MARITIME SOLUTIONS FOR A CHANGING WORLD

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TERRA ET AQUA

TRENCHING MODEL

MODELLING THE CABLE TRENCHING PROCESS ON SAND DUNES

BENEFICIAL USE
Promoting viable uses for sediments to stakeholders

EXPERTISE EXPORTER
Engineer takes expertise in nature-first development abroad

HIGHLIGHT

TRENCHING MODEL

MODELLING THE CABLE TRENCHING PROCESS ON SAND DUNES

Numerous offshore wind farms have been recently installed in the southern part of the North Sea. Their infield and export cables are buried for protection against dropped or dragged objects. In sandy soils, burial is carried out by remotely operated tracked vehicles. Two swords with waterjets are used to fluidise the sand and generate a backward flow of the water-sediment mixture. The area's highly variable seabed topography – characterised by sand waves and mega-ripples – can significantly influence the trenching process. At the moment, it is not possible to make an accurate estimate of the influence of sand dunes on the trenching process.

The trench formation process is split into two parts: a front section where the seabed is eroded by waterjets (erosion model) and a rear section where the sand grains are settling in a backward flow (sedimentation model). A team of authors from Delft University of Technology and DEME Offshore present the combined fluidisation, sedimentation and cable model which is validated against full-scale field data. **Read more on page 34.**

CONTENTS

CAN THE DREDGING INDUSTRY **BE MADE SAFER?**

Frank Verhoeven
President, IADC

Safety awareness remains a top priority in the dredging industry. By encouraging the creation of safety solutions as well as bringing them into public discourse via publication in *Terra et Aqua*, the IADC continues its mission to improve safety in the dredging industry and its projects on water and land by sharing strategies.

In that context IADC has unveiled the safety innovations nominated for its annual Safety Award 2019. At fourteen innovations, this year's group is *the largest* to be nominated in a single year. These submissions address all facets of the industry, from land to sea and to the office: Equipment to enable safer inspections underwater or from the air, a protective barrier during regular processes on deck, a programme to instill a safety mindset at any moment of the day, and an application with step-by-step instructions to save lives during medical emergencies at sea or in remote areas.

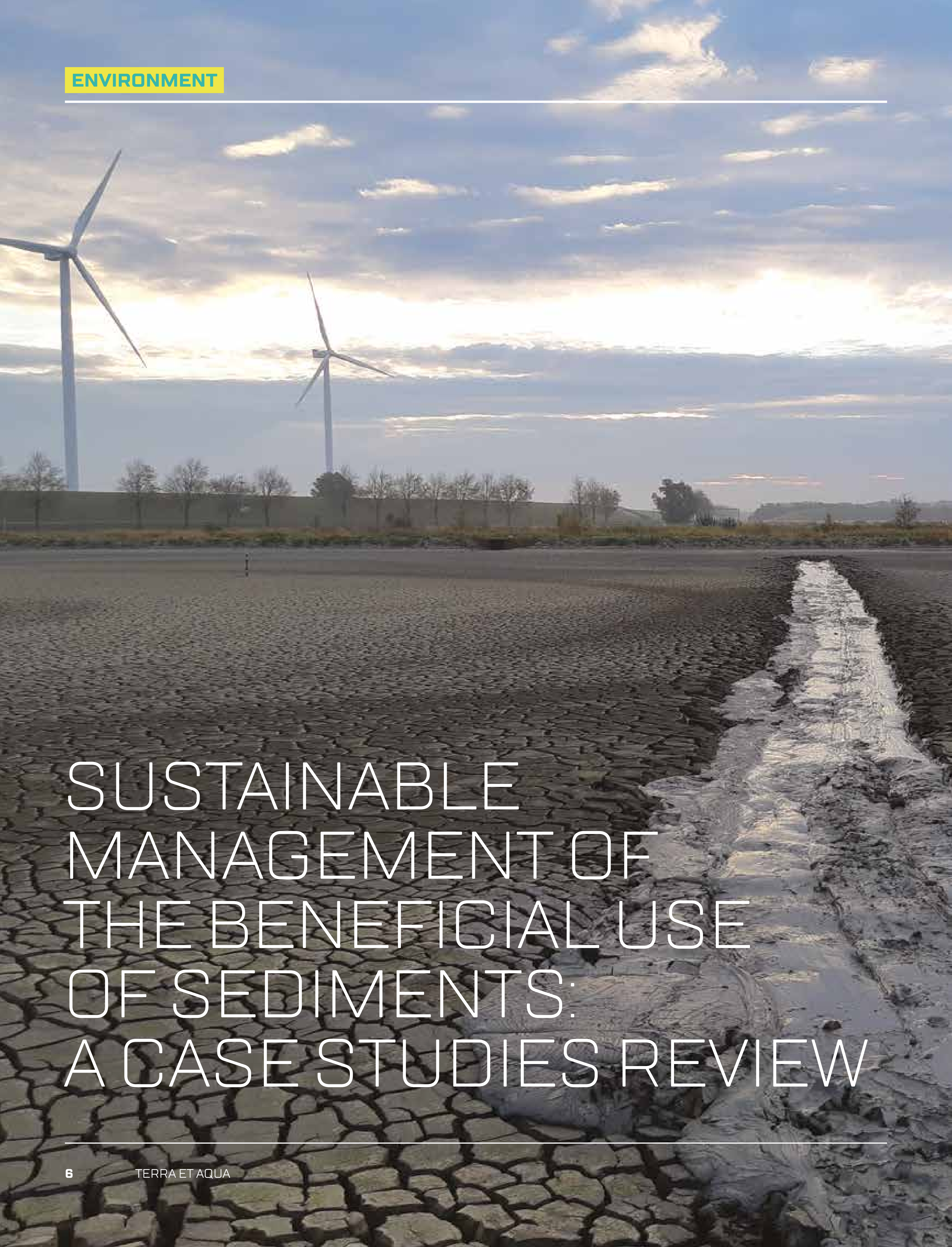
Looking over the span of four years, more than forty safety innovations have been nominated for IADC's Safety Award.

Of course, when it comes to safety, quality always wins over quantity, but the numerous Safety Award nominations prove you can have both. And with more innovations, from engineers, safety experts, and crewmembers, the greater the safety awareness in the industry and the fewer accidents and incidents. This year's Safety Award winner will be announced at IADC's Annual General Meeting in New Delhi, India in October.

In addition, in conjunction with the AGM, IADC is hosting a conference on Dredging for Sustainable Infrastructure in New Delhi, bringing its publication *Dredging for Sustainable Infrastructure* – made in collaboration with the Central Dredging Association – to an international audience in Asia.

Speaking of sustainability, in this issue of *Terra*, CEDA's Working Group on Beneficial Use presents a categorised collection of case studies which demonstrate sustainable solutions for working with sediment, a resource which is increasingly addressed in the industry's dialogue. Director of Ecoshape Henk Nieboer discusses the importance of Building with Nature and the future of the programme. And lastly, a model to estimate the influence of sand dunes on the trenching process is presented, a situation encountered while burying cables for offshore wind farms.

Safety awareness remains a top priority in the dredging industry.



SUSTAINABLE MANAGEMENT OF THE BENEFICIAL USE OF SEDIMENTS: A CASE STUDIES REVIEW

Over the last few decades there has been an increasing recognition that dredged sediment is a resource which should be utilised beneficially for human development activities and/or enhancement of ecological habitats.

Through its latest publication, the Central Dredging Association (CEDA) Working Group on the Beneficial Use of Sediments informs stakeholders and practitioners about the recent advances, ongoing international initiatives and programmes, and best management practices for the beneficial use and value of sediments using relevant case studies.

Sediment as a resource

By describing the importance of sediments in the context of sustainable development and impact of climate change, this article aims to inspire international government agencies and policy makers, contractors, project proponents and international donors (i.e., World Bank) to encourage the implementation of sustainable sediment management strategies.

This review elaborates on previous literature and experience on this topic (e.g., PIANC 2009; IADC 2009; CEDA 2010). The Working Group on the Beneficial Use of Sediments (WGBU) researched and collated details from 38 case studies. The studies collected involved contaminated, as well as, clean sediments. These included studies that have been undertaken in 11 countries over the last 30 years, specifically focusing on the last decade. These case studies highlight many effective methods for beneficial use, supported by specific pilot and commercial project applications, assembled by an active community of practitioners with more than two decades of experience in this environmental area. This review intentionally focused on the technical aspects of these case studies to demonstrate feasibility. This article does not address legislation, economical, or governance aspects in detail. While very important, these are often country-specific, which would distract from the central scope of this article.

Based on the case studies collected, beneficial use examples range from dredged materials affected by anthropogenic sources and natural sediments, to be used for construction applications, or to help restore freshwater and marine habitats, with nature-based solutions becoming a prominent driver for sustainable sediment use in the last decade. In this article, we define beneficial use as the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development.

While this article illustrates technical feasibility and success, to date, beneficial use of natural and dredged sediment remains below its overall potential. Technical aspects are often outweighed by country-specific legislation, policy, economics and public and industry perception (Brils et al. 2014). This complexity hampers the beneficial use of (dredged) sediments. Therefore, we recommend addressing these important aspects in a future publication in an effort to promote beneficial use practice to a level in which full potential can be realised and further in line with sustainable human development.

This article intends to demonstrate that beneficial use applications exist for clean, as well as, sediments contaminated with low-level pollutants. Dealing with contamination is perceived as challenging (both operationally and publicly); therefore, a separate complementary Position Paper by the Central Dredging Association (CEDA) was produced in 2019, by this same WGBU, that focuses on the risk management and beneficial use opportunities of sediments with various degree of contamination. For this article, case studies were made available by the WGBU members and their industrial contacts. Because the overview given in the article is not exhaustive, the authors openly invite the professional community to share their experiences with the CEDA community. The archival platform and email contact are available on the CEDA website to facilitate submission of additional and future case studies, and mutual knowledge exchange regarding the beneficial use of sediments worldwide.

Why sediment matters

The surface of the earth is being fractionised into sand, silt, and clay by the natural process of rock weathering. The fractions, or sediments, are (re)distributed over the earth's surface through erosion and sedimentation processes induced by ice, water, and air. In this way, nature shapes the landscapes of the Earth through continuous and episodic events. However, the impact of Man on these dynamic natural processes has increased tremendously in the last century, especially due to the development of (land or waterborne) infrastructural works. In 2017, *The Economist* stated 'humans now move more sediments than the natural processes of erosion'.

This likely, exaggerated, overstatement indicates that human interaction with natural processes is significant. Humans move sediment to enable and optimise:

- transport and logistics (e.g., dredging of ports and waterways for navigation);
- space for living and commercial activities (e.g., fill for land reclamation and remediation/brownfields);
- flood safety and water management (e.g., construction of dykes, breakwaters, dams); and
- natural ecosystem protection and enhancement (e.g., contaminated sites or wetland restoration, improving water clarity and quality).

Human interventions interact with the natural dynamics of sediment accumulation and erosion processes, which often disturbs the natural dynamic. Examples include: sediment trapped behind dams is not available to feed downriver floodplains or nourish a beach near the river mouth (Vörösmarty et al. 2003); sediment from river mouths, reallocated offshore, is not available to nourish a wetland anymore; excess deepening of estuaries is suspected to increase turbidity in major rivers (Winterwerp and Wang 2013; Winterwerp et al. 2013) and erosion of banks. Where disturbance to natural processes of sediment accumulation and erosion occurs, it can contribute to increase the vulnerability of natural systems and human developments, such as: coastal erosion and loss of land, flooding from sea or rivers, decrease of productivity and environmental quality of ecosystems (Winterwerp and Wang 2013; Winterwerp et al. 2013). Climate change, resulting in more frequent and more intense events (i.e., storms and hurricanes) and sea level rise, aggravates these risks and impacts further.

FIGURE 1

The restoration of an eroded coastline in Northern Java, Indonesia. Photo EcoShape

Dredging of sediments

Humans move most sediment by dredging. Unlike natural processes, like those that build and reduce shorelines seasonally, man-made infrastructure is static and less tolerant of dynamic sediment processes. The largest driver for dredging comes from the need to remove accumulated sediment from ports, harbours, and shipping channels in order to maintain their function as the backbone of our economy. Historically, the most common sediment management approach employed in many countries has been aquatic disposal of the dredged sediments at sea, or simply relocated in mid-river. This is particularly true for finer silts that are maintenance dredged from ports and harbors. In the UK alone, for example, around 22 to 44 million cubic meters (m^3) of sediment is dredged from ports and harbours every year (ABPmer 2017).

Over the last few decades there has been an increasing recognition that dredged sediment is a resource which should be utilised beneficially for human development activities and/or enhancement of ecological habitats. The need to seek beneficial use opportunities was identified as a priority within the International Maritime Organisation (IMO) (London Convention and London Protocol (IMO, 2014) and other dredged material management reviews and guidance (IADC 2009; CEDA 2010; OSPAR 2014; and HELCOM 2015). In 1992 and 2009, the World Association for Waterborne Transport Infrastructure (PIANC) established workgroups focused on preparing guidance regarding the beneficial use of dredged material (PIANC 1992; PIANC 2009). The PIANC (2009) report by the PIANC EnviCom

FIGURE 2

Dyke reinforcement underway in Hamburg, Germany. Photo Julia Gebert, TUD

Beneficial use may involve clean or contaminated sediments, when appropriately managed or treated, and when they provide added value.

Working Group 14 (chaired by CEDA) provided a forum for the development of guidance, for future consideration, of uses for dredged material on a routine basis. Since the publication of the PIANC paper, many new examples and initiatives have focused on the beneficial use of dredged sediments, as reported in this review. An appendix to this report provides wide-ranging case studies that demonstrate how dredged material has been used successfully worldwide.

Beneficial use of sediment

Beneficial use of sediment is herein defined as the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development. Beneficial use may involve clean or contaminated sediments, when appropriately managed or treated, and when they provide added value. Considered in the context of the three pillars of sustainability (economic value, social gain and environmental benefit), many beneficial use projects typically achieve at least two of these objectives. Those projects which focus on habitat restoration have the potential to directly deliver all three. Since the mid- to late-1900s, knowledge about the natural environment – and its processes and dynamics – has advanced significantly. Environmental considerations, nature-based approaches, value engineering and win-win solutions (i.e., benefits/value for all stakeholders) are increasingly considered an integral part of dredging projects from an early stage. These advances highlight the central role of sediment management and have facilitated the development and implementation of innovative sediment uses. Several international programmes and initiatives seek to support the sustainable development of infrastructure through improved alignment and integration of engineering and natural systems.

International initiatives and programmes

There are several world-wide initiatives and programmes that are centered on sustainable, and nature-based, development of hydraulic and civil infrastructures. Beneficial use of sediment is a key, constant, theme across these programmes. Some of the most recent initiatives include:

- **Engineering with Nature (EwN)** was initiated by the US Army Corps of Engineers' Engineer Research Development Center (ERDC). The EwN programme has a specific focus on developing knowledge and practical experience regarding the use, and re-use, of dredged sediment in light of resilience and nature restoration. Their work is documented in many completed and ongoing case studies.
- **The Living Lab for Mud (LLM)** is hosted by EcoShape (EcoShape 2017). Similarly, and in partial collaboration with the EwN, the LLM is a living platform that brings together various EcoShape pilots related to sustainability, with nature (fine) sediments management to facilitate cross-pilot and international knowledge and experience exchange.
- **Working with Nature (WwN)** is similar to Building with Nature (BwN), EwN and PIANC, promoting the development of navigation-related projects based on the 'with nature' concept (PIANC 2008). Integrated and circular dredged sediment use is a central theme of this initiative.
- **SEABUDS (Precipitating a SEA Change in the Beneficial Use of Dredged Sediment)** which was led by the UK's Royal Society for the Protection of Birds (RSPB), involves reviews and meetings by key regulators and advisors to evaluate policy and practice in the field of beneficial use with a view to implementing more projects in the future (Ausden M et al., 2018).
- **Solent Forum (BUDS) Regional Strategic Review** is a project which is underway to strategically identify beneficial use project sites in the Solent (south coast of the UK) which has been underpinned by an innovative new study (by ABPmer http://www.abpmer.co.uk/buzz/cost-benefitanalysis-of-using-dredged-sediment-to-restore-andcreate-intertidal-habitat/) which reviews the costs

and benefits of using dredged sediment for marine habitat restoration, based on examples in Europe.

- **Using Sediment As a Resource (USAR)** and Promoting Integrated Sediment Management (PRISMA), are two European Union, North Sea Region initiatives covering England, France, The Netherlands and Belgium (Flanders). These programmes centre on developing alternative options, at no added cost, for the processing, treatment and beneficial use of sediments in estuaries and coastal waterways, from dredging to recycling, in lieu of the circular economy.
- **European Sediment Network (EU SedNet) Working Group on Sediment Quantity Management – Sediments on the Move From the Mountains to the Sea** (https://sednet.org/), with main objectives to increase the general awareness for sediment quantity management with the entire watershed system and to promote the sharing of experiences and best management practice in this field, in line with the CEDA WGBU.

Over the years, other beneficial use sediment programmes have contributed to the overall knowledge base, focusing on materials science (e.g., structural or geotechnical aspects) and sediment treatment (i.e., in the context of destroying or immobilising contaminants).

These include: SEDI.PORT.SIL, CEAMas, SETARMS, SEDILAB, GeDSET, the Sedimateriaux Approach and the USEPA/NJDOT New York and New Jersey Harbour Sediment Decontamination Programme. These programmes have been at the forefront of changing the perception of sediments from a 'waste' to a sustainable resource.

Several case studies and information included in this article are derived from these initiatives and therefore are concrete examples of achieving socially acceptable, economically viable and environmentally sustainable projects.

Classification of beneficial use of sediments

There are many different types of beneficial use applications, as well as different nomenclature and terminology associated with it. Therefore, adopting a unified classifying approach is not simple. For example, it is quite common to frame beneficial use potential in terms of geotechnical/structural material types (e.g., clay, rock, sand and silts). Alternatively, beneficial uses may be separated into categories based on final objective and end-use (i.e., engineering and/or environmental) or based on the dredging equipment/technique used (e.g., backhoe bucket mechanical dredge, trailing suction hopper dredge). In this article, beneficial uses are categorised according to five *end-use functions* the project fulfils (i.e., the application) and to the general operational *technique* used in the application.

Five major functions are here defined as 'the Five Rs':

1. **Raw Material**: substitution for virgin manufactured soil or building materials, such as tiles or aggregates.
2. **Remediation**: clean-up of contaminated sites, brownfields or closure of landfills and mines.
3. **Reclamation**: creating new, or expanding existing, land mainly for human/commercial development activities.
4. **Restoration**: creation of habitat to support aquatic organisms and wetlands to improve natural value.
5. **Resiliency**: shoreline nourishment and (dyke) reinforcement for defence against floods and extreme climatic events.

It is certainly recognised that some, in fact most, beneficial use applications fulfil more than one function. For example, dredged material can be a substitute for raw material, which can be used as a top layer of a landfill closure project or for dyke reinforcement; a contaminated site can be remediated as part of land reclamation for further redevelopment; a coastal nourishment can create habitat and improve flood safety and sea level rise resiliency; remediation of a mine can be part of a reclamation and restoration function to repair and mitigate a century of environmental impacts. In all these cases, the various applications are categorised following the major function, yet mentioning, and perhaps integrating, the other functions explicitly.

Furthermore, the various beneficial use applications can be divided into four broad techniques categorising the method used to implement the activity. These techniques are:

A. **On Land, Natural or Enhanced Treatment**: sediment is pumped and treated on land, such as drying/dewatering and ripening fields and dewatering plants (see Figure 3).

B. **In Water, Reallocated at a Final Location**: sediment is transported and pumped, or deposited, at final locations, such as

FIGURE 3

In Technique A, sediment is deposited on land, and in this illustrative case, into drying cells. Sediment is possibly treated and reclaimed for other subsequent beneficial uses such as dyke reinforcement.

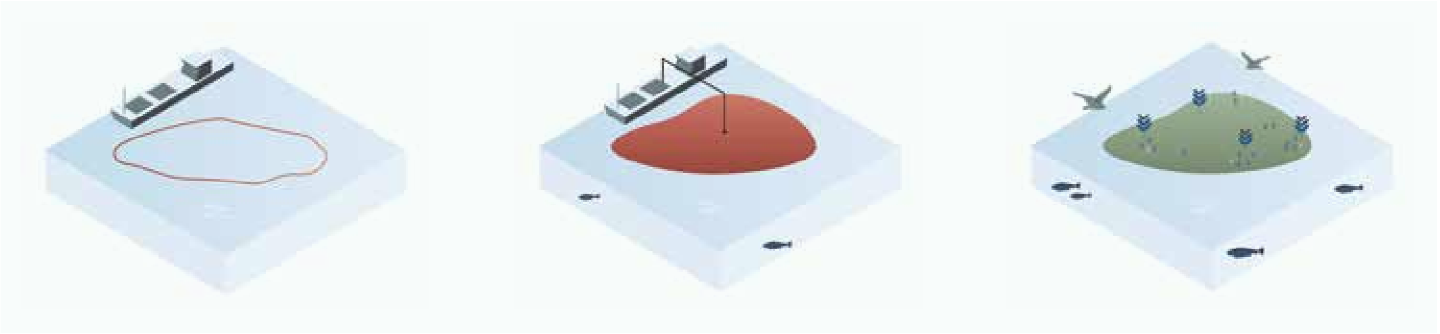


FIGURE 4

In Technique B, sediment is reallocated in water at the final location. Demonstrated in this case, the final location is an island with a major function of nature restoration.

