LOWER FOX RIVER CLEAN UP: removing PCBs to restore natural beauty

WILL PORTS BECOME FORTS?: preparing for climate change impacts

PUMPING SAND AND SHELLS critical velocity keeps pipelines open

Maritime Solutions for a Changing World
Guidelines for Authors

*Terra et Aqua* is a quarterly publication of the International Association of Dredging Companies, emphasising “maritime solutions for a changing world”. It covers the fields of civil, hydraulic and mechanical engineering including the technical, economic and environmental aspects of dredging. Developments in the state of the art of the industry and other topics from the industry with actual news value will be highlighted.

- As *Terra et Aqua* is an English language journal, articles must be submitted in English.
- Contributions will be considered primarily from authors who represent the various disciplines of the dredging industry or professions, which are associated with dredging.
- Students and young professionals are encouraged to submit articles based on their research.
- Articles should be approximately 10-12 A4s. Photographs, graphics and illustrations are encouraged. Original photographs should be submitted, as these provide the best quality. Digital photographs should be of the highest resolution.
- Articles should be original and should not have appeared in other magazines or publications. An exception is made for the proceedings of conferences which have a limited reading public.
- In the case of articles that have previously appeared in conference proceedings, permission to reprint in *Terra et Aqua* will be requested.
- Authors are requested to provide in the “Introduction” an insight into the drivers (the Why) behind the dredging project.
- By submitting an article, authors grant IADC permission to publish said article in both the printed and digital version of *Terra et Aqua* without limitations and remunerations.
- All articles will be reviewed by the Editorial Advisory Committee (EAC). Publication of an article is subject to approval by the EAC and no article will be published without approval of the EAC.
EDITORIAL

CLEAN UP OF THE LOWER FOX RIVER, WISCONSIN OPERABLE UNITS 2 – 5
RICHARD FEENEY, BASTIAAN LAMMERS AND GREG SMITH

To clean up a 13 mile stretch of the river, PCB contamination from industrial plants is being remediated by a unique combination of dredging, capping and separating clean sand and dewatering the fine sediments with membrane presses.

WILL PORTS BECOME FORTS? CLIMATE CHANGE IMPACTS, OPPORTUNITIES AND CHALLENGES
AUSTIN BECKER, DAVID NEWELL, MARTIN FISCHER AND BEN SCHWEGLER

The Stanford University Policy and Engineering Responses to Sea Level Rise (SUPERSLR) project is examining various solutions and the constraints for worldwide ports which could face the challenges of sea-level rise all at roughly the same time.

HYDRAULIC TRANSPORT OF SAND/ SHELL MIXTURES IN RELATION WITH THE CRITICAL VELOCITY
SAPE A. MIEDEMA AND ROBERT C. RAMSDELL

When pumping shells through a pipeline, a much higher velocity is required to make them erode and go back into suspension, because although the settling velocity of shells is much lower than equivalent sand particles, the erosion velocity is much higher.

BOOKS/PERIODICALS REVIEWED

SEMINARS/CONFERENCES/EVENTS
IADC and CEDA present a Forum on Early Contractor Involvement, as well as a seminar on environment, CEDA Dredging Days, WEDA/TAMU conference and more.
As the new year and the new decade begin, a look back at the last few challenging economic years seems appropriate. Although China, India, Brazil, Australia and Canada showed continuous economic growth, the financial crisis in 2008 led to a deep recession in Europe and the United States. This was followed by a big dip in world trade in 2009, one which most experts predicted would continue for quite a while. Remarkably, however, in 2010, world trade turned around and grew at a faster pace than expected. As the size of the dredging market is related to world trade, energy prices and the global GDP, the dredging industry remained stable and was not seriously effected by the downturn. This was especially true of the larger internationally active companies. And only three months into 2011, the dredging and maritime construction industry seems to be quite optimistic about market developments.

Why is there stability for the dredging industry in an otherwise erratic economic climate? Because dredging activities form the basis for many important aspects of our civilised, industrialised world. Dredging is vital to social and economic development, in particular to the construction and maintenance of much of the infrastructure upon which our economic prosperity and social and environmental well-being depend. The world’s population relies heavily on dredging solutions for creating and maintaining ports for global trade, coastal defence against erosion and flooding, urban development for homes and industry, offshore energy supplies be it oil, gas, or windfarms, as well as leisure and tourism, such as beaches, cruise harbours and fishing.

Dredging can be characterised as a capital-intensive industry requiring significant investments in equipment, research and development and people. This constant attention to innovation, research and an educated, well-trained workforce are the pillars upon which the industry is built and which allows it to adapt to the current needs of society and to find economical solutions.

In this issue of Terra, the articles reflect these research efforts. To start, a major cleanup project in Northern Wisconsin, which will continue over many years, is profiled. It demonstrates the high tech, innovative approaches available to remediate contamination caused by industrial waste and restore rivers and waterways to their natural beauty.

The two following articles demonstrate the cooperation between the maritime industry and major universities. In one case, Stanford University in California has launched a major project examining the effects of climate change on 180 worldwide ports, establishing a system to evaluate what the needs of these global ports will be as a result of sea level rise and the ability of the construction industries to meet these potential demands. At the same time, Delft University of Technology, Department of Dredging, in the Netherlands continues its tradition of research into the high tech needs of the dredging industry, specifically, examining how to improve the efficiency of hydraulic transport through pumps.

These research efforts represent the industry’s dedication to planning for the future. And these efforts are not exceptional – they are in fact typical of the modern-day dredging industry – always looking forward, one step ahead in finding optimal solutions for their clients.

Koos van Oord
President, IADC
ABSTRACT

The Fox River Cleanup Project is designed to reduce risk to human health and the environment caused by the presence of PCBs in Fox River sediment. It is a multi-year cleanup effort that includes dredging, capping with coarse sand, gravel and quarry stone, the separation of clean sand and dewatering of the fine sediments with membrane presses. It is currently one of the largest cleanup projects of its kind in the world, and its unique project approach will remove approximately 3.8 million cubic yards (CY) (2.9 million m$^3$) of PCB contaminated sediments and will place a protective cap or sand cover over 600 acres (243 ha). In addition, billions of gallons of water removed from the river will be treated and returned.

Because of the process used, the volume of the hydraulic dredge slurry is reduced and portions are prepared for beneficial use (e.g., separated sand) or recycled to the river (treated water), the transportation and disposal costs are significantly reduced.

This is particularly important with regard to the hazardous Toxic Substances Control Act (TSCA) dredged material.

INTRODUCTION

The Fox River Cleanup Project aims to remediate PCB-impacted sediments from a 13.3-mile (21.3-km) stretch of the Lower Fox River between Little Rapids Dam and the mouth of the Fox River at Green Bay, Wisconsin (Figure 1). The cleanup project is designed to reduce risk to human health and the environment caused by the presence of PCBs in Fox River sediment. The client is the Lower Fox River Remediation LLC. The regulatory agencies comprise a consortium representing the United States Environmental Protection Agency (EPA), the Wisconsin Department of Natural Resources and prominent members from private industry, collectively known as the Agencies/Oversight Team (A/OT).

This is a multi-year cleanup effort that includes dredging, capping with coarse sand, gravel and quarry stone, the separation of clean sand and dewatering of the fine sediments with membrane presses. It is currently one of the largest cleanup projects of its kind in the world and its unique project approach will remove approximately 3.8 million cubic yards (CY) (2.9 million m$^3$) of PCB contaminated sediments and will place a protective cap or sand cover over 600 acres (243 ha). In addition, billions of gallons of water removed from the river will be treated and returned.

Above: The natural beauty of the Fox River in northern Wisconsin, USA, is visible in this aerial view. The riverbed, however, is contaminated with PCBs caused by industrial plants along the riverbanks. It is now being cleaned by a combination of dredging, capping with coarse sand, gravel and quarry stone, and separating clean sand and dewatering the fine sediments with membrane presses.
**PROJECT APPROACH**

The project approach is unique as it is a single stream process where dredged sediments from three hydraulic dredges are directly piped to the land-based processing facility. Dewatering with eight membrane filter presses has been selected as the most economical and efficient means of dewatering the sediment prior to off-site disposal. The design of the sediment desanding and dewatering system required careful balancing of the flow of solids and water through the entire system, from the point of dredging through final production of sand and filter cake and water treatment.

The Lower Fox River OU 2-5 cleanup is being executed as a fast track design-build project, with Tetra Tech EC, Inc. as the prime contractor and Stuyvesant Environmental Contracting Inc., an affiliate of the Dutch based company Boskalis Dolman, and J.F. Brennan as key sub-contractors. Design of the processing facility began in March 2008. Process site clearing and earthwork activities were initiated in July of that year. Mechanical construction was complete by April 2009, followed by several weeks of pre-operational testing and start-up. A six-acre (2.5 ha) building encloses substantially all of the process operations (Figure 2). Deep concrete foundations and floor slabs, the building superstructure and all of the process equipment, piping and electrical systems were erected in about nine months time. Operations on this complex project officially started with dredging and processing on April 28, 2009, ahead of the mandated target of May 1. The first season of dredging, capping and sand covering concluded in mid-November 2009.

In terms of dredging productivity, the ambitious first season goals were exceeded by about 16% with nearly 545,000 CY (417,000 m³) of impacted sediment removed from the river. After the winter shutdown and maintenance period, operations re-started in early April 2010 for the second season of this cleanup project and at the end of the 2010 season more than 720,000 CY (550,000 m³) were removed. Thus about one-third of the total amount of sediment expected to be dredged over the life of the project was accomplished by the end of the second season.

The objective of the Fox River processing facility is to minimise the volume of contaminated sediment for disposal at the landfill by using a three-stage separation approach. The process facility screens, conditions, and dewater the slurry. During this process the volume of the hydraulic dredge slurry is reduced and portions are prepared for beneficial use (e.g., separated sand) or recycle to the river (treated water), significantly reducing transportation and disposal costs. This is particularly important.
with regard to the hazardous Toxic Substances Control Act (TSCA) dredged material, which must be transported to Michigan with higher disposal costs than the non-TSCA material.

**PROJECT TEAM**

The team of contractors on this complex project are part of the Fox River Cleanup Group. Tetra Tech EC, Inc. is the general contractor. There are two primary subcontractors working with Tetra Tech. J.F. Brennan is responsible for the dredging, capping and sand covering scope of this project. Stuyvesant Environmental Contracting Inc. obtained the contract for the sediment desanding and dewatering services. For this project Stuyvesant Environmental Contracting Inc. worked with its Netherlands-based sister company Boskalis Dolman bv. Boskalis Dolman is responsible for the design, engineering and operation of the sediment desanding and dewatering equipment.

**SCOPE OF PROJECT**

The scope of work includes the remediation of PCB-impacted sediments from a 13.3-mile (21.3-km) stretch of the Lower Fox River between Little Rapids Dam and the mouth of the Fox River at Green Bay. Note that the Fox River is unusual in that it flows from south to north and remedial activities are carried out in that sequence. At mile marker #4 lies the heart of the project – the Green Bay processing facility. The remediation is designed as a combined remedy that includes the dredging of 3.8 million CY (2.9 million m³) of sediments and the capping or sand covering of about 600 acres (242 ha).

A J.F. Brennan 12” hydraulic cutterhead dredge is used to remove large amounts of sediments. Two smaller 8” dredges are then used in shallower areas and to complete dredge areas that were initially (production) dredged by the 12” dredge (Figures 3 and 4). The sediments are pumped to the processing facility through HDPE pipelines over a maximum distance of 10 miles (16 km). Booster stations are used at one-mile (1.6-km) intervals to pump the slurry to the processing facility. Monitoring efforts to date have determined that there is minimal re-suspension of contaminated sediment associated with the hydraulic dredging process since this is a suction operation.

Capping is performed in areas with lower levels of PCBs and where dredging would not be effective or economically feasible. Capping is often performed in conjunction with areas that have been dredged, i.e., dredging of the more highly contaminated shallow sediment followed by the installation of an engineered cap over the lower contaminated level deeper sediment left in place. The initial layers of the engineered cap consist of sand and gravel. These layers are placed with a patented broadcast system to reduce mixing and over-placement in terms of area or thickness (Figure 5). The larger armour stone (e.g., quarry spall) is placed mechanically on top of the previous two layers to protect them against erosion or displacement from the effects of propeller action impacts.

**INTEGRATED APPROACH**

The project approach emphasises the “integration” of all of the performing parties. This includes the client, the regulatory agencies,
local stakeholders and the contractors performing various aspects of the work.

Local stakeholders include municipalities nearby the project operations and haul route and numerous private and commercial property owners along the river. In a sediment project such as this, communication and cooperation amongst the general contractor, the marine contractor and the sediment-processing contractor are critical in achieving the level of success which has been reached on the Lower Fox River project. The basis for this success, amongst other things, is the mutual understanding of the need for an integrated approach. The team therefore signed a MOU to concretise this approach.

**SITE CHARACTERISATION AND TREATABILITY TESTING**

Sediment sampling (Figure 6) and bench-scale testing were performed in November 2007. The objectives of the testing included the development of a proper characterisation of the sediment properties as well as selection and sizing of the appropriate sediment processing approach and equipment. Perhaps the most critical pieces of equipment that needed to be specified and purchased early, considering delivery lead-time, were the eight large membrane filter presses manufactured in Europe.

Transportation and disposal costs and beneficial reuse options were considered and evaluated during the selection process, while the estimated dredge production rate was critical when sizing the equipment. Particular attention was given to redundancy of equipment items or trains in both the sediment desanding and dewatering process (SDDP) and the water treatment plant (WTP) with regard to ensuring that the rate of dredging would not be impacted. The added expense of designing and installing surplus or redundant processing capacity has proven to be worthwhile.

Thousands of core samples were taken over the stretch of the river to map levels of PCBs, in terms of depth and area, and to determine the sediment characteristics in the river. This extensive chemical characterisation of the river bottom is needed to perform geostatistical modelling of the 1 ppm cleanup level and produce a neatline profile. The GPS based computer controls on the hydraulic dredges can then remove target sediments along the neatline much more precisely than would be accomplished by typical mechanical dredging, saving project operational costs and preserving landfill space.
The neatline design and hydraulic dredging combination is significantly more efficient in removing a higher proportion of the sediment above 1 ppm while leaving in place a greater degree of non-target material less than 1 ppm that would have been removed by a mechanical dredge implementing a typical dredge prism design.

A detailed analysis of available sediment data was performed to design an appropriate sediment desanding and dewatering system that would be able to accommodate the range of anticipated dredge production rates and the overall project schedule. Based on this analysis, a system of eight large membrane filter presses with a total maximum filter cake production of 14 CY (10.7 m$^3$) per hour was selected. The membrane filter presses dewater the filter cake at a pressure of 225 psig, achieving a typical solids percentage of nearly 55%.

Pilot-scale testing was performed at the Fox River OU 2-5 sediment processing site in June 2008. The objectives of the pilot testing were to evaluate the performance of polymers and filter cloth materials that could be utilised for the dewatering operation, and to evaluate the quality of the filter cake produced by each filter cloth. The pilot testing at the site was performed using scaled-down versions of key process components, including a scalping screen, slurry tank, hydrocyclone separator, pre-thickener tank, polymer dosing system, and filter press.

For each pilot test performed using a different filter cloth, representative sediment samples were obtained from the Fox River and slurried with river water to feed the pilot plant. Each filter cloth was tested by running at least 55 gallons (208 liters) of slurried sediment through the process, producing filter cake, and obtaining filtrate samples for total suspended solids (TSS) analysis.

The filter cloth materials evaluated included woven polypropylene filters. The filtration efficiency of each material was evaluated based on the TSS present in the filtrate from the pilot filter press. The quality of the filter cake produced was evaluated by performing a suite of analytical and geotechnical tests, including total PCBs, grain size, density, percent solids, and shear strength. As a result of the pilot testing, it was determined that a combination of coagulant and polymer would provide optimal results in terms of filter cake properties and filtrate quality and acceptable cycle times for the equipment.

**PROCESSING PLANT**

The SDDP and WTP are installed within a 250,000 square foot (23,225 m$^2$) building that was erected for the purpose of this project. The building also has a large area for indoor storage and handling of the filter cake and houses administrative office space for project staff. Boskalis Dolman designed, mobilised and constructed the SDDP within a short 8-month period to meet the overall project schedule (Figures 7 and 8).
During desanding operations are pumped to the dewatering process equipment, which includes pre-thickener tanks, sludge holding tanks, and membrane plate and frame filter presses. The filter presses designed for the Fox River are sized to process approximately 14 CY (10.7 m³) of solids per hour per press, with a compression factor of 1.3 and a cycle time of 75 minutes. The number of presses needed was calculated based on the anticipated range of flow rates through the dewatering system, an assumed uptime for the presses ranging from 75 to 100%, a range of 20 to 40% sand removal, and the hourly production rate for each press (Figures 14 and 15). It was determined that eight presses would be needed; however, space has been allocated and foundations installed for two additional presses.

The end product is a filter cake which is initially stored within the building. From there the cake is loaded in trucks and transported to a landfill for final disposal. For non-TSCA materials the filter cake is disposed of nearby the processing plant at approximately 30 miles (48 km) distance. The TSCA material is trucked to a disposal site in the state Michigan at a distance of 465 miles (744 km), which takes approximately 7.5 to 8 hours to drive with a truck (Figures 16 and 17).

Process water is re-used in the operation. Surplus water from the SDDP is treated and

Figure 11. The vibrating screen receiving sediments from dredgers.

Figure 12. Hydrocyclones for sand separation.

Figure 13. Separated sand for beneficial use.
Objective No. 2:
Complete building electrical, mechanical and HVAC systems installation and interior construction finishing activities.
- The building electrical, mechanical and HVAC systems installation and interior construction finishing activities were completed by approximately March 1.
- Project management activities moved to the administrative section of the building on about March 11.

Objective No. 3:
Complete start-up and testing of all SDDP and WTP equipment.
- Pre-operational testing – pressure testing, electrical check-outs, instrumentation inspections – occurred from about April 1 through April 24.
- Start-up and operational testing of the SDDP and WTP systems occurred from about April 28 through May 8 while dredging was conducted for about 12 hours per day.

Objective No. 4:
Perform site development activities at the OU3 secondary staging area.
- The 17-acre (6.8 ha) secondary staging area, located at Brown County Land Parcel ED-50-1 (near 2646 Old Plank Road), De Pere, Wisconsin, was leased from Irvin and Viola Peeters on May 5.
- Site development activities at the OU3 Staging Area began on June 1 and were completed on approximately June 26.

Objective No. 5:
Complete installation of fused pipelines and booster pump stations to support OU2 and OU3 dredging activities.
- Booster stations 1 through 9 and the necessary dredge pipeline were installed in time to begin dredging operations in OU2 on June 8.
- Dredge piping and booster station no. 9 were removed on June 26 based on completion of dredging activities in OU2.
- Additional dredge pipeline and booster station no. 8 were removed on August 27 based on completion of dredging activities south of Area D9.
- Additional dredge pipeline and booster station no. 7 were removed on September 15 based on completion of dredging activities south of Area D11/12.
- Additional dredge pipeline and booster station no. 6 were removed on October 28 based on completion of dredging activities south of Area D16.

Objective No. 6:
Begin dredging and processing operations by May 1, 2009.
- Dredging and processing operations began on April 28. Initially work was performed for approximately 12 hours per day.
- On May 11 24-hour dredging and processing operations began.
Objective No. 7:
Complete dredging adjacent to the processing facility, to the degree necessary, to allow for installation of the sheet pile bulkhead wall, including removal of approximately 10,000 CY (7650 m³) of TSCA material.
- Dredging at the processing facility, designated as D58, began on April 28 and was completed on June 27, 2009. Sufficient PCB-impacted sediment and debris were removed to allow for installation of the sheet pile bulkhead wall.
- Approximately 51,235.5 CY (39,172 m³) of non-TSCA material were removed from D58 in 2009.
- Approximately 7,403 CY (5,660 m³) of TSCA material were removed from D58 in 2009.

Objective No. 8:
Begin installation of the sheet pile bulkhead wall and back fill to elevation 577 feet (176 metres) followed by installation of the wick drains and gravel drainage layer.

As discussed with the A/OT, installation of the sheet pile bulkhead wall was postponed until the 2010 operations season because of an unexpectedly low yield of sand from the dredged material. There is no impact to project progress as a result of this change to the original objective.

Objective No. 9:
Remove, process and dispose of approximately 468,900 CY (358,568 m³) of target TSCA and non-TSCA material from the river.
- Dredging began on April 28 and continued until the morning of November 14.
- During this time, a total of 544,535 in situ CY (416,326 m³) of target sediment was removed from the river.

Objective No. 10:
Installation of sand cover, as the primary remedy, and armoured caps was not scheduled to begin until 2010.
- Placement of sand cover as a primary remedy began in OU2 on August 17.
- Installation of armor stone began in OU2 on August 31.

Objective No. 11:
Comply with all ARARs (Applicable or Relevant and Appropriate Requirement) identified for work in OU2-5 of the Fox River.
- The list of ARARs that pertain to the Lower Fox River OU2-5 work is included in Section 1.3 of the 2009 Phase 2B Remedial Action Work Plan. They include Federal chemical-specific, Federal action/location specific, State chemical-specific and State action/location-specific standards. For construction and remedial action work performed in 2009, the Tetra Tech team has complied with all of these ARARs.

CONCLUSIONS

The first operations season exceeded the 2009 targets for dredging and processing. In addition, despite the extremely aggressive construction period and nearly two years of operations, with more than 750,000 hours worked, there have been no lost time incidents on the project.

This extremely important project is being used as a model by various agencies and other companies as an example of how to clean up rivers with similar conditions. Remediation work in 2010 continued very well with more than 720,000 CY (550,800 m³) of sediment removed from the river. Last year’s total was exceeded in mid-September.

The 2010 amount is above the 550,000 to 700,000 CY (420,500 to 535,200 m³) range that was planned for this year before the season began.

At the end of 2010, therefore, approximately 1,265,000 CY (967,162 m³) of PCB contaminated sediment will have been removed from the Fox River, representing about 33% of the total estimated before the remedial action began.
ABSTRACT

While many studies characterise the causes of sea-level rise, attempt to measure and predict its rate of change, the focus on planning for the response that would be required to protect coastal communities in the event that sea-level rise does occur on a significant scale has been comparatively small. Understanding that many ports could face similar challenges at roughly the same time and the constraints for such a response caused by this has also been given little attention. This article presents the Stanford University Policy and Engineering Responses to Sea Level Rise (SUPERSLR) project that has examined various solutions featuring “hard” (e.g., seawalls) and “soft” (e.g., managed retreat) measures that would be suitable for the different conditions found at coastal and port cities worldwide. Three particularly important areas of investigation are reviewed here:

1. The quantification of resources, time, and cost required to implement the “hard” solution of constructing coastal defenses. By aggregating on a global scale the maximum industry capacity required for the simultaneous construction of protection structures around the globe has been estimated. Based on foreseeable growth trends in the construction industry, preliminary results show that current capacity would be exceeded. Indicators of the kind of industry strain ahead include the challenges faced by the U.S. construction industry in responding to the ravage of Hurricane Katrina (Kates et al. 2006).

2. A survey of the world’s port authorities. Conducted in cooperation with the International Association of Ports and Harbors (IAPH) and the American Association of Port Authorities (AAPA), a survey found that the majority of ports are concerned...
about the impacts of sea-level rise, but not are yet implementing adaptation strategies. 3 Barriers to decision making in seaport systems. Through case studies, the research team is working with local decision makers to identify site-specific strategies for climate change adaptation, the path to implementation, and an understanding of barriers that the decision-making system faces to carry out large-scale changes such as those needed for building coastal resilience.

Climate change motivation
Amongst the many predicted scenarios likely to result from climate change is an increase in the mean sea level (MSL) of between 0.6 and 2 metres on a planetary scale by 2100 (Intergovernmental Panel on Climate Change (IPCC) 2007; Rahmstorf 2010) and an intensification of tropical cyclones. Although the sea-level changes and storm effects differ depending on the location in question (IPCC 2007; NRC 2010), it is clear that at some point additional protection in the form of dikes, levees, sea walls, fill, and such, will be required to protect ports, harbours, and other coastal developments where the cost, resource requirements, and practicality of relocation or port elevation from the current grade is believed to outweigh the constructed alternative (Nicholls 2007).

Given the expected life span of port infrastructure it seems prudent to understand the potential impacts of MSL and the related effects on port infrastructure and operation and to identify the most critical constraints for a response.

Why ports?
Using seaports as a unit of study sets clear boundaries for analysis, since ports have fixed locations and simple measures for determining economic value in the form of shipping volume. Ports also serve as an example of infrastructure that explicitly relies on coastal locations. Unlike other coastal uses, ports must be situated in areas that are vulnerable to the impacts of climate change. As 80% of the world’s freight moves by ship, ports serve a critical and central role in the global economy (International Maritime Organization (IMO) 2008). National and international organisations have identified that climate impacts on maritime infrastructure is an area of great concern in which little work has been completed (Moser 2008; UNCTAD 2008; USCOP 2004; USEPA 2008).

Ports require special treatment because of their economic importance as essential links in supply chains, their locations in the heart of sensitive estuarine environments, their reliance on waterfront locations, and the significant existing infrastructure that links them to inland transportation networks. Unlike other coastal uses like residential or retail, ports cannot be relocated to safer locations. Lacking practical options for retreat, engineered solutions such as armouring must be considered seriously if ports are to continue operating as they have in recent history.

A recent United States Environmental Protection Agency (USEPA 2008) report on climate impacts on seaports states, “most [U.S.] ports do not appear to be thinking about, let alone actively preparing to address, the effects of climate change” (USEPA 2008). Results of a survey conducted by the SUPERSLR team confirms this propensity on a global scale (Becker et al., in review). Policy makers, insurers, the international community, and the ports themselves will all play a role in preparations for sea-level rise.

For the past three years, the Stanford teaching team has brought undergraduate and graduate students together in SUPERSLR courses to study various aspects of these issues. Experts from a wide variety of institutions discuss engineering, science, industry and policy perspectives on climate change adaptation and the coastal built environment. Over 50 independent studies have been conducted, each exploring a particular area, including specific port case studies, environmental impacts, and international policy frameworks. Students choose their own projects that fit into various themes selected by the teaching staff to contribute to the overall project. This degree of freedom gives students the opportunity to explore one of their interest areas in a unique class setting.

CREDIBLE MINIMUM-CRITERIA COASTAL PROTECTION DESIGN FRAMEWORK
In order to study the “hard” protection strategy for ports around the world, a traditional engineering study of each port would have required an inordinate amount of time to complete a site-specific design. To counter this problem, researchers at Stanford developed a minimum-criteria design frameworks for various hard structures to get an estimate of the amount of materials required without the time required to study each port in extensive detail. The keystone for this part of the project is a system for handling geographic data and running computer models inside Google Earth, called “Sebastian.”

Figure 1. Sebastian GeoData results for Marseilles, France displayed in Google Earth.
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Will Ports Become Forts? Climate Change Impacts, Opportunities and Challenges

Resource Production
The charts below show the differences in cement, gravel, and sand production throughout the world.

Cement

Figure 2. Data tables and graphs of calculated materials.

Sebastian GeoData System
The credible minimum-criteria design framework provides a sufficient level of credibility for an order-of-magnitude study of the amount of materials required to protect seaports against sea-level rise using a hard structure. The most complete design to date is a dike structure that is currently used in the Sebastian GeoData System. This system generates material requirements to allow for global materials demand data analysis. While using this particular dike design for any particular port is not advocated per se, it is a solution that could feasibly work at any port and thus provides useful outputs for global estimations. Since this project only seeks to begin the planning process for responses to sea-level rise, it is not logical to invest a significant amount of time in a full bespoke engineering study for every individual port where a conceptual design is sufficient to answer the questions researchers have posed.

The Sebastian GeoData System follows a simple framework to model a hard protection structure for any port worldwide. Using Google Earth’s built-in drawing tools, the protection area is specified by the user along with the start and end areas for the dike. Then, the computer model uses topography and bathymetry data to build a dike pathway that minimises the length and depth, optimising the amount of materials required. The result is then displayed in Google Earth (as shown in Figure 1 for Marseilles, France).

Sebastian aggregates these calculated materials requirements for every port analysed and displays summary information as data tables and graphs inside of Google Earth (as shown in Figure 2). Through these steps, a series of ports may be analysed by users from around the world and the results promptly compiled to inform decision makers and other stakeholders. The Sebastian tool is designed to be flexible so that it may grow to incorporate future solutions as they are developed.

Which ports?
Stanford researchers selected the 180 economically most important ports based on various factors, including ports that serve a population of greater than 1 million or are in the top 50 in terms of shipping volume by tonnage or containers, which captures approximately 2/3 of all shipping traffic. These important ports provide a good subset for study, since it would be unrealistic and extremely time-intensive to investigate all 3,000-4,000 ports worldwide.

Global construction industry capacity
To understand the particular limiting factors in responding to sea-level rise, it is necessary to determine the current availability resources. The SUPERSLR Research Database contains
these data and when combined with the output from Sebastian port models, the limiting factors are revealed. The research methodology for understanding the global construction industry’s capacity, as well as some of the preliminary results is described in the following sections.

Construction materials
The primary construction materials currently used in coastal defenses are concrete and steel. Thus, it is important to investigate the known supplies and regional accessibility of cement, coarse aggregate, and fine aggregate. Various public repositories contain data for the estimate of global material supply availability for common construction materials (USGS 2010). Preliminary results indicate that the global capacity for producing these materials is insufficient for constructing the protective structures around each of the world’s top economic ports in less than 50-60 years. Although fill is also a critical component of most protection structures, it would most likely be available locally and procured through dredging, and is thus not expected to be a limiting factor.

Coastal engineers
Researchers are in the initial stages of determining how many coastal engineers are presently available globally. Preliminary estimates for the United States indicate that fewer than 5,000 coastal engineers are employed by various firms across the country, and no more than 10,000 worldwide (Greenfield 2009). These data point to a shortage of coastal engineers in the future, particularly if this dike concept were to be applied at many ports worldwide.

Costs and time to complete
Using data from RS Means construction costs and labour guides, researchers estimated both the time to complete the construction of each port’s defence design as modelled using Sebastian and the costs associated with this construction. While most of these figures from RS Means are not specified for coastal engineering projects, they are fairly accurate when compared with past dike construction projects. Preliminary findings suggest that, on average, each port would require 520,000 work-hours (about 12.5 years using a 20-employee team) to construct a modelled design solution to protect against 2 metres of SLR, and each defense would cost over US$1.2 billion (Reed Construction Data Inc. 2008).

Dredging
Coastal defense structures generally require seabed preparation before construction may begin. Dredges perform this operation. Additionally, in the case of our dike design, dredged material with the appropriate properties could be used for the fill, which makes up the majority of the structure. This research considered only the dredging required to prepare the sea floor for the structure’s foundation. Across all 180 seaports, the average dredging volume required is about 5.9 million cubic metres for a total volume of 935 million cubic metres, or approximately three times the annual U.S. waterways dredging (Verna and Pointon 2004).

In the construction of the Oosterschelde storm-surge barrier in the Netherlands, a minimum of five dedicated ships were built specifically to meet project requirements (Deltawerken 2011). For the Port of Rotterdam’s new Maasvlakte 2, between 3 and 10 dredges are in operation at any time (Port of Rotterdam 2010).

Although dredging jobs are described by the type of material dredged, this research considered sand, for which only trailing suction hopper dredges and cutter suction dredges would be appropriate. There exist 492 and 405 of each of these dredges, respectively (Oilfield Publications Limited 2010). If these dredges could move 30,000 and 50,000 cubic metres of sand per day, respectively, and work 80% of the year, the total amount of sand that could be moved in one year is 10.2 billion cubic metres. In other words, the increased demand generated by this global project would be about 9% over current annual capacity, not a dramatic change, but definitely an increase in available work.

Results
As of November 2010, Stanford researchers had analysed 168 of the prescribed set of 180 ports, shown in Figure 3. Extrapolating these data points to all 4,235 ports from 195 countries in the “World Port Source” database, (www.worldportsource.com), the estimated demands for cement, sand, and gravel are shown in Table I. The capacity and demand requirements under this scenario reveal a need for 1.4 years of current cement production and over 6 years of sand and gravel production.

While it is certainly possible to procure this amount of materials, it would strain the

Table I. Resource production and demand requirements for the global market. Production and demand in billion metric tons. (Data current as of January 21, 2011).

<table>
<thead>
<tr>
<th>Resource</th>
<th>Yearly Production</th>
<th>Estimated Demand</th>
<th>Est. Years of Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>2.93</td>
<td>4.14</td>
<td>1.41</td>
</tr>
<tr>
<td>Sand</td>
<td>1.52</td>
<td>10.4</td>
<td>6.84</td>
</tr>
<tr>
<td>Gravel</td>
<td>2.71</td>
<td>16.4</td>
<td>6.05</td>
</tr>
</tbody>
</table>
industry, and new supplies of sand and gravel would need to be developed if this project were to proceed. Some research remains, but it is certain that this type of response would greatly affect the coastal construction industry as the demand for equipment and materials grows substantially. Preparing for sea-level rise could bring dramatic changes to how the coastal construction industry conducts its business.

**GLOBAL SURVEY OF PORT AUTHORITIES**

Information in this section has been adopted from Becker, A., Fischer, M., Inoue, S., Schwegler, B. (2011 in press), “Climate change impacts on seaports: A global survey of perceptions and plans”, Journal of Climatic Change. To assess the current state of knowledge, researchers distributed surveys to 342 port authorities from around the world to ascertain how administrators feel climate change might impact their operations, what sea-level change would create operational problems, and how they plan to adapt to new environmental conditions.

This research aimed to discover what policies, if any, ports already have in place to address adaptation issues. Ninety-three port directors, engineers, environmental managers, and planners representing 89 ports responded to the survey giving a broad picture of the current state of the world’s ports with respect to climate change. 63% of respondents reported that they had at least one policy that specifically addressed potential climate change effects or that they discussed adaptation in staff meetings. The survey responses showed few significant differences between ports of different sizes or regions, but indicated that US Gulf Coast ports appeared to be the most prepared. This higher level of preparedness probably results from the large number of recent storms in the Gulf.

The design lifetime of port infrastructure is 30-50 years, but often infrastructure like roads, bridges, piers, and rail yards will last much longer (UNCTAD 1985). Much infrastructure built today will still stand as climatic conditions change over the course of the century. As these projects compete for resources with other business or community needs, long-range implications of today’s choices often have less of a sense of urgency than more immediate priorities. Survey results indicate that capital planning cycles at ports are typically 5 to 10 years. This mismatch between planning cycles and infrastructure lifetimes may be at the root of many structural organisational difficulties in addressing this complex issue.

To establish a general sense of how ports plan for future expansion and development of their infrastructure and cargo-handling facilities, the survey asked about planning horizons and specific plans for future projects. Though, of course, there are various “planning horizons” for different types of projects and outcomes, the survey asked specifically about plans for capital improvements, expansion, and maintenance.

Most ports planned on a 5-10 year horizon (Figure 4) and the majority were planning for some level of expansion of their facilities. Those with planned projects indicated that most plans were for more terminals and berths or for land acquisition (Figure 5). Only a small percentage of ports have upcoming projects like new breakwaters or storm barriers that would increase their defenses against flooding and wave damage.

The specific risks associated with climate change are no different in nature than historic risks. Most ports face some amount of wind, wave, and flooding risk already and have already built infrastructure to protect port operations. However, the degree of risk will likely change as storms become more intense and sea levels rise. In an open-ended question which asked respondents to list the top three impacts climate change might have on their port’s operations, “sea level rise” was listed by 27 respondents. Other impacts of note included storms, flooding, shifts in markets, wave and wind impacts, environmental regulations and dredging.

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**Figure 4. Ports’ planning horizons in years.**

**Figure 5. Design standards and new construction plans for all respondents.**

* 16% of those planning new infrastructure also plan on building new storm protections.

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![Design standards and new construction plans in the next 10 years](image-url)
Since most respondents represent ports that are in coastal areas prone to storm events, they will likely design new structures with a particular extreme-event threshold in mind.

Survey results indicate that most ports in Europe, North America, and Oceania followed a 100-year return period planning standard. This means that a structure will be designed to withstand a storm that has a one-percent chance of occurring in any given year. However, 30% of Asian ports and 43% of ports in Central/South America planned with the most recent storm in mind. A few ports planned for a much longer return periods, with one port answering that they planned for a 1-in-1000 year storm event. It should be noted that storm forces are different in different areas of the world. For example, a 1-in-1000 year event in the Netherlands has roughly the same forces as a 1-in-100 year event in New Orleans. Thus, there is no universal storm period standard for designing structures to withstand storm events and it may not be feasible for all areas to implement such a high standard as the 1-in-1000 year event (Peter Wijsman, personal communication, May 15, 2009).

To get a better sense of what policies had already been actually implemented at the port, respondents were asked to identify which of seven policies they had already implemented (Figure 7).

Many respondents either did not know or said they were not addressing these issues at this time (47%). When asked about protective measures currently in place at the port, only 22% of respondents were found to have a storm plan in place and only 23% carried specific storm insurance. There was no correlation between a port’s location relative to the storm belt and its plans to develop new protective structures in the next 10 years, nor between insurance coverage and protection plans.

A rough scoring system assigned a point for each answer selected from the list of choices in Figure 6 and tallied the points for each port. The highest “score” was a five, meaning that the respondent indicated that the port had five of the potential seven options in place. The lowest score was a zero and the mean for all ports was 1.18 (1.24 standard deviation). Although this scoring system is not perfect, it enables some rough comparisons between ports. Ports were compared by size, World Bank status, location, and other categorisations. Most comparisons showed little or no significant difference. However, ports that carried standard insurance averaged 1.5 points, a bit higher than those that were self-insured (1.17), carried co-op insurance (0.7), or carried no insurance at all (1.3). Geographically, ports located in high-income nations averaged 1.3, 1.0 in upper and middle-upper income averaged 1.0, 0.75 in low income (0.75), and 0.5 in lower-middle income nations.

This scoring system offers insights into how ports compare relative to current climate preparation. In most cases, scores were within a standard deviation (SD = 1.24) of each other. The finding that high-income nations have more policies in place could be an initial step in discovering which ports have already thought about adaption problems and could provide models for those wishing to develop similar programmes.

Additionally, further investigation should be directed at the difference found between ports with standard insurance versus ports with other types of insurance in place.

Perhaps, for example, insurance companies are requiring ports to implement new policies. The highest scoring category was Gulf Coast Ports (with an average score of 2). Gulf Coast Ports have faced numerous hurricanes in the past decade. Land subsidence is also considerably greater on the Gulf Coast.

Overall, survey results show that the world port community is very concerned with impacts of climate change, but generally is not taking proactive action to adapt. This situation must be resolved if decisions are to be made that will protect both the port infrastructure itself and the economic systems that depend on a resilient and efficient maritime industry.

**IMPLEMENTING ADAPTATION STRATEGIES: A CASE-STUDY APPROACH TO INTEGRATED DECISION MAKING**

Continuing research at Stanford uses seaports as a case study to develop a better understanding of how institutional systems define resilience, how they can change in order to adapt to climate change, and what stands in the way of implementing adaptation strategies. A comparative case study of three seaports addresses the primary question: *What are the decision-making barriers to improving storm resilience?*

Data collected in interviews and focus groups with local decision makers will be used to quantify, compare, and contrast individual and system-wide constructs of resilience-building within the port systems and ultimately define the primary impediments to change. Climate change adaptation requires a holistic and sustainability-based perspective, as climate extremes place new demands on both human-built infrastructure and the natural environment.

This research will analyse the port as a system of decision-making actors and develop the concept of the “port decision-making system” as an example of a knowledge system that centres around primarily economic, but also social and environmental, goals for a well-functioning port. A testable framework will describe the impacts of extreme events on port systems in general and the options and tools at the knowledge systems’ disposal for enhancing resiliency. This work addresses the need for
CONCLUSIONS

Responding to sea-level rise and intensification of storm events requires a suite of strategies and an implementation schedule that decision makers can agree upon. By looking at the feasibility of engineered solutions, the perceptions and plans of ports themselves, and the decision-making system as a whole, the research team at Stanford University is developing approaches necessary to meet the new demands of a changing environment. While current operational challenges may make it difficult for individual companies to devote resources to this long-term issue, the implications of climate change impacts on many industries, including dredging, will be quite profound as evident from these preliminary results.

Interested parties are invited to work with Stanford and industry associations may wish to take the helm at the forefront of aggregating information that informs this issue and connects parties to collaborate and work toward solutions. The Stanford researchers’ current body of work and ongoing projects, including the aforementioned global survey of port administrators, may be found through their website: www.seaports2100.org.

REFERENCES


ABSTRACT

When pumping shells through a pipeline one must consider that shells are not spherical, but more disc-shaped. When shells settle they will settle like leaves where the biggest cross section is exposed to the drag. But they will settle in the same orientation, flat on the sediment, so the sides of the shells are exposed to the horizontal flow in the pipeline. Since the side cross section is much smaller than the horizontal cross section, a much higher velocity is required to make them erode and go back into suspension.

The settling velocity is much smaller because of the large area of the cross section. Even when the slurry velocity exceeds the settling velocity, some shells will reach the bottom of the pipe owing to the combination of settling velocity and turbulence. Once these shells are on top of the sediment they are hard to remove by erosion, because they lay flat on the surface and only a small cross section is exposed to the flow compared with the weight of the shell.

So although their settling velocity is much lower than equivalent sand particles, the erosion velocity is much higher. On a shell-covered beach, shells are always visible on top of the sand. In fact, these shells are shielding the sand from erosion. Bigger shells will also shield the smaller pieces, because smaller pieces settle faster. Shells settle more slowly than sand grains, so they will be on top of the bed (if there is a bed) just as on the beach.

These shells are hard to erode, in fact, they protect the bed from being eroded, even if the line speed is increased. The combination of high erosion velocity and the shells “protecting” the bed means that even a small amount of shells can lead to relatively thick bed in the pipeline. But there will always be a velocity above the bed that will make the shells erode.

This article describes the settling and erosion process of shells and the consequences of this on the critical velocity when pumping a sand/shell mixture through a pipeline. A mathematical model of the processes involved will be presented.

INTRODUCTION

When pumping shells through a pipeline one must consider that shells are not spherical, but more disc shaped. When shells settle they will settle like leaves where the biggest cross section is exposed to the drag. But when they settle, they will settle in the same orientation, flat on the sediment, so the side of the shells is exposed to the horizontal flow in the pipeline. Since the side cross section is much smaller than the horizontal cross section, a much higher velocity is required to make them erode and go back into suspension. The settling velocity is much smaller because of the large area of the cross section. Normally pipeline resistance is calculated based on the settling velocity, where the resistance is proportional to the settling velocity of the grains. The critical velocity is also proportional with the settling velocity. Since shells have a much lower settling velocity than sand grains with the same weight and much lower than sand grains with the same sieve diameter, one would expect a much lower resistance and a much lower critical velocity, matching the lower settling velocity.

This is only partly true. As long as the shells are in suspension, on average they want to stay in suspension because of the low settling...
velocity. But settling and erosion are stochastic processes because of the turbulent character of the flow in the pipeline. Since we operate at Reynolds numbers above 1 million, the flow is always turbulent, meaning that eddies and vortices occur stochastically making the particles in the flow move up and down, resulting in some particles hitting the bottom of the pipe. Normally these particles will be picked up in the flow because of erosion, so there exists equilibrium between sedimentation and erosion, resulting in not having a bed at the bottom of the pipeline.

In fact the capacity of the flow to erode is bigger than the sedimentation. If the line speed decreases, the shear velocity at the bottom of the pipe also decreases and less particles will be eroded, so the erosion capacity is decreasing. This does not matter, because as long as the erosion capacity is bigger than the sedimentation, there will not be sediment at the bottom of the pipeline. As soon as the line speed decreases so much that the erosion capacity (erosion flux) is smaller than the sedimentation flux, not all the particles will be eroded, resulting in a bed to be formed at the bottom of the pipe. Having a bed at the bottom of the pipe also means that the cross section of the pipe decreases and the actual flow velocity above the bed increases. This will result in a new equilibrium between sedimentation flux and erosion flux for each bed height.

From the moment there is a bed, decreasing the flow will result in an almost constant flow velocity above the bed, resulting in equilibrium between erosion and sedimentation. This equilibrium however is sensitive for changes in the line speed and in the mixture density. Increasing the line speed will reduce the bed height; a decrease will increase the bed height. Having a small bed does not really matter, but a thick bed makes the system vulnerable for plugging the pipeline.

The critical velocity in most models is chosen in such a way that a thin bed is allowed. As said before, some shells will always will reach the bottom of the pipe owing to the combination of settling velocity and turbulence. Once these shells are on top of the sediment they are hard to remove by erosion, because they lay flat on the surface and have a small cross section that is exposed to the flow compared with the weight of the shell. So although their settling velocity is much lower than equivalent sand particles, the erosion velocity is much higher. Looking at a beach in an area with many shells, there are always shells visible on top of the sand, covering the sand. In fact the shells are shielding the sand from erosion, because they are hard to erode. The bigger shells will also shield the smaller pieces, because the smaller pieces settle faster. Compare this with leaves falling from a tree, the bigger leaves, although heavier, will fall slower, because they are exposed to higher drag. The same process will happen in the pipeline. Shells settle more slowly than sand grains, so they will be on top of the bed (if there is a bed), just as on the beach.

Since they are hard to erode, in fact, they protect the bed from being eroded, even if the line speed is increased. But there will always be velocities above the bed that will make the shells erode. Now the question is how to quantify this behaviour in order to get control over it.

One must distinguish between sedimentation and erosion. First of all assume shells are disc shaped with a diameter d and a thickness of \( \alpha \cdot d \) and let's take \( \alpha = 0.1 \) this gives a cross section for the terminal settling velocity of \( \pi / 4 \cdot d^2 \), a volume of \( \pi / 40 \cdot d^3 \), and a cross section for erosion of \( d^2 / 10 \). Two processes have to be analysed to determine the effect of shells on the critical velocity: the sedimentation process and the erosion process.

**THE SEDIMENTATION PROCESS**

The settling velocity of grains depends on the grain size, shape and specific density. It also depends on the density and the viscosity of the fluid the grains are settling in and upon whether the settling process is laminar or turbulent. Discrete particles do not change their size, shape or weight during the settling process (and thus do not form aggregates). A discrete particle in a fluid will settle under the influence of gravity. The particle will accelerate until the frictional drag force of the fluid equals the value of the gravitational force, after which the vertical (settling) velocity of the particle will be constant.

In general, the settling velocity \( v_s \) can be determined with the following equation:

\[
v_s = \sqrt{\frac{4 \cdot g \cdot (\rho_p - \rho_f) \cdot d \cdot \psi}{3 \cdot \rho_f \cdot C_d}}
\]  

The settling velocity is thus dependent on: the density of the particle and fluid, diameter (size) and shape (shape factor \( \psi \)) of the particle, and flow pattern around the particle. The Reynolds number of the settling process determines whether the flow pattern around the particle is laminar or turbulent. The Reynolds number can be determined by:

**The drag coefficient for different shape factors**

![Figure 1. Drag coefficient as a function of the particle shape (Wu and Wang, 2006).](image-url)
\[ Re_p = \frac{v_s \cdot d}{v} \]  

[2]

The viscosity of the water is temperature dependent. If a temperature of 10° is used as a reference, then the viscosity increases by 27% at 0° and it decreases by 30% at 20° centigrade. Since the viscosity influences the Reynolds number, the settling velocity for laminar settling is also influenced by the viscosity. For turbulent settling the drag coefficient does not depend on the Reynolds number, so this settling process is not influenced by the viscosity.

**The drag coefficient**

The drag coefficient \( C_d \) depends upon the Reynolds number according to Turton and Levenspiel (1986), which is a 5 parameter fit function to the data:

\[ C_d = \frac{24}{Re_p} \left( 1 + 1.73 \cdot Re_p^{0.667} \right) + \frac{0.413}{1 + 16300 \cdot Re_p} \]  

[3]

It must be noted that in general the drag coefficients are determined based on the terminal settling velocity of the particles. Wu and Wang (2006) recently gave an overview of drag coefficients and terminal settling velocities for different particle Corey shape factors. The result of their research is reflected in Figure 1. Figure 1 shows the drag coefficients as a function of the Reynolds number and as a function of the Corey shape factor.

For shells settling the Corey shape factor is very small, like 0.1, resulting in high drag coefficients. According to Figure 2 the drag coefficient should be like:

\[ C_d = \frac{32}{Re_p} + 2 \text{ up to } C_d = \frac{36}{Re_p} + 3 \]  

[4]

For shells lying flat on the bed, the drag coefficient will be similar to the drag coefficient of a streamlined half body (0.09), which is much smaller than the drag coefficient for settling (3).

So there is a large asymmetry between the settling process and the erosion process of shells, while for more or less spherical sand particles the drag coefficient is considered to be the same in each direction.

**Terminal settling velocity equations from literature**

The shape factor was introduced into equation (1) by multiplying the mass of a sand particle with a shape factor \( \psi \). For normal sands this shape factor has a value of 0.7. Zanke (1977) has derived an equation for the transitional region (in m and m/sec):

\[ v_s = \frac{10 \cdot \nu}{d} \left[ 1 + \frac{R_d \cdot g \cdot d^3}{100 \cdot \nu^2} - 1 \right] \]  

[5]

With the relative density \( R_d \) defined as:

\[ R_d = \frac{p_s - p_w}{p_w} \]  

[6]

Figure 3 shows the settling velocity as a function of the particle diameter for the Stokes, Budryck, Rittinger and Zanke equations. Instead of using the shape factor in equation (1), it is better to use the actual drag coefficient according to equation (4) giving the shape factor a value of 1.

**Hindered settling**

The above equations calculate the settling velocities for individual grains. The grain moves downwards and the same volume of water has to move upwards. In a mixture, this means that when many grains are settling, an average upwards velocity of the water exists. This results in a decrease of the settling velocity, which is often referred to as hindered settling. However, at very low concentrations the settling velocity will increase because the grains settle in each other's shadow. Richardson and Zaki (1954) determined an equation to calculate the influence of hindered settling for volume concentrations \( C_v \) between 0.05 and 0.65. Theoretically, the validity of the Richardson and Zaki equation is limited by the maximum solids concentration that permits solids particle settling in a particulate cloud.

This maximum concentration corresponds with the concentration in an incipient fluidised bed (\( C_v \) of about 0.57). Practically, the equation was experimentally verified for concentrations not far above 0.30. The exponent in this equation is dependent on the Reynolds number. The general equation yields:

\[ \frac{v_s}{v_c} = (1 - C_v)^\beta \]  

[7]

The following values for \( \beta \) should be used (using the following definition does give a continuous curve):

\[ Re < 0.1 \quad \beta = 4.65 \]
\[ Re > 0.1 \text{ and } Re < 1.0 \quad \beta = 4.35 \cdot Re^{-0.03} \]
\[ Re > 1.0 \text{ and } Re < 400 \quad \beta = 4.45 \cdot Re^{-0.1} \]
\[ Re > 400 \quad \beta = 2.39 \]  

[8]

Other researchers found the same trend with sometimes different values for the power \( \beta \), as shown in Figure 4.

**Erosion**

In Miedema (2010), a model for the entrainment of particles as a result of fluid (or air) flow over a bed of particles has been developed. The model distinguishes sliding, rolling and lifting as the mechanisms of entrainment. Sliding is a mechanism that occurs when many particles are starting to move and it is based on the global soil mechanical parameter of internal friction. Both rolling and lifting are mechanisms of
individual particles and are based on local parameters such as the pivot angle and the exposure and protrusion rate. Equations (9), (10) and (12) give the Shields parameter for these 3 mechanisms.

**Sliding**

\[
\theta_{sliding} = \frac{u^2}{g \cdot d} \cdot \frac{4}{3} \cdot \frac{1}{\alpha} \cdot \frac{\mu}{\rho} \cdot \frac{\delta_{sliding}}{\rho_d g d} \cdot \frac{f}{C_l L_f} \cdot \frac{1}{C_l} \text{ [9]}
\]

**Rolling**

\[
\theta_{rolling} = \frac{u^2}{g \cdot d} \cdot \frac{4}{3} \cdot \frac{1}{\alpha} \cdot \frac{1}{\mu} \cdot \frac{\delta_{rolling}}{\rho_d g d} \cdot \frac{f}{C_l L_f} \cdot \frac{1}{C_l} \text{ [10]}
\]

With the effective rolling friction coefficient \( \mu_{rolling} \):

\[
\mu_{rolling} = \frac{\sin(\psi + \phi_{rolling})}{\delta_{rolling} - \rho_d g d} \cos(\psi + \phi_{rolling}) \text{ [11]}
\]

**Lifting**

\[
\theta_{lifting} = \frac{u^2}{g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{C_l}{C_l} \cdot \frac{1}{C_l} \text{ [12]}
\]

**Non-uniform particle distributions**

In the model for uniform particle distributions, the roughness \( k_s \) was chosen equal to the particle diameter \( d \), but in the case of non-uniform particle distributions, the particle diameter \( d \) is a factor \( d^+ \) times the roughness \( k_s \), according to:

\[
d^+ = \frac{d}{k_s} \text{ [13]}
\]

The roughness \( k_s \) should be chosen equal to some characteristic diameter related to the non-uniform particle distribution, for example the \( d_{50} \).

**Laminar region**

For the laminar region (the viscous sub layer) the velocity profile of Reichardt (1951) is chosen. This velocity profile gives a smooth transition going from the viscous sub layer to the smooth turbulent layer.

\[
u_{top} = \frac{uy_{top}}{u*} = \frac{\ln(1 + k \cdot y_{top}^+)}{k} - \frac{\ln(1/9) + \ln(k)}{k} \text{ [14]}
\]

For small values of the boundary Reynolds number and thus the height of a particle,
the velocity profile can be made linear to:

\[ u_{top}^* = y_{top}^* = d^+ \cdot E \cdot \text{Re}_* = d^+ \cdot E \cdot k_+^* \]  

[15]

Adding the effective turbulent velocity to the time averaged velocity, gives for the velocity function \( \alpha_{lam} \):

\[ \alpha_{lam} = y_{top}^* + u_{\text{eff}}(y_{top}^*) \]  

[16]

**Turbulent region**

Particles that extend much higher into the flow will be subject to the turbulent velocity profile. This turbulent velocity profile can be the result of either a smooth boundary or a rough boundary. Normally it is assumed that for boundary Reynolds numbers less than 5 a smooth boundary exists, while for boundary Reynolds numbers larger than 70 a rough boundary exists. In between in the transition zone the probability of having a smooth boundary is:

\[ P = e^{-0.95 \cdot \frac{\text{Re}_*}{k_+^*}} = e^{-0.95 \cdot \frac{\text{Re}}{k_+^*}} \]  

[17]

This probability is not influenced by the diameter of individual particles, only by the roughness \( k_+ \) which is determined by the non-uniform particle distribution as a whole. This gives for the velocity function \( \alpha_{\text{turb}} \):

\[ \alpha_{\text{turb}} = \frac{1}{k_+} \ln \left( 95 \cdot \frac{y_{top}^*}{k_+} + 1 \right) \cdot P + \frac{1}{k_+} \]

The velocity profile function has been modified slightly by adding 1 to the argument of the logarithm. Effectively this means that the velocity profile starts \( y_{bottom} \) lower, meaning that the virtual bed level is chosen \( y_{bottom} \) lower for the turbulent region. This does not have much effect on large exposure levels (just a few percent), but it does on exposure levels of 0.1 and 0.2. Not applying this would result in high (not realistic) shear stresses at very low exposure levels.

**The exposure level**

Effectively, the exposure level \( E \) is represented in the equations (9), (10) and (12) for the Shields parameter by means of the velocity distribution according to equations (16) and (18) and the friction coefficient \( \psi \) or the pivot angle \( \psi \). A particle with a diameter bigger than the roughness \( k_+ \) will be exposed to higher velocities, while a smaller particle will be exposed to lower velocities. So it is important to find a relation between the non-dimensional particle diameter \( d^+ \) and the exposure level \( E \).

**The angle of repose and the friction coefficient**

Miller and Byrne (1966) found the following relation between the pivot angle \( \psi \) and the non-dimensional particle diameter \( d^+ \) with \( c_p = 61.5^\circ \) for natural sand, \( c_p = 70^\circ \) for crushed quartzite and \( c_p = 50^\circ \) for glass spheres.

\[ \psi = c_p \cdot (d^+)^{-0.3} \]  

[19]

Wiberg and Smith (1987A) re-analysed the data of Miller and Byrne (1966) and fitted the following equation:

\[ \psi = \cos^{-1} \left( \frac{d^+ + z^*}{d^+ + 1} \right) \]  

[20]

The average level of the bottom of the almost moving grain \( z \), depends on the particle sphericity and roundness. The best agreement is found for natural sand with \( z^* = -0.045 \), for crushed quartzite with \( z^* = -0.320 \) and for glass spheres with \( z^* = -0.285 \). Wiberg and Smith (1987A) used for natural sand with \( z^* = -0.02 \), for crushed quartzite with \( z^* = -0.16 \) and for glass spheres with \( z^* = -0.14 \). The values found here are roughly 2 times the values as published by Wiberg and Smith (1987A). It is obvious that equation (20) underestimates the angle of repose for \( d^+ \) values smaller than 1.

**The equal mobility criterion**

Two different cases have to be distinguished. Particles with a certain diameter can lie on a bed with a different roughness diameter. The bed roughness diameter may be larger or smaller than the particle diameter. Figure 5 shows the Shields curves for this case (which

**LIST OF SYMBOLS USED**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L )</td>
<td>Surface or cross section</td>
</tr>
<tr>
<td>( C_c )</td>
<td>Pivot angle at ( d^+ = 1 )</td>
</tr>
<tr>
<td>( C_d )</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>( C_v )</td>
<td>Lift coefficient</td>
</tr>
<tr>
<td>( C_k )</td>
<td>Volumetric concentration</td>
</tr>
<tr>
<td>( d )</td>
<td>Diameter of particle or sphere</td>
</tr>
<tr>
<td>( d^+ )</td>
<td>Dimensionless particle diameter</td>
</tr>
<tr>
<td>( f_d, f_s )</td>
<td>Drag and lift surface factor</td>
</tr>
<tr>
<td>( F_{\text{down}} )</td>
<td>Submerged gravity force (downwards)</td>
</tr>
<tr>
<td>( F_{\text{up}} )</td>
<td>Drag force (upwards)</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravitational constant</td>
</tr>
<tr>
<td>( k_+ )</td>
<td>Bed roughness</td>
</tr>
<tr>
<td>( P )</td>
<td>Probability related to transition smooth/rough</td>
</tr>
<tr>
<td>( R_a, R_{Re} )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( \text{Re}, \text{Re}_* )</td>
<td>Temperature</td>
</tr>
<tr>
<td>( u, \text{Velocity} )</td>
<td>Friction velocity</td>
</tr>
<tr>
<td>( u, \text{Velocity} )</td>
<td>Dimensionless velocity</td>
</tr>
<tr>
<td>( u_{top}^+, \text{Dimensionless velocity at top of particle} )</td>
<td>Dimensionless effective turbulent added velocity</td>
</tr>
<tr>
<td>( U, \text{Average velocity above the bed} )</td>
<td>Terminal settling velocity including hindered settling</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Terminal settling velocity</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Volume of particle or sphere</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Dimensionless height of particle</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Coefficient</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Coefficient</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Velocity coefficient</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Shields parameter</td>
</tr>
<tr>
<td>( \delta_\psi )</td>
<td>Hindered settling coefficient</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Thickness of the viscous sub-layer</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Dimensionless thickness of the viscous sub-layer</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Von Karman constant</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Friction coefficient (see Moody diagram)</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Density of quarts</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Water density</td>
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<tr>
<td>( \psi )</td>
<td>Shape factor particle</td>
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<tr>
<td>( \psi )</td>
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<td>Friction coefficient</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Drag arm factor</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Additional lever arm for drag</td>
</tr>
</tbody>
</table>
are different from the graph as published by Wiberg and Smith (1987A), combined with the data of Fisher et al. (1983), and based on the velocity distributions for non-uniform particle size distributions. Fisher et al. carried out experiments used to extend the application of the Shields entrainment function to both organic and inorganic sediments over passing a bed composed of particles of different size.

Figure 5 shows a good correlation between the theoretical curves and the data, especially for the cases where the particles considered are bigger than the roughness diameter (d / kₜ > 1). It should be noted that most of the experiments were carried out in the transition zone and in the turbulent regime. Figure 5 is very important for determining the effect of shells on a bed, because with this figure the critical Shields parameter of a particle with a certain diameter, lying on a bed with a roughness of a different diameter, can be determined. In the case of the shells the bed roughness diameter will be much smaller than the shell diameter (dimensions). To interpret Figure 5 one should first determine the bed roughness diameter and the roughness Reynolds number and take the vertical through this roughness Reynolds number (also called the boundary Reynolds number). Now determine the ratio d / kₜ and read the Shields parameter from the graph. From this it appears that the bigger this ratio, the smaller the Shields value found. This is caused by the fact that the Shields parameter contains a division by the particle diameter, while the boundary shear stress is only influenced slightly by the changed velocity distribution. Egiazaroff (1965) was one of the first to investigate non-uniform particle size distributions with respect to initiation of motion. He defined a hiding factor or exposure factor as a multiplication factor according to:

$$\theta_{cr,d} = \theta_{cr,d_0} \left( \frac{\log(19)}{\log (19 \frac{d}{d_0})} \right)^2$$

[21]

The tendency following from this equation is the same as in Figure 5, the bigger the particle, the smaller the Shields value, while in equation (21) the d₀ is taken equation to the roughness diameter kₜ. The equal mobility criterion is the criterion stating that all the particles in the top layer of the bed start moving at the same bed shear stress, which matches the conclusion of Miedema (2010) that sliding is the main mechanism of entrainment of particles. Figure 6 shows that the results of the experiments are close to the equal mobility criterion, although not 100%, and the results from coarse sand from the theory as shown in Figure 5, matches the equal mobility criterion up to a ratio of around 10. Since shells on sand have a d / kₜ ratio bigger than 1, the equal mobility criterion will be used for the interpretation of the shell experiments as also shown in Figure 5.

Shells

Dey (2003) has presented a model to determine the critical shear stress for the incipient motion of bivalve shells on a horizontal sand bed, under a unidirectional flow of water. Hydrodynamic forces on a solitary bivalve shell, resting over a sand bed, are analysed for the condition of incipient motion including the effect of turbulent fluctuations. Three types of bivalve shells, namely Coquina Clam, Cross-barred Chione and Ponderous Ark, were tested experimentally for the condition of incipient motion. The shape parameter of bivalve shells is defined appropriately.

Although the model for determining the Shields parameter of shells is given, the experiments of Dey (2003) were not translated into Shields parameters. It is interesting however to quantify these experiments into Shields parameters and to see how this relates to the corresponding Shields parameters of sand grains. In fact, if the average drag coefficient of the shells is known, the shear stress and thus the friction velocity, required for incipient motion, is known, the flow velocity required to erode the shells can be determined. Figure 7 and Figure 8 give an impression of the shells used in the experiments of Dey (2003). From Figure 7 it is clear that the shape of the shells match the shape of a streamlined half body lying on a surface and thus a drag coefficient is expected of about 0.1, while sand grains have a drag coefficient of about 0.45 at very high Reynolds numbers. Figure 8 shows that the results of the experiments are close to the equal mobility criterion, although not 100%, and the results from coarse sand from the theory as shown in Figure 5, matches the equal mobility criterion up to a ratio of around 10. Since shells on sand have a d / kₜ ratio bigger than 1, the equal mobility criterion will be used for the interpretation of the shell experiments as also shown in Figure 5.

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Using this definition, results in useful Shields values. Since convex upwards is important for the critical velocity analysis, this case will be analysed and discussed. It is clear however from these figures that the convex downwards case results in much smaller Shields values than the convex upwards case as was expected. Smaller Shields values in this respect means smaller shear stresses and thus smaller velocities above the bed causing erosion. In other words, convex downwards shells erode much easier than convex upwards.

Although the resulting Shields values seem to be rather stochastic, it is clear that the mean values of the Chione and the Coquina are close to the Shields curve for $d / k_s = 1$. The values for the Ponderous Ark are close to the Shields curve for $d / k_s = 3$. In other words, the Ponderous Ark shells are easier to erode than the Chione and the Coquina shells.

Looking at the shells in Figure 8 it is visible that the Ponderous Ark shells have ripples on the outside and will thus be subject to a higher drag. On the other hand, the Ponderous Ark shells have an average thickness of 2.69 mm (1.95-3.98 mm) as used in the equation of the Shields parameter, while the Coquina clam has a thickness of 1.6 mm (0.73-3.57 mm) and the Chione 1.13 mm (0.53-2.09 mm). This also explains part of the smaller Shields values of the Ponderous Ark. The average results of the tests are shown in Table I.
How can this critical velocity be combined with the erosion behavior of shells? As mentioned above, there are different models in literature for the critical velocity and there is also a difference between the critical velocity and the minimum friction velocity. However, whatever model is chosen, the real critical velocity is the result of an equilibrium of erosion and deposition resulting in a stationary bed. This equilibrium depends on the particle size distribution, the slurry density and the flow velocity. At very low concentrations it is often assumed that the critical velocity is zero, but based on the theory of incipient motion, a certain minimum velocity is always required to erode an existing bed.

The problem can be looked at in two ways: one can compare the Shields values of the shells with the Shields values of sand particles with a diameter equal to the thickness of the shells, resulting in the factors as mentioned in the previous paragraph or one can compare the shear stresses occurring to erode the shells with the shear stresses required for the sand beds used. The latter seems more appropriate because the shear stresses are directly related to the average velocity above the bed with the following relation:

$$ \rho_w \cdot u_*^2 = \frac{\lambda}{8} \rho_w \cdot U^2 $$

Implicit in most models of slurry transport is the idea that the system can transition smoothly in both directions along the system resistance curves. So if the dredge operator inadvertently feeds too high of a concentration, dropping the velocity close to the minimum friction or even the critical velocity, he can recover by slowly lowering the mixture concentration, which in turn lowers the density in the pipeline and allows the velocity to recover. Alternatively the operator can increase the pressure by turning up the pumps to raise the velocity. In a sand-sized material this works because the critical and minimum friction velocities are fairly stable, so raising the pumping velocity or lowering the concentration will be enough to start the bed sliding, then erode the bed and return to stable operation.

With a sand-shell mixture, as described above, the critical velocity and minimum friction velocities become time-dependent parameters. The stochastic nature of the process means that some fraction of the shells will fall to the bottom of the pipe. The asymmetry between deposition and erosion velocity means that these shells will stay on the bottom, forming a bed that grows over time, increasing the critical velocity and minimum friction velocity. Unless the system is operated with very high margins of velocity, the new critical velocity and Vmin eventually fall within the operating range of the system, leading to flow instability and possible plugging.
Where the left hand side equals the bed shear stress, \( \lambda \) the friction coefficient following from the Moody diagram and \( U \) the average flow velocity above the bed. The average shear stresses are shown in Table II.

The Shields values for both sands are about 0.035, resulting in shear stresses of 0.45 Pa for the 0.8 mm sand and 0.17 Pa for the 0.3 mm sand. The ratios between the shear stresses required eroding the shells and the shear stresses required to erode the beds are also shown in Table II. For the shells laying convex upwards on the 0.8 mm sand bed these ratio’s vary from 1.24-1.60, while this is a range from 2.18-3.41 for the 0.3 mm sand bed. These results make sense, the shear stress required for incipient motion of the shells does not change much because of the sand bed, although there will be some reduction for sand beds of smaller particles owing to the influence of the bed roughness on the velocity profile according to equation (14). Smaller sand particles with a smaller roughness allow a faster development of the velocity profile and thus a bigger drag force on the shells at the same shear stress.

The main influence on the ratios is the size of the sand particles, because smaller particles require a smaller shear stress for the initiation of motion.

This is also known from the different models for the critical velocity, the finer the sand grains, the smaller the critical velocity. In order words, the smaller the velocity to bring the particles in a bed back into suspension. It also makes sense that the ratio between shell erosion shear stress and sand erosion shear stress will approach 1 if the sand particles will have a size matching the thickness of the shells and even may become smaller than 1 if the sand particles are bigger than the shells. Since the velocities are squared in the shear stress equation, the square root of the ratios has to be taken to get the ratios between velocities. This leads to velocity ratios from 1.11-1.26 for the 0.8 mm sand and ratios from 1.48-1.89 for the 0.3 mm sand.

Translating this to the critical velocity can be carried out under the assumption that the critical velocity is proportional to the average flow velocity resulting in incipient motion.

Although the critical velocity results from an equilibrium between erosion and deposition of particles and thus is more complicated, the here derived ratios can be used as a first attempt to determine the critical velocities for a sand bed covered with convex upwards shells. For the coarser sands (around 0.8 mm) this will increase the critical velocity by 11%-26%, while this increase is 48%-89% for the finer 0.3 mm sand. Even finer sands will have a bigger increase, while coarser sands will have a smaller increase.

As stated, the shear stress required to erode the shells is almost constant, but decreasing a little bit with decreasing sand particle diameters, an almost constant critical velocity for the shells is expected. From the measurements it is also clear, that very smooth shells (Coquina Clam and Cross Barred Chione) are harder to erode and will have a higher critical velocity than the rough shells (Ponderous Ark) (Figure 10).

**Table I. Average Shields values.**

<table>
<thead>
<tr>
<th></th>
<th>( d_{50}=0.8 \text{ mm} )</th>
<th>( d_{50}=0.3 \text{ mm} )</th>
<th>( d_{50}=0.8 \text{ mm} )</th>
<th>( d_{50}=0.3 \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re.</td>
<td>( \theta )</td>
<td>( \theta )</td>
<td>( \rho_w \cdot u^2 )</td>
<td>( \rho_w \cdot u^2 )</td>
</tr>
<tr>
<td>Coquina Clam</td>
<td>19.78 0.0277 6.71 0.0225 1.60 2.00 5.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross Barred Chione</td>
<td>17.51 0.0378 6.24 0.0333 1.13 1.41 3.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ponderous Ark</td>
<td>18.46 0.0129 5.76 0.0086 2.69 3.36 8.97</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table II. Average shear stresses.**

<table>
<thead>
<tr>
<th></th>
<th>( d_{50}=0.8 \text{ mm} )</th>
<th>( d_{50}=0.3 \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re.</td>
<td>( \theta )</td>
<td>( \rho_w \cdot u^2 )</td>
</tr>
<tr>
<td>Coquina Clam</td>
<td>19.78 0.0277 0.72 1.60 6.71 0.0225 0.58 3.41</td>
<td></td>
</tr>
<tr>
<td>Cross Barred Chione</td>
<td>17.51 0.0378 0.69 1.53 6.24 0.0333 0.61 3.59</td>
<td></td>
</tr>
<tr>
<td>Ponderous Ark</td>
<td>18.46 0.0129 0.56 1.24 5.76 0.0086 0.37 2.18</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. The critical shear stresses of the shells compared with sand.
CONCLUSIONS

The critical velocity for the hydraulic transport of a sand-water mixture depends on a number of physical processes and material properties. The critical velocity is the result of equilibrium between the deposition of sand particles and the erosion of sand particles. The deposition of sand particles depends on the settling velocity, including the phenomenon of hindered settling as described in this article. The erosion or incipient motion of particles depends on equilibrium of driving forces, like the drag force, and frictional forces on the particles at the top of the bed. This results in the so-called friction velocity and bottom shear stress. Particles are also subject to lift forces and so-called Magnus forces, owing to the rotation of the particles. Particles that are subject to rotation may stay in suspension owing to the Magnus forces and they do not contribute to the deposition. From this it is clear that an increasing flow velocity will result in more erosion, finally resulting in hydraulic transport without a bed. A decreasing flow velocity will result in less erosion and an increasing bed thickness, resulting in the danger of plugging the pipeline.

Shells lying convex upwards on the bed in general are more difficult to erode than sand particles, as long as the sand particles are much smaller than the thickness of the shells. The shells used in the research had a thickness varying from 1.13 to 2.69 mm. So the shells armour the bed and require a higher flow velocity than the original sand bed. Now as long as the bed thickness is not increasing, there is no problem, but since hydraulic transport is not a simple stationary process, there will be moments where the flow may decrease and moments where the density may increase, resulting in an increase of the bed thickness. Since the shells are armouring the bed, there will not be a decrease of the bed thickness at moments where the flow is higher or the density is lower, which would be the case if the bed consists of just sand particles.

This means a danger of a bed thickness increasing all the time and finally plugging the pipeline. The question arises, how much does one have to increase the flow or flow velocity in order to erode the top layer of the bed where the shells are armouring the bed.

From the research of Dey (2003) it appears that the bottom shear stress to erode the shells varies from 0.56-0.72 Pa for a bed with 0.8 mm sand and from 0.37-0.61 Pa for a bed with 0.3 mm sand. It should be noted that these are shear stresses averaged over a large number of observations and that individual experiments have led to smaller and bigger shear stresses. So the average shear stresses decrease slightly with a decreasing sand particle size owing to the change in velocity distribution. These shear stresses require average flow velocities that are 11%-26% higher than the flow velocities required to erode the 0.8 mm sand bed and 48%-89% higher to erode the 0.3 mm sand bed. From these numbers it can be expected that the shear stresses required to erode the shells, match the shear stresses required to erode a bed with sand grains of 1-1.5 mm and it is thus advised to apply the critical velocity of 1-1.5 mm sand grains in the case of dredging a sand containing a high percentage of shells, in the case the shells are not too fragmented.

REFERENCES


DREDGING FOR DEVELOPMENT
EDITED BY NICK BRAY AND MARSHA COHEN

Since its first appearance in 1983 each edition of Dredging for Development has kept pace with the ongoing advances and changes in the dredging industry.

Dredging for Development is a prime guide for anyone dealing with the planning and execution of projects with a dredging component. Think of the creation or extensions of harbours, landfills for industrial and residential areas, highways, airports. Or to projects to protect the ever-increasing population in coastal areas by means of beach nourishment, dikes and flood-control systems.

This latest edition reflects some significant changes from earlier versions:
- New forms of contracts
- New forms of partnering, alliance contacts
- Early involvement of dredging companies and cooperating stakeholders in the planning stages of a project
- Identification and resolution of environmental issues when creating necessary new infrastructure.

Dredging is important for the development of coastal areas with its predicted, impending over-population. Demographic developments indicate increased human involvement with water-related issues. Further globalisation of markets requires enhanced and additional shipping infrastructure, such as harbours, access-channels and port-related industrial areas.

When planning the “Development Process”, the emphasis is on its sustainability. Project planning also covers the Preliminary Planning and Design aspects. New information is provided about the addition of The Equator Principles with guidelines for determining social and environmental risk in project financing.

When implementing maritime development, it is of importance to identify all stakeholders and bring them into the project as early as possible. This may lead to Partnering between the Public Client body and Private Partners. All organisations benefit by allocating project risks to the parties best suited to take these risks.

Other considerations are the use of employer-owned equipment, sources for landfill requiring permits from (foreign) concessionaires, placement permits for (polluted) dredged materials.

Attention is given to the varying contractual issues of the agreement between client and contractor. Fair contract conditions and competition rules will make life much easier and transparent when managing the development and execution of the project and should be part of the project procurement strategy. Tender documents, clearly drafted and including all available and necessary information to obtain responsible tenders often lead to the most economical contract price with the least amount of surprises and risks.

Then there is a short but comprehensive description of the dredging process is given, starting with the detailed engineering design package to develop a set of specifications suitable for soliciting tenders. This design is also the basis for a reliable cost estimate useful to be able to evaluate the tenders. Significant elements in the design process are:
- the results of a comprehensive site investigation,
- dredged material characterisation,
- expected siltation during dredging operations and
- the re-placement of dredging materials.

A clear overview of the variety of available dredging equipment is also given. Compared with earlier editions one can see the enormous changes over the years. Especially the size and capacities of trailing suction hopper dredgers (TSHD) and cutter suction dredgers (CSD) have increased dramatically. The largest TSHD capacities increased from 1997(4th edition) to 2010 from around 18,000 m$^3$ hopper capacity to 46,000 m$^3$. CSD installed power increased from 20,000 kW to over 27,000 kW.

All major dredging contractors have embarked on extensive investment programmes, not only to build new TSHDs and self-propelled CSDs, but also on large hydraulic backhoes with 50 m$^3$ buckets, rock dumping fall-pipe vessels for offshore projects, 10,000 m$^3$ capacity sand-carriers, split-barges and so on.

The age of the old bucket-dredger is over. Of the nearly 200 working in 1997, less than 30 are still active in 2010.
Socio-economic aspects of dredging are playing an increasingly important role in port and navigation project development. Over time, the dredging industry has followed scientific evidence and current public attitudes in its concern for and care of the environment. Awareness and considerations of the effects of dredging in sensitive environments such as coral reefs and mangrove areas as well as the effects of relocating contaminated dredged sediments, have resulted in the requirement to have pre-project environmental assessment and monitoring during project execution.

In addition, research, development and training are necessities to improve dredging efficiency but also to enhance environmental awareness of dredging staff. Future research topics include further development of environmentally sensitive dredging techniques, assessment of the real impact of physical changes to the environment and long-lasting effects of contaminated dredged material.

International, Regional and National Agencies to support the development projects in providing financial assistance and guarantees are listed in the final sections. Focus is on the achievement of the Millennium Development Goals, such as insurance of environmental sustainability and development of a global partnership for development.

The extensive “recommended list of publications” on dredging and port development as included at the end of this publication is very helpful and may serve to further enhance knowledge of specialized items.

For dredging professionals or anyone involved in the sustainable development of navigation and port projects, Dredging for Development offers indispensable and up-to-date insights into an important industry.

HANS POIESZ

FACTS ABOUT BUILDING WITH NATURE
INTERNATIONAL ASSOCIATION OF DREDGING COMPANIES
December 2010. 4 pp. Available free of charge online and in print.

This is the most recent information update in the IADC series of concise, easy-to-read “management summaries”, which give overviews of essential information on specific dredging and maritime construction subjects.

Facts About Building with Nature introduces a new approach to planning, designing and operating dredging and maritime infrastructure projects. Rather than presuming the worst – that a project will harm the natural environment and thus act defensively – Building with Nature seeks positive, pro-active opportunities using the dynamics of the natural system as the starting point.

The concept “Building with Nature” began in 1979 with the Dutch engineer Honzo Svašek and over the last thirty years has been expanded and promoted by Dr. Ronald E. Waterman who linked it to a policy of “integrated coastal and delta strategy”. With his support and advice, