opening to be enlarged for easy access to the wear parts. Fortunately a useful property of Dyneema is that, by simply pressing the folds down using a wedge, they become completely watertight. Subsequent testing demonstrated that this can be done hundreds of times without damaging the textile. A range of weavings and clamps were tested, starting with a simple clamp and then moving through different formats until a clamp which met the specified requirement of being watertight to 25 atmospheres was found.

The newly-developed clamps are fabricated using the lost-wax casting process (see Figure 4A). They were engineered using finite element calculations and are optimised for weight at just three kilos a piece, making handling easy (see Figure 4B). The result is a pleasingly organic-looking design and they can be fitted on any pump type and size. The Dyneema shell is also lightweight and easily carried by one

> **As a textile, Dyneema is also proven when it comes to high stress environments.**

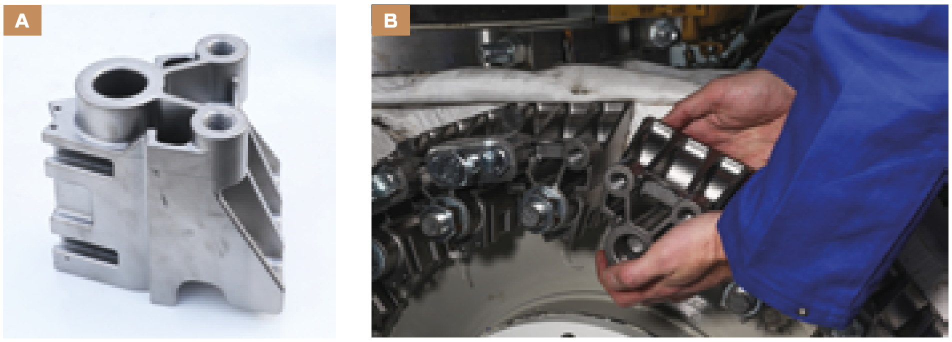


FIGURE 4

The Dynacover's clamps are fabricated with a lost-wax casting process [A] and weigh only three kilos each which enables easy handling [B].

FIGURE 5

The outer cover is partly removed to show the clamps.

man. Its initial installation and all subsequent openings for inspections can therefore be done without hoisting tools. Indeed, the only tool needed is a wrench.

The final test

For the full-size water test, the inner pump housing was sealed off using flanges, but a connection was made between the inner space of the inner pump housing and the outer Dynacover pump (see Figure 5) housing to allow the pressure to equalise between the two. This was done to prevent the inner pump casing from collapsing under the high external pressure. The casing was then filled with tap water and then, once all the air was removed and replaced by water, the high-pressure pump was connected and activated. The Dynacover was pressurised up to 20 atmospheres, at which point some minor leakage occurred.

This test resulted in the design of the flexible housing undergoing an improvement in which the biggest fold was reduced in size by cutting the textile and gluing the fabric together again. A final, full-size water test proved the effectiveness of the modification at eliminating the leakage. It also ultimately resulted in the reduction of the height of the clamps (see Figure 6).

A new era for pump housing

The introduction of the Dynacover opens a new chapter in the story of the double-walled dredge pump. It delivers substantial advantages over the traditional double-walled pump, its dramatically reduced weight and smaller dimensions eliminate the main disadvantages of the existing concept. Any CSD – new or old – can be fitted out with the system, while replacing the traditional steel double-walled pump housings in trailing suction hopper dredgers will also allow them to accommodate greater payloads, thereby delivering greater fuel economy. All users will appreciate the safety and environmental gains. Additional benefits include ease of handling, fitting and servicing, and cost efficiencies. Installation on an existing mounting takes less than four hours. Once again, a Damen R&D initiative has delivered efficiencies and performance gains by applying new materials technologies to old issues.

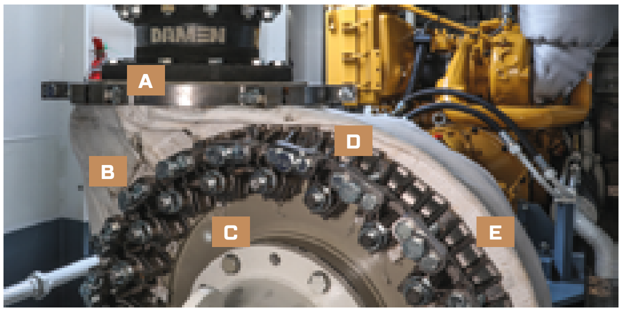


FIGURE 6

The complete Dynacover includes a 6-parted clamp [A], Dyneema [B], pump cover [C], clamps at the pump cover [D] and a wedge for folds [E].

Benefits for both CSDs and TSHDs

With CSDs generally compact vessels of limited space and shallow draft, making it not possible to position the dredge pump much below the waterline. Raising it so as to fit a double-walled pump housing only reduces the pump efficiency even further. With the pump often mounted inside the engine room, if it does suffer a major leakage then the risk is that the entire engine room is flooded, causing significant damage to the engines and electronics. The Dynacover is therefore ideal for use in these circumstances.

Trailing Suction Hopper Dredgers are generally much larger, with the dredge pump mounted well below the waterline in a dedicated pump room. Damage from flooding is therefore not an issue, however the weight of the double-walled housing is, and its replacement with a Dynacover makes the vessel more efficient through the ability to carry additional payload.

It delivers substantial advantages over the traditional double-walled pump, its dramatically reduced weight and smaller dimensions eliminate the main disadvantages of the existing concept.

Summary

For many years the steel double-walled pump housing has been the preferred solution for isolating dredging pumps within dredgers so as to minimise damage from sudden failure and any subsequent leakage. However, it has significant disadvantages in the form of weight, space required and loss of pump efficiency. To address this, Damen initiated a research programme to find an alternative form of housing that would retain the same levels of protection but without the negatives. The solution is the Dynacover, a lightweight, flexible casing made from Dyneema, a proven ultra-high molecular weight polyethylene fibre, which is fastened to the pump casing using special clamps. As well as performing to the required specification in terms of pressure and durability, it also allows easy access to the pump for maintenance, is easy to handle and simple to retrofit.

Ewout van Duursen
Ewout studied mechanical Engineering at the University of Applied Sciences before starting work at Voith Paper Fabrics Haaksbergen. In 1998 he joined Damen Dredging Equipment as a sales engineer. Currently he is working in the Research, Development and Innovation department. He is responsible for the general engineering of the standard range of Cutter Suction Dredgers build by Damen Shipyards. He introduced the application of CFD of dredge pumps and is involved with several innovative solutions for Damen Shipyards.

TECHNICAL

CAN A PRELIMINARY MODEL DESCRIBE CSD SPILLAGE DUE TO CENTRIFUGAL ADVECTION?

Photo © Robert Collaro

Depending on its size and installed power, a Cutter Suction Dredger (CSD) is capable of cutting a wide range of soil types from silts and clays to fractured or solid rocks. Its high precision allows for utilisation in a variety of dredge operations including navigational channel deepening, port construction and pipeline trenching. In spite of being considered relatively efficient, a CSD can spill significantly. This article proposes a classification of the concurrent sources of CSD spillage as well as a analytical model for a priori computation of spillage due to high rotational velocity-induced flow. As of yet, in literature, no analytical models exist that describe spillage due to centrifugal advection.

To compensate for reduced depth due to spillage, CSD operators resort to 'overdepth cutting' which entails cutting more material than theoretically required.

Introduction

Den Burger (2003) defines spillage as 'the soil that is cut during the dredging process, but is not sucked up by the suction pipe'. This article approaches spillage as perceived by the dredging industry and defines spillage as 'any soil that may be dislodged above the lowest cutter tip trajectory, but is not sucked into the suction pipe'. In contrast to Den Burger's definition, this includes any soil in the vicinity of the cutter and above the cutter profile, which may not directly be in contact with the cutting equipment.

A CSD is equipped with a rotating cutter head that is mounted in front of a suction mouth. A hoistable ladder carries the installation and along with a set of swing winches, provides sufficient weight and force to laterally maneuver the rotating cutter head through the soil. When the swing velocity and the tangential velocity at the top of the cutter align, a scenario arises that is referred to as 'over-cutting' (back swinging), while opposing vectors render an 'under-cutting' (dig swinging) scenario. See Figure 1 for a visual representation of these scenarios where v_s is the swing velocity and ω the rotational (angular) velocity. Typically, the axisymmetrical cutter head consists of 5 or 6 blades with a series of (staggered) teeth that mechanically cut and suspend bank material in order to be sucked up by the suction mouth. According to Den Burger, spillage can be attributed to the cutting process as well as the mixture forming process.

To compensate for reduced depth due to spillage, CSD operators resort to 'overdepth cutting' which entails cutting more material than theoretically required. In stiff or hard material, overcutting results in energy overuse, reduced efficiency and greater wear. In areas where the cut depth is restricted, spillage limits the borrow area yield or requires costly cleanup to leave grade.

In the water column, plumes resulting from spillage may cause environmental loss as light reduction and sedimentation affect sensitive receptors (Becker et al., 2014; Nakai, 1978). Also, turbidity plumes can reduce oxygen levels and interfere with fish respiration and feeding. In addition, the release of adsorbed pesticides, herbicides, toxic metals and synthetic organic compounds may contaminate the water column (Nakai, 1978). Environmental gains can be expected from the release of nutrients and the supply of fine sediments to silt rich habitats (Becker et al., 2014).

As of yet, in literature, no analytical models exist that describe spillage based on the suction velocity and the rotational velocity of

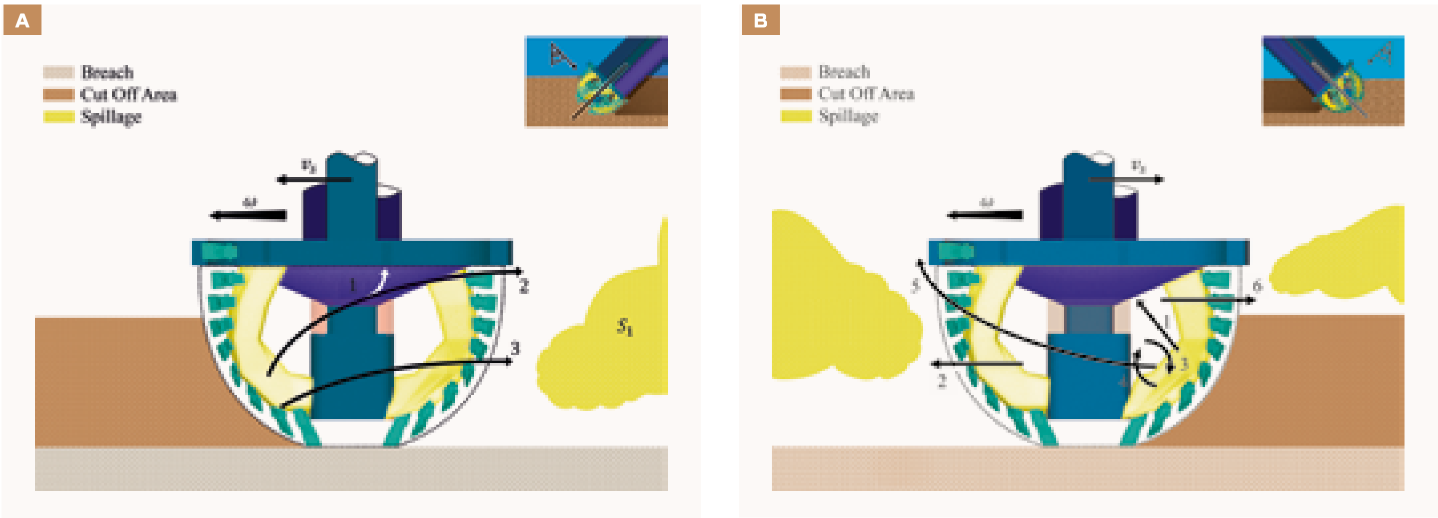


FIGURE 1

Centrifugal advection spillage for over-cutting (A) and under-cutting (B) as found in particle trajectory experiments by Den Burger (2003). Particle trajectories relevant to high rotational velocities are denoted with numbers 1, 2, 3, 5, 6. A fourth trajectory was neglected at higher velocities.

the cutter. This article presents a preliminary analytical model for spillage due to high rotational velocity-induced advection and calibrates the model using experimental data taken from Miltenburg (1983) and Den Burger (2003). As these datasets do not differentiate between individual spillage sources, contributions of other spillage sources are neglected.

Spillage type classification

Six types of spillage sources pertaining to CSD cutting are identified. A brief overview of the types of spillage is given, followed by a detailed discussion of centrifugal advection.

High Rotational Velocity-Induced Advection

High rotational velocity-induced spillage is a primary spillage source for CSD cutting. In its axial trajectory towards the suction mouth, entrained aggregates are accelerated by the rotational moment of the cutter, resulting in centrifugal advection along a section of the cutter contour. Centrifugal advection leads to a plume in the water column before sediments redeposits into the bed. Spillage due to centrifugal advection S_1 [-] is most pronounced with small grain sizes, high rotational

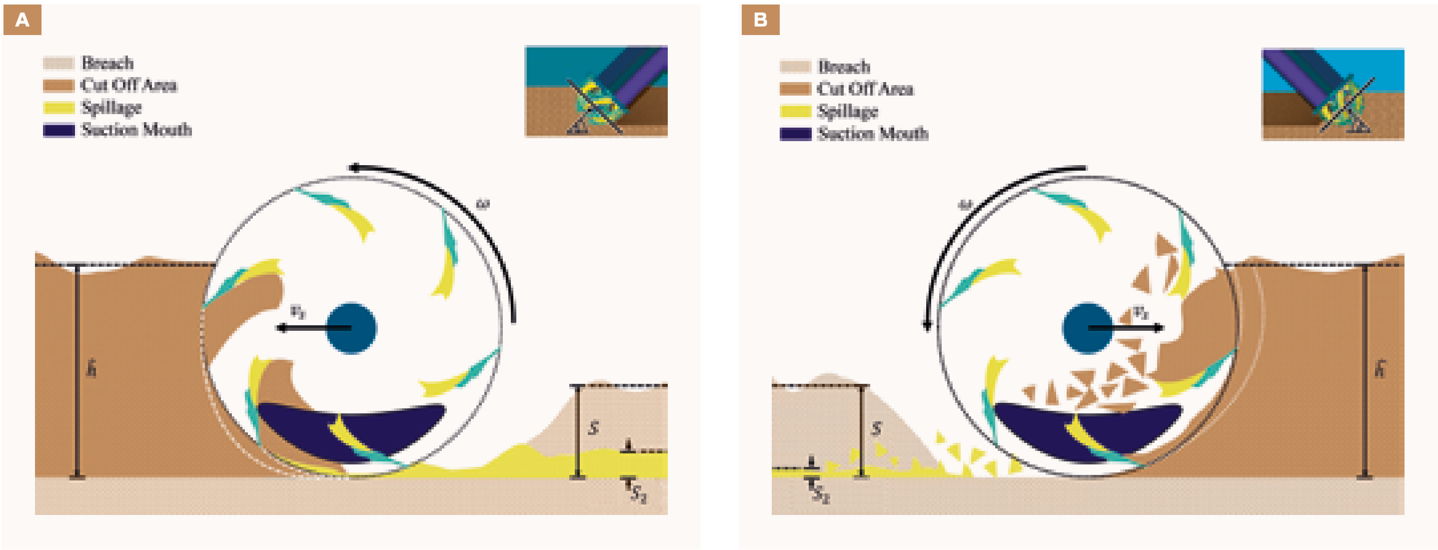


FIGURE 2

Rapid redeposition-induced spillage for over-cutting (A) and under-cutting (B).

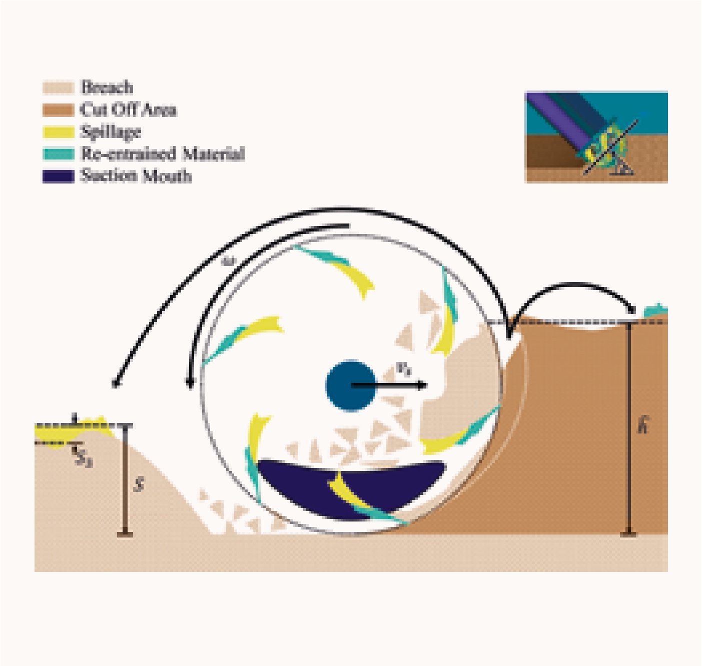


FIGURE 3

Spillage due to violent cutting for an undercutting scenario.

velocities and low mixture velocities. Figure 1 schematically depicts the trajectory of a single particle for the over- (A) and under-cut (B) scenario. Although not identical, centrifugal advection spillage of similar magnitude is observed for each flow pattern (den Burger, 2003).

Rapid redeposition

The acceleration of suspended material resulting from the cutting of the blades may be offset by gravitational acceleration and cause particles to rapidly redeposit. Spillage from rapid redeposition S_2 [-] is highly dependent on particle size and rotational velocity. This can be explained by the higher inertia of larger particles that are more difficult to suspend. Industry observations indicate a significantly lower production rate for over-cutting scenarios. In over-cutting, the tangential velocity of a blade in the fore coincides with the gravitational acceleration and swing velocity respectively. Dislodged sediment will therefore accelerate downwards past the suction zone of influence to redeposit immediately (see Figure 2A). In under-cutting, the opposing rotational and gravitational force vectors result in a particle trajectory characterised by relatively high suspension rates and improved mixing in the cutter as depicted in Figure 2B. Sediment passes through the suction zone of influence with lower velocity.

Violent cutting

Violent cutting is a CSD aspect that pertains to particle suspension and subsequent transportation to an area beyond reach of the CSD head. This type of spillage S_3 [-] is most visible when digging rock and cemented material. As the blades and teeth of the cutter head penetrate the bank, soil disintegrates in front of the cutter and some particles will be lifted due to the rotational motion of the cutter head as depicted in Figure 3. Furthermore, a high swing velocity can cause a bulldozing effect on the bank which lifts and suspends particles. Particles that redeposit in front of the cutter may be encountered by the cutter head again. Particles that settle behind the cutter contribute to spillage.

Buried cutting

When dredging a bank height that exceeds the effective height of the cutter head, the undermined soil will fail and rest onto the cutter head. Generally, this soil volume will be entrained into the cutter head, thereby increasing production. However, the cutter head may reach saturation or swing too fast, upon which remaining particles will move past the cutter head and fall behind the cutter head as illustrated in Figure 4. Spillage due to buried cutting S_4 [-] is generally determined by the height of the bank and the swing speed.

Breaching

When the cutter head breaches the bank, the slope angle of the breach may be larger than the internal friction angle of the bank material. With the absence of capillary forces below the water line, the steep slope will cause bank instability for granular materials. Van Rhee et al. (2015) describes that the bank wall following a dredger passage can be temporarily

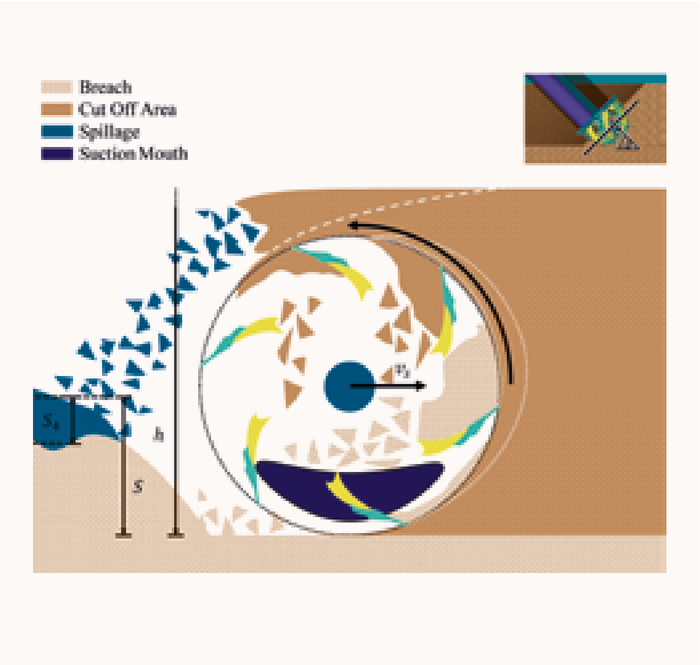


FIGURE 4

Spillage due to buried cutting for an under-cutting scenario.

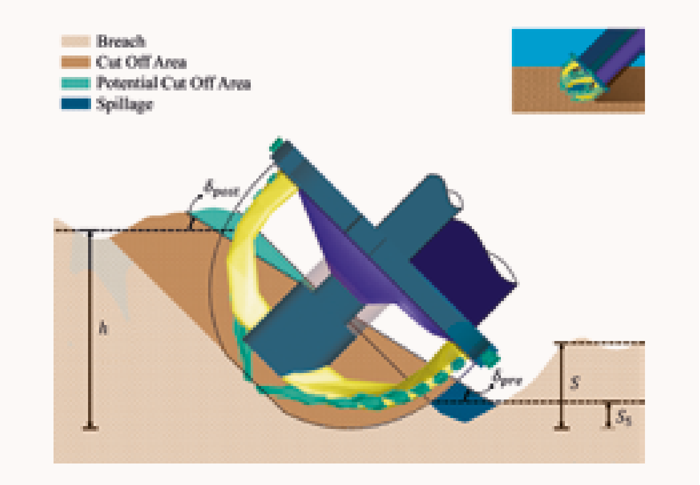


FIGURE 5

Spillage due to bank instability.

steep for sand due to dilatancy-induced plastic deformation of the breach. Shear deformation increases the pore volume of sand and an increased dilatancy causes an under-pressure in the pores resulting in an inflow of water. This process temporarily increases the effective pressure on the bank, yielding a temporarily stable bank slope. The slope will collapse when maximum possible dilatancy is reached.

Figure 5 depicts a situation in which the bank wall has collapsed after the previous swing. It can be seen that the newly created slope extends towards the area that has already been dredged. Hence, this soil remains on the seabed and is considered spillage. Spillage due to bank instability S_5 [-] is mostly dependent on the porosity, particle size and swing speed.

When the slope angle below a temporary stable wall is smaller than the existing slope angle, the breaching process is considered unstable (van Rhee, 2015). Typically, unstable breaching occurs at stationary bulk dredging operations with large bank heights where spillage is less relevant.

Cutter geometry

Inherent to the geometry of the cutter head, a relatively small spillage source S_6 [-] can be observed. As the cutter travels forward in discrete step sizes, a portion of the soil above the lower cutter tip depth is undisturbed (see Figure 6). Based on tradeoffs between the magnitude of inertia and the irregularity of cut areas, cutter geometry has evolved from cylindrically-shaped heads to parabolically-shaped heads (Vlasblom et al., 2006).

Other factors: vessel movement and survey disparity

Operations in ports, canals, rivers and offshore locations make the CSD subject to a variety of environmental conditions. Translational and rotational vessel movements (mainly surge, heave and pitch) result in unexpected cutter head movements. Furthermore, soil type estimations and bathymetry measurements are complex and prone to errors. The effect of vessel movement and erroneous estimations are inherently difficult to measure directly, and can magnify other spillage sources.

Existing models for spillage

The three-dimensional nature and complex geometry of the cutter head, combined with the difficulty of accurately quantifying spillage types, encumber CSD spillage modeling and validation. Additionally, observations from experiments and empirical models are subject to scaling difficulties. The mechanical excavation of the cutter scales according to Froude's number since inertial and gravitational forces are governing. However, the suction mouth process is characterised by dominant inertial and viscous forces, rendering Reynolds scaling most appropriate. When gravity and viscosity dominate, the model becomes highly sensitive to the viscosity and density (Slotta, 1978).

Empirical models

Industry practices commonly estimate spillage by linearly scaling the total amount of fines subject to dislodgement by an empirically-derived coefficient as evidenced by equation (1) (Becker et al., 2014). This expression presumes that a certain fraction of fines is representative or in its entirety responsible for spillage due to centrifugal advection.

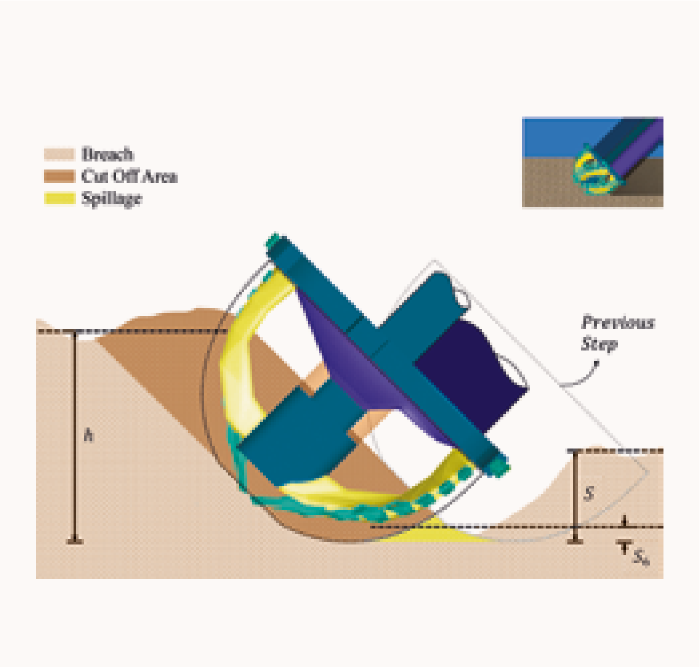


FIGURE 6

Spillage due to cutter geometry and step size.

$$m_{eq} = \sigma_{eq}\rho_d V_{situ} f_{<63\mu m}$$

(1)

Where m_{eq} is the total cutter head related mass of fines (dry solids) brought into suspension [kg], σ_{eq} is an empirical source term fraction associated with cutter head spillage [-], ρ_d is the dry solids density [kg/m^3], V_{situ} is the in situ dredge volume [m^3] and $f_{<63\mu m}$ is the fraction of fines smaller than 63 μm [-]. The fraction of fines during the dredge operation may increase due to degradation (Ngan-Tillard et al, 2009). Empirical source term fractions are typically proprietary data.

Regression analyses

Joanknecht (1976) found empirical relations for dimensionless similitude criteria obtained from experimental data for a cylindrical cutter head. It was observed that Froude scaling complemented with the ratio of the terminal velocity and the mixture velocity v_m [m/s] resulted in appropriate scaling. The experiments indicated that over-cutting spillage was positively correlated with the ratio of the swing velocity v_s and the tangential velocity of the blade tip, whereas under-cutting spillage remained insensitive to this ratio.

Slotta (1978) utilised the Buckingham Π theorem to find empirical relations with the Euler, Reynolds and Froude numbers, a diameter ratio and a ratio of the rotational velocity and the mixture velocity. Experimental data indicated that Reynolds scaling should be applied for the suction inlet.

Hayes (1986) performed a linear regression study for dimensionless variable groups obtained from observed suspended sediment concentrations resulting from CSD operations at Calumet harbour (Hayes et al., 1988). Collins (1995) expanded this dataset with three field operations and two experimental studies and performed a similar linear regression. The improved empirical model could, however, 'not explain suspended sediment variations very well' (Hayes et al., 2000). Earlier research by Andrassy et al. (1988) in which CSD operation parameters were used in a correlation study for a similar dataset, was unable to identify statistically significant relationships.

Hayes et al. (2000) performed a dimensional criteria study to support a dimensionless regression analysis based on the Buckingham Π theorem to find spillage correlations. The '106 observation data set used in this study represents a too limited range of operating parameters to generate model applicable to a wider variety of conditions', however reasonable accuracy was obtained for spillage data. Additional validation is needed to substantiate the model.

Experimental and numerical findings

A joint research effort from a group of Dutch contractors united under the name Combinatie Speurwerk Baggertechniek (CSB), Ministerial Agency of Public Works Rijkswaterstaat and research institute WL|Delft Hydraulics conducted a series of experiments to gain a better understanding of the internal flows in and around the cutter. As summarised by Den Burger (2003), the experimental results indicate that the cutter head resembles a combination of an axial pump as well as a centrifugal pump. A numerical model based on Unsteady Reynolds Averaged Navier Stokes equations by Nieuwboer et al. (2017) supports the conclusion that flow patterns can be associated with centrifugal and axial pump effects. Moreover, the model indicates that 'water movement caused by the passing of the blades does accelerate the particles outward' with spillage as a consequence.

The mixture velocity was varied in the experiments at WL|Delft Hydraulics. Depending on the mixture velocity, a transition value was observed for the rotational velocity. The data showed that there is an inward flow along the entire contour of the cutter head for rotational velocities below the transition value. However, above this threshold an outwards flow near the back plate was observed that increased with rotational velocity. This outward flow contains suspended particles which may not re-enter the cutter head. Figure 7 schematically depicts the flow that is generated by these pump effects as well as the location along the contour line of the cutter head where inflow reverses to outflow.

Particle trajectories in the under-cut and over-cut situation appeared very different. However, for both situations they appeared insensitive to variations of the rotational velocity and mixture velocity. Also, the ratio of the transition value for the rotational velocity and the mixture velocity appeared relatively constant and identical for the under-cut and over-cut situation. Den Burger describes that the rotational velocity and mixture velocity do influence the magnitude of the velocities in both situations as was found by Moret (1977a).

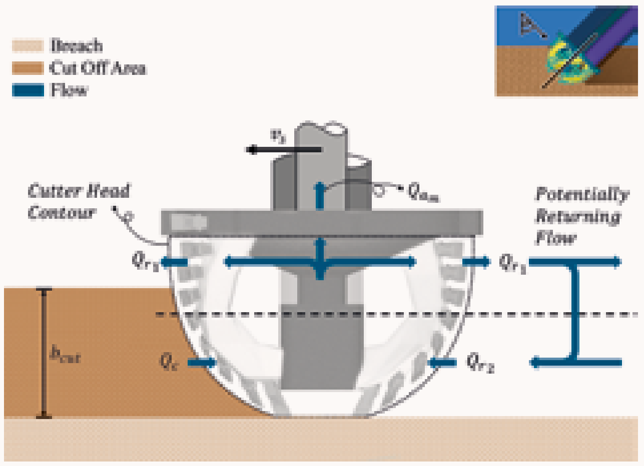


FIGURE 7

Simplified representation of flow pattern in and around the cutter from a top perspective.

Model development

Miedema (2017) and Nieuwboer (2018) conceptualised a analytical model based on the observations by Den Burger (2003) and Nieuwboer et al. (2017). In this article, a heavily simplified preliminary model is presented in which only spillage due to centrifugal advection is considered (S_1). A virtual radial discharge impeller is hypothesised in the cutter head. The impellers simulate the influence of the rotation of the cutter head on the hydraulic transport inside the cutter head. It is assumed that the cutter head contains infinitely many virtual impeller blades with infinitesimally small blade thicknesses. The impellers are presumed geometrically similar and operated at dynamically similar conditions.

Similarity of flow

Let us consider flow similitude for a centrifugal pump, i.e. the ratio of the average fluid velocity c [m/s] and the tangential impeller velocity u [m/s] equals a constant dimensionless flow number:

$$\frac{c}{u} = \Phi$$

(2)

Where Φ represents the flow number [-]. The average fluid velocity exits the pump over an area equal to the circumference of the pump, multiplied by the impeller width and limited by a factor f_γ [-] that accounts for limitations to the outflow area, i.e. $f_\gamma \pi Db$. Assuming incompressible flow and flow equilibrium, the fluid velocity inside the volute chamber follows from volume continuity and reads:

$$c = \frac{Q}{f_\gamma \pi Db}$$

(3)

Where Q is the pump discharge [m^3/s], D is the pump diameter [m] and b the impeller width [m]. The tangential velocity of the impeller is found through multiplication of the angular velocity ω [rad/s] and the cutter radius [m] ($u=\omega D/2$). Substitution of the velocity ratio in equation (2) and subsequent reordering yields an expression for the discharge as a function of the angular velocity as evidenced in equation (4).

$$Q = \Phi\frac{\pi}{4} f_\gamma b\omega D^2 = \hat{\Phi} f_\gamma b\omega D^2$$

(4)

Where $\hat{\Phi}$ is an adapted flow number [-]. Physically, the coefficient $\hat{\Phi}$ can be considered a dimensionless ratio of the velocity components in the tangential direction and the radial direction. The fluid viscosity is captured by this dimensionless measure.

Centrifugal pump pressure

Simulating a pump effect for the cutter head requires an expression for the force that is exerted by the fluid on the hypothetical volute chamber. This centrifugal force for a rotating mass is given in equation (5).

$$F_{cf} = 2\Psi\frac{mu^2}{D}$$

(5)

Where m is the fluid mass ($\rho\pi/4D^2b$) inside the cutter [kg] and Ψ is a coefficient that scales the centroid of the fluid mass [-], commonly referred to as the dimensionless head. The meridional exit area A [m^2] of the virtual volute chamber equals πDb, hence the internal pressure p^- [Pa] that is exerted on the volute chamber can be found by again substituting $u=\omega D/2$

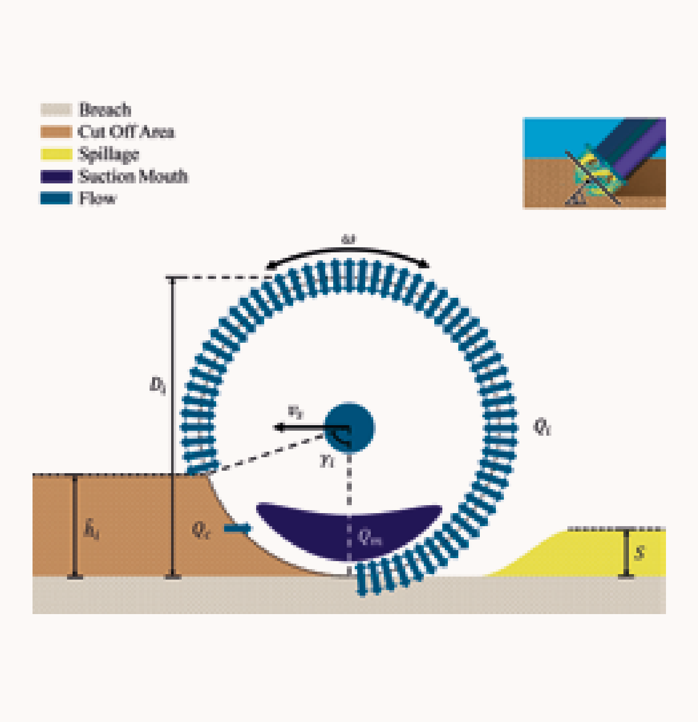


FIGURE 8

Simplified representation of flow pattern in and around the cutter from a front perspective.

$$p^- = \frac{1}{8}\Psi\rho\omega^2 D^2 = \hat{\Psi}\rho\omega^2 D^2$$

(6)

Expressions (4) and (6) can be combined in order to find the volumetric flow rate induced by the angular velocity of the supposed centrifugal effect, and rewritten, to find the induced pressure as a function of the angular velocity:

$$Q = \frac{\hat{\Phi} f_\gamma}{\hat{\Psi}}\frac{p^- b}{\rho\omega} \Leftrightarrow p^- = \frac{\hat{\Psi}}{\hat{\Phi} f_\gamma}\frac{\rho\omega Q}{b}$$

(7)

Distinguishing flow terms

For this preliminary model, a series of assumptions is made. First, water is taken incompressible and fluid densities are considered equal for all flow terms. Second, hydraulic transport through the bank is neglected. Third, the open cutter head is considered a control volume and is divided into segment (disc) 1 and 2, with the latter closest to the bank. The interface between these segments is located at the cutter diameter where inflow reverses to outflow (see Figure 7). An outflow Q_1 [m³/s] at segment 1 may (partially) return inside the control volume at segment 2, where an inflow Q_2 [m³/s] is considered.

The volumetric flow rate for the dislodged bank material into the cutter is Q_c [m³/s] and an independent volumetric flow rate Q_m [m³/s] represents the flow withdrawn by the suction mouth. Inflows into the control volume will have a positive contribution and outflows have a negative contribution. The volume balance equation for the control volume reads:

$$Q_c - Q_m - Q_1 + Q_2 = 0$$

(8)

Figure 8 schematically represents the flow pattern as found by Den Burger (2003) and Nieuwboer (2017) with the given volumetric flow rates as viewed from above (A) and in front (B).

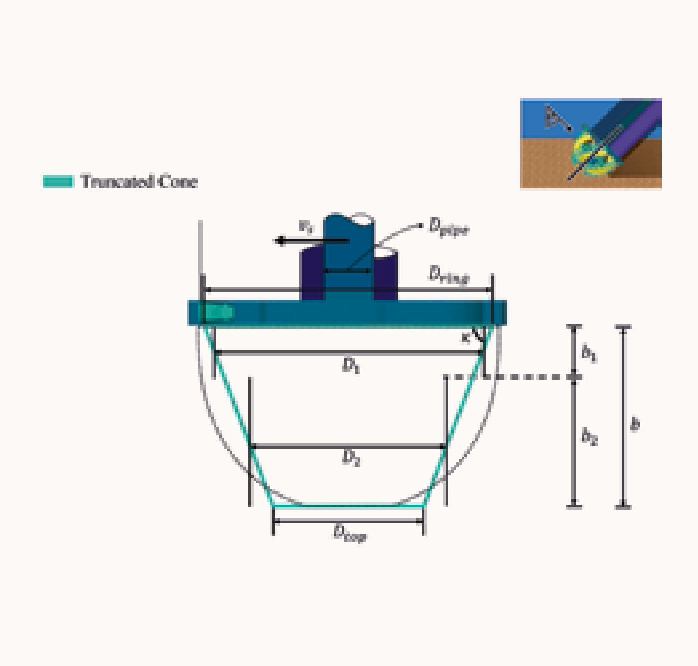


FIGURE 9

Simplification of the cutter geometry.

Cutter geometry

In order to describe the flows in this model, the control volume is heavily simplified by reducing the cutter head geometry to a segmented cylinder geometry as proposed by Louis (2017). First, the geometry is reduced to a truncated cone shape. Next, the cylinder diameters are found through linear interpolation within the truncated cone. These diameters are representative for the flow through the full heights b_1 [m] and b_2 [m] of the respective segments of the cutter as depicted in Figure 9 and expressed in equations (9) and (10).

$$D_1 = D_{ring} - \frac{b_1}{2\,tan\,\kappa}$$

(9)

$$D_2 = D_{top} - \frac{b - b_1}{2\,tan\,\kappa}$$

(10)

Where D_1 is the average diameter of segment 1 [m], D_2 is the average diameter of segment 2 [m], D_{ring} is the diameter of the cutter ring [m], D_{top} is the diameter of the cutter top [m] and κ represents the angle between the truncated cone and the cutter ring [deg].

Bank geometry

For simplicity purposes, the cutter head is considered penetrated in the bank under an angle λ [deg] of 45 degrees into an inclined bank angle of 45 degrees. In reality, this is highly uncommon since the high suction mouth placement induces rapid redeposition. Figure 10 depicts the cutter placement for this model.

The cut off area of the bank A_{cut} [m²] is related to the placement of the cutter and can be mapped onto the segmented cutter head shape by introducing the effective bank height (slope length) $\hat{h}$ [m], i.e. the height of the bank in the coordinate system of the cutter. Choosing a lower bank height h [m] and thus effective bank height allows for the distribution of cut face towards segment 1 of the simplified shape. It is assumed that the tip of the simplified cutter geometry can be identified as the lower end of the effective bank height of segment 2 $\hat{h}_2$ [m].

As depicted in Figure 8B, the angle γ_i [rad] associated with the intersecting circumference of the cutter and the bank geometry can be expressed as a function of the cutter diameter and effective bank height as evidenced in equation (11). Note that this equation is only valid when the bank and ladder angle are equal and for $\hat{h}_1 \leq D_i/2$. Additional geometry formulations are required for larger bank heights.

$$\hat{h}_i = \frac{D_i}{2}(1 - cos\,\gamma_i) \Leftrightarrow \gamma_i = cos^{-1}\left(1 - \frac{2\hat{h}_i}{D_i}\right)$$

(11)

Discretisation of the cutter head requires a geometry criterion to determine segment contributions to the cut face. Equation (12) relates a linearised estimation of the cut depth to the cut off area.

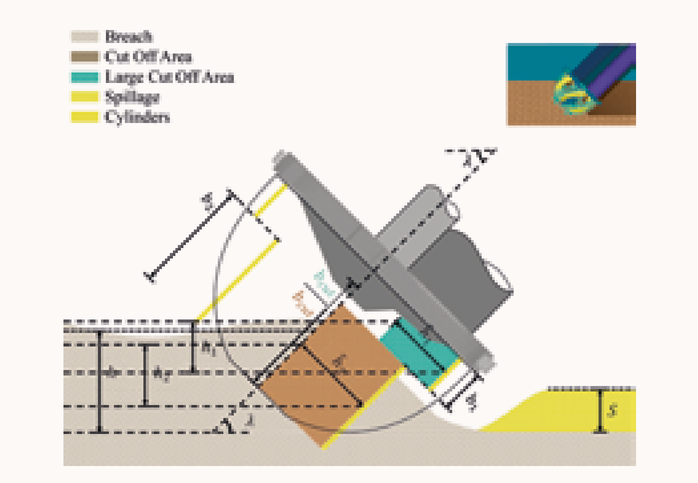


FIGURE 10

Schematic visualisation of the relation between bank height and effective bank height (b).

$$b_{cut} = \frac{A_{cut}}{\hat{h}}$$

(12)

Where b_{cut} is an estimate for the depth of the cut for the given bank-cutter interaction [m]. Consequently, a sequence of geometry expressions allow for the computation of the parameters relevant to the cutting contributions of segment 1 and 2 for any given D_1 and D_2 as outlined in equation (13) and (14).

$$\widehat{h_2} = \begin{cases} \frac{A_{cut}}{b_2}, & b_{cut} < b_2 \\ \hat{h}, & b_{cut} \geq b_2 \end{cases}$$

(13)

$$\widehat{h_1} = \begin{cases} 0, & b_{cut} < b_2 \\ \frac{A_{cut} - \widehat{h_2} b_2}{b_1}, & b_{cut} \geq b_2 \end{cases}$$

(14)

Where $\hat{h}_1$ is de effective bank height of segment 1 [m]. Since flows through soil are neglected, the active flow contribution areas of segment 1 and 2 are found using the bank contact angle γ_i [rad] (see Figure 8B). The bank contact angle is used to determine the dimensionless factor f_γ [-] that was introduced to account for the free flow factor of the impeller exit area presented in equation (3).

$$f_{\gamma_i} = 1 - \frac{\gamma_i}{2\pi}$$

(15)

Fundamental pressure assumption

The pressures p_1^- and p_2^- on exerted on the virtual volute chambers of segment 1 and segment 2 [Pa] can be found using equation (7). The adapted dimensionless coefficients are considered equal for both segments by assuming dynamic similarity of flow, i.e. Reynolds number scaling. Note that these pressures p_1^- and p_2^- as given below are denoted as negative due to their corresponding velocity directing outwards of the control volume.

$$p_1^- = \frac{\hat{\Psi}}{\hat{\Phi} f_{\gamma_1}} \frac{\rho \omega Q_1}{b_1}$$

(16)

$$p_2^- = \frac{\hat{\Psi}}{\hat{\Phi} f_{\gamma_2}} \frac{\rho \omega Q_2}{b_2}$$

(17)

In a realistic two-dimensional situation, as depicted in Figure 11A, the pressure p_1^-(navy) and p_2^-(teal) along the segmented control volume are expected to drop quadratically upon further propagation into the surrounding environment of the cutter. In this analytical model, the interaction of the pressures outside the control volume is heavily simplified as depicted in Figure 11B.

Miedema (2017) proposes a fundamental pressure assumption for the contour of segment 2 by relating the potentially returning flow from segment 1 to the pressure outside of segment 2. It is assumed that the pressure that is generated by the centrifugal pump in segment 1 remains constant over a wide area beyond the control volume, including at the boundary of segment 2. The external propagation of the pressure that is generated internally at segment 2 is neglected outside of the control volume. Consequently, the pressure p_2^+ [Pa] at the contour of segment 2 is taken as:

$$p_2^+ = p_2^+ = p_1^-$$

(18)

Justification

Justification of the fundamental assumption of a uniform pressure contour centered around the boundary of segment 1 is subject to discussion. It can be argued that the square relation between the pressure and the segment diameter allows for a significantly larger pressure generation at segment 1, rendering the generated pressure at section 2 negligible. Second, in reality the dimensionless coefficient $\hat{\Psi}_i$ from equations (16) and (17) will be higher for segment 2 due to the fact that larger impellers are more efficient. This supports the assumption that p_1^- is significantly larger than p_2^-.

The fundamental pressure assumption can be undermined upon realisation that the pressures in segment 1 and 2 are generated with different densities. The density of the inflow Q_2 would be smaller than that of Q_1 due to the fact that the suspended sediment is larger inside the control volume and particles may not re-enter the cutter head. Since p_1^+ will be generated with a higher density, the lower density of the inflow at section 2 affects the assumed propagation of pressure from segment 1. Additionally, the pressure at segment 1 acts on the full circumference of the segment, whereas equation (15) indicates that the acting pressure at segment 2 is limited by a relatively larger bank contact area ($f_{\gamma 2} > f_{\gamma 1}$). The assumption should be substantiated with further research but can be used for a preliminary model.

Derivation of volumetric flow rates

The volumetric flow rate at segment 1 can be found using the discharge-pressure relationships of equation (7). Since this model assumes outflow at segment 1, the vicinity of segment 1 to the suction mouth requires a flow condition that guarantees positive or zero flow despite the suction pressure generated by the suction inlet.

$$Q_1 = \begin{cases} \frac{\hat{\Phi} f_{\gamma_1}}{\hat{\Psi}} \frac{p_1^- b_1}{\rho \omega}, & Q_1 \geq 0 \\ 0, & Q_1 < 0 \end{cases}$$

(19)

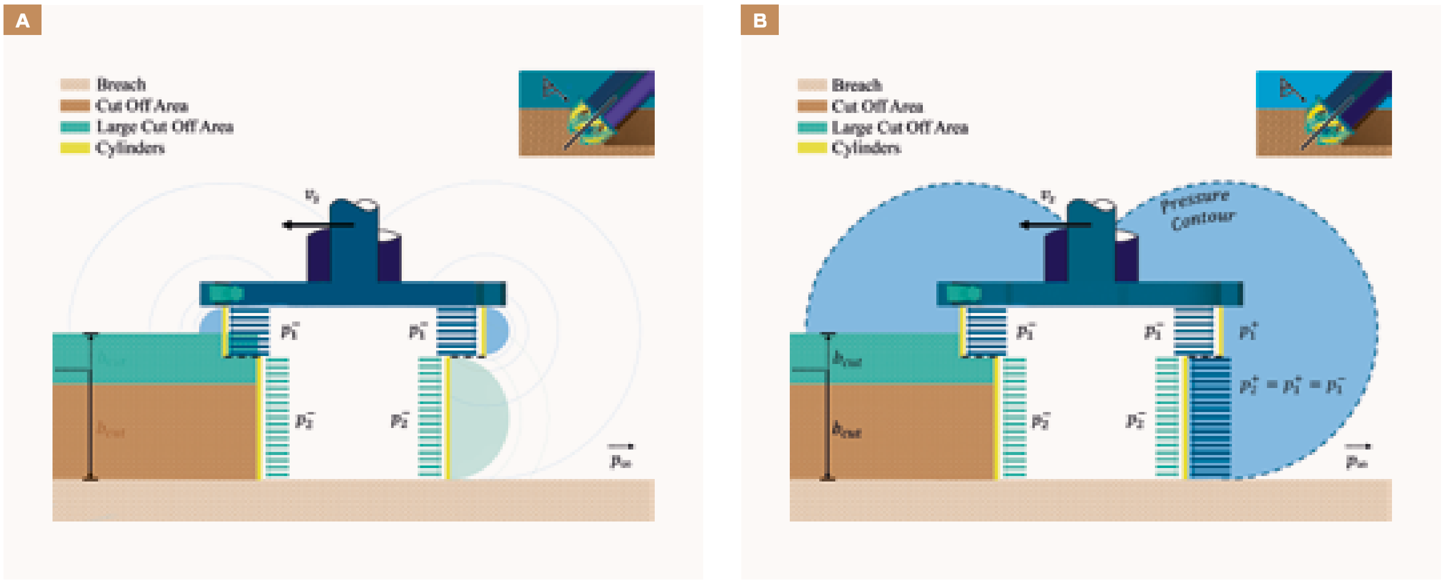


FIGURE 11

Expected external pressure contours (A) and pressure contours according to Miedema (B).

Flow circulation

The volumetric flow rate found in equation (19) can be adapted to find an expression for the specific flow rate q_i per unit height of the cutter [m^2/s]. Implicitly, a function for the difference in specific flow rate can be found as a function of the pressure gradient as specified in the latter expression of equation (20).

$$q_i = \frac{\hat{\Phi} f_{\gamma_i}}{\hat{\Psi}} \frac{p_i}{\rho\omega} \Rightarrow \Delta q_i = \frac{\hat{\Phi} f_{\gamma_i}}{\hat{\Psi}} \frac{\Delta p_i}{\rho\omega}$$

(20)

With $p_2^+ = p_1^+ = p_1^-$ from equation (18), the resulting pressure gradient over the boundary of segment 2 reads:

$$\Delta p_2 = p_2^+ - p_2^- = p_1^- - p_2^-$$

(21)

Substitution of equation (21) in equation (20) results in an expression for Q_2 as evidenced in equation (22).

$$Q_2 = \Delta q_2 b_2 = \frac{\hat{\Phi} f_{\gamma_2}}{\hat{\Psi}} \frac{\Delta p_2}{\rho\omega} b_2 = (p_1^- - p_2^-) \frac{\hat{\Phi} f_{\gamma_2}}{\hat{\Psi}} \frac{b_2}{\rho\omega}$$

(22)

In situ dredge flow rate

The in- and outflow of water at the cutter head due to the swing velocity v_s [m/s] is considered negligible. Finding an expression for the volumetric flow rate of the suspended sediment Q_c involves determining the flow of sediment that enters the control volume as the cut off area A_{cut} moves through the bank with velocity v_s. The in situ dredge flow rate is approximated by:

$$Q_c = A_{cut} v_s$$

(23)

Production (mixture) flow rate

The volumetric flow rate of the entrained flow Q_m is subject to variations of the suction inlet velocity and is easily found as:

$$Q_m = \pi R_{pipe}^2 v_m$$

(24)

Where R_{pipe} is the radius of the suction pipe [m] and v_m the mixture velocity through the suction pipe [m/s]. Figure 12 provides an overview of the volumetric flow rates.

Derivation of segment heights

Substitution of equation (19) and (22) in equation (8) results in an equation for the volumetric flow rate given as:

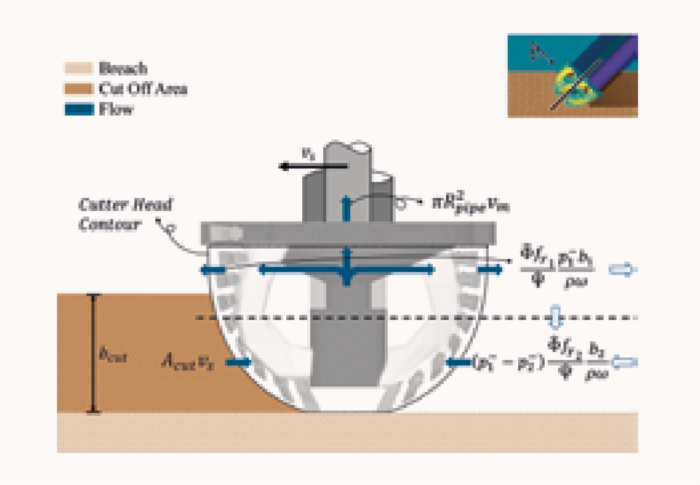


FIGURE 12

Final expressions for volumetric flow rates in the cutter control volume.

$$Q_c - Q_m - \frac{\hat{\Phi} f_{\gamma_1}}{\hat{\Psi}} \frac{p_1^- b_1}{\rho\omega} + (p_1^- - p_2^-) \frac{\hat{\Phi} f_{\gamma_2}}{\hat{\Psi}} \frac{b_2}{\rho\omega} = 0$$

(25)

The objective is to find the location on the contour line where the flow reverses from inflow to outflow, i.e. the magnitude of the ratio between of b_1 and b_2. Equation (25) can be substituted with $b_2 = b - b_1$ as well as $p_1^- = \hat{\Psi}\rho\omega^2 D_i^2$ from equation (16) and (17). Subsequent isolation of on the left-hand side yields:

$$b_1 = \frac{f_{\gamma_2} f_D b + \frac{1}{\hat{\Phi}} \frac{1}{\omega D_1^2} (Q_c - Q_m)}{f_{\gamma_1} + f_{\gamma_2} f_D}$$

(26)

Where $f_D = (D_1^2 - D_2^2)/D_1^2$ [-]. Finally, equation (26) is substituted with Q_c and Q_m as found in equation (23) and (24) respectively to yield an expression for b_1 that is based on geometric and dimensional operational parameters as well as the dimensionless number $\hat{\Phi}$. Since the segment height cannot be rendered negative due to the volumetric flow rate Q_1, a requirement is set so that $b_1 > 0$. The expression for the height of segment 1 is given in equation (27). It can be concluded that this model suggests an increase in swing speed promotes spillage, whereas an increase in mixture velocity reduces spillage.

$$b_1 = \begin{cases} \dfrac{\hat{\Phi} f_{\gamma_2} (D_1^2 - D_2^2) b\omega + A_{cut} v_s - \pi R_{pipe}^2 v_m}{\hat{\Phi} \left(f_{\gamma_1} + f_{\gamma_2} \right) D_1^2 \omega - \hat{\Phi} f_{\gamma_2} D_2^2 \omega}, & b_1 \geq 0 \\ 0, & b_1 < 0 \end{cases}$$

(27)

Iterative solution

The diameters from equation (27) use expressions for the cutter diameters as described in equation (9) and (10). This is an implicit problem due to the interdependency of the diameters D_1 and D_2 and heights b_1 and b_2 respectively. The solution is found through iteration of b_1 by making use of a threshold value for accuracy. A solution approach is given in Figure 13.

FIGURE 13

Example script for computation of with references to equation numbers in parentheses.

```
Find $A$ from data
Determine $h$
Compute $\hat{h} = h \sin(90 - \lambda)$
Compute $b_{cut}$                                Eq. (12)
Set convergence coefficient $relax$
Set accuracy coefficient
Estimate $\hat{b}_1$
While $error > threshold$
    $\hat{b}_2 = b - \hat{b}_1$
    Compute $D_1$ and $D_2$                      Eq. (9) and (10)
    Compute $\hat{h}_1$ and $\hat{h}_2$          Eq. (13) and (14)
    Compute $\gamma_1$ and $\gamma_1$            Eq. (11)
    Compute $f_{\gamma 1}$ and $f_{\gamma 2}$    Eq. (15)
    Compute $b_1$                                Eq. (27)
    $error = | b_1 - \hat{b}_1 |$
    $\hat{b}_1 = \hat{b}_1 (1 - relax) + b_1 (relax)$
End
```

Adding suspended sediment

Spillage can be found through the addition of suspended sediment to the obtained volumetric flow rates. It was assumed that the densities of the flow terms are equal. To obtain a representation of spilled sediment, the flow terms are retrospectively complemented with a concentration measure c_i for the amount of suspended solids per unit volume [-]. Caution with the model results should be observed since the actual effect of suspended solids on flow density is neglected in this preliminary model.

It is assumed that hydraulic transport is homogeneous in concentration within segment 1, i.e. $c_m = c_1$ with c_1 being the concentration of the hydraulic transport exiting the cutter head at segment 1 [-] and c_m being the concentration of the suction flow that is sucked up to the vessel [-]. A concentration c_c of the volumetric flow rate of the cut flow is considered [-] as well as a concentration c_2 for the volumetric flow rate Q_2 [-] which is assumed zero. This assumption neglects the effect of suspended particles recirculating from segment 2 to segment 1.

As a consequence, the considered mass flow rate balance reduces to equation (28) from which the concentration c_1 directly follows. The outflow concentration should not exceed the inflow concentration, hence a condition is added in equation (29) to maintain sensible results.

$$Q_c c_c - c_1 Q_m - c_1 Q_1 = 0$$

(28)

$$c_1 = \begin{cases} \dfrac{Q_c c_c}{Q_1 + Q_m}, & c_1 < c_c \\ c_c, & c_1 \geq c_c \end{cases}$$

(29)

Spillage due to centrifugal advection S_1 [-] can be found by computing:

$$S_1 = \frac{c_1 Q_1}{c_c Q_c}$$

(30)

Which concludes a parameterised analytical model for the determination of high rotational velocity-induced spillage in which the pressure-discharge relationships are based on adapted pump affinity laws.

Model calibration

Supported by experiments, Den Burger (2003) found that particle trajectories in a CSD are governed by the centrifugal force F_{cf} in the cutter [N], the gravitational force F_g [N] and the product of the particle volume and hydrodynamic pressure gradient in the suction mouth F_s [N]. The ratio of these terms provide a convenient alternative to known dimensionless scaling coefficients. Since this model focuses on centrifugal advection rather than rapid redeposition, the presumed governing spillage number is taken as the ratio of centrifugal force and the product of the particle volume and pressure gradient, i.e:

$$\frac{F_{cf}}{F_s} \propto \frac{\rho_p}{\rho_w}\left(\frac{\omega R_{ring}^3}{v_m R_{pipe}^2}\right)^2$$

(31)

Where ρ_p is the particle density [kg/m³], ρ_w is the water density [kg/m³], R_{ring} and R_{pipe} are the cutter ring and pipe radii [m]. In earlier work by Steinbusch et al. (1999) and Dekker et al. (2003) the inverse term of the expression between brackets in equation (31) was identified as a characteristic flow number for the ratio of the cutter-induced velocity and the suction velocity.

Adapted Flow Number

An adapted flow number, $\hat{\theta} = \theta^{-1}$ [-], was specifically deterministic for sand cutting as evidenced in analyses of experimental data from Mol (1977a) and Miltenburg (1983) by Den Burger. Moreover, this number was proven effective in the validation of a model for flow velocities in a cutter head as evidenced by results from Nieuwboer et al. (2017). Calibration is chosen to be performed using this adapted flow number, defined as:

$$\hat{\theta} = \theta^{-1} = \frac{\omega R_{ring}^3}{Q_p}$$

(32)

For calibration of the model, a dataset by Den Burger (2003) is used that contains production rates corresponding to adapted flow numbers for sand and rock. Data for rock were obtained through experiments with gravel and scaled. An overview of parameters relevant to experiment data is given in Table 1.

It should be noted that the cutter inclination angle is non-typical for dredge operations since that would place the bottom of the suction mouth high relative to the bank. Therefore, calibration is hindered as alternative spillage sources are expected as well.

Den Burger (2003) used the adapted flow number to perform a polynomial regression (n=2) to obtain the general trend for the production ratio η [%] with respect to the velocity ratio $\hat{\theta}$ for an under-cut scenario. Experiments suggested that for over-cutting 'the trend of the production curve has changed' and requires further research. The preliminary model does not differentiate with respect to under- and over-cutting, but is calibrated on the under-cut experiments from Den Burger. Calibration is performed by finding a value for $\hat{\Phi}$ for which spillage as a function of the velocity ratio follows the spillage curves from Miltenburg and Den Burger as found through $S_1 = 100 - \eta$ [%]. According to Nieuwboer et. al (2017), the dimensionless adapted flow numbers in the dredging industry have typical values between 1.6 and 3.7.

TABLE 1

Experiment parameters for Miltenburg (1983) and Den Burger (2003). [1]Particle diameter is presumed 'similar to practice'. [2] Estimation for segmented values of the model. [3] Estimated value. [4] Only rock density given.

		Sand (Miltenburg, 1983)		**Rock (Den Burger, 2003)**		
Property	**Symbol**	*Prototype*	*Experiment*	*Prototype*	*Experiment*	**Units**
Particle diameter	d_{50}	180E-3[1]	180E-3	80	10	mm
Bed concentration	c_c	0.4	0.4	0.42	0.42	-
Particle density	ρ_p	2650	2650	2200[4]	2650	Kg/m³
Bulk density (wet)	$(\rho_{b,wet})$	2000	2000	2200[4]	2058	Kg/m³
Diameter of the cutter ring	D_{ring}	2.80	0.40	3.12	0.4	m
Diameter of the cutter top	D_{top}	2.11[2]	0.18	2.11[2]	0.28	m
Diameter of the suction pipe	D_{pipe}	0.7	0.1	0.95	0.1	m
Height of the cutter head	b	2.5[2]	0.265	2.50[2]	0.265	m
Swing velocity	v_s	0.2	0.1	0.2	0.1	m/s
Cut off area	A	1.4[3]	0.023[2]	1.4[3]	0.03	m²
Bank angle	ρ	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$	rad
Cutter inclination angle	$\hat{\rho}$	45	45	45	45	deg
Rotational velocity	ω	π	$10/3\,\pi$	π	3π	rad/s
Cutting scenario	-	under-cut	under-cut	under-cut	under-cut	-

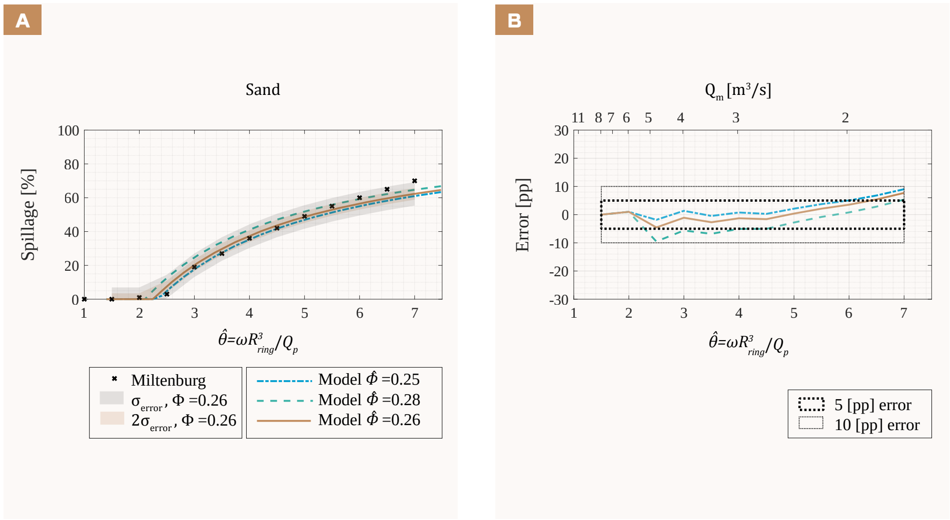


FIGURE 14

Spillage percentage (A) and error [percentage point] (B) vs. adapted flow number $\hat{\theta}$ for sand. Calibration data from Miltenburg (1983), interpreted by Den Burger (2003). In (B) Q_m [m³/s] is given for a 3.12 [m] cutter head rotating at 30 [rpm].

Results for sand

Figure 14 displays the model results for a comparison to sand data from Miltenburg (1983). In Figure 14A, the experimental data and model results (spillage percentage) of three values for $\hat{\Phi}$ are plotted against the adapted flow number $\hat{\theta}$. Figure 14B displays the error for the plotted models [percentage point] as a function of $\hat{\theta}$ as well as the volumetric flow rate Q_m. The mixture flow is found using a typical estimate of 30 revolutions per minute for a large [m] diameter cutter head. Note that in this article, $\hat{\Phi}$ refers to the dimensionless ratio of the velocity components in the tangential direction and the radial direction and approximates the centrifugal pump effect.

For $\hat{\Phi} = 0.26$, the model curve as well as the standard deviation σ and double standard deviation 2σ of the deviation from the experimental data is plotted. The other plots represent estimates for a lower ($\hat{\Phi} = 0.25$) and upper ($\Phi = 0.28$) bound. The best approximation for $\hat{\Phi}$ was visually identified by searching for the minimum error within a typical $\hat{\theta}$ range of (1.6,3.7) corresponding to Q_m in the range of approximately (3.5,7.5) [m³/s]. For $\hat{\Phi} = 0.26$, the error steadily remains within the 5 [pp] bandwidth for the applicable interval. Furthermore, the shape of the model plot appears to resemble that of the experimental results accurately, i.e. the model is in good agreement with the experimental data.

Results for rock

The same estimation method and visualisation method was used to find the model parameter $\hat{\Phi}$ that corresponds best with scaled experimental data for gravel from Den Burger (2003) that are scaled to represent the cutting of rock. Figure 15 displays the model curves (A) and errors (B) with respect to the experimental data. For $\hat{\Phi} = 0.40$, reasonable model accuracy can be observed for Q_m values of approximately (4,6) [m³/s]. Low volumetric flow rates in the range of (2.5,4) [m³/s] for the suction flow are best represented by the model with $\hat{\Phi} = 0.54$ since the errors fall within the 10 percentage point bandwidth. However, the model curve does not follow the experimental data well.

For higher numbers of the velocity ratio, it can be observed that the spillage ratio is consistently underestimated for rock. This can be explained in a number of ways. First, the calibration data includes other spillage sources of which rapid redeposition may be most pronounced for rock. Second, the deviation suggests that the model is not capable of capturing the full centrifugal effect on larger suspended particles. Equation (31) can be used to demonstrate that observations suggest a quadratic relationship between particle withdrawal and angular velocity, whereas the spillage contribution width of b_1 equation (27) only scales linearly with angular velocity. Last, it is stressed that further research is required to verify the series of assumptions in the model and how larger particles are particularly affected.

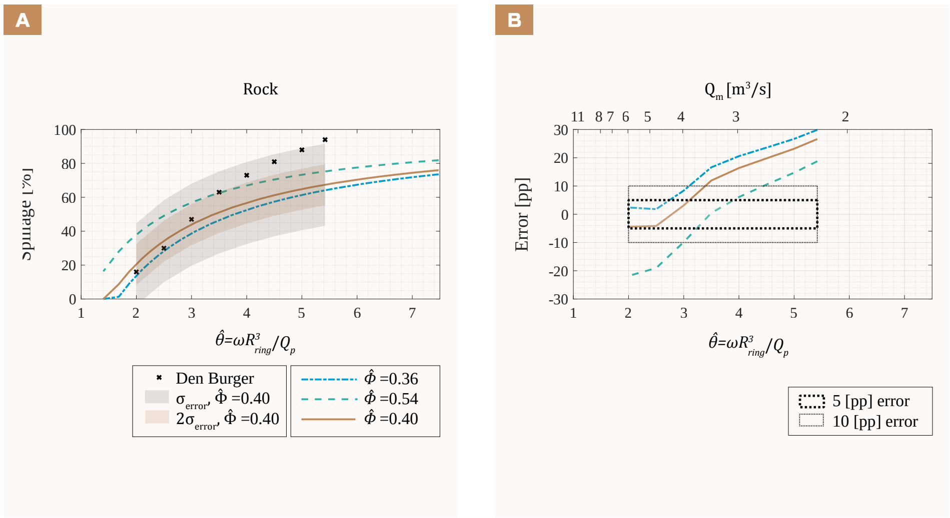


FIGURE 15

Spillage percentage (A) and error [percentage point] (B) vs. adapted flow number $\hat{\theta}$ for rock (scaled gravel). Calibration data from Den Burger (2003). In (B), Q_m [m3/s] is given for a 3.12 [m] cutter head rotating at 30 [rpm].

Conclusions

An adaptation of a dimensionless velocity ratio proposed by Steinbusch et al. (1999) and Dekker et al. (2003) is used as a governing number for model calibration using experimental data for sand from Miltenburg (1983) and rock from Den Burger (2003). Model parameters were identified for which sand spillage can be estimated within a 5 percentage point bandwidth of the experimental data. Moreover, the shape of the model plot appears to resemble that of the data for sand accurately, i.e. the model is a good tool for a priori spillage calculations. The model underestimates spillage rates for rock-sized particles except at relatively low cutter speeds or high mixture flow rates, suggesting that either centrifugal advection is not the main source of spillage or that the model does not capture the centrifugal pump effect well for larger particle diameters.

The most fundamental assumption in the model is the concept that the pressure outside the cutter is uniform and equal to the pressure generated near the cutter ring in segment 1. Furthermore, the model assumes a volumetric flow rate balance with equal densities for all flow terms. Currently, only two cutter head segments are considered. Improvement of the model can be achieved by incorporating flow density differences and further discretisation of the cutter head. In combination with a further specification of the pressure gradient along the cutter contour, a highly discretised cutter with differentiated diameters will probably yield most accurate results. However, a reliable estimate of the pressure gradient used in this pseudo-analytical model can only be obtained through more elaborate research methods such as experiments as well as advanced computational fluid dynamics.

The model calibration is based on a single cutter geometry as well as a single set of operational and hydrological parameters. The influence of other spillage sources that may contribute concurrently is neglected in the calibration. In order to substantiate the model, the model production curves should be calibrated with a wider variety of geometrical and operational parameters from different case studies. Further detailing of the model parameters is recommended.

Summary

Depending on its size and installed power, a Cutter Suction Dredger (CSD) is capable of cutting a wide range of soil types from silts and clays to fractured or solid rocks. Its high precision allows for utilisation in a variety of dredge operations including navigational channel deepening, port construction and pipeline trenching. In spite of being considered relatively efficient, a CSD can spill significantly. This article proposes a classification of the concurrent sources of CSD spillage as well as a analytical model for a priori computation of spillage due to high rotational velocity-induced flow.

Den Burger (2003) and Nieuwboer et al. (2017) describe that the flow inside a cutter head borrows characteristics from that of within both a centrifugal and axial flow pump. Based on hypotheses by Miedema (2017) and Nieuwboer (2018), a preliminary model is established that uses measurable cutting variables, or a simplification thereof. In this model, the axial pump effect is not explicitly accounted for and the pressures exerted on the cutter head contour are heavily simplified. An adaptation of the flow number $\hat{\theta}$ for the ratio between centrifugal and mixture flow rates (Steinbusch et al., 1999; Dekker et al., 2003) is used for model calibration using experimental data for sand from Miltenburg (1983) and rock from Den Burger (2003). Model parameters were identified for which sand spillage can be estimated within a 5 percentage point accuracy for volumetric mixture flow rates in the range of (3.5,7.5) [m^3/s]. Moreover, the plot shape of the model appears to resemble that of the plot shape for sand closely, i.e. the model is in agreement with the experimental data. The preliminary model is not capable of accurately estimating rock spillage rates over a wide range of the adapted flow number. This inaccuracy may be ascribed to the concurrence of different spillage sources. Furthermore, the preliminary model may not entirely capture the centrifugal effect of the cutter head for larger grain sizes. Recommendations are given for further detailing.

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Jeroen obtained his Civil Engineering bachelor's degree at Delft University of Technology with a minor in quantitative economics from the University of Melbourne. The complex balances between engineering challenges and cost effectiveness are what led Jeroen to pursue a MSc in Offshore and Dredging Engineering. In 2015, he co-initiated Project Yogya, a student-run volunteer project in Indonesia that provided the Indonesian Ministry of Public Works with a feasibility and development assessment of the Yogyakarta harbor. His graduation research, commissioned by Great Lakes Dredge and Dock in Chicago, focuses on CSD spillage models.

Bas Nieuwboer

After his MSc in Hydraulic Engineering at Delft University of Technology, Bas accepted a PhD position at the Dredging Group in Delft. His work combines a numerical and experimental approach to describe spillage when cutting rock with cutter suction dredges. The experiments are designed to validate the numerical model. He therefore designed a simplified cutter to measure the fluid velocities and particle positions. For the model, he implemented a method for modelling big chips of rock in a rotating cutter using relatively coarse grids, allowing the model to simulate rock trajectories in the cutter with decent computation times.

Alden Louis

After obtaining his bachelor's degree in Mechanical Engineering, Alden acquired an MSc degree in Offshore and Dredging Engineering from Delft University of Technology in 2017. His graduation thesis involved cutter suction spillage at Great Lakes Dredge & Dock in Oak Brook, Illinois, USA. After graduating, he joined Royal IHC as a product engineer in the excavation equipment group. Within IHC, he is involved in the design of cutter heads and dredging wheel units.

Robert Ramsdell

Robert obtained his BA degree in Mathematics at the University of California at Berkeley in 1987. From 1989 through 1996 he worked for Great Lakes Dredge & Dock Company as Field Engineer, and Project Engineer on a variety of projects in the United States and internationally. In 1996 he joined the Great Lakes Dredge & Dock Production Department as a Production Engineer, becoming Director of Production Engineering Manager in 2005. In the department, Robert's focus has been on developing methods and software for estimating dredge production, recruiting and training Production Engineers, and developing methods to analyse and improve dredge operations.

Sape Miedema

Sape obtained his MSc in Mechanical Engineering with honours at the Delft University of Technology in 1983 and his PhD in 1987. From 1987 to the present he has been an assistant, then associate professor at the Chair of Dredging Technology, then as a member of the management board of Mechanical Engineering and Marine Technology. From 1996 to 2001 he was appointed head of studies of Mechanical Engineering and Marine Technology, whilst remaining associate professor of Dredging Engineering. In 2005, he was appointed head of studies of the MSc programme of Offshore & Dredging Engineering and Marine Technology.

Improvement of the model can be achieved by incorporating flow density differences and further discretisation of the cutter head.

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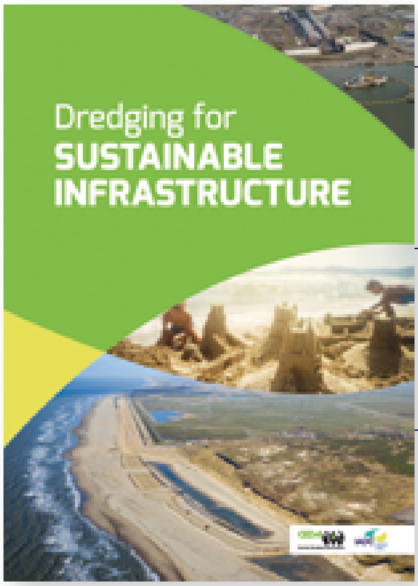
BOOK REVIEW

DREDGING FOR SUSTAINABLE INFRASTRUCTURE

This book's presented insights result from a wealth of knowledge pooled by a team of scientists and practicing industry experts which has been moderated by an Editorial Board comprised of CEDA and IADC representatives.

Project owners, regulators, consultants, designers and contractors looking for an up-to-date reference of solutions for designing, implementing and managing water infrastructure projects with a dredging component should find this guidebook to be an essential tool.



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With growing environmental awareness and increasing climate pressures on low-lying deltas, modern-day society puts incredibly strong demands on the sustainability of water infrastructure projects. Classic approaches towards the design and implementation of such projects no longer suffice in satisfying these demands.

Radically different methods are needed which demand multidisciplinary project teams to adopt entirely new ways of thinking, acting and interacting. Application of these new methods results in innovative water infrastructure solutions that meet the primary functional requirements while at the same time delivering added value for nature and society as an inherent part of project development.

Dredging for Sustainable Infrastructure promotes marine infrastructure projects with a dredging component, that full their primary functional requirement, while adding value to the (natural and socio-economic) system. Whether the project is a port development, river deepening, canalisation, flood defence measure or reclamation, this publication promotes the message that through a thorough understanding of these systems and with proactive engagement of stakeholders throughout a project's phases, a value-added project can be successfully achieved.

Implementation of water infrastructure involving dredging has traditionally been an essential activity in civilisation's development and prosperity. By excavating material from the sea, river or lake bed and its relocation elsewhere, dredging has an environmental impact. It has also been recognised as a useful tool for remedying historic environmental interferences, such as contaminated sediments resulting from industrial discharges. More recent approaches look beyond the scope of isolated dredging activities and embrace a wider context, considering water infrastructure development projects as an opportunity to also add value to the natural and socio-economic systems in order to achieve more sustainable projects.

The international dredging community has shifted from mainly dealing with negative impacts – often at the end of the project design and the start of the construction phase – towards a much more proactive approach where water infrastructure projects are being considered as part of the natural and socio-economic system in which they are situated, and stakeholders are being engaged much earlier in the project development process to facilitate the search for opportunities to create added value.

This change in attitude has a huge influence on the initiation, planning and design, execution and maintenance of water infrastructure projects. Comprehensive guidance on how to bring this into practice has been lacking. A wide range of professionals have attempted to collect and integrate their experiences and best practices to deliver this state-of-the-art guidance book.

Dredging for Sustainable Infrastructure aims to provide answers to the following questions:

- What is the role of dredging in the global drive for more sustainable development?
- How can we design more sustainable infrastructure that aligns with the natural and socio-economic system?
- How can we assess and stimulate the potential positive effects of infrastructure development and compare these with the potential negative effects?
- What equipment and which sediment management options do we have?
- What tools and information do we have to make choices and control the process?

Armed with the latest developments and a comprehensive analysis of the social, environmental and economic costs and benefits of a project, readers can ensure their projects are technically better, financially attractive and more acceptable to stakeholders. This book offers applicable background information, relevant examples and informative case studies to help understand the process. With evidence from finished projects, this book proves how the sustainability of water infrastructure projects is increased in practical terms by using dredging solutions. It shows how a proactive design can mean that the overall value of the project, in terms of the range of services it provides, can be increased, costs, both monetary and non-monetary (e.g. environmental impacts) can be reduced, and, how the three pillars of sustainability can expect a more balanced distribution of the value and costs of the project. A number of key projects realised over the last ten years show this.

The book is structured as a timeline of the design and execution of a dredging project while also allowing readers to go straight to the chapters or sections of direct interest

> **This change in attitude has a huge influence on the initiation, planning and design, execution and maintenance of water infrastructure projects.**

to them and be read independently. For a reader-friendly publication, terminology and technical language is consistent and simplified without losing meaning or technical content. Key topics which emerge during a marine infrastructure project are addressed including:

- Integrating dredging into sustainable development
- Sustainability in project initiation, planning and design
- Assessment and management of sustainability
- Equipment and methods
- Dredged material management
- Models and tools
- Monitoring and data

Chapter 2 describes the aim of the book and the principles of sustainability and their implications for a dredging project. Clear guidance is given on how to make sustainable outcomes happen. The aim is to create added value for the society in dredging and placement projects based on thorough understanding of the natural system, including hydrology, ecology, and morphology, nature-based solutions and proactive engagement of stakeholders. In the design phase, all the decisions and choices that influence the outcome and effects of a project will be taken and are outlined in Chapter 3, which also explains how to design the project while creating added value.

The dredging process and dredging machines are the focus of Chapter 5. It describes how dredging machines carry out their work, what effects this may have on the environment and how these effects may be mitigated or eliminated. After dredging, the material has to be managed. How this is done and the options available, for example, beneficial use, aquatic deposition and even, when needed, treatments are described in Chapter 6. It also details the positive and negative effects of these approaches. In Chapters 4, 5 and 6, the effects of the dredging are explained, and the models needed to determine these effects are outlined in Chapter 7. Monitoring plays an important role in the whole life cycle of a dredging project. Monitoring gives information regarding the present state of the environment of the project and if the changes are what is expected. The available tools and the conditions to use these tools are given in Chapter 8.

NETWORK TO EXCHANGE KNOWLEDGE

Meet international stakeholders involved in the many facets of marine infrastructure projects.

The Tenth International Conference on Remediation and Management of Contaminated Sediments

11-14 February 2019
Hilton New Orleans Riverside
New Orleans, Louisiana, USA
www.battelle.org/newsroom/conferences/sediments-conference

Battelle's Tenth International Conference on Remediation and Management of Contaminated Sediments settles in New Orleans for a four-day forum to share research results, practical experiences and opportunities dedicated to restoring the environmental and economic vitality of waterways. As many stakeholders are needed for the management of aquatic systems due to diverse environmental, economic, political and social aspects, this conference serves as a forum to discuss these complex issues. Opportunities for networking will be integrated into the programme to facilitate interaction.

A programme of 13 short courses, 43 technical sessions, 78 exhibitors and the introduction of 11 learning lab demonstrations will collectively reflect emerging issues and initiatives in sediments remediation and management and serve to expand upon the programme of 2017's conference. Previous conferences have had an international audience of scientists, engineers, regulators, remediation site owners and other environmental professionals representing universities, government agencies, consultants, and R&D and service firms.

WODCON XXII

22-26 April 2019
Shanghai International Convention Center
Shanghai, China
http://woda.org/wodcons/

A World Dredging Congress (WODCON) is organised by the World Organization of Dredging Associations every three years. Hosted by the Eastern Dredging Association (EADA) and the China Dredging Association (CHIDA), WODCON XXII is a five-day congress set to take place in Shanghai, a city which serves as China's financial, trade and shipping centre and is the leading city in the Yangtze River Economic Belt.

The congress's theme, Enhance the Harmony between Dredging and Ecology, aims to encourage harmonious development between dredging and natural ecology. Presentations will share successful dredging projects realised throughout the world as well as the results of dredging technology and equipment innovation. A visit to Yangshan Deepwater Port – the world's largest automated terminal and deep-water port – and China's dredging development achievements exhibition is part of the programme. Experts and members of the international and Chinese dredging industry will be in attendance.

WEDA Dredging Summit & Expo '19

4-7 June 2019
Hilton Chicago
Chicago, Illinois, USA
https://dredging-expo.com

Organised by the Western Dredging Association (WEDA), the Dredging Summit & Expo '19 is a technical conference which will descend on downtown Chicago. With a theme of Waves of Change: Oceans of Opportunity, topics will emphasise the importance of understanding and development of solutions for problems related to the protection and enhancement of the marine environment as well as improving communications, technology transfer, and cooperation among associations and societies. The annual three day forum will offer high quality presentations and an exhibition with over 90 exhibitors. A lively social programme with ice breakers, ice cream socials and gala dinners is planned.

Representing all facets of the dredging industry, attendees will convene and share knowledge on dredging, navigation, marine engineering and construction. The audience will be comprised of contractors working in dredging, navigation, coastal and inland flood protection, deep-sea mining, offshore wind energy, and oil and gas production fields as well as marine engineers, manufacturers, dredging technology providers, harbour & port representatives, consultants, port engineers, hydrographic surveyors and geologists, environmental managers, infrastructure managers, public authorities, suppliers, universities, research institutes, civil engineers, and geotechnical engineers.

Hosted by CEDA and IADC, the Dredging for Sustainable Infrastructure Conference brought together presenters to share with attendees their expertise about four of the book's key enablers: using an ecosystems approach, investing in stakeholder engagement, applying adaptive management and seeking win-win solutions through beneficial use of sediments. Following each presentation, the audience participated in four diverse activities designed to apply the knowledge through a series of challenges with choices. Participants were invited to leave behind their chairs, move around the room, form groups, discuss and weigh options, make informed decisions and even compete against other groups in mock situations. A microphone was tossed among participants so they could share their ideas with everyone.

Photo Mees van den Ekart

A lively social programme with ice breakers, ice cream socials and gala dinners is planned.

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