FIGURE 5

In Technique C, sediment is reallocated in water at a strategic location. Tidal flow and waves transport the sediment to the final location. In this illustrative case, the function is wetland restoration in front of a sea dyke with a consequential reduction of flood risk.

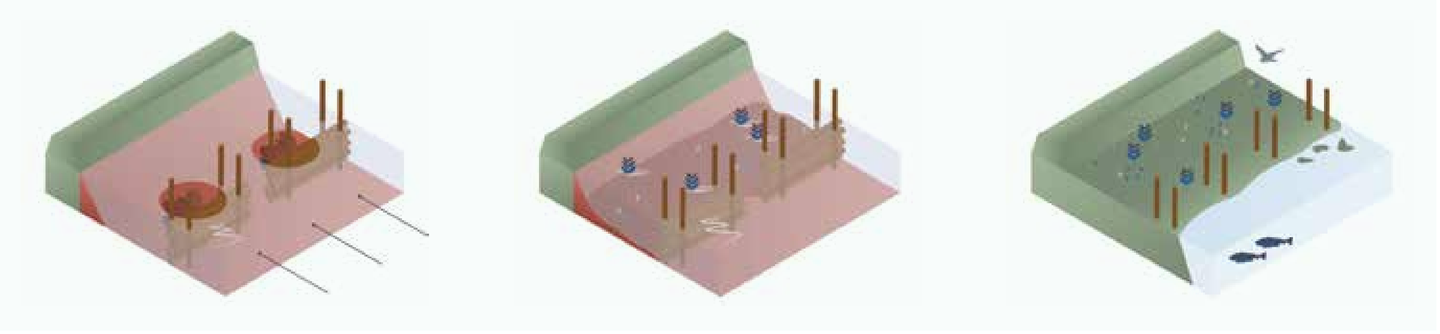


FIGURE 6

In Technique D, the trapping of sediment is enhanced. This illustrative case demonstrates the use of permeable dams to favour wetland restoration through mangroves.

It is certainly recognised that some, in fact most, beneficial use applications fulfil more than one function.

nourishments, land reclamation, waterfront redevelopment (see Figure 4).

C. **In Water, Reallocated at a Strategic Location**: sediments are disposed at a strategic location, letting the local natural processes (e.g., hydrodynamic forces) transfer and trap the sediment at the final location, such as sand or mud engine (see Figure 5).

D. **In Water, Enhanced Trapping**: improving the trapping capacity of the natural system, for example strategic mangrove or wetland restoration projects (see Figure 6). In this case sediments are not dredged or transported by humans but use natural systems and engineering tools as sediment management measures.

Human intervention decreases from techniques A through D, with techniques C and D mostly relying on nature-based approaches. Technique A often involves the use of chemical or physical treatments to sequester contaminants or improve sediment properties. Techniques A through D (Figures 3 through 6) are consistent with those proposed by the EcoShape – Building with Nature Initiative, Living Lab for Mud (EcoShape 2017). EcoShape is working with their partners on five pilot projects to develop knowledge about the sustainable use of fine sediments.

Case studies

Case studies were collected during the preparation of this article by WGBU members and associates. In total 38 case examples, undertaken in 11 countries over the last 30 years, with the focus on the last decade were collected. All case studies are described in standard two-page summaries, all of which are available on the CEDA website at: https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies

TABLE 1

Case studies classified after Function (Rows) and Technique (Columns). Rows 1 through 5 refer to Function and columns A through D refer to Technique. Case study nomenclature includes a reference to the Function, Technique, the year at project start, and the country location of the project. Underlining indicates contamination present. Case studies in *italics* indicate treatment (see Position Paper for details on treatment techniques).

Technique Function	A. On Land, Natural or Enhanced Treatment	B. In Water, Reallocated at Final Location	C. In Water, Reallocated at Strategic Location	D. In Water, Enhanced Trapping
1. Raw Material	R1A_1985_DE *R1A_1993_DE* *R1A_1996_DE* R1A_2006_DE R1A_2006_NL *R1A_2012_FR* *R1A_2015_US* *R1A_2017_IT* *R1A_2018_US*			
2. Remediation	*R2A_1988_DE* *R2A_1995_NL* *R2A_2015_DE*			
3. Reclamation	R3A_2016_US R3A_2018_NL	*R3B_2006_NZ* *R3B_2010_NO* *R3B_2018_SE*		
4. Restoration	R4A_2010_NL	R4B_2002_US R4B_2005_US R4B_2008_US R4B_2016_NL R4B_2016_UK(A) R4B_2016_UK(B)	R4C_1999_NL R4C_2002_US R4C_2007_US R4C_2016_NL	
5. Resiliency	*R5A_2004_DE* *R5A_2005_BE* *R5A_2013_FR* R5A_2018_NL *R5A_2019_BE*	R5B_1990_UK R5B_2006_NL R5B_2010_US	R5C_2008_US	R5D_2015_ID

TABLE 2

List of case studies by title and classification code.

Classification Code	Case Study Title
R1A_1985_DE	*Production of raw material through dewatering fields, Hamburg – DE*
R1A_1993_DE	*Production of raw material through a dewatering plant, Hamburg – DE*
R1A_1996_DE	*Use in ceramic industry through industrial treatment, Hamburg – DE*
R1A_2006_DE	*Use as agricultural soil after dewatering, Ihrhove – DE*
R1A_2006_NL	*Reclamation of clean sand through sand separation, Rotterdam – NL*
R1A_2012_FR	*Use in road construction after immobilisation and stabilisation, Dunkirk – FR*
R1A_2015_US	*Use in civil and environmental applications after stabilisation via Pneumatic Flow Tube Mixing, New Jersey – US*
R1A_2017_IT	*Use in civil and environmental applications after multiple phase cleaning and sorting process, Palermo – IT*
R1A_2018_US	*Production of grade cement after thermo-chemical high temperature treatment and immobilisation,New Jersey – US*
R2A_1988_DE	*Use as sealing material after dewatering, Hamburg – DE*
R2A_1995_NL	*Use as landfarming through bioremediation, Oostwaardhoeve – NL*
R2A_2015_DE	*Use as substitute for sand to backfill former harbour-basins, Hamburg – DE*
R3A_2016_US	*Raise elevation of near-shore agricultural fields after natural dewatering, Ohio – US*
R3A_2018_NL	*Raise elevation of low-lying peatlands and production of high value soil through blending with local organic waste, Krimpenerwaard – NL*
R3B_2006_NZ	*Use in expansion of port terminal after blending with cement, Auckland – NZ*
R3B_2010_NO	*Use in expansion of port terminal after blending with cement and stabilisation contaminated sediments, Oslo – NO*
R3B_2018_SE	*Use in civil applications after testing with various binders, Gothenburg – SE*
R4A_2010_NL	*Raise elevation of low-lying peatlands after natural dewatering in confined facilities, Jisperveld – NL*
R4B_2002_US	*Creation of natural habitat and morphological stabilisation through strategic deposition, New Jersey – US*
R4B_2005_US	*Counter subsidence and creation of natural habitat through strategic deposition, California – US*
R4B_2008_US	*Habitat restoration through creation of islands, Wisconsin – US*
R4B_2016_NL	*Habitat restoration through creation of islands, Lelystad – NL*
R4B_2016_UK(A)	*Habitat and wetland restoration through strategic deposition, Brightlingsea – UK*
R4B_2016_UK(B)	*Habitat and wetland restoration in three locations through strategic deposition, Hampshire – UK*
R4C_1999_NL	*Feeding the natural system through natural dispersive processes, Wadden Sea – NL*
R4C_2002_US	*Creating islands through natural dispersive processes, Louisiana – US*
R4C_2007_US	*Beach replenishment and lagoon restoration through natural dispersive processes, California – US*
R4C_2016_NL	*Wetland enhancement through of natural dispersive processes, Harlingen – NL*
R5A_2004_DE	*Use in dyke construction reinforcement to enhance flood resilience after industrial dewatering, Hamburg – DE*
R5A_2005_BE	*Use in dyke construction reinforcement to enhance flood resilience after dewatering and treatment, Dendermonde – BE*
R5A_2013_FR	*Use in breakwater components to enhance flood resilience after dewatering and treatment, Dunkirk – FR*
R5A_2018_NL	*Use in dyke construction reinforcement to enhance flood resilience after natural ripening, Delfzijl – NL*
R5A_2019_BE	*Use in dyke construction reinforcement to enhance flood resilience after dewatering and treatment, Waasmunster – BE*
R5B_1990_UK	*Coastal defence and habitat restoration through strategic disposal, Essex - UK*
R5B_2006_NL	*Making room from rivers through various beneficial uses, various location in NL*
R5B_2010_US	*Use for coast defence and nature restoration through strategic placement, Mississippi – US*
R5C_2008_US	*Use for coast defence and nature restoration through strategic placement and use of natural processes, California – US*
R5D_2015_ID	*Use for coast defence and local economy enhancement through natural trapping, Demak – ID*

These case studies include general information about a specific project, technical information of the beneficial use application, and illustrations. Should the reader be interested in more information, a contact reference is also provided. All case studies were classified after function and technique, as described in the previous section of this article, uniquely named, and included in the summary table (see Table 1). The nomenclature of the case studies includes the year of project initiation and the country.

This table also identifies those case studies that involved contaminated sediments and (chemical/physical) treatment. For further clarity, Table 2 provides a list of the case studies by title and cross-referenced against their classification.

Historical and enhanced beneficial use case studies

Table 1 shows that beneficial sediment use is not a new concept but began in the 1960s with the flushing fields at the Port of Hamburg, Germany, and updated in the 1980s with dewatering fields being an iconic example. In the 1990s, the Port of Hamburg built a large-scale facility for the Mechanical Treatment of Harbour Sediments (METHA plant) for enhanced dewatering and treatment of the (mildly) contaminated portion of the dredged sediment in the harbour (5%-20% of the total – depending on annual sedimentation behaviour). The beneficial use output, of the METHA plant, was used for reclamation and restoration projects as well as for the manufacturing of bricks and ceramics. The remaining clean sediment is reallocated downstream of the Elbe river. Two decades later, the Port of Antwerp followed with a similar plant, the AMORAS. In France similar sediment output is utilised as a sub-base material for road construction. Sediment treatment, such as mixing with Portland cement and/or other binders, has been successfully implemented for the stabilisation of contaminants and modification of the geotechnical properties of the dredged material, mostly fines, in order to meet geotechnical specifications for specific project applications in remediation, and redevelopment projects (including port development) in the United States, Norway and Sweden. Stabilisation focuses on minimising segregation of different grain sizes, increasing strength and reducing water content and permeability. Stabilisation is not only used to stabilise contaminated sediments, but also has a role in coastal resiliency in the construction of seawalls, levees and dykes. For dredged materials not suited for aquatic placement, upland stabilisation for geotechnical construction purposes, mine reclamation, road subbase, landfill and brownfield caps, are examples of routine value-added beneficial use applications.

FIGURE 7

Depositing dredged sediment to enhance wetlands. Photo Exo Environmental

Nature-based case studies, the focus of the 21st century

Since the early 2000s more case studies implement nature-based techniques and focus on restoration and resilience functions (see Table 1). Nature-based solutions (NBS) rely on natural processes (i.e., currents, waves, the deposition and erosion of sediment, and plant growth) that are directly incorporated in the design and construction methods (Borsje et al. 2011; De Vriend and van Koningsveld 2012; De Vriend et al. 2015). This requires an understanding of the specific natural system, its main forces, their variation, the ecosystem, and the societal and governance structure. For this reason, there is not a 'one solution fits all' but instead an appropriate solution needs to be strategically considered for each site, river basin, estuary, coastal system, community and country. Nature-based projects must therefore be integrated in the large-scale, long-term development of the social and physical (eco)system. NBS does not mean green or nature-based only but are often a combination of green and grey (i.e., conventional approaches) with the proportion of each depending on the project objective, specific environment, the (natural and social) ecosystem and the potential for sustainable outcomes. The beneficial results of nature-based sediment use are often to be achieved and appreciated in the longer term and larger scale. Design, planning, construction, testing, long-term monitoring, and adaptive management should account for appropriate time and spatial scales.

Given the scarcity and cost of sand, many case studies begin to explore the effective implementation of soft fine sediments (or mud). These case studies are often brought forward by the international initiatives mentioned before (i.e., Building/Engineering/Working with Nature, USAR, PRISMA). These initiatives rely heavily on NBS and fine sediments management. Sediment and beneficial use are critical considerations for all types of NBS, and the link between NBS and beneficial sediment (re-)use is intrinsically strong. Examples of nature-based projects, based on beneficial use, collected during this study are varied in scope. They include:

- using natural products and processes such as manure, vegetation and ripening, to stabilise sediments (e.g., Kleirijperij or Krimpenerwaard in The Netherlands);

- using stabilised sediment directly or indirectly for land reclamation, raising subsiding land or strengthening dykes (e.g., Vlassenbroek in Belgium, Auckland in New Zealand, Sandvika in Norway, Hamburg in Germany, and Lowlands in The Netherlands, see Figure 2);
- depositing of dredged sediments in thin or thick layers on marine wetlands and retreating or vulnerable coastlines (e.g., at Horsey Island, Lymington, or Brightlingsea in the UK, see Figure 7);
- creation of artificial nature islands to improve flood safety and/or improve the habitat biodiversity and the natural value of the specific area (e.g., Marker Wadden Restoration Project in The Netherlands, Cat Island and Deer Island in the United States);
- attempting to extend coastal wetlands by depositing dredged material at a strategic location and relying on coastal processes for transport (e.g., Koehoal in The Netherlands); and
- implementation of old Dutch techniques to trap sediments (i.e., permeable dams) in front of eroding coastlines, to trap sediment and restore mangrove forest, so improving the resilience against flooding of rural communities (e.g., Demak in Indonesia, see Figure 1).

Given their integration with natural processes, the selection of the location of nature-based solutions is critical. Strategic reviews are being carried out to actively explore where projects can be best located. One recent example includes the UK Solent Forum Study, which identified economic criteria for site selection. An online map for potential project locations, in the Southampton area, was developed (ABPmer 2018). These sites should be taken forward to affirm economic and ecological merits.

Conclusions

This article demonstrates that dredged sediment is a valuable resource, reinforcing the findings from past reviews on this subject. Sediments can be used to support the sustainable development of many important human activities in harmony and in integration with nature. Vice versa, failure to do so will likely reduce resiliency and increase the vulnerability to natural forces. The numerous case studies provided in this article demonstrate that technical knowledge and experience with beneficial use of sediment is significant.

The practice of beneficial use is well-established, particularly in relation to production of alternative raw material to support civil infrastructural projects. More recently, innovative applications and pilot projects have been explored on how to best use natural forces and processes, implementing NBS, that incorporate beneficial use of sediment. Successful projects include wetland restoration and coastal nourishment studies to improve resilience against coastal flooding and extreme climatic events. A community of practitioners lies behind these numerous successful applications, with over two decades of experience to draw upon. The collected case studies unequivocally demonstrate that applications of beneficial use of sediments, contaminated by low-level pollution, are implementable. A parallel Position Paper is produced that describes how to evaluate and mitigate risk, to successful beneficial use, when contamination is present.

This number of applications demonstrate that many possibilities for beneficial use exist, offering the opportunity for its prioritisation in dredging and sediment management activities. In some instances, the benefits of beneficial use applications may only be realised long after project implementation, or may be less directly quantifiable, such as indirect ecosystem service benefits. Successful applications may also require long-term maintenance or adaptive management approaches. This is the logical consequence of implementing NBS, where natural processes intrinsically need time to respond and adapt to changes.

This article focused on technical feasibility, only indirectly touching on legislation or economic components (which are often country-specific). However, case studies did generally discuss these project aspects, and non-technical challenges critical for the success of a beneficial sediment use project, especially when implementing NBS. These are, for example: definition of beneficiaries and funding mechanism; clear policy and legal framework to regulate, permitting design, implementation and maintenance; and managing institutional and public perception. In early 2019 PIANC, initiated WG 214 on the same topic of beneficial sediment use. WG 214 includes various CEDA members who worked on this article, which serves as a solid technical baseline. It is the ambition of the PIANC WG to include a wider analysis of the non-technical success or failure factors, to provide a broader perspective on how to consistently implement beneficial sediment use in large scale applications.

Finally, as a call for ongoing collaboration, the authors invite the reader and the professional community to share their experience, knowledge and further case studies by sending them to ceda@dredging.org. As identified in Murray (2008), ongoing active communication on this subject is vital in order to see more and larger projects achieved. Therefore, CEDA will provide a platform for ongoing knowledge and experience exchange on the subject of beneficial sediment use.

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Summary

This article is based on a paper which has been prepared by the Central Dredging Association (CEDA) Working Group on the Beneficial Use of Sediments (WGBU). The WGBU was initiated by CEDA's Environmental Commission in 2017. This article intends to inform sediment stakeholders and practitioners about the recent advances, on-going international initiatives and programmes, and best management practices regarding the beneficial use of sediments and the value of sediments as a natural resource in the context of sustainable development using relevant case studies.

This article was first published as an Information Paper presented by the Central Dredging Association (CEDA), an independent, international organisation with an extensive professional network, a centre of expertise on dredging and reclamation, and an easy-to-access forum for knowledge exchange. The article has been prepared by a working group of international experts of broadly diverse backgrounds and range of expertise, under the remit of the CEDA Environment Commission.

Citation

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Some members from the CEDA BU WG are concurrently participating in the ongoing PIANC EnviCom WG 214 on Beneficial Sediment Use.

REFERENCES

ABPmer (2017)
White Paper: *Using dredge sediment for habitat creation and restoration: A cost benefit review, A summary of the techniques, costs and benefits associated with using fine dredge sediment to 'recharge' intertidal habitat*, ABPmer Internal White Paper, Report No. R.2865.

ABPmer (2018)
Beneficial use of dredge sediment in the Solent (BUDS), Phase 1 project scoping and partnership building, ABPmer Report No. R.2845.

Ausden M, Dixon M, Lock L, Miles R, Richardson N & Scott C. (2018)
SEA Change in the Beneficial Use of Dredged Sediment. Royal Society for the Protection of Birds.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J. and de Vries, M.B. (2011)
How ecological engineering can serve in coastal protection – a review. Ecological Engineering, 37, pp. 113-122.

Bridges, T. S., Bourne, E.M., King, J.K., H. Kuzmitski, H.K., Moynihan, E.B. and Suedel, B.C. (2018)
Engineering with Nature: an atlas. ERDC/EL SR-18-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/27929. [Accessed: May 2019].

Brils J., de Boer P., Mulder J., de Boer E. (2014)
Reuse of dredged material as a way to tackle societal challenges. Journal of Soils and Sediments, DOI 10.1007/s11368-014-0918-0.

CEDA (2010)
Dredged Material as a Resource: Options and Constraints. Information Paper. Available at: http://www.dredging.org/documents/ceda/downloads/publications-2010-6-ceda_information-paperdredgedmaterialasaresource.pdf [Accessed: May 2019].

CEDA (2019)
Assessing the Benefits of Using of Contaminated Sediments. Position Paper. Available at: http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2019-05-BUC S-pp.pdf [Accessed: May 2019].

De Vriend, H. J. and Van Koningsveld, M. (2012)
Building with Nature: thinking, acting and interacting differently. EcoShape, Building with Nature, Dordrecht, The Netherlands.

De Vriend, H. J., Van Koningsveld, M., Aarninkhof, S. G. J., De Vries, M. B. and Baptist, M. J. (2015)
Sustainable hydraulic engineering through building with nature. Journal of Hydro-environment Research, 9, pp.159-171.

EcoShape (2017)
The living lab for mud. Available at: https://www.ecoshape.org/en/projects/living-lab-mud/ [Accessed: May 2019].

HELCOM (2015)
HELCOM Guidelines for management of dredged material at sea. Adopted by HELCOM 36-2015 on 4 March 2015. Available at: http://www.helcom.fi/Lists/Publications/HELCOM%20Guidelines%20for%20Management%20of%20Dredged%20Material%20at%20Sea.pdf [Accessed: May 2019].

IADC (2009)
Facts about dredged material as a resource. An information update from the IADC – Number1–2009. Available at: https://www.iadc-dredging.com/ul/cms/fck-uploaded/documents/PDF%20Facts%20About/facts-about-dredgedmaterial-as-a-resource.pdf [Accessed: May 2019].

IMO (2014)
Revised Specific Guidelines for the assessment of dredged material. Tech. Rep., International Maritime Organization, London, UK. 146, 152.

Murray, L. (2008)
Dredged material as a resource. Terra et Aqua, September, Number 112, pp. 3-10. https://www.iadcdredging.com/ul/cms/terraetaqua/document/2/4/0/240/240/1/article-dredged-material-as-a-resource-terra-et-aqua-112-1.pdf [Accessed: May 2019].

OSPAR (2014)
Guidelines for the management of dredged material. Available at: www.ospar.org/documents?d=34060 [Accessed: May 2019].

PIANC (1992)
Beneficial uses of dredged material: A practical guide. Report of PIANC Working Group 19, PTC II.

PIANC (2008)
Working with Nature. PIANC Position Paper.

PIANC (2009)
Dredged material as a resource: Options and constraints. Report of PIANC EnviCom Working Group 14, No 104.

The Economist (2017)
Improving the Oceans: Getting serious about overfishing, Printable Edition, May 27th, 2017.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P. and Syvitski, J.P. (2003)
Anthropogenic sediment retention: major global impact from registered river impoundments. Global and planetary change, 39(1), pp.169-190.

Winterwerp, J.C. and Wang, Z.B. (2013)
Man-induced regime shifts in small estuaries – I: theory. Ocean Dyn., 63 (11–12), pp. 1279-1292.

Winterwerp, J.C, Wang, Z.B., van Braeckel, A., van Holland, G. and Kösters, F. (2013)
Man-induced regime shifts in small estuaries – I: a comparison of rivers. *Ocean Dyn.*, 63 (11–12), pp. 1293-1306.

14 INNOVATIONS

FACE OFF FOR SAFETY AWARD 2019

Each year IADC gives the Safety Award to one innovation which proves it is the best in its class. This year, fourteen innovations addressing challenges faced within the dredging industry have been nominated to compete for the Safety Award 2019.

The Safety Award is an annual initiative conceived by IADC.

Combatting risk by increasing safety

As an association, IADC is committed to promoting safety in the dredging industry. 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. As a representative of contractors in the dredging industry, IADC 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.

The Safety Award is an annual initiative conceived by IADC. By giving this award, IADC intends to encourage the development of safety skills on the job by rewarding individuals and companies demonstrating diligence in safety awareness in the performance of their profession. A particular project, product, ship, team or employees can receive the award, serving to recognise the exceptional safety performance which their innovation demonstrates.

Nominated for IADC's Safety Award 2019, fourteen solutions address the safety of equipment as well as routine processes and situations encountered in the workforce of the dredging industry.

Boskalis has integrated real-time sonar imaging on diving helmets to increase sight in zero-visibility conditions

Diving for marine projects is not a risk-free activity. Divers work in hazardous situations subsea and one of the basics for safe diving is understanding where you are and where you need to go, especially in an emergency. Divers sometimes encounter zero visibility under water. By integrating real-time sonar imaging technology in existing diving helmets, Boskalis is creating a helmet that provides vision in zero-visibility conditions, access to images and task plans subsea. This will keep divers safer and be more efficient and cost effective.

To understand, just imagine Google glasses for diving helmets. By integrating a HUD (Heads Up Display) into a diving mask and linking this to a sonar imaging system (mounted on the diving helmet), divers will be able to work safely and efficiently in zero-visibility conditions. By providing a display to the divers, other information becomes available as well. For example, real-time images of the online NAV screen, and drawings, dive plans and sketches at the worksite which otherwise would not be available on the subsea worksite.

The idea originated with the United States Navy, which has been investigating the technology. Some helmet suppliers are starting to provide options and Boskalis has taken the opportunity to be an innovator and early adopter by embracing this technology now. Technically speaking, the idea is feasible because it integrates existing technology and componentry into dive helmets.

Within Boskalis (and within the industry) diving incidents are in the top three risks and this innovation will improve safety. This innovative helmet is in the early engineering stages, as suppliers investigate technical restrictions on components available such as power requirements, data transfer and capture. Suppliers need to identify the best components on the market to integrate into the system (considering equipment cost, reliability, image quality and ease of integration. Once a design is complete, Boskalis plans to procure the components and integrate them into its existing helmet in order to test the equipment subsea. Extensive training will be needed. Development of a new product is an intensive process but well worth it as an integrated diving helmet will increase the divers' efficiency and help complete jobs more quickly and safely.

FIGURE 1

By integrating a HUD (Heads Up Display) into a diving mask and linking this to a sonar imaging system (mounted on the diving helmet), divers will be able to work safely and efficiently in zero-visibility conditions.

Bender Benelux's monitoring box for mobile generators prevents electrical shocks

During construction of offshore wind farms, windmills have no electrical source. The tower teams, who are installing cables leading to these windmills at sea, must carry their own mobile generators. But there is a problem – these generators are not sufficiently grounded because the yellow transition pieces are sealed in a coating meant to last for 25 years in a saline underwater environment. As a result, the standard circuit breaker is not adequate and this can lead to unsafe situations for workers as well as for equipment.

Recently, when Boskalis wanted to update their mobile generators, Bender Benelux, supplier of these generators, decided to investigate UK law and requirements. The supplier found that the present systems did not meet safety requirements so they set to work to build a new 'line insulation monitoring box' with specifications that meet present-day safety standards.

In building the wind towers at sea, small electrical winches to lift equipment to the windmill were running on mobile generators equipped with earth-leakage circuit breakers (ELCB) sensitive to 230V. The ECLB is a safety device used in electrical installations to prevent shock. It detects small stray voltages on the metal enclosures of electrical equipment, interrupting the circuit if dangerous voltage is detected. Bender Benelux determined that these mobile generators did not meet the safety requirements for the installation of cables in the sea.

Bender concluded that instead of 230V for the generator, the maximum should be 110V and that the standard ELCBs should be replaced with a line insulation monitoring box. This unique monitoring box continuously measures the insulation resistance in the electrical circuit. As soon as the resistance becomes too low (and voltage too high), the circuit is automatically interrupted. It serves as an extra fuse and, whereas the old system reacted after there was a short circuit, this box offers a proactive solution. It reacts before a shock occurs and using lower voltage is also safer because a shock from 110V is less likely to injure a worker if something malfunctions.

In principle, these line insulations monitoring boxes can be used in every industry as a standard precaution. Specifically, this new line insulation monitoring box is a safe application for work in the vicinity of water.

The Bender line insulation monitoring box has been installed in all Boskalis mobile generators and once installed, it did not entail any additional conditions of use. This innovative device could and should be easily applied to all standard generators or electrical installations industry-wide.

FIGURE 2

The new line insulation monitoring box by Benelux Bender is a safety device for work in the vicinity of water.

Cspect's state-of-the-art drones help in safely inspecting inaccessible spaces

FIGURE 3

CSpect's drones enable the workforce to stay out of harm's way.

CSpect's flying robot is making inspections by rope access, scaffolding and cherry pickers obsolete. The CSpect drone is an intuitive, reliable and precise indoor inspection tool that reduces the number of personnel needed and alleviates the administrative burden associated with inspections. By eliminating the human interface, operations with practically zero risk can be achieved. By using CSpect's drones, the workforce stays out of harm's way while reducing downtime and inspection costs.

CSpect drones enable remote visual inspection in any indoor environment and keep workers away from hazardous areas such as confined spaces, extreme heights, and places with energised equipment. CSpect robots can be prepared for visuals within a minute and an entire inspection is performed in a matter of hours instead of days. CSpect drones have conducted inspections in complex areas, such as: hopper walls; pipe lines with a diameter bigger than 500 mm; spuds from the inside; inside transition pieces and towers of wind turbines; cranes; storage, ballast tanks; jetties; areas at heights; bridges; large boilers; and towers.

CSpect's technology includes cutting-edge drone data capture capabilities, which ensures flawless inspections from the very first flight. A typical drone-based inspection starts with a reconnaissance flight, which identifies all areas of interest deserving a closer look. CSpect's experience gathered through a wide variety of missions has shown that for most infrastructures 10 minutes is sufficient to perform the reconnaissance flight. Based on the information gathered during the reconnaissance flight, further flights are planned to more deeply inspect defined points of interest through the capture of close-up images. After each segment of the inspection the drone is brought back to the operators to review the images in detail and refine/update the inspection plan on-the-go based on actual data.

In addition, the CSpect drone is the first collision-tolerant drone and is equipped with an innovative wireless communication system that provides a live video feedback. This allows the pilot to bring the drone to the most inaccessible places up to multiple hundreds of metres beyond the line of sight. The video output is directly available to third parties, who can analyse the live footage.

The fact that the same scope of inspections is also available below water as above has been a bonus, providing sea-water cross-over inspections on board of vessels as well as ballast tank inspections. The combination of above and below water inspections makes CSpect drones unique in the market and suitable for use in the dredging and maritime industries. Most importantly, CSpect drones are approved by the major Classification Societies: Bureau Veritas, Rina and ABS, to perform inspections by means of Remotely Inspection Techniques (RIT).

MedAssist is an app for medical support at sea

No doctor on board? Ship owners agree: MedAssist gives needed medical support to ships at sea. The MedAssist Skills Application provides offline step-by-step instructions for basic medical skills and procedures on board a ship when there is no doctor present or the ship is at a remote location. The app is a low-cost way for the captain to improve his crew's medical care when they are far away from professional medical staff and facilities. It also helps maritime employers to comply with international safety regulations and legislation for medical care.

The initiative for this long-distance medical support grew from the experiences of doctors at the Emergency Control - Maritime Training (ECMT) - Training Center in Rotterdam, The Netherlands. At ECMT each year around 500 captains and officers from various companies are trained to perform medical procedures. The requests from clients for digital training and support materials for their ships, led to the development of this 'Skills app'. The Skills app contains the 18 most important (STCW) medical procedures that a captain or officer must be able to perform, such as stitching a wound, setting-up a drip, or stabilising a neck.

FIGURE 4

The MedAssist app presents information in an intuitive and simple way, using instructional audio, video and photos that give a step-by-step guide to the safe and professional preparation and execution of medical procedures and after-care.

FIGURE 5

The Skills app contains the 18 most important (STCW) medical procedures that a captain or officer must be able to perform.

The app presents information in an intuitive and simple way, using instructional audio, video and photos that give a step-by-step guide to the safe and professional preparation and execution of medical procedures and after-care. The instructions are based on the use of medical resources available on board.

Another application is the Heart App, which consists of an easy-to-use heart rate monitor and the accompanying software on a tablet. With this app, a captain or officer can make a hospital-quality electrocardiogram in a straightforward way, resulting in a PDF file. With one click this PDF can be sent to a doctor onshore to help making a faster and better diagnosis.

These apps also provide support for on board training for the crew. Personnel should take note of the topics on the apps and, for instance, with the electrocardiogram, time should be taken to practice doing this. The app also provides an overview of important phone numbers for contact with various Radio Medical Services and other practical information that may be urgently needed on board. The app also works offline and can be made available in 45 languages. At present, a patented 2-Way-Augmented Reality Application – called MedAssist Live- is being developed, so an onshore doctor can really work together with the captain to solve a medical problem in real-time.

The cost of the Skills app was only 200 euros per tablet per vessel per year, a reasonable price to pay to safeguard crew members. Ship owners have used these apps and see them as a useful addition to the mandatory medical training that their officers complete on a regular basis. Medassist.online's apps combine medical know-how, practical nautical experience and IT knowledge in a simple and effective way, taking into account the often limited bandwidth on board ships. The apps can be made available on a ship's server or on dedicated tablets in a rubber encasing.

Jan De Nul's Full Mission Simulator safely prepares crews for risky conditions at sea

The Full Mission Simulator (FMS) is a 360° simulator of a dredger's bridge where real situations can be practised in a safe environment. The simulator trains officers on project-specific ship power management of a designated vessel by setting up the parameters as they are known for a specific project area and scope of work. In this way, the crew gains an understanding of the ship and the project and can assess best approaches before operating in the real world.

In a cooperative operation amongst VDAB (the Flemish government), Jan De Nul and others at Zeebrugge, a dredging simulator was used to simulate a specific project risk. In this case, trailing suction hopper dredgers (TSHDs) needed to discharge full power through a spray pontoon on a Dynamic Positioning (DP) track. The TSHDs needed to sail with the same speed and heading, taking into account the floating pipeline forces, wind and current, in combination with limited power on the propellers. In total five sessions were organised to include masters and Officers of Watch (OOWs) of two TSHDs. The worst possible conditions were simulated in regards to power management, bridge resource management and third party pleasure vessels.

Using the Full Mission Simulator helped the crews be better prepared for the actual project risks, resulting in better operational control and thus improved safety. Based on the positive experiences of Jan De Nul and its partners, more of such exercises should be conducted when dredging close to the operational limits. This is no easy task, just as the daily work of dredging crews is not easy, and competent instructors are crucial to the successful use of the simulator.

The FMS, which was used to recreate conditions at Zeebrugge, dates from 2005 and the success of the operation led Jan De Nul to order a new model with expected delivery in 2020. The cost of the FMS is not prohibitive for the dredging industry and the results as reported by Jan De Nul, 'no incidents, no damages and no delays' makes the FMS as a safety tool worth the investment.

FIGURE 6

Using the Full Mission Simulator helped the crews be better prepared for the actual project risks, resulting in better operational control and thus improved safety.

Boskalis' remote control Floating Line Connecting System eliminates dangerous manual operations

FIGURE 7

The FLCS is based on another Boskalis innovation, the 'mooring actuator' and the coupling pontoons are specially designed for remote coupling.

Boskalis' in-house technical department has developed an innovative Floating Line Connecting System (FLCS), where floating pipes are connected safely by remote control, without the need for people to get close to the pipelines, eliminating manual operations entirely. This results in fewer crew transfers and fewer safety risks.

The high risk operation of connecting pipelines was identified by the crews doing the work and the consensus was, there must be a better way. The first step was developing a self-floating pipeline that could handle sharp materials. The flexibility of this pipeline meant that 100-metre-long pieces could be placed instead of 20 metres long as is normal with steel pipes. This meant an immediate reduction in the number of connection points so fewer people were put in risky situations less often. But still people were a necessary element. Brainstorm sessions led to various designs and demands, but it took ten years before all the pieces fell in place and a final design was made. A patent has now been applied for and the Boskalis inventors continue to look at ways to improve the design.

The FLCS is based on another Boskalis innovation, the 'mooring actuator' and the coupling pontoons are specially designed for remote coupling. The pontoons are brought into position without people entering the 'line of fire'. In so many ways, the new system represents a tremendous safety innovation. People are no longer at risk of injuring hands or fingers or come close the waterline. The system has already been applied to the project in Duqm, Oman and it will soon be rolled out and be applied to future Boskalis projects. But it is indeed a generic application for floating pipes that could be of value to others in the dredging industry.

At DEME, every day – rain or shine – begins with a Safety Moment

The search for ways to improve a safety culture is continuous. DEME's management team came up with a direct, simple proposal to make sure everyone is always aware of safety. The idea is to start every meeting with a 'Safety Moment' in which in the first few minutes of every meeting, a safety topic of choice will be discussed with all participants. To facilitate this idea, the QHSE-S department developed a straightforward tool to guide colleagues reminding them of safety when they enter the meeting room.

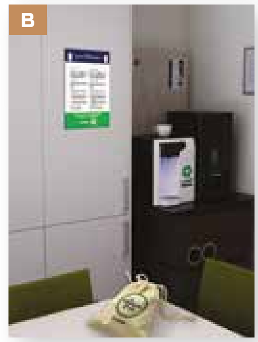
The instrument is simple: In the meeting room, a board with instructions, together with a branded cotton bag is placed on the wall. When participants enter the room they see the bag immediately. As this sight is not traditional, it immediately stands out, sparking conversation and interest. Next an individual takes the bag and passes it around the room for every employee to deposit his/her ID badge in the bag. An innocent hand then draws the lucky one who gets to present his/her prepared safety moment.

Like a pop quiz at school, you must be prepared in advance. Since the presenter is drawn randomly, all employees should have a safety moment of their choice ready at all times, so they can present it when chosen. While safety moments are by no means new in the dredging industry, DEME's approach adds an element of surprise. It forces all employees to be prepared at all times to hold a safety moment, which means that safety must be on everyone's mind all the time. By choosing a topic and researching it to give a short presentation, employees become more aware of the risks they face every day at work and the safety measures they should be taking. By sharing safety experiences and knowledge with others, employees start seeing their jobs and those of their colleagues in a different way.

DEME's 'Safety Moment' at the start of every meeting is a simple direct way to remind employees about safety and to emphasise the need for leadership, communication collaboration and engagement in staying safe.

A

B



C

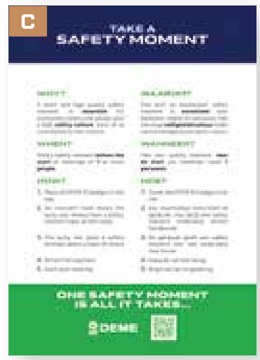


FIGURE 8

To remind colleagues of safety when they enter the meeting room, colleagues see a branded cotton bag placed on the wall [A]. An individual takes the bag and passes it around the room for every employee to deposit his/her ID badge in the bag [B]. By choosing a topic and researching it to give a short presentation, employees become more aware of the risks they face every day at work and the safety measures they should be taking [C].

Van Oord's 'Safety News Alert' is a hard-hitting film followed by open, honest team discussions

An increase in accidents during Q1 2019 led Van Oord to seek a new approach to improving safety awareness worldwide. To start, an analysis was done of the root causes of the accidents, which occurred under all sorts of circumstances, during full scale work, during routine and non-routine jobs and in all business units. Extensive research resulted in a 'Safety News Alert' that was released throughout the entire organization. This was a combination of a hard-hitting film meant to inform, make an impact and inspire, followed by open and honest team discussions that were playful, inspirational and motivating.

Via a worldwide kick-off on 14 May 2019 in a 'news cast' film, the Executive Board emphasised the importance of safety and 5 accidents were highlighted and discussed by colleagues. These were accidents to which many colleagues could relate and the film was followed by team meetings during which colleagues from all offices, projects, vessels and yards discussed safety statements in an open and honest way and made clear team agreements. These agreements and group photos were actively shared on the Van Oord intranet. The involvement and commitment on all levels – from senior management to colleagues at all work locations throughout the entire organisation made this Safety News Alert an across the board success.

The statements and toolkits provided by Van Oord were tailored to a team's work location and were set up in a creative, playful and interactive way. By involving both projects/vessels/yards and office, the tools were available for an open and honest discussion that resulted in a variety of personal and relatable team agreements. Response and participation exceeded expectations.

The strength of the entire Safety News Alert (both film and follow-up team meeting) is the usability for all employees. Supplying local managers, who act as moderators, with a clear and easy to use manual enabled them to organise the Safety News Alert at any location.

The Safety News Alert concept can easily be used by others in the dredging industry. It is important to decide on a proper script about

FIGURE 9

Released throughout the entire organisation, the 'Safety News Alert' was a combination of a hard-hitting film meant to inform, make an impact and inspire, followed by open and honest team discussions that were playful, inspirational and motivating. Photo Van Oord situations that have occurred within the company and to film these situations without any judgment, to determine dilemmas to stimulate safety discussions, to createa platform that encourages participation, and to exchange information within the organisation about the answers and actions taken by different teams.

At Van Oord the results have been clear: Since the kick-off, safety numbers are improving, safety awareness has increased and people are giving more feedback. Registrations for the safety leadership training have increased and loads of data from the team meetings has been delivered, giving Van Oord tangible data to act upon.

Falling overboard is always a danger but Jan De Nul's hopper crew found a solution

No one knows better than the crew of a dredger where the dangers lie on board a vessel. When the crew of the Capitan Nunez, a Jan De Nul trailing suction hopper dredger, pointed out that the area where the trunnion is located is a risky spot, management was listening. The trunnion is a part of a rotating joint that is inserted into cylinder that has moving parts. There are also open gaps in the railings at that spot because it is the exact location where the dredge pipe goes over the vessel's side. It is also the spot where human intervention, such as checks of the pipe heads, is needed. This gap in the railing at a point where people are actively working presents an obvious risk to someone falling overboard.

Acting on this observation, the crew of the hopper Capitan Nunez took it upon themselves to solve the problem and protect their own. Working with Jan De Nul's Technical Department, they invented a system to close the openings in the railing. They designed, constructed and welded a railing that opens and closes simultaneously with every movement of the dredge pipe. It creates a safe barrier between the working zone and the sea, without limiting the movements of the pipe. This system is automatic and needs no manual handling.

Recognising this is the most dangerous area on their ship, the crew solely invented this system and constructed this risk control. Crew of Capitan Nunez is rightly proud of this system and happy it is currently being implemented on board of other trailing hoppers as well.

FIGURE 10

On Capitan Nunez, an automated system creates a safe barrier between the working zone and the sea, without limiting the movements of the pipe.

Manual lifting is a thing of the past with IHC's hydraulic release shackles

IHC Handling Systems has developed an easy-to-use hydraulic release shackle device for lifting modules, templates, jackets and other objects, which is safer and more efficient than traditional manual handling of shackles.

A traditional shackle is a hinged metal loop secured with a quick-release locking pin that is used for lifting. The lifting operation is usually executed manually, often with multiple people working together to lift. It is a job that can be a safety hazard and which, because of the physical input from workers, increases occupational health risks significantly by increasing the chance of injuring hands and feet and putting extra burdens on backs and spines.

IHC's hydraulic release shackle device reduces these health risks to workers. By adding this hydraulic tool to a shackle it makes lifting objects in the range of 25-1,500t shackles easier and safer to handle and operate a shackle. The device is designed to be lifted above or beneath water and it is available in two versions – as a standard type, with maximum depth to 500 metres and as a deep-water type, with a maximum to 3,000 metres. Several different backup systems are possible (hot stab receptacle, double cylinders, accumulators and separate hydraulic circuits) as well as lifting pad eyes. The success of the device has led to the suggestion to make it available for a broader range of shackle weights. It is already available in the offshore industries for even bigger shackles. The device is able to work in salt laden and corrosive wind driven dust and heavy rain. And IHC is able to modify the hydraulic shackle device for a wide number of shackle brands.

FIGURE 11

By adding this hydraulic tool to a shackle, it makes lifting objects in the range of 25-1,500t easier and safer to handle and operate a shackle [A]. The device is designed to be lifted above or beneath water and it is available in two versions – as a standard type, with maximum depth to 500 metres and as a deep-water type, with a maximum to 3,000 metres. [B].

Safer and flexible, the CSpect mini ROV replaces risky diving teams

CSpect's mini ROVs are faster, cheaper and more flexible than the mobilisation of a dive team. Diving is and will always be a risky operation. Diving fatalities have a major impact on the family left behind, loss of income, lost business, insurance premium increases and high litigation costs.

CSpect uses and co-engineers world-leading mini Remotely Operated Vehicle technology to deliver a safe and cost-effective solution compared to inspections performed with divers. Their mini ROVs, which are merely the size of a basketball, are used to visually inspect underwater structures such as marine warranty; in- and out-hire surveys; hull inspections on damages, fouling, bottom doors, spud cans; quay inspections; tank inspections; touchdown monitoring; oceanography, seabed inspections and oil spill monitoring; and fish farming cages surveys. In addition, underwater inspections in lieu of dry dock for pontoons and vessels provided with azimuth thrusters (vessels where no clearances of rudder and propulsion shaft bearings can be measured) can be carried out. This is a direct saving for the customer because dry-docking a vessel for inspection can be replaced by an in-water survey, which is much cheaper to perform.

The mini ROVs are equipped with a GPS positioning system and Low-Light High Definition cameras supported by a dimmable light system with a maximum intensity of 5000 lumens, which provides superb video footage of the inspected area. A stabilised camera system is controlled by an Inertial Measurement Unit (IMU), in contrast to a camera attached to the face mask of a diver which is subject to the movements inherent to a diver. In addition, the video and images taken are not disturbed by the air bubbles of the diver, eliminating cloudy images and video recordings.

The mini ROV can dive up to 150 metre depth, can sustain 2.5 knots (whereas a diver is limited to 0.5 knots) and can stay submerged for longer periods than a diver. The mini ROV can be hand carried onto a plane and no Port Permits are required, so practically speaking, the mini ROV can be deployed almost immediately upon arrival on the worksite, without the heavy administrative burden attached to diving missions. In addition, the mini-ROV is approved by the major Class Societies (Bureau Veritas, Rina and ABS) to perform underwater inspections.

With the size and shape of a basketball, the mini ROV has a symmetric drag profile, which ensures that when the vehicle turns, it will hold its ground and not get swept downstream. It can also be equipped with a gripper, thickness gauge, spot cleaning system and micro sonar. Power is supplied by a battery system on the ROV which results in more stability. With an on board power supply, the mini ROV can work with an extremely thin tether cable, making the drag of the cable very limited compared to standard ROVs in the market.

Compared to dive teams, where a three-person operation is mandatory, the mini ROV can be deployed by one person, at any time, day or night, and can stay submerged for longer periods. Increased currents and depths are no threat and the risk of human injuries is decreased because there is no human interface underwater. The practical result is a zero risk of diving injuries and fatalities because fewer people are involved in the day-to-day operations and a safer work environment.

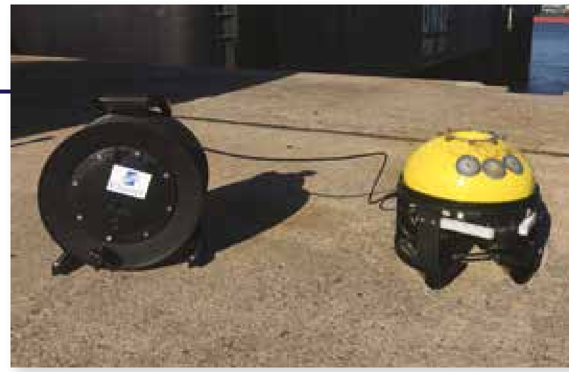


FIGURE 12

The mini ROV can be hand carried onto a plane and no Port Permits are required so the mini ROV can be deployed almost immediately upon arrival on the worksite.

Jan De Nul's hopper crew designed, built and installed a safety platform to protect their crewmates

After each dredge cycle on a trailing suction hopper dredger, the pipe operator must grease and/or inspect the underwater block of the hoisting dredge pipe. This is a dangerous job on a slippery and uneven surface. To carry out the work, the pipe operator normally needs to wear a 'fall arrest' harness and prepare extensive risk management paperwork, a time consuming task. This process on Jan De Nul's hopper Charles Darwin is now a thing of the past.

The crew of the Charles Darwin has designed, built and installed a platform, with railings, access ladders and grip polls that allow safer access to the dredge pipe's underwater block. The platform, ladders and railings are installed on the dredge pipe at the exact location of the underwater block, which reduces the chance of trips, slips and falls.

This intervention tremendously increases the safety level for the pipe operators and allows them to work more efficiently as well. According to the experienced crew of Charles Darwin, this was the best safety improvement onboard in the last year. Furthermore, it can easily be implemented onboard of all hopper dredgers without major costs. The installed platforms are designed to withstand all dredging conditions during project execution. The original design, sketched by the crew of Charles Darwin, was calculated and approved

FIGURE 13

The crew of the Charles Darwin has designed, built and installed a platform, with railings, access ladders and grip polls that allow safer access to the dredge pipe's underwater block.

by the Fleet Management to insure that the installation would be built to last and get the proper material, and to set up a maintenance regime. After approval, the crew set to welding, constructing and installing the platform themselves. This working process can easily be communicated to all crews on hopper dredgers. They are all crews with similar experience level as on the Charles Darwin and are perfectly capable of implementing this system as well.

Implementation of this improvement requires that the ship has a particular dredge pipe configuration and room to build the access platform. The costs are limited, needing some steel and grid mesh plus a day's work for the ship's welder.

The work of the pipe operator can now be done in 5 minutes instead of 20. Efficiency is higher and the risk 'cost' is lower. Simple safety solutions are often the most effective ones. Listening to the people in the field and giving them the freedom to come up with ideas is often the best way to improve safety in their working environment and conditions.

Van Oord's pre-assembled onshore 'CPS Storage & Handling system' avoids the risks of crane lifting

When a subsea power cable is laid, there is an area where the cable may be subjected to increased dynamic forces, which the cable is not necessarily designed to survive over the lifetime of the installation. A Cable Protection System (CPS) is used to protect the subsea power cables against these negative impacts over the long term. The installation of this protective CPS is traditionally done using an on board crane. The crane picks up all parts of the CPS independently from an open top container and then places the parts on the cable highway for installation. This is an operation that has many risks including dropping objects and suspended loads falling on workers. To improve safety and eliminate these risks during the lifting operations, including those caused by the assembly of CPS on deck, a special 'CPS Storage & Handling system' has been designed and mobilised on Van Oord's cable laying vessel 'Nexus'. This new system eliminates the need for offshore craning to install the CPS protection during cable installation.

With this new CPS Storage & Handling system the CPS are completely assembled onshore and placed as a whole in racks. Then, when the vessel is in port, the complete rack is placed on the vessel. This saves time and handling of different components and mitigates many risk factors. By eliminating offshore lifting there are no more suspended loads, no one walks below the suspended load and there can be no dropped objects. The system also features a vertical sliding ramp. This ramp, placed in front of the CPS rack is movable, and is pulled by a winch, avoiding the need for manual handling, and allowing workers to slide out any CPS at any time. In addition, the system is weatherproof because no lifting by crane is necessary, operations can continue regardless of whether wind speeds exceed the crane limits. All these factors have created a safer work environment during day-to-day operations.

The CPS rack can store up to 48 CPS systems, in different layers. Any CPS size can be installed at any time. This means there is more flexibility during cable installation, which results in higher production.

The system was designed digitally (in 3D) and after completion of the design, and all calculations were done, the system was directly built and installed on the Nexus. The system is operational and works as expected. Although the CPS is more efficient and installation is done more quickly, which leads to higher production rates and a shorter installation cycle, the real plus is the increased safety for crew.

FIGURE 14

The CPS rack can store up to 48 CPS systems, in different layers.

Boskalis reduces risk by securing containers with simple container twist locks

When mobilising for (short-term) projects, there are always a few things that cost time, and always recur, and are almost always last minute. One of these things is sea-fastening and securing containers twist locks. Normally a bolt or a piece of solid round welding is used to safeguard a container's twist lock. This process takes approximately 45 minutes per container. Boskalis has adopted new and simple system for securing container twist locks that requires no welding and no grinding, saves time and can be implemented safely during mobilisation.

A small thin plate of 1.5 or 2mm slides into the dovetail where the twist lock comes on top. As soon as the container is placed on it, you simply bend the lip up, and the container twist lock is sea fastened and secure. The idea to implement this came after doing several quick mobilisations in recent years. Although all containers were placed on the right spot, they still had to be secured. Realising that this is a recurring task that frequently has to be done at the last minute, Boskalis sought a more efficient method and found the answer by looking at the Logistics industry.

The system can be used on every project where dovetails and twist locks are used and container twist locks need to be sea fastened. It is especially useful on projects where the deck lay-out changes often. By using this simple secure plate, this task can be done more quickly, saving time and money, and the process is safer. Applying it to the dredging industry is straightforward and it is already being used by Boskalis on several projects.

FIGURE 15

To save time and work more safely during mobilisation, Boskalis has adopted new and simple system for securing container twist locks that requires no welding and no grinding.

The winner of the IADC's Safety Award 2019 will be announced at the IADC's Annual General Meeting in New Dehli, India on 17 October 2019.

INTERVIEW

DIRECTOR OF ECOSHAPE AND ADAELTA HENK NIEBOER

‘WE HAVE TO PUT MORE EFFORT INTO THE DEMAND SIDE, **FIND WAYS TO BRIDGE THE VALLEY OF DEATH.’**

Engineering and entrepreneurship, preferably in an international setting, have determined the course of Henk Nieboer’s path. As a director of Witteveen+Bos, he showed how to conquer new markets in the field of hydraulic engineering across borders. With the innovation programme Building with Nature, he proved that sustainability and engineering can go hand-in-hand providing added value for society. Self-employed in Adaelta, he now focuses on the next challenge: to convince decision makers that nature-based solutions are the answer.

Interview by Astrid Kramer

You started working for Witteveen+Bos right after your graduation in 1987. In 2017, you stepped down as director and in July of this year, you left the company completely. How does it feel to say goodbye to the company where you worked over 30 years?
Well, it feels quite good. It has been great working for Witteveen+Bos for such a long time and it has been great until the end. But although it was a really great time, a good experience to work there and I look back with pride and much pleasure, it is also good that I left.

When you became a director of Witteveen+Bos, you defined three goals: internationalisation, increasing entrepeneurship and putting Witteveen+Bos on the map in the field of delta technology. Did you leave Witteveen+Bos because you accomplished your goals?
Well, with these goals, there is of course always more work to be done. So, I wouldn't say 'mission accomplished'. My main reason for leaving was that it was time for a new challenge. I had worked in many different positions, first as a specialist engineer, then as a project leader, group leader followed by business unit leader. In 2006, I became a member of the board of directors and in 2017, I was advisor to the board. When you have been in charge of a whole company, it is a very special experience to step down and remain in the company. In the end, I felt that my career within the company was complete.

Which project during your Witteveen+Bos career are you most proud of?
Actually, there are quite a few. When I travel from the east of The Netherlands to the northwest, I am always very proud when I pass the aqueduct Hardersluis between Harderwijk and Flevoland and the naviduct, a special class of navigable aquaduct, at Enkhuizen. In the early nineties, I was the project leader of the team that came up with the concepts of these objects and they were actually built.

I am also very proud of the Kapuk project on Java, Indonesia. This involved a reclamation area of 1100 hectares which was designed into a residential area. A construction of five polders, areas with managed ground water tables which we made using the old-fashioned Dutch art of constructing ring dykes, building pumping stations, pumping the water out, letting the soil ripen and bring in a drainage layer. If you go there now, it is mainly middle-class housing areas. I am proud to walk around there and see all the families living happily in their houses.

You have to think about which factors are driving the system.

In August 2015, you became director of EcoShape. When did you become aware of Building with Nature?
In the early 2000s there was a platform in The Netherlands called Waterfront where a group of people informally discussed the organisation and improvement of the knowledge infrastructure in our sector. We already spoke about Building with Nature because at that time, the need for nature-based solutions was apparent. Especially the dredging industry was having trouble with environmental regulation and legislation. So, already at that time we were thinking about what to do about that. But in the end, we didn't proceed with starting EcoShape because we didn't have the means and concluded that the level we were talking at was too low.

And then the dredging industry stepped in?
Building with Nature escaped from my view for a few years until we, from the hydraulic engineering sector, were called to the office of Van Oord in Rotterdam in 2006. Frank Verhoeven of Boskalis – and IADC's current president – and John van Herwijnen of Van Oord told us they wanted to initiate an innovation programme focusing on the environmental aspects of our work. We had brainstorms and tendered for subsidy from Economic Affairs. We lost, resubmitted and lost again. But then in the coalition agreement of the cabinet Balkenende-Bos, innovation money was reserved from which we received a contribution starting in 2008. The programme at that time was financed 50-50% by the public and private sector.

I always thought it was an important initiative of the dredging sector, not only because the theme is important, but also

Meet Henk Nieboer

In the run-up to becoming a director of Witteveen+Bos in 2005, Henk Nieboer defined his ambition to bring internationalisation, entrepreneurship and a top position in the field of delta engineering to the company. Over the span of a decade, he successfully taught employees worldwide how to start something new from scratch.

In 2019, he decided it was time to set a new goal and start something new himself. Guided by his entrepreneurial spirit and passion for hydraulic engineering, he left Witteveen+Bos and founded his own company Adaelta. He is now dedicated to enabling the showcasing of nature-based solutions worldwide in the field of climate adaptation projects.

Additionally, he currently holds the appointed position of Honorary Consul of the Republic of Kazakhstan in The Netherlands and director of EcoShape, the foundation based in Dordrecht, The Netherlands, which runs the innovation programme Building with Nature.

because it was a good opportunity for knowledge institutes and public and private parties to work together. I had a lot of experience with the innovation programmes of the 1990s which were financed by our government from natural gas revenues. I was always very disappointed in them because these programmes were always managed by either knowledge institutes or public parties, and the private sector could only learn from the results in reports or courses. In my opinion, this was not very efficient. It was my ambition to create opportunities where private and public parties could work together with knowledge institutes on innovation questions or challenges. I saw the innovation programme Building with Nature as a good opportunity to prove that this would work.

So in 2008, the Building with Nature movement really started up?

Yes, I put a lot of effort in the initial brainstorming and formation of ideas. Later on, in the programming of the topics, I became a member of the scientific advisory board – the only one who didn't have his PhD. After completion of the first programme, I was a member of the international usability review board who assessed whether the results were useful or not. When it was decided to start the second phase in 2012, I thought my time was up. I asked another representative of Witteveen+Bos to follow up and decided to concentrate on being a director of Witteveen+Bos. But three years later, EcoShape came back and asked if I wanted to fulfil the position of director. My primary reaction was: 'this is not possible because I am a director of Witteveen+Bos' but while saying it, I realised I was going to do it anyway because I wanted it.

What do you like about working at EcoShape?

First of all, it is a great topic to be working on. A completely new way of looking at solutions and products in our sector and trying to get a grip on that. How does it work? What do we need to know? We now have developed quite a lot of knowledge. Of course, we are nowhere as far as we are with the so-called 'grey infrastructure' so there is still a lot to learn. A lot of progress is possible. What I also like is the challenge that it is still quite difficult to get nature-based solutions accepted by clients. We need to overcome that.

The content, the challenge is interesting, but the way of working is also really interesting. To work with a small group of focused people, driving a much larger group of people, creating the context so that they can do their research. It is a wonderful job.

Despite the positive results of the Building with Nature pilots and the effort made by the EcoShape partners to promote the concept, full-scale applications seem rare.

If you look in the *Engineering with Nature Atlas* by the US Army Corps of Engineers, you see dozens of project examples that have been realised. Some of them do not meet our criteria of Building with Nature solutions but many of them do. Application of the concept does exist.

However, one of the problems is: everybody wants it, but nobody buys it. There is still the perception among infrastructure managers that Building with Nature solutions are relatively unpredictable. So, if I buy it, *what* am I buying? What will it be in five- or ten-years' time? Because it is a natural system, it is difficult to predict how it will behave and what the management efforts are to maintain it. In our global society, there is a lot of willingness to invest a lot of money up front in a project but there is no willingness to compete for cash flow to do long-term maintenance. Capital expenditure is okay but operational expenditure should be as low as possible.

At the EcoShape conference last year, there was a presentation by Cees Brandsen, one of the directors of Rijkswaterstaat. He said he *wants* nature-based solutions, but he *needs* to know the predictability. That is something we cannot give him yet; not with the same reliability as with grey infrastructure. We do not know what the mangrove will look like after five years. Therefore, we should work with asset managers and convince them, show them or experiment together with adaptive management so that they learn to cope with and appreciate the unexpected developments that nature-based solutions will demonstrate.

Are there other issues with Building with Nature?

Well, one thing is: what am I buying? The other thing is, defining the term. There is no common perception on what a Building with Nature solution is. People have different ideas about it. Sometimes you are talking to people and when you get down to the details, you understand that you have been talking about different things. We need to have some kind of common language and visualise it. We need to create showcases – exactly what EcoShape did – to prove to people that it works. You can show it, take people there so you can make them experience it.

There is no transactional language for nature-based solutions. With a monofunctional design you can determine, calculate or show the dimensions and determine if the desired function will be fulfilled for an acceptable amount of money. But nature-based solutions are always multi-purpose, they bring different benefits, but it is very hard to quantify these benefits and very often these benefits are not a benefit for the client that you are working for. Because they produce multiple benefits; they also influence more stakeholders compared with a traditional solution. This also means that in a planning process you need to involve more stakeholders which is complicated in the planning process.

One of the arguments used for lack of upscaling is that money is available, but that it cannot be reached. Do you agree with this?

Yes, and this is exactly what I want to dedicate my further career to. We need to go to these people, the financers. We need to go out and talk to them, find out what is keeping them from investing in it and try to remove these barriers for them. To connect them to other parties and show that nature-based solutions will work.

Is there a good tool or method to calculate how much is lost and how much is earned?

A societal cost benefit analysis is such a tool. You have to make a cost benefit analysis across the whole spectrum, not only monetary aspects but also other aspects. However, this is far from settled science. People are still investigating a lot but there is not yet consensus on how to measure all

Brundtland Report's Definition of Sustainability

In 1983, the then Secretary General of the United Nations approached Gro Harlem Brundtland to assume an enormous undertaking: forming and chairing the World Commission on Environment and Development (WCED). The independent commission was tasked with conceiving 'a global agenda for change', addressing topics of long-term environmental strategies for the upcoming millennium, ways to encourage collaboration between countries at diverse stages of economic and social development, and ways to deal with environmental concerns among others. This would require defining perceptions of the issues at hand.

The ensuing 1987 publication of *Our Common Future*, widely known as the Brundtland Report, defined sustainable development as: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. This definition laid the fundamental groundwork for future initiatives. After the Brundtland Report's publication, the commission was dissolved and replaced with an organisation named after the report, Center for Our Common Future, to address the findings of the report. Although this organisation ceased activity in 2002, other initiatives culminated with the United Nations Sustainable Development Goals (UN SDGs) in 2015.

these positive aspects. As long as we do not have consensus on the method, we cannot compare projects. You cannot say this project has more value than that. Like in tendering, you cannot say this contractor is better than that one.

If we understand how to build with nature, then creating new nature through infrastructural development is the next step.

Sustainability has become an important concept in engineering over the last two decades. What is the key to sustainability for you?

I am always very much impressed by the original Brundtland definition stating that we should provide the needs of the present generation without compromising the opportunities for future generations to meet their needs. At the moment, we are not there yet. Therefore, we have to take a look at all our processes, all our activities to see where we can optimise these in such a way that we can be convinced that in the future, people also meet their needs. That is, for me, the key aspect of sustainability.

Both the book *Dredging for Sustainable Infrastructure* and the Building with Nature concept talk about placing a project in a bigger picture. How big should this picture be?

This fully depends on the assignment or question you are working on. Nature-based solutions can exist at relatively small scales but also on enormous scales. With nature-based solutions, your ambition is to make use of the natural system as much as possible, so you have to understand the system very well.

Therefore, you have to start each project with a good system analysis. For instance, where is the sediment coming from? What is driving the sediment? Where does it silt up? What is keeping the sediment in place? What does the accumulation lead to? You have to think about which factors are driving the system. The area that you want to study may be small, but the sediment source may be a river 20 kilometres away.

If the functioning of your nature-based solution depends on the supply of sediment, you also have to take a good look at where the river gets its sediment from. How will that be in the future? If you see that there is quite a lot of sediment runoff from an area that will be urbanised in the coming ten years, then it could be quite dangerous to rely on a nature-based solution. The system analysis determines the scale you have to look at.

What do you think is the relevance of Building with Nature for the industry and society in general?

I see Building with Nature as an opportunity for our sector not only to innovate or to get a better image but also to reach out to new potential clients and stakeholders. It brings us new products with which we can solve societies' challenges. If you work in a limited segment of society, for instance the oil and gas industry or infrastructure, and you tailor or optimise your product for that segment, it will be very difficult to reach out to new clients.

For society as a whole, I see that willingness to work with nature means that our projects are going to contribute to the conservation of nature. As soon as human functions become dependent on the conservation of nature, the natural processes, humans will do their best to conserve this nature and to keep the processes ongoing. It is an opportunity for conservation but also for restoration. If we understand how to build with nature, then creating new nature through infrastructural development is the next step. This is needed because so much has already been lost. If we learn how to work with nature in the future, then we may be able to see every infrastructure project as an opportunity to revive something that has been lost instead of creating even more loss.

Is there a role for EcoShape to train people in Building with Nature?

We contribute to several courses, for instance to the Building with Nature curriculum at the TU Delft and TU Twente. I also spoke at the IHC summer school this year. We do contribute but it is a relatively modest role.

Good news is that we have now have a professor in ecological engineering, Peter Herman. He knows exactly what Building with Nature is and he is training a new generation of engineers. Stefan Aarninkhof and Mark van Koningsveld have also become professors. They both worked at EcoShape for several years and are among the founding fathers of this concept in The Netherlands.

What about the training of decision makers and clients outside The Netherlands?

One of the results of this phase of the EcoShape programme will be a book of concepts. This is not a technical book or a book with guidelines but a book showing people what can be achieved with Building with Nature solutions. We want to present it in such a way that decision makers get passionate and inspired. They do not have to live it through first-hand, but they have to facilitate it. We want to touch them with inspiration.

Then again, this book will not be enough. You have to go out there yourself and talk to people, and I think that is mainly a task for the consortium members of EcoShape. After all, EcoShape is not a goal in itself, it is a supporting vehicle for the ambitions of our partners.

What is EcoShape?

Founded in 2008, EcoShape is the foundation that manages the public-private innovation programme known as Building with Nature (BwN). After four years of consultations, BwN was launched in 2012 to shift the direction of engineering solutions toward concepts that encourage building with natural materials as well as utilising the forces and interactions present within the natural system.

EcoShape brings together diverse parties including contractors, engineering companies, research institutions, government and NGOs to develop and spread knowledge about BwN. These parties cooperate under a common goal: to provide durable solutions in the water, by letting nature to do its work. Through collaboration with ecologists and economists, innovative hydraulic infrastructure solutions can be conceived which serve the environment, society, and economy.

The foundation is dedicated to creating awareness of BwN solutions, developing tools to support the implementation and assessment of BwN solutions through field experiments, and expanding its knowledge base. Through pilot projects, EcoShape acquires knowledge which can be applied in other locations around the world, supporting its belief that knowing the system is key to designing a sustainable solution.

One BwN solution is the project along the Norfolk coast in the UK, known as Sandscaping which is based on the Sand Engine concept developed along the Delfland coast in The Netherlands. Photo Chris Taylor

How do you keep expanding your vision on sustainability in your personal life?

By reading an enormous amount of information. Ten years ago, we were frontrunners on this topic but currently there are so many related initiatives worldwide. I am following these through social media and try to keep track of the publications, absorbing as much as possible.

It is incredible how much information is out there. In Europe, you have Think Nature, OPLA, Enable and Horizon 2020 programmes. The World Bank is publishing guidelines. The ADB is doing it. IUCN is making a standard. But the thing is, everybody is using their own terms and slightly different definitions. This adds to the confusion at the clients and recipient's side. That needs to be solved in the future. There are several attempts to make a central platform, some more alive than others.

Has there been a project in your career which you would like to redo according to the Building with Nature philosophy?

In 1989 I worked on the Kapuk project in Indonesia and one day I stood in a strip of mangroves, perhaps some 25 metres wide. I realised this relatively quiet area would soon be a city and the monkeys in the trees would move away. Behind the mangrove was open water, perhaps 20 or 25 metres, followed by the levy, protecting the houses behind it. We decided to keep a strip of mangrove intact as the first wall of sea protection. What is very interesting now is that over the years, the strip of mangrove expanded to over 100 metres deep. And the monkeys came back.

If I could go back to the beginning of my career with the knowledge I now have, I would make a masterplan for the Bay of Jakarta using the concept of mangrove formation. Create an enormous city inside a mangrove, make real parks, green areas for people to walk in and create conditions for this coast to accrete so there will be a very large band of mangrove in front of it.

One of the big issues of the bay of Jakarta is that there are still 10.000 people earning their money as traditional fishermen. Maybe we could then create living areas for these people on this spontaneously accreting land.

How do you see the future for nature-based solutions outside of The Netherlands?

I see it as very bright. Everybody wants them. Everybody thinks they need them. One way or another they will be used and created. There is a lot of research being done. The only thing is that – but you see this in many sectors – there is a period between the supply and demand called the 'valley of death'. We saw demand and we reacted with a new proposition. Now we have a proposition which has become much more than we originally wanted but we do not see large scale demand for this proposition yet. We have to put more effort into the demand side. That is what we still have to cope with. We have to find ways to bridge the valley of death.

It is very often the case that the science and policy world want it. What we need to do – besides upscaling – is to connect this world. We have to connect knowledge institutes, governmental bodies and public parties to the private sector.

Why is this connection important?

What I see is that they are mainly talking among themselves. It was the same in The Netherlands. The large knowledge development programmes executed with the revenues from natural gas were done without any involvement of the private sector. How was the private sector able to learn what was done? By attending courses and reading the publications. That does not work. You have to *experience* the whole process together and *live* it in order to be able to *apply* it.

Does large-scale application of Building with Nature fit in with competitive commercial hydraulic engineering?

I see no reason why not. I think the good thing about the commercial world is that if a client wants to work with a commercial party, he is forced to clearly express what he needs in order to make a contract. If you want to realise a solution, be it nature based or not, you have to know what you need, what you expect from it. Because, otherwise, the other party cannot design what you need or cannot make what you asked for.

What about sharing knowledge in a competitive industry?

Well you have pre-competitive and competitive knowledge. Pre-competitive knowledge, for instance, is the impact of a group of worms on soil ripening. If you know this, you can use the worms and the silts as construction material by making use of the worms. But what you do with the construction material, what you design and how you use it to create added value, that is the creative part. That you cannot share. Here you can prove your added value.

The current Building with Nature programme ends in 2020. Is there a future for EcoShape?

EcoShape manages the innovation programme Building with Nature. If the programme stops, then EcoShape in its present form has no use anymore. Therefore, the real question is: Will there be a third programme?

I see potential for that. Along with many people, I am convinced that it would be great if we could come up with a new programme. However, experience with previous four-year innovation programmes showed that it is important that follow up programmes are better shaped in a different formula, because otherwise the programme may lose its charm and energy. Therefore, we need to look for a different formula and maybe also for different people. With new ambitions, new insights. This is currently being discussed.

If I could go back to the beginning of my career with the knowledge I now have, I would make a masterplan for the Bay of Jakarta using the concept of mangrove formation.

Resumé

2015–Present
Director of EcoShape

www.ecoshape.org

2015–Present
Member of Supervisory Board of Deltares

www.deltares.nl

2012–Present
Chairman of the Kazakhstan Chamber of Netherlands Council for Trade Promotion

www.internationaalondernemen.nl

2009–Present
Board Member of Witteveen+Bos Pension Fund

2010–2016
Vice President of KIVI

www.kivi.nl

2017–2019
Engineer of Witteveen+Bos

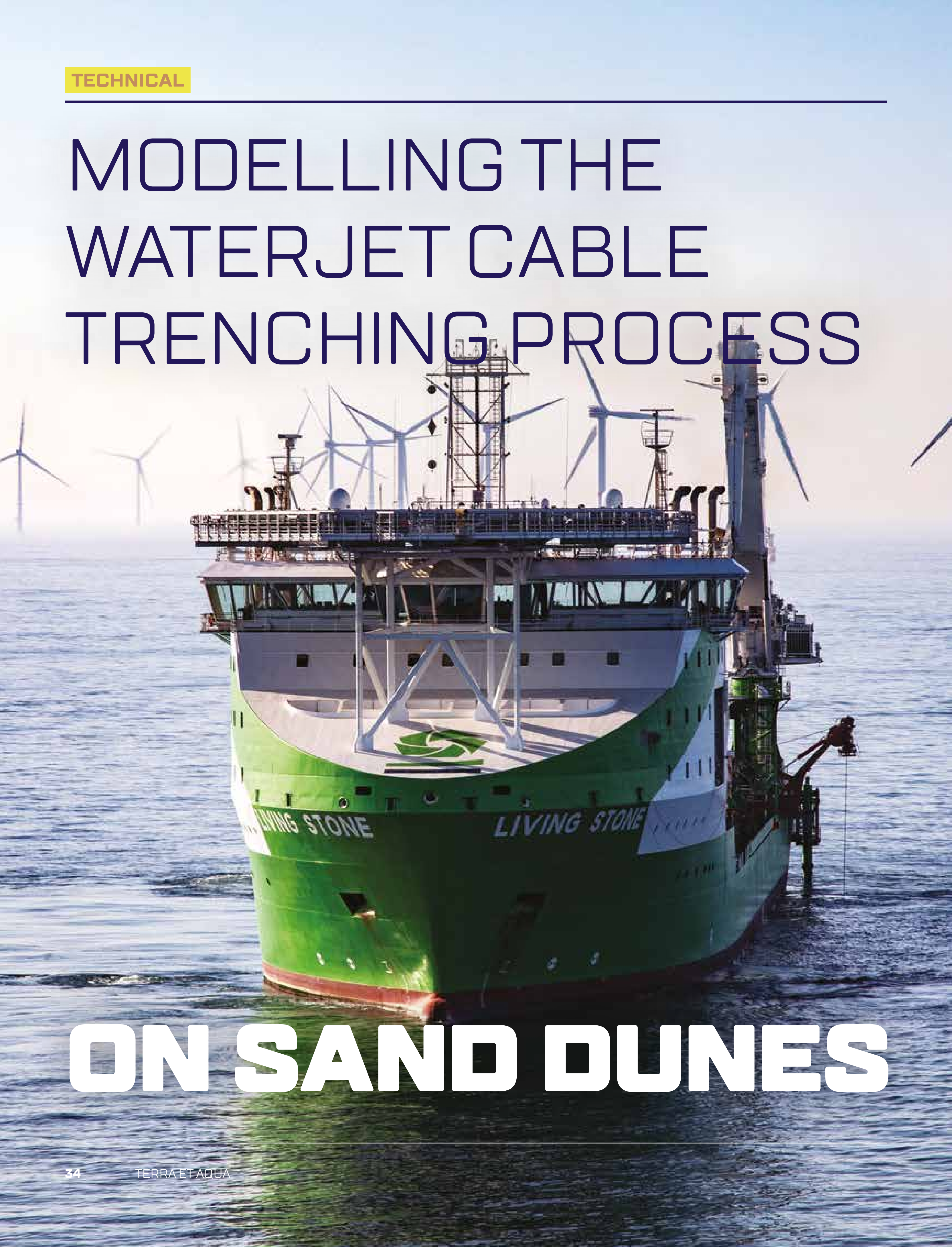
2006–2017
Director of Witteveen+Bos

1987–2006
Various positions at Witteveen+Bos

www.witteveenbos.com

TECHNICAL

MODELLING THE WATERJET CABLE TRENCHING PROCESS ON SAND DUNES



Numerous offshore wind farms have been recently installed in the southern part of the North Sea. Their infield and export cables are buried for protection against dropped or dragged objects. In sandy soils, burial is carried out by remotely operated tracked vehicles. Two swords with waterjets are used to fluidise the sand and generate a backward flow of the water-sediment mixture. The area's highly variable seabed topography, characterised by sand waves and mega-ripples, can influence the trenching process. At the moment, it is not possible to make an accurate estimate of the influence of sand dunes on the trenching process.

The trench formation process is split into two parts: a front section where the seabed is eroded by waterjets (erosion model) and a rear section where the sand grains are settling in a backward flow (sedimentation model).

The erosion model is made based on the assumption that the specific energy required to fluidise sand is equal to the specific energy required to cut sand with a blade. The blade is considered to have a small blade angle and to operate at zero meter water depth, following Miedema (2015). For a given jetting configuration and trench dimensions, this results in a limiting trencher velocity. A volume balance between situ soil, waterjet flow and entrained flow gives the backwash flow rate and concentration. The last two are used as input for the sedimentation model.

The sedimentation model relates water flow, sediment transport, bed evolution and trench width evolution, based on the shallow water equations. The governing equations represent horizontal momentum and mass conservation of the water-sediment mixture and horizontal mass conservation of the sediment. A numerical one-dimensional finite volume model is proposed which is solved on a staggered grid.

An elastic cantilever beam model is used to determine the cable shape as it sinks in the trench. Subsequently, the depth of lowering of the cable is determined by the intersection of the cable and trench shape. The combined fluidisation, sedimentation and cable model is validated against full-scale field data.

Introduction

Offshore cables are commonly buried for protection against dropped or dragged objects. In sandy soils, burial is carried out by remotely operated tracked vehicles, see Figure 1A. Two swords with waterjets are located in

Offshore cables are commonly buried for protection against dropped or dragged objects.

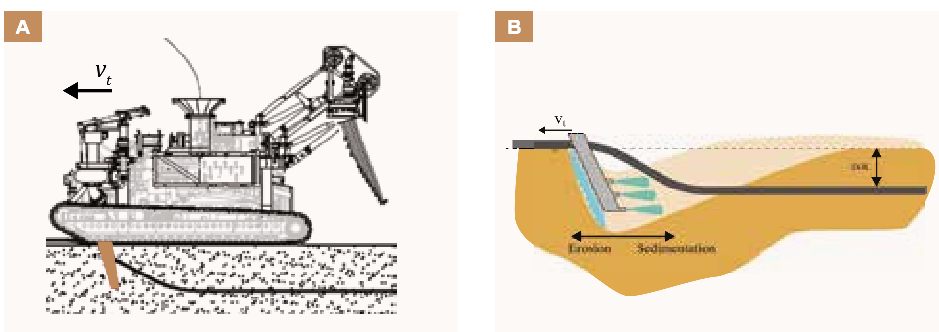


FIGURE 1

Typical waterjet trencher with the jet swords indicated in red (A) as well as an illustration of the erosion, sedimentation and cable component of the jet trenching model (B).

between the tracks of the vehicle, on either side of the cable. Water is pumped through the swords to fluidise the sand and generate a backward flow of the water-sediment mixture, see Figure 1B. The cable located on the seabed is lowered into the water-sediment mixture due to its own weight. Due to waves, tides and currents, sandy seabeds are often not flat but can contain seabed features such as sand waves and mega-ripples. When burying a cable in these seabed features, the achieved depth of lowering shows an oscillating profile with the maximum depth of lowering achieved at the peaks of these features and minimum at their troughs. Models to predict the achieved depth of lowering are currently not able to account for the influence of seabed features, therefore an attempt has been made in modelling the effect of seabed features on the depth of lowering.

To make an accurate prediction of the depth of lowering of a cable, modelling is divided into three parts: a model for the erosion section, a model for the sedimentation section and a model for the cable deflection. The erosion model determines the maximum trencher velocity at which the seabed can still be eroded. Furthermore, it provides flow input values for the sedimentation model. The sedimentation model determines the shape of the trench behind the vehicle. By iteratively calculating the cable shape in the cable deflection model, the point of intersection with the trench shape is determined. It is assumed that cable remains fixed in this point of intersection, hereby giving the achieved depth of lowering. See Figures 2 and 7A for an illustration of the jet trenching model working principle.

Erosion model

At the front of the trench, sand is eroded by the water flow from the jet swords. It is assumed that the erosion process results in well-mixed backward flow of water and sediment. Via a volume balance the backward flow rate and sediment concentration is determined. Via a specific energy approach the maximum trencher velocity is determined at which the jets are still able to sufficiently erode the seabed. It is assumed that below this trencher velocity there are no problems to erode the seabed.

Limiting trencher velocity using a specific energy approach

Miedema (2015) derived a theory for the in-situ production of jets in a draghead. It is based on the assumption that the specific energy required to fluidise sand is equal to the specific energy required to cut sand with a blade, having a small blade angle and at zero-metre water depth. The in-situ production Q_{situ} (sand plus pore water) of the jet trencher is given by equation (1), where d_{max} and b_0 are initial trench depth and width respectively and v_t is the trencher velocity. The in-situ production can also be defined by dividing jet power P_j by specific energy E_{sp}.

$$Q_{situ} = A_{trench} \cdot v_t = d_{max} \cdot b_0 \cdot v_t = \frac{P_j}{E_{sp}}$$

(1)

The specific energy is determined by assuming it to be equal to that of non-cavitating cutting, given by equation (2). Where ε is dilatency, k_m is mean permeability and ρ_w is seawater density. Horizontal force coefficient c_1 must be calibrated using experiments, Miedema (2015) suggests a value of 0.12. This value is based on calibration with experiments done by *Combinatie Speurwerk Baggertechniek* published by Jong (1988).

$$E_{sp} = c_1 \cdot \rho_w \cdot g \cdot h_i \cdot v_t \frac{\varepsilon}{k_m}$$

(2)

For cutting sand with a blade the parameter h_i is the layer thickness. Since the jet swords have numerous jets spaced vertically, this does not directly relate. A reasonable assumption is to consider the trench as a whole and therefore assume h_i to be equal to the trench depth d_{max}. The ratio of mean permeability to dilatancy can be approximated using the Kozeny Carman equation, resulting in the following relation.

$$\frac{k_m}{\varepsilon} \approx 10 \cdot k_0$$

(3)

Total jet power P_j is given by the product of jet pressure and flow rate, where flow rate is determined by jet pressure p_j and nozzle diameter D_j. By combining the equations mentioned before, the maximum trench depth d_{max} is found as a function of soil parameters, jetting parameters and trencher speed v_t. Since the sword depth is an input, the maximum trencher velocity can be determined by the intersection of sword depth and maximum trench depth d_{max}.

$$d_{max} = \left[\frac{p_j \cdot n_j \sqrt{\frac{2p_j}{\rho_w}} \cdot \frac{\pi}{4}(\alpha_c \cdot D_j)^2 \cdot 10 \cdot k_0}{c_1 \cdot v_t^2 \cdot \rho_w \cdot g \cdot b_0}\right]^{1/2}$$

(4)

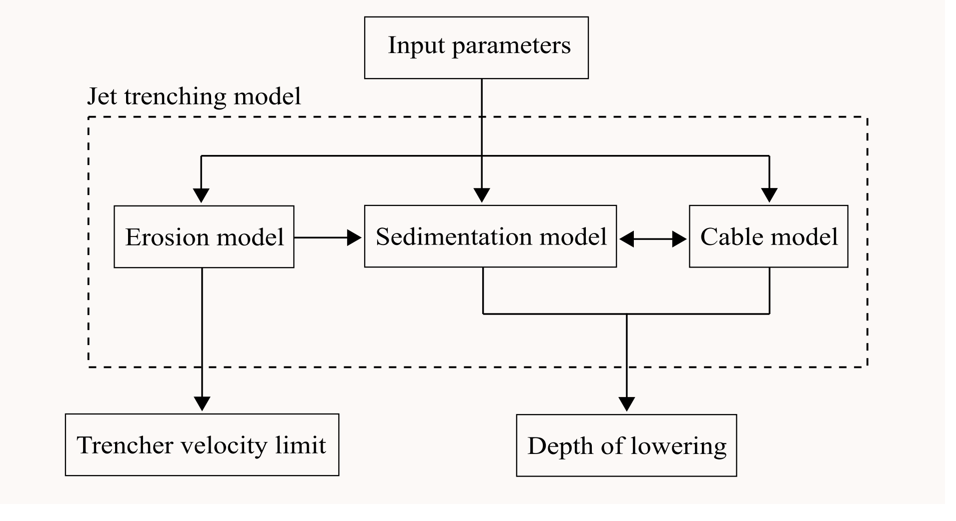


FIGURE 2

Schematisation of the interaction between erosion, sedimentation and cable model with corresponding outputs.

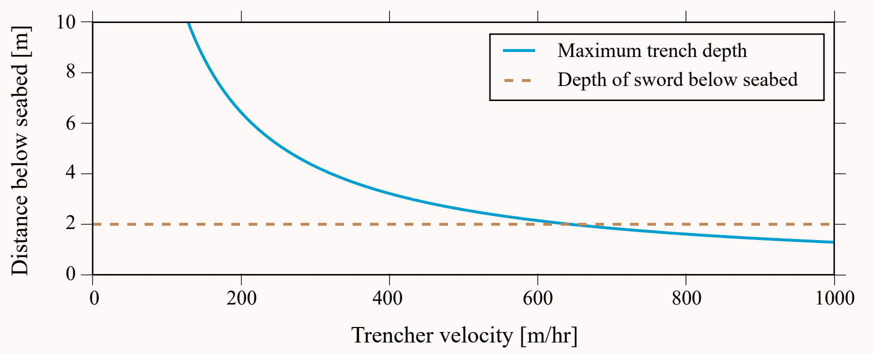


FIGURE 3

Maximum trench depth based on the specific energy approach (blue line) and depth of sword below the seabed (dashed red line). Plotted example is for typical trencher parameters.

An example of this relation is given in Figure 3 from which can be concluded that the trencher should not have any problem to fluidise the seabed up to a trencher velocity of approximately 600 m/hr.

Volume conservation

To determine the flow rate and concentration at the interface between the erosion and sedimentation section a volume conservation is applied. The flow rate and concentration are used as input for the sedimentation model. The interface flow rate Q_i is simply determined by the sum of the in-situ soil flow rate Q_{situ}, waterjet flow rate Q_j and flow rate of clear seawater entrained in the flow Q_E, see equation (5) and Figure 4.

$$Q_i = Q_j + Q_{situ} + Q_E =$$
$$(Q_{j,fwd} + Q_{j,iwd} + Q_{j,bw}) + Q_{situ} + Q_E$$

(5)

In which Q_j is the total jet flow rate and thus the sum of forward, inward and backwash jets, see equation (5). Jet flow rates are calculated by using the Bernoulli theory, see equation (6) for the flow rate of a single nozzle, ignoring internal pressure losses.

$$Q_{j,single} = \sqrt{\frac{2 \cdot \Delta p_j}{\rho_w}} \frac{\pi}{4} (\alpha_c \cdot D_j)^2$$

(6)

In-situ flow rate

In-situ flow rate Q_{situ} is defined as the maximum trench cross sectional area times the trencher velocity. Maximum trench depth is given by the depth of the swords below the seabed plus a certain overdepth h_{OD}. The over-depth is calculated as a fraction (α_{OD}) of maximum trench depth d_{max}, calculated by the specific energy approach. By using this method, the over-depth is dependent on trencher velocity, jetting power and seabed permeability. After calibration a reasonable assumption was found to be α_{OD} = 0.03.

$$h_{OD} = \alpha_{OD} \cdot d_{max}$$

(7)

The initial trench width b_0 is assumed to be approximately the same as the sword separation distance (outside to outside), plus a small margin. The in-situ flow rate is now given by equation (8).

$$Q_{situ} = v_t \cdot A_{trench} = v_t \cdot (h_{sword} + h_{OD}) \cdot b_0$$

(8)

Entrainment of ambient water

A certain amount of ambient water will entrain the flow before reaching the transition between erosion and sedimentation. Due to the complex flow pattern and lack of experimental data it is difficult to say which mechanisms are taking place. Therefore, to estimate the entrainment flow rate some simplifications and assumptions have to be made.

- Flow entrainment is based on entrainment calculations for free non-cavitating jets.
- Water is only entrained at the backside of the jet (see Figure 5A). On the front side of

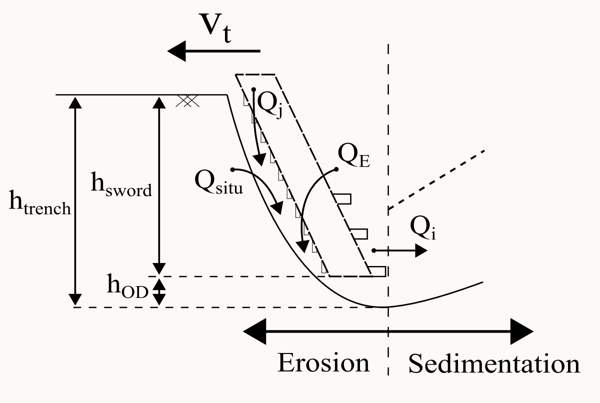
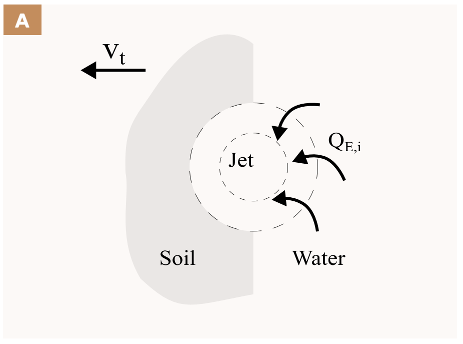


FIGURE 4

Flow idealisation of the erosion section; volume balance of in-situ, jet and entrained flow rate.



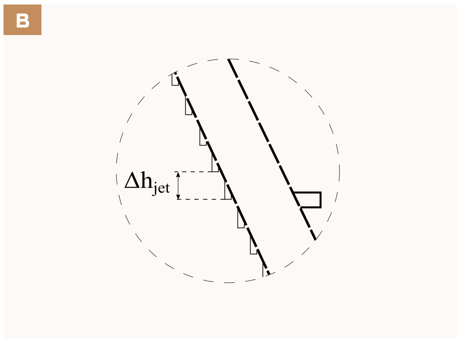


FIGURE 5

Cross-section of jet flow where water is only entrained at the backside (A), an illustration of vertical jet spacing (B).

the jets, in-situ soil is loosened which is not considered as entrainment but is included in the volume conservation.

- Water is entrained in an individual jet over a distance equal to the vertical spacing between individual jets, Δh_{jet} (see Figure 5).
- Water is only entrained in the forward jets located on the top half of the jet swords, the inward and backwash jets are neglected.

The total entrained flow rate is determined by the summation of entrainment per individual jet. For a single jet sword the number of forward jets at the top half of the sword is given by N. Consequently, the total entrained flow rate is given by equation (9).

$$Q_E = 2 \cdot \sum_{i=1}^{N} Q_{E,i}$$

(9)

Of which the entrainment for a single jet, for a distance from zero to Δh_{jet} *is given by* equation 10.

$$Q_{E,i} = \alpha_E \cdot \pi \int_0^{\Delta h_{jet}} r_u(s) \cdot u_u(s)\, ds$$

(10)

In a free turbulent jet, two regions can be defined: a region of flow development and a region of fully developed flow. For the flow development region, the entrainment coefficient is half of the fully developed flow region entrainment coefficient. For a free non-cavitating jet, a reasonable assumption is α_E = 0.085 in the fully developed flow region and a value of k = 77 for the empirical constant k, as given in Nobel (2013). Also the development of the uniform flow velocity u_u and jet radius r_u is different in the flow development region and region of fully developed flow. Analytical expressions are derived in Lee and Chu (2003) and are given by equations (11), (12), (13) and (14).

$$\text{For } s < s_{dr}: \quad u_u(s) = u_0 \frac{D_j\sqrt{k/2}}{s + D_j\sqrt{k/2}}$$
$$r_u(s) = \frac{1}{\sqrt{2k}} s + \frac{1}{2} D_j$$

(11, 12)

$$\text{For } s \geq s_{dr}: \quad u_u(s) = \frac{1}{2}\sqrt{\frac{k}{2}}\, u_0 \frac{D_j}{s}$$
$$r_u(s) = \sqrt{\frac{2}{k}}\, s$$

(13, 14)

The position s_{dr} where the transition from flow development region to developed flow region is, can be determined by $s_{dr} = k/2 \approx 6.2D_j$. Now, equations (10), (11), (12), (13) and (14) can be combined and simplified resulting in equation (15). The first term gives the entrainment in the flow development zone and the second term is the entrainment in the developed flow region up to a distance Δh_{jet}

$$Q_{E,i} = \pi \frac{\alpha_E}{2} \int_0^{6.2D_j} \left(\frac{1}{\sqrt{2k}} s + \frac{1}{2} D_j\right)\left(u_0 \frac{D_j\sqrt{k/2}}{s + D_j\sqrt{k/2}}\right) ds + \frac{\pi}{2}\alpha_E \cdot u_0 \cdot D_j\left(\Delta h_{jet} - 6.2 \cdot D_j\right)$$

(15)

Output to sedimentation model

The flow rate and concentration are determined by equations (16) and (17). Where the entrained flow rate is corrected by a factor $(1\text{-}c_0)$. This correction results from the assumption that the entrained water is not completely sediment-free but has a concentration equal to the output concentration. Equation (16) is therefore implicit and must be solved iterative.

$$c_0 = \frac{(1 - n_0) \cdot Q_{situ}}{Q_{situ} + Q_j + Q_E \cdot (1 - c_0)}$$

(16)

$$Q_0 = Q_{situ} + Q_j + Q_E \cdot (1 - c_0)$$

(17)

Sedimentation model

The sedimentation model describes the backward flow containing water and suspended sediment. Input variables used from the erosion model are initial trench dimensions, flow rate and sediment concentration. Included in the sedimentation model is breaching of trench sidewalls, entrainment of ambient water and erosion/sedimentation of the trench bottom. Breaching is included via the active wall velocity, v_{wall} in Figure 7B. The sidewalls are assumed to be and remain vertical. Furthermore, it is assumed that the material coming from the side walls is mixed instantaneous in the backward flow, hereby conserving the rectangular trench shape. All main parameters are illustrated in Figures 7A and B. Notable are the constant concentration c and velocity u over the vertical axis, and the distinction between initial seabed porosity n_o and re-settled seabed porosity n_s.

Shallow water equations for flow in a rectangular channel with variable cross-section

To model the flow of water and sediment behind the trencher, the so-called Shallow Water Equations (SWE) *are* used. Since they were first proposed by Saint Venant (1871), these equations are also referred to as the Saint-Venant equations. It is assumed that the flow is one-dimensional, hereby reducing the system of equations to only three.

- continuity of the total fluid volume (water plus sediment), see equation (18)
- continuity of sediment volume, see equation (19)
- conservation of momentum, see equation (20)

Furthermore, it is assumed that all quantities are uniform over the cross-section and vertical velocities are neglected. To simplify the solving of the momentum equation, it is rewritten so that the concentration is not present in the time derivative anymore, similar to He et al. (2014) and Cao et al. (2004).

$$\frac{\partial(hb)}{\partial t} + \frac{\partial(hub)}{\partial x} = (v_E - v_{sed}) \cdot b + 2 \cdot v_{wall} \cdot d_{tr}$$

(18)

$$\frac{\partial(hbc)}{\partial t} + \frac{\partial(hbuc)}{\partial x} = -v_{sed}(1 - n_s)b + 2 \cdot v_{wall}(1 - n_0)d_{tr}$$

(19)

$$\frac{\partial(hbu)}{\partial t} + \frac{\partial(hbu^2)}{\partial x} + \frac{1}{2} g \frac{\partial(bh^2)}{\partial x} = S_{bed} + S_f + S_{sed} + S_c + S_w$$

(20)

Where h is flow height, b is trench width, u is mean flow velocity and c is sediment concentration. Furthermore, v_E is the entrainment velocity, v_{sed} the sedimentation velocity (i.e. vertical velocity of the bed), v_{wall} the active wall velocity due to breaching, n_0 and n_s are the porosity of the initial and re-settled seabed respectively and d_{tr} the trench depth. The source terms on the right hand side in the momentum equation in equation (20) are given separately in equations (21), (22), (23), (24) and (25) for improved readability. These source terms S_{bed}, S_f, S_{sed}, S_c and S_w account for the bed gradient, bed friction, sediment exchange, concentration gradient and divergence of the trench width respectively. The source term S_w is not present in the classical form of the shallow water equations where the width is considered constant. However, it arises in the derivation of the shallow water equations in a channel of varying width, see for example Robert and Wilson (2011) or Siviglia et al. (2008).

$$S_{bed} = -g \cdot h \cdot b \left(\frac{\partial z}{\partial x} - \tan(\theta)\right)$$

(21)

$$S_f = -u_*^2(2 \cdot d_{tr} + b)$$

(22)

$$S_{sed} = v_{sed} \cdot u \cdot b \frac{(\rho_{settled} - \rho)}{\rho}$$

(23)

$$S_c = -\frac{1}{2} g \cdot b \cdot h^2 \frac{(\rho_s - \rho_w)}{\rho} \frac{\partial c}{\partial x}$$

(24)

$$S_w = \frac{1}{2} g \cdot h^2 \frac{\partial b}{\partial x}$$

(25)

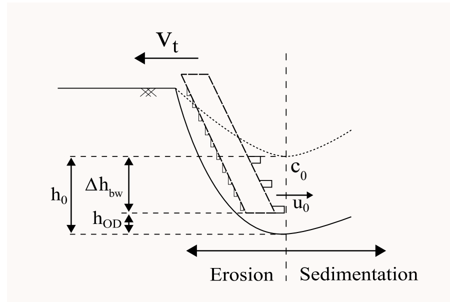


FIGURE 6

Output values to the sedimentation model in case of a supercritical flow (u_0 and h_0) or subcritical flow (Q_0).

The system of equations is completed with the description of the evolution of trench width b in time, see equation (26), and evolution of bed evolution z in time, see equation (27).

$$\frac{\partial b}{\partial t} = 2 \cdot v_{wall}$$

(26)

$$\frac{\partial z}{\partial t} = v_{sed}$$

(27)

Lastly, the definition of mixture density ρ is given by equation (28) and the density of the seabed after it has re-settled again by equation (29).

$$\rho = c \cdot \rho_s + (1 - c) \cdot \rho_w$$

(28)

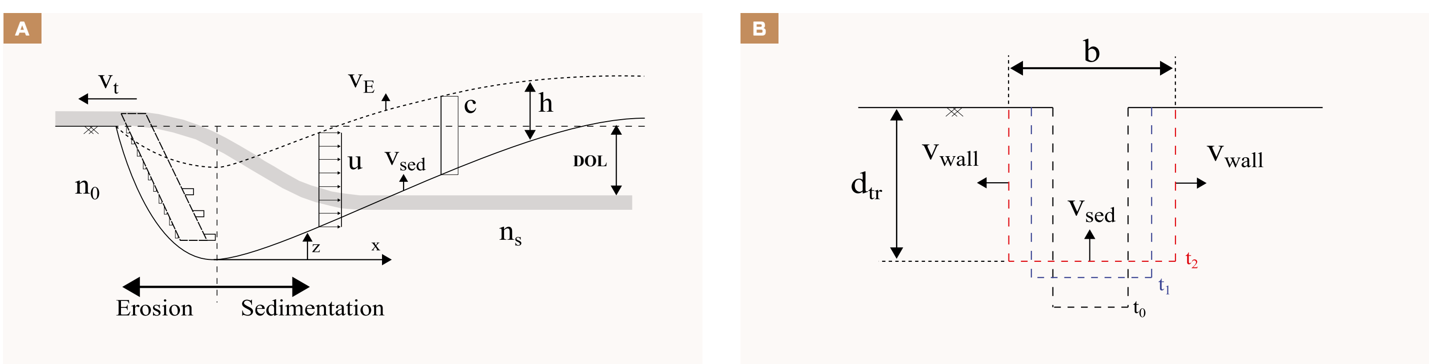


FIGURE 7

Trench side view (A) and cross-section (B), showing all main parameters used in the sedimentation model. ($t_0 < t_1 < t_2$).

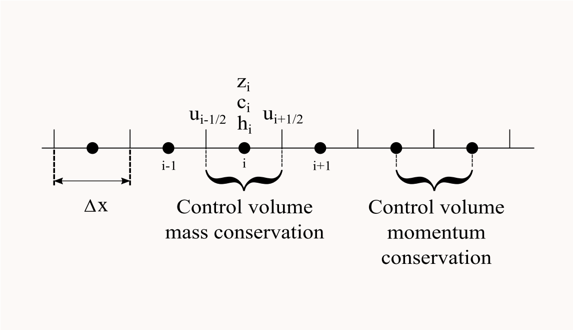


FIGURE 8

Definition of the discrete variables on the staggered grid, with corresponding control volumes.

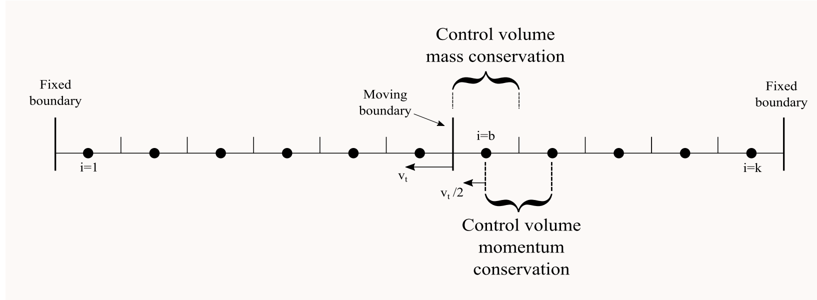


FIGURE 9

Illustration of spatial grid, indicating the moving and fixed boundaries. Growth velocity of control volumes for mass and momentum conservation are indicated by v_t and $v_t/2$ respectively.

$$\rho_{settled} = n_s \cdot \rho_w + (1 - n_s) \cdot \rho_s$$

(29)

One-dimensional finite volume scheme on a staggered grid

The equations are solved on a one-dimensional staggered grid, using a finite volume scheme. In the staggered grid the flow height h and concentration c are discretised at the center of each cell. The flow velocity u is discretised at the interfaces between the cells. Corresponding to the discretised variables, the control volume for continuity equations is centered around the h, c and u variables, whereas the control volume of the momentum equation is centered around velocity u and is thus staggered with respect to the continuity control volume (see Figure 8). The change in width is only a function of the wall velocity which is a known constant, see equation (26). Therefore, the width is known at every grid point and every time step and thus no approximations are required. The continuity equation for the total volume and the continuity equation for the sediment volume are discretised explicit in time and upwind for the fluxes, see equations (30) and (31). The variables that are not defined on the grid are denoted with a hat and determined via an upwind approximation. Time steps are indexed by superscript n and space steps by subscript i.

The momentum equation is discretised on a staggered grid, see equation (32) for the discretised equation.

With the discretised source terms given by equations (33), (34), (35), (36) and (37).

$$\frac{h_i^{n+1} b_i^{n+1} - h_i^n b_i^n}{\Delta t} + \frac{\hat{h}_{i+1/2}^n u_{i+1/2}^n b_{i+1/2}^n - \hat{h}_{i-1/2}^n u_{i-1/2}^n b_{i-1/2}^n}{\Delta x} = [(v_E)_i^n - (v_{sed})_i^n] b_i^n + 2 v_{wall} (d_{tr})_i^n$$

(30)

$$\frac{h_i^{n+1} b_i^{n+1} c_i^{n+1} - h_i^n b_i^n c_i^n}{\Delta t} + \frac{\hat{h}_{i+1/2}^n b_{i+1/2}^n u_{i+1/2}^n \hat{c}_{i+1/2}^n - \hat{h}_{i-1/2}^n b_{i-1/2}^n u_{i-1/2}^n \hat{c}_{i-1/2}^n}{\Delta x}$$
$$= -(v_{sed})_i^n (1 - n_s) b_i^n + 2 v_{wall} (1 - n_0) (d_{tr})_i^n$$

(31)

$$\frac{\hat{h}_{i+1/2}^{n+1} b_{i+1/2}^{n+1} u_{i+1/2}^{n+1} - \hat{h}_{i+1/2}^n b_{i+1/2}^n u_{i+1/2}^n}{\Delta t} + \frac{h_{i+1}^n b_{i+1}^n (\hat{u}_{i+1}^n)^2 - h_i^n b_i^n (\hat{u}_i^n)^2}{\Delta x}$$
$$+ \frac{1}{2} g \frac{(h_{i+1}^n)^2 b_{i+1}^n - (h_i^n)^2 b_i^n}{\Delta x}$$
$$= (S_{bed})_{i+1/2}^n + \left(S_f\right)_{i+1/2}^n + (S_{sed})_{i+1/2}^n + (S_c)_{i+1/2}^n + (S_w)_{i+1/2}^n$$

(32)

$$(S_{bed})_{i+1/2}^n =$$
$$-g \hat{h}_{i+1/2}^n b_{i+1/2}^n \left(\frac{z_{i+1}^n - z_i^n}{\Delta x} - \tan(\hat{\theta})_{i+1/2}^n \right)$$

(33)

$$\left(S_f\right)_{i+1/2}^n = -(u_*^2)_{i+1/2}^n [2 \cdot (d_{tr})_{i+1/2}^n + b_{i+1/2}^n]$$

(34)

$$(S_{sed})_{i+1/2}^n =$$
$$(v_{sed})_{i+1/2}^n \, u_{i+1/2}^n \, b_{i+1/2}^n \frac{\left(\rho_{settled} - \hat{\rho}_{i+1/2}^n\right)}{\hat{\rho}_{i+1/2}^n}$$

(35)

$$(S_c)_{i+1/2}^n = -\frac{1}{2} g \left(\hat{h}_{i+1/2}^n\right)^2 (c_{i+1}^n - c_i^n) \frac{(\rho_s - \rho_w)}{\hat{\rho}_{i+1/2}^n}$$

(36)

$$(S_w)_{i+1/2}^n = \frac{1}{2} g \left(\hat{h}_{i+1/2}^n\right)^2 \frac{b_{i+1}^n - b_i^n}{\Delta x}$$

(37)

The evolution of trench width in time and the bed evolution in time is given in discretised version by equations (38) and (39) respectively.

$$\frac{b_i^{n+1} - b_i^n}{\Delta t} = 2 \cdot v_{wall}$$

(38)

$$\frac{z_i^{n+1} - z_i^n}{\Delta t} = (v_{sed})_i^n$$

(39)

To prevent the trench width from diverging unbounded, the width evolution is stopped when the trench depth has decreased up to a certain threshold value. This threshold value is set at 0.05 metres. Furthermore, the mixture density at the cell faces is given by equation (40).

$$\hat{\rho}^n_{i+1/2} = \rho_s \hat{c}^n_{i+1/2} + \rho_w\left(1 - \hat{c}^n_{i+1/2}\right)$$

(40)

As stated before, the variables not defined on the grid are denoted with a hat and are determined via an upwind approximation (see equations 41, 42 and 43).

$$\hat{h}^n_{i+1/2} = \begin{cases} h^n_i & if\ u^n_{i+1/2} \geq 0 \\ h^n_{i+1} & if\ u^n_{i+1/2} < 0 \end{cases}$$

(41)

$$\hat{c}^n_{i+1/2} = \begin{cases} c^n_i & if\ u^n_{i+1/2} \geq 0 \\ c^n_{i+1} & if\ u^n_{i+1/2} < 0 \end{cases}$$

(42)

$$\hat{u}^n_{i+1/2} = \begin{cases} u^n_{i-1/2} & if\ \frac{1}{2}\left(u^n_{i-1/2} - u^n_{i+1/2}\right) \geq 0 \\ u^n_{i+1/2} & if\ \frac{1}{2}\left(u^n_{i-1/2} - u^n_{i+1/2}\right) < 0 \end{cases}$$

(43)

The sedimentation velocity v_{sed}, entrainment velocity v_E and friction velocity u_* are defined as a function of h, u and c on either the cell centers or faces. The explicit upwind approximations are used when a variable that is not defined on the grid is required.

Treatment of moving boundary cell

The trencher is moving to the left in a fixed grid, thus being located in different grid cells in time. Due to stability issues, it is not possible for the trencher boundary to move exactly one grid cell every time step. It will take several time steps for the trencher to move one grid cell. As a result, the boundary cell – denoted by subscript b – will grow in size with velocity v_t for the continuity control volumes – see equation (44) – and with velocity $v_t/2$ for the momentum control volume. See Figure 9, where Δx^n is the old boundary cell size and Δx^{n+1} is the size of the boundary cell in the new time step. The flux going through the left boundary should therefore be corrected with the growth velocity of the boundary cell.

$$\Delta x^{n+1}_b = \Delta x^n_b + v_t \cdot \Delta t$$

(44)

To give the treatment of the boundary cell in a readable expression, the continuity equation for shallow water flow with constant width is used in equation (45). This is a simplified version of equation (18), with all the source terms included in variable S.

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} = S$$

(45)

For an explicit treatment of the source terms and the fluxes, the discretised expression of equation (45) is now given by equation (46), which can be solved for h^{n+1}_b.

$$\frac{h^{n+1}_b \Delta x^{n+1}_b - h^n_b \Delta x^n_b}{\Delta t} =$$
$$= S^n_b \cdot \Delta x^n_b - \left[(hu)^n_{b+1/2} - \left(h(u + v_t)\right)^n_{b-1/2}\right]$$

(46)

Empirical equations for model closure

The last unknowns in the set of equations are the active wall velocity v_{wall}, sedimentation velocity v_{sed}, entrainment velocity v_E and friction velocity u_*. The wall velocity for a vertical wall is given by equation (47) (Rhee, 2015), where k_0 is initial permeability, given by equation (48) by Adel (1987), φ is the internal friction angle, $\Delta = (\rho_s - \rho_w)/\rho_w$, ν is kinematic viscosity, n_0 initial porosity and D_{15} 15th percentile grain size.

$$v_{wall} = -10 \cdot k_0 \cdot \Delta \cdot \frac{\sin(\phi - \pi/2)}{\sin \phi} =$$
$$-10 \cdot k_0 \cdot \Delta \cdot \cot(\phi)$$

(47)

$$k_0 = \frac{g}{160 \cdot \nu} D^2_{15} \frac{n^3_0}{(1 - n_0)^2}$$

(48)

The sedimentation velocity is given by equation (49), where S and E are sedimentation and erosion flux respectively and ρ_s is sediment density. For a detailed explanation of the sedimentation and erosion fluxes, see Rhee (2010).

$$v_{sed} = \frac{S - E}{\rho_s \cdot (1 - n_s - c)}$$

(49)

The entrainment velocity is included via equation (50) where entrainment coefficient α_E is determined via an empirical function in equation (51) proposed by Parker et al. (1987). The function convergences to 0.075 for non-stratified flow. The Richardson number is defined as $Ri = g' h/u^2$, with reduced gravity $g' = g(\rho_m - \rho_w)/\rho_w$ where ρ_m is mixture density and ρ_w water density.

$$v_E = \alpha_E \cdot u$$

(50)

$$\alpha_E = \frac{0.075}{(1 + 718 \cdot Ri^{2.4})^{1/2}}$$

(51)

The friction velocity is included to account for the friction of the flow at the bed and sidewalls of the trench. The friction velocity is given by equation 52, where f is an empirical factor and u the layer averaged flow velocity. A bed friction factor of f = 0.024 is used, within the range mentioned in Garcia (1990).

$$u_* = \sqrt{\frac{f}{8}} \cdot u$$

(52)

Boundary and initial conditions

On the left (moving) boundary, the flow height, width, concentration and velocity are imposed. In the case of a subcritical flow it is sufficient to specify only the flow rate instead of both the height, width and velocity. However the volume flux trough the moving boundary is $h \cdot b(u + v_t)$, which cannot be replaced by a flow rate q due to the presence of v_t. Therefore, flow velocity u_0 is determined manually as an input, and can be tweaked to make sure the simulation is stable.

The right boundary is an outflow boundary, where a zero-gradient boundary condition is imposed. For this assumption to be valid, fluctuations should be minimal towards the right boundary. The initial conditions are therefore chosen such that the bed elevation and trench width are constant close to the right boundary. To achieve this, the initial location of the moving boundary is set at a certain distance (default 5 metres) from the right boundary. The bed elevation is set at zero and the flow velocity, height and width are set equal to the output values of the erosion model. The bed elevation and trench width are then constraint such that they will remain constant in this section.

Stability of the scheme

For the scheme to be stable it has to satisfy the Courant-Friedrichs-Lewy (CFL) condition, given by equation 53. Where CFL is the

FIGURE 10

Comparison of the dam-break analytical and numerical solution for the staggered upwind scheme. Shown is flow elevation (A) and velocity (B), snapshot at T = 9 seconds.

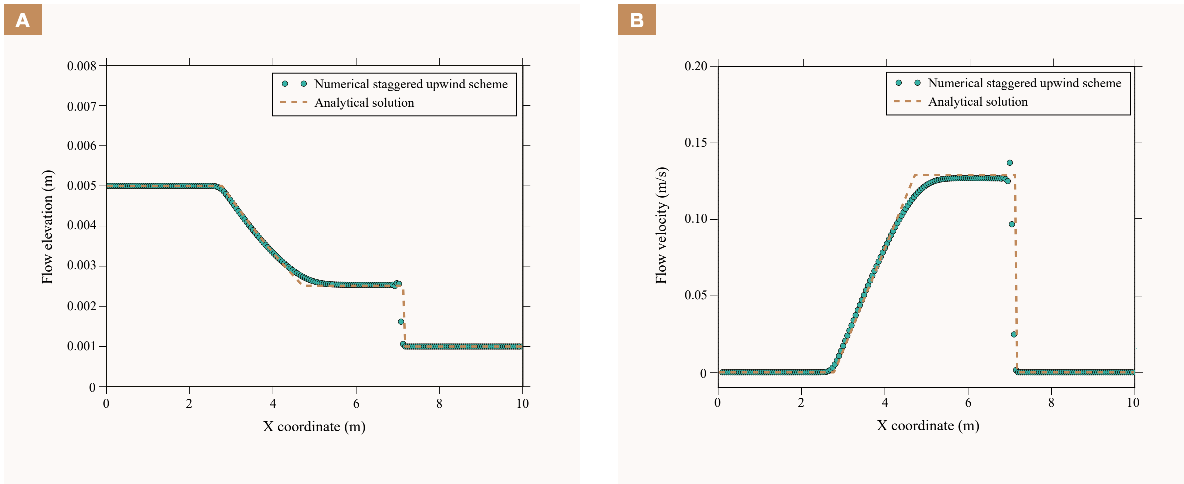
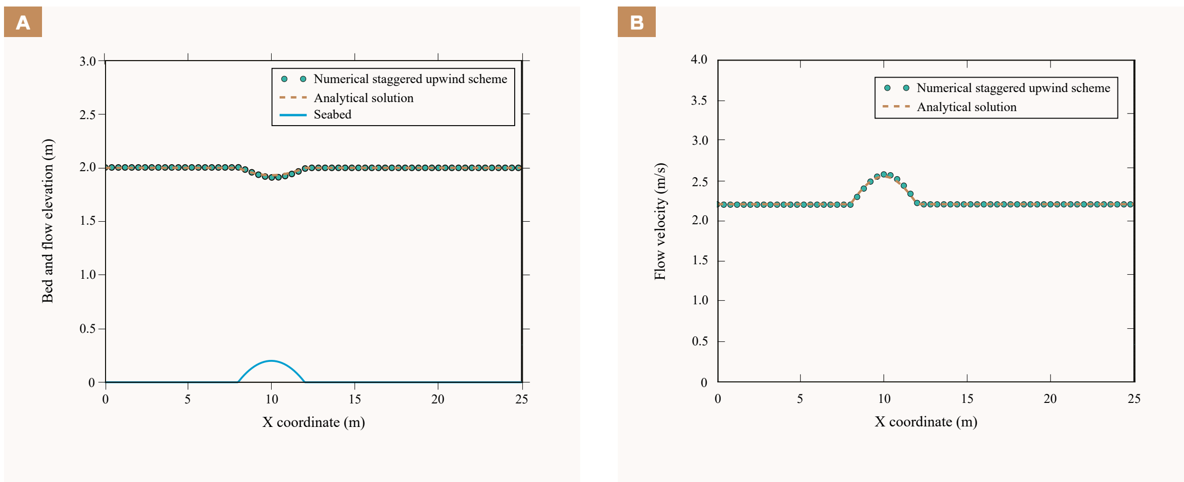


FIGURE 11

Comparison of analytical and numerical solution of the staggered upwind scheme for a subcritical flow over a bump. Shown is flow elevation (A) and velocity (B).



dimensionless CFL number, u_{max} is the maximum velocity in the domain, Δt the time step and Δx_{min} the smallest possible grid size in the domain.

$$CFL = \frac{|u_{max}| \cdot \Delta t}{\Delta x_{min}} \leq 1$$

(53)

The trencher boundary moves to the left in the grid in time, dependent on trencher velocity and time step. In one-time step, the boundary cell will grow by a distance equal to Δx_{min}, which is also the smallest grid size occurring in time. The CFL condition for this cell is given by equation 54. From this relation it can be concluded that the CFL condition for the boundary cell can only be fulfilled if the trencher velocity is greater or equal to the flow velocity ($v_t \geq |u_{max}|$). In other words, the stability of the scheme, with regard to the CFL condition for the boundary cell, is independent of the time step. However, since a quite robust scheme (explicit, upwind) is used, the CFL number can be higher than one. Also, since there is only one grid cell that does not fulfill the CFL condition, the error created dampens out in the rest of the domain.

$$CFL = \frac{|u_{max}| \cdot \Delta t}{v_t \cdot \Delta t} = \frac{|u_{max}|}{v_t}$$

(54)

Verification

This section aims to verify whether the proposed numerical scheme is able to capture the phenomena that can occur in shallow water flows. Examples of these phenomena are propagating shocks and transitions between subcritical and supercritical flows and vice versa (hydraulic jumps). To do this verification, the numerical scheme is applied on several scenarios for which exact analytical solutions are known. Analytical solutions are taken from the SWASHES library (Delestre et al., 2016), in which numerous analytical solutions for the shallow water equations are summarised. Four different cases are used for this verification; a dam-break, subcritical flow over a bump and transcritical flow over a bump with and without a hydraulic jump. Results are given in Figures 10, 11, 12 and 13.

Results of the verification show that the scheme is shock-capturing and performs reasonably well. Some deviation in the discharge is observed at the hydraulic jump location in Figure 13. However, this is not an issue within the current application of the scheme since an overall trench profile is the objective and not accurate local values of the discharge.

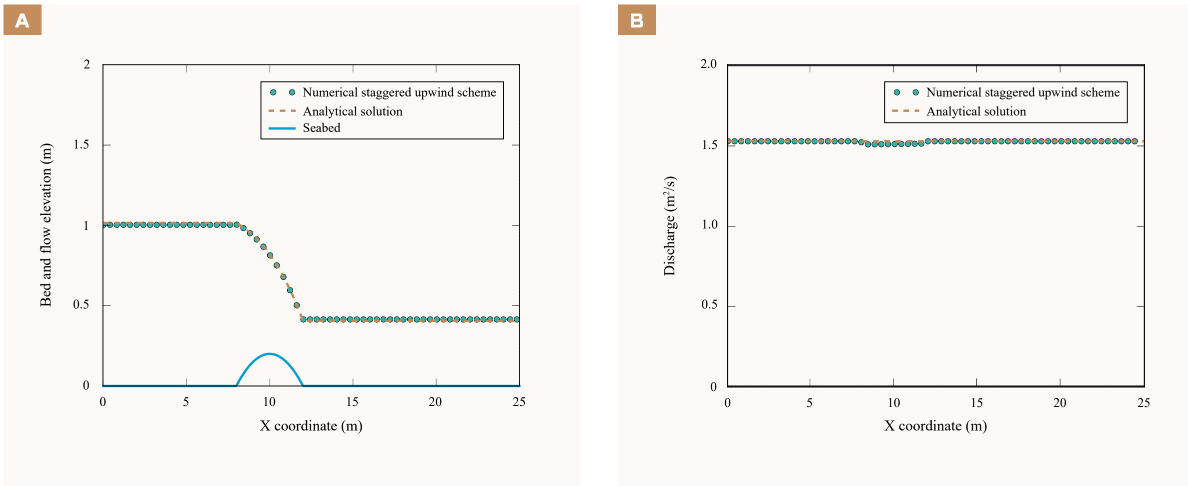


FIGURE 12

Comparison of analytical and numerical solution of the staggered upwind scheme for a transcritical flow over a bump, without hydraulic jump. Shown is flow elevation (A) and discharge (B).

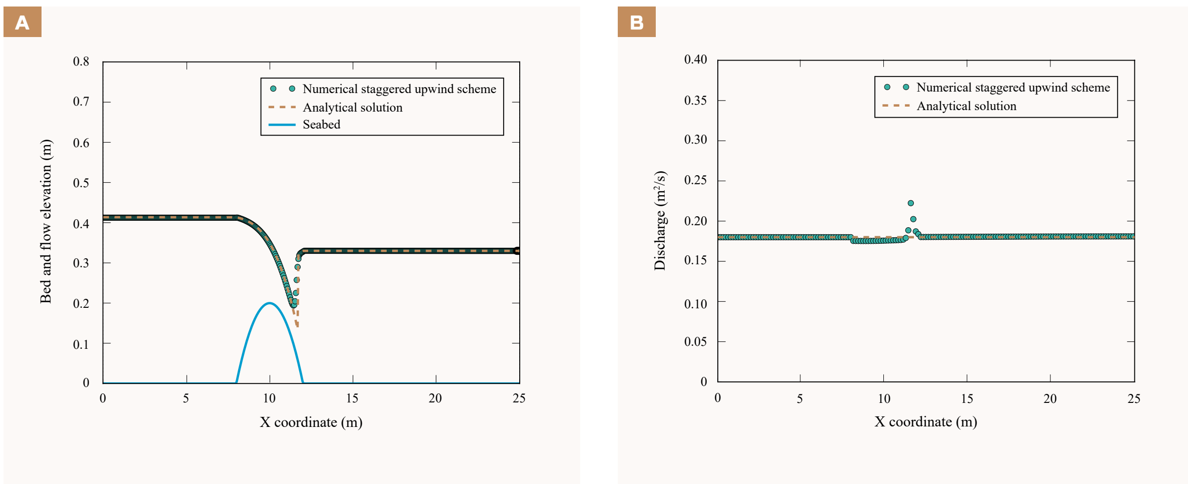


FIGURE 13

Comparison of analytical and numerical solution of the staggered upwind scheme for a transcritical flow over a bump, with hydraulic jump. Shown is flow elevation (A) and discharge (B).

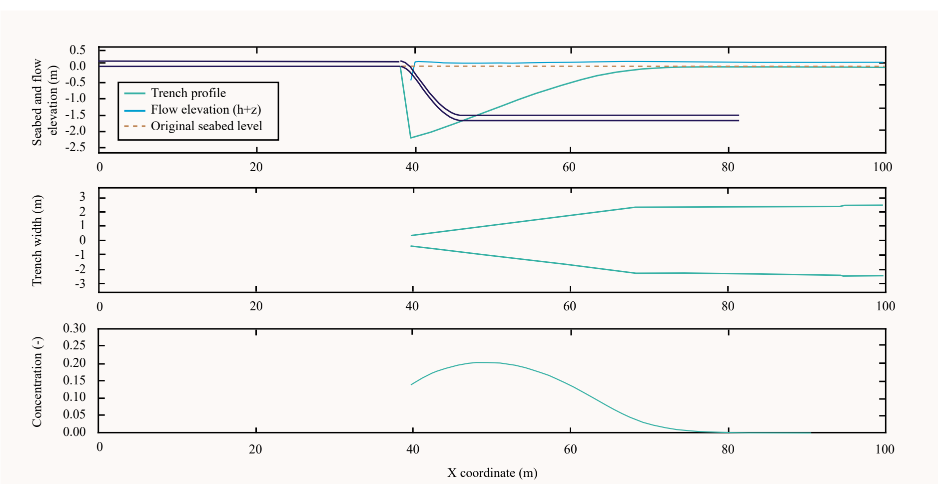


FIGURE 14

Model results for D_{15} = 0.15mm, D_{50} = 0.3mm and v_t = 0.1m/s. Plots show a side view of the trench (A), a top view of the trench with the development of trench width (B) and the depth averaged sediment concentration (C).

Cable deflection model

The burial depth of the cable is determined by the intersection of the cable shape and the re-settled seabed. The cable shape is based on an elastic, hyperstatic cantilever beam model which is uniformly loaded. The left hand side is completely fixed and the right hand side is restrained in rotation. The residual lay tension in the cable is applied at the right hand side of the cantilever beam. It is assumed that the position of the cable remains fixed when the touchdown point intersects with the trench shape. The analytical solution for the cantilever beam is given in Vanden Berghe et al. (2011). Exact assumptions in the derivation of the equation are unknown, therefore a verification has been done by comparing the analytical solution to numerical solutions generated by OrcaFlex, which is a dynamic analysis package used within the offshore industry.

$$z(x) = -\left[\frac{qL}{T}\cdot\sqrt{\frac{EI}{T}}\cdot\frac{\cosh\left(\sqrt{\frac{T}{EI}}L\right)}{\sinh\left(\sqrt{\frac{T}{EI}}L\right)}\cdot\left[\cosh\left(\sqrt{\frac{T}{EI}}x\right) - \tanh\left(\sqrt{\frac{T}{EI}}x\right)\cdot\sinh\left(\sqrt{\frac{T}{EI}}L\right) - 1\right] - \frac{q}{2T}x^2 + \frac{qL}{T}x\right]$$

(55)

Where z is the cable deflection measured from the seabed, q is cable weight, T is residual lay tension, L is distance until touchdown point, EI is bending stiffness and x is the distance from start of the trench. The cable deflection equation is incorporated in the sedimentation model and is solved each time a new grid cell is created at the moving boundary. The cable is not lowered in clear water but in a mixture of sediment and water, the cable weight should thus be corrected. A single reference concentration is chosen to correct the cable weight. This reference concentration is chosen to be equal to the concentration at the interface of erosion and sedimentation model.

$$q_{slurry} = q_{water} + c_{ref}\cdot D^2\cdot\frac{\pi}{4}\cdot(\rho_w - \rho_s)\cdot g$$

(56)

Where q_{slurry} is the cable weight in the water sediment mixture, q_{water} is the cable weight submerged in water, c_{ref} the reference concentration of sediment, D is cable diameter, ρ_w and ρ_s are water and sediment density respectively.

Results

A typical output of the model is given in Figure 14, showing a side view, top view and the concentration development behind the trencher.

Model validation

To validate the jet trenching model, averages of the depth of lowering are taken per cable section (monopile to monopile). To account for uncertainties in grain size and residual cable tension, a minimum and maximum depth of lowering case is considered. The minimum case is based on (d_{15} = 0.2mm, d_{50} = 0.4mm, T = 5*kN*) *and* the maximum case on (d_{15} = 0.1mm, d_{50} = 0.25mm, T = 2*kN*). Per individual cable section the average jet pressure and trencher velocity is extracted from logs recorded during trenching. Furthermore, the sword depth and

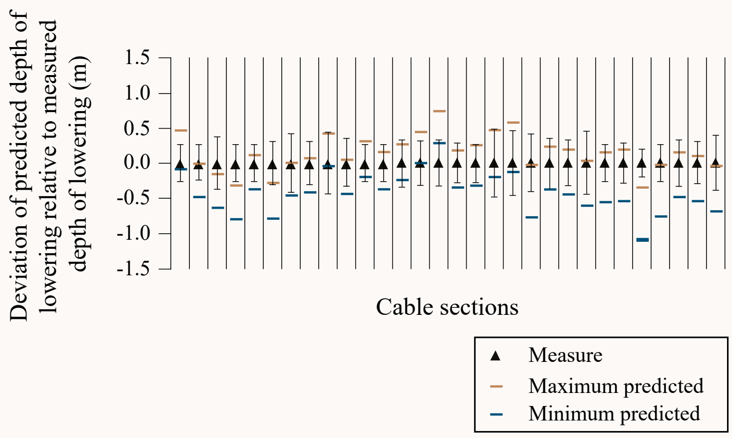


FIGURE 15

Validation of the jet trenching model by comparing predicted range to measured results during a reference project. Error bars indicate standard deviation in measured depth of lowering.

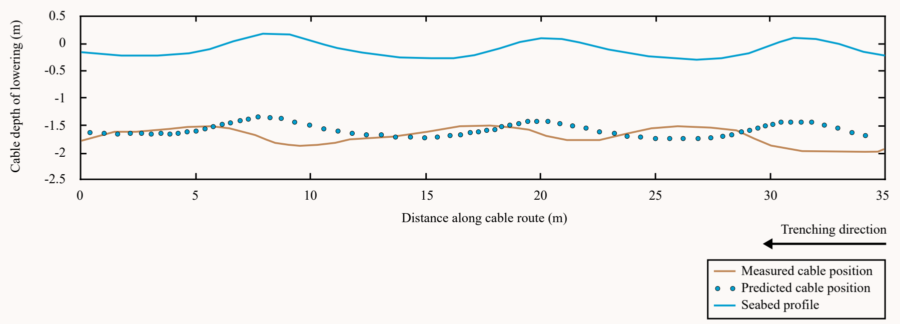


FIGURE 16

Seabed profile used as model input and measured/predicted cable position.

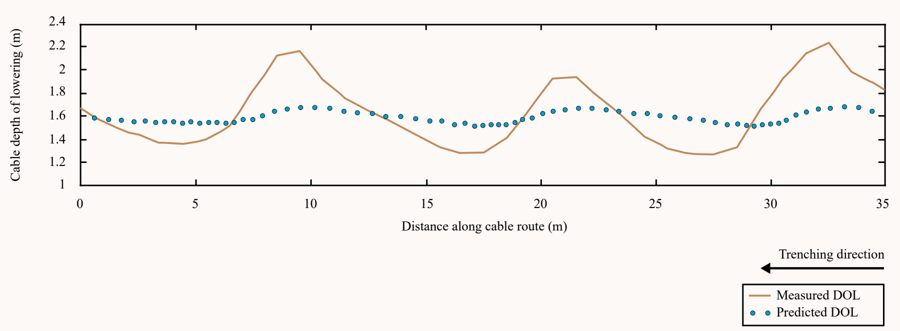


FIGURE 17

Measured and predicted depth of lowering.

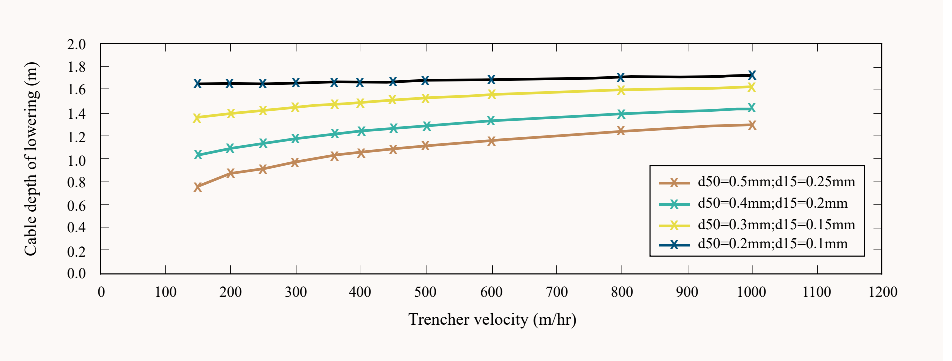


FIGURE 18

Cable depth of lowering for a range of trencher velocities and four different d_{50}

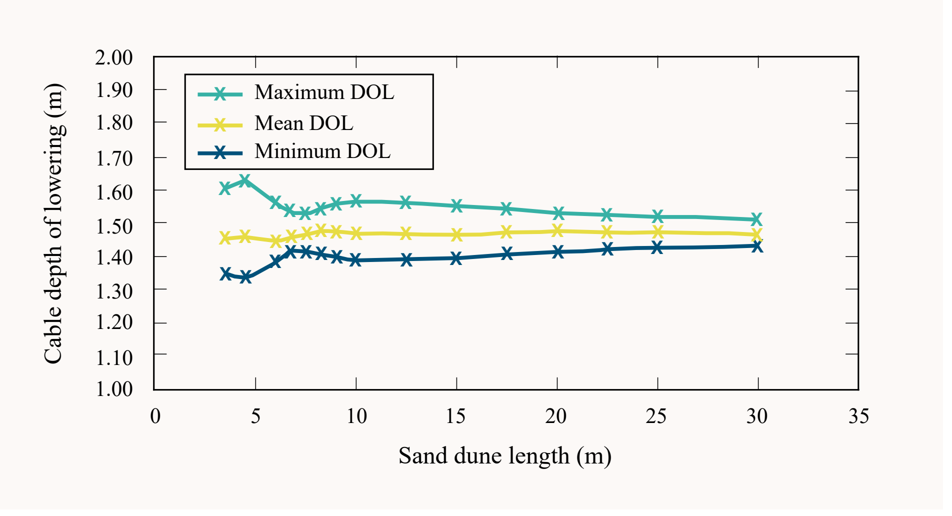


FIGURE 19

Cable depth of lowering for a range of sand dune lengths and constant sand dune height of 0.4 metres.

nozzle configuration are known per cable section. As a result a minimum and maximum depth of lowering is calculated per cable section, indicated by the red and blue lines in Figure 15. The results show that approximately 83% of the cable sections are within the predicted range.

Although the average depth of lowering is hardly influenced by sand dunes in the model, the local depth of lowering can be higher or lower due to the presence of sand dunes. To validate whether this effect is correctly included in the model, the depth of lowering for a cable section is compared to that measured during a reference project. The selected section of seabed profile has a sand dune height and length of approximately 0.5m and 12.5m respectively (see Figure 16). The seabed profile is somewhat smoothened by applying a moving average before importing it into the model. In Figure 16, the smoothened seabed profile is plotted together with the measured and predicted cable position. The cable position predicted by the model follows a pattern in phase with the sand waves, whereas the measured cable position shows an out of phase pattern with the sand dunes. However, not the absolute cable position but the cable position relative to the seabed (depth of lowering) is important. The measured and predicted depth of lowering are plotted in Figure 17. Difference between minimum and maximum depth of lowering measured is approximately 0.8m, whereas the predicted difference is approximately 0.2m, this is thus a significant underestimation.

Model Results

The effect of having a higher trencher velocity depends on grain sizes. In coarse sand, the increase in depth of lowering is larger than in fine sand for the same increase in trencher velocity (see Figure 18). Therefore, it is more important to have a high trencher velocity in coarse sand than in fine sand.

Sand dunes, characterised by their height and length, are modelled as a simple sinusoidal profile. Due to the seabed profile, also the depth of lowering shows an oscillating profile. To indicate this behaviour, the bandwidth (minimum and maximum values) and mean depth of lowering is plotted. To investigate sensitivity of sand dune length, the height is kept constant and only dune length is varied (see Figure 19). The bandwidth shows a clear local minimum at a wavelength of approximately 7.5 metres. This is an interesting wavelength since it is approximately equal to the layback of the cable (distance from start of trench to touchdown point of cable). For a wavelength of half the layback and 1.5 times the layback, there is a maximum in the bandwidth. Thus when the start of the trench is in phase with the touchdown point of the cable the variation of depth of lowering is minimum. However, the mean depth of lowering is hardly influenced.

A similar plot but now for sand dune height is given in Figure 20. The bandwidth shows to increase almost linearly with sand dune height, and again the mean depth of lowering is hardly influenced by sand dune height.

Discussion

The amplitude at which the depth of lowering oscillates when buried in sand dunes, is shown to be underestimated by the model compared to field data. An explanation could be the relatively simple cable equation used in the model. This equation takes the tension as a constant and uses this to calculate the cable shape. However, it is expected that while the cable is being lowered in the trench on sand dunes, the tension in the

cable varies. This might have a significant influence on the depth of lowering, but requires further investigation.
Although the current model is able to cope with hydraulic jumps, it is not possible to include a supercritical inflow at the moving boundary. The high flow velocity required for this supercritical inflow results in instabilities initiated at the boundary cell. The inflow is therefore taken to be subcritical with a large flow height and low flow velocity. By applying a cell merging technique on the boundary cell, the stability can be increased allowing for a supercritical inflow.

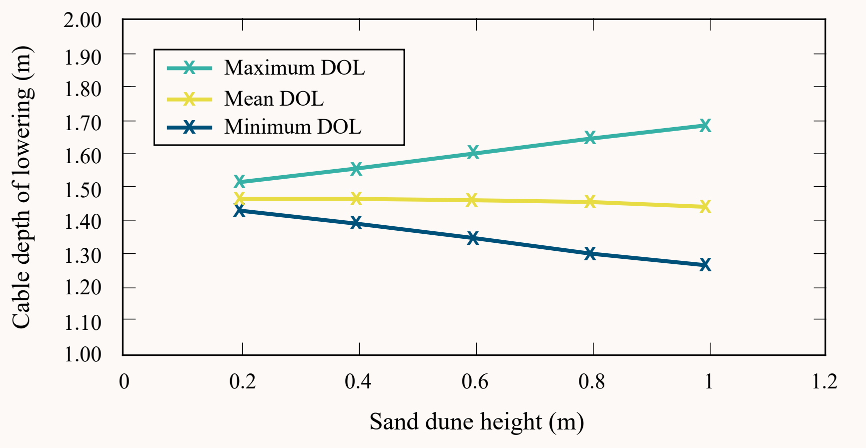


FIGURE 20

Cable depth of lowering for a range of sand dune heights, and constant sand dune length of 12.5 metres.

Conclusions

A jet trenching model is proposed which includes breaching, erosion, sedimentation and entrainment to make an accurate prediction of the depth of lowering of a cable buried in sand. By verification against analytical solutions of the shallow water equations, the numerical scheme of the sedimentation model shows to be shock-capturing and performing accurately. When considering cable burial in sand dunes, an oscillating depth of lowering trend is observed, with the maximum depth of lowering at sand dune crests and minimum at the troughs. This pattern is resulting both from field measurements and model simulations. However, the amplitude in depth of lowering variation is significantly underestimated by the model. Validation shows that the depth of lowering of approximately 83% of the cable sections of a reference project is within the range predicted by the model. By investigating the effect of grain sizes and trencher velocity, it has been shown by the model that it is more important have a high trencher velocity in coarse sand than in fine sand.

Summary

Numerous offshore wind farms have been recently installed in the southern part of the North Sea. Their infield and export cables are buried for protection against dropped or dragged objects. In sandy soils, burial is carried out by remotely operated tracked vehicles. Two swords with waterjets are used to fluidise the sand and generate a backward flow of the water-sediment mixture. The southern part of the North Sea has a highly variable seabed topography characterised by sand waves and mega-ripples. These seabed features can significantly influence the trenching process. At the moment, it is not possible to make an accurate estimate of the influence of sand dunes on the trenching process.

The trench formation process is split into two parts; a front section where the seabed is eroded by waterjets (erosion model) and a rear section where the sand grains are settling in a backward flow (sedimentation model). Both models as well as an elastic cantilever beam model – to determine the cable shape as it sinks in the trench – are delineated in this article. The combined fluidisation, sedimentation and cable model is validated against full-scale field data.

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REFERENCES

Adel, H. den (1987)
"Heranalyse doorlatendheidsmetingen door middel van de forch-heimer relatie (in Dutch)".

Cao, C., Pender, G., Wallis, S., and Carling, P. (2004)
"Computational Dam-Break Hydraulics over Erodible Sediment Bed". *Journal of Hydraulic Engineering 130(7),* 689–703.

Delestre, O., Lucas, C., Ksinant, P. A., Darboux, F., Laguerre, C., Vo, T., James, F., and Cordier, S. (2016)
"SWASHES: a compilation of shallow water analytic solutions for hydraulic and environmental studies". *International Journal for Numerical Methods in Fluids 72(3), 269–300.*

Garcia, M. (1990)
"Depositing and eroding sediment-driven flows: Turbidity currents". University of Minnesota.

He, S., Liu, W., Li, X., and Ouyang, C. (2014)
"An improved coupling model for water flow, sediment transport and bed evolution". Journal of Geoscientific Model Development 7, 2429–2454.

Jong, P. de (1988)
"Een productie optimalisatie van het gebruik van spuiters op de sleephopperzuiger Volvox Delta". MA thesis. Technische Universiteit Delft.

Lee, J. and Chu, V. (2003)
Turbulent jets and plumes: A lagrangian approach. Kluwer Academic Publishers. Miedema, S. (2015). *OE4607 Introduction to Dredging Engineering.* 2nd ed. Delft University of Technology.

Nobel, A. (2013)
"On the excavation process of a moving vertical jet in cohesive soil". PhD thesis. Delft University of Technology.

Parker, G., Garcia, M., Fukushima, Y., and Yu, W. (1987)
"Experiments on turbidity currents over an erodible bed". *Journal of Hydraulic Research 25(1), 123–147.*

Rhee, C. van (2010)
"Sediment Entrainment at High Flow Velocity". *Journal of Hydraulic Engineering* 136(9), 572–582.

Rhee, C. van (2015)
"Slope failure by unstable breaching". *Proceedings of the ICE - Maritime Engineering*
168, 84–92.

Robert, S. and Wilson, P. (2011)
"A well balanced scheme for the shallow water wave equations in open channels with (discontinuous) varying width and bed". *Austral. Mathematical Soc. 52, 967–987.*

Saint Venant, A. (1871)
"Theorie du mouvement non-permanent des eaux, avec application aux crues des rivieres et a l'introduction des marees dans leur lit". *Comptes Rendus de l'Academie des Sciences* 73, 147–154.

Siviglia, A., Nobile, G., and Colombini, M. (2008)
"Quasi-Conservative Formulation of the One-Dimensional Saint-Venant–Exner Model". *J. Hydraul. Eng. 134(10),* 1521–1526.

Vanden Berghe, J., Pyrah, J., Gooding, S., and Capart, H. (2011)
"Development of a jet trenching model in sand". *Frontiers in Offshore Geotechnics* 2, 889–894

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Sjoerd obtained his Bachelor's degree in Mechanical Engineering in 2014. As a next step, he pursued an MSc in Offshore and Dredging Engineering at the Delft University of Technology, developing a particular interest in fluid mechanics and dredging processes specifically. During his graduation thesis, published at the WODCON XXII in Shanghai, he focused on numerical modelling of water-sediment flow in order to enhance cable burial processes. Currently, he is working as Research and Development Engineer on cable installation and burial activities for DEME Offshore.

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

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Prior to joining DEME Offshore, Cristina received her MSc in Civil Engineering in 2013 from the Delft University of Technology. The interest in cable trenching was sparked during an internship at VSMC and has determined a shift of interest from bearing to breaking capacity of soils. As a Discipline Lead specialised in Geotechnical and Trenching Engineering, Cristina has been involved in numerous burial and protection projects for both cables and pipelines as well as trenching equipment research and development.

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Each participant will receive a Certificate of Achievement in recognition of the completion of the coursework.

Meet participants and lecturers

Face-to-face contact is invaluable. An additional dimension to this stimulating course is a mid-week dinner where participants, lecturers and other dredging employees can interact, network and discuss the real, hands-on world of dredging.

The fee for this seminar is €1,200. This includes all tuition, proceedings, workshops and a special dinner for participants but excludes travel costs, and accommodation.

Register for the seminar at

http://bit.ly/2EdpepD

For further questions contact:

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Photo Marco Hofsté Photography

WODCON XXIII: World Dredging Congress

16-20 May 2022
Tivoli Congress Center
Copenhagen, Denmark
www.wodcon2022.org

On behalf of World Organization of Dredging Associations (WODA), the Central Dredging Association (CEDA) has announced the next World Dredging Congress, WODCON XXIII, will take place from 16-20 May 2022, at the Tivoli Congress Center, Copenhagen, Denmark.

WODCON is held once every three years rotating among the world regions of WODA members, CEDA (representing the EMEA countries), WEDA (Western Dredging Association, serving the Americas) and EADA (Eastern Dredging Association, serving Asia, Australia and the Pacific region).

The theme of the 23rd WODCON will be 'Dredging is Changing' – which has a double meaning. Not only are dredging activities an agent of change, modifying the environment, dredging itself is also changing in terms of the positive impacts it has on the natural and socio-economic environment.

According to Johan Pennekamp, Chair of the WODCON XXIII Organising Committee, 'Apart from stating that our way of dredging is changing – just think: advances in dredging technology, novel solutions for adaptation to climate change, nature-based approaches, circular design, benefits/value for all stakeholders, corporate social responsibility, sustainable approach – the three words, "dredging is changing", actually have a more philosophical depth too.' He added, 'Dredging always means changing the environment whether it is capital dredging or even maintenance. Dredging always aims to create a new or improved situation and this aspect is quite often not recognised or appreciated.'

The WODCON organisers have chosen Copenhagen, the capital of Denmark to host the conference. With a safe and comfortable environment, cosmopolitan and yet cosy, it is an ideal place for new trends, business and relaxation. An exciting video about the conference and the city can now be downloaded from the official WODCON XXIII website.

CEDA is also delighted to announce the first sponsor to the congress, Rohde Nielsen, headquartered in Copenhagen. It invites the international dredging community to join in and support this major triennial event where the worldwide dredging community will gather in 2022.

In November, IADC is holding a three-day long seminar in Mumbai, India. Photo Marco Hofsté Photography

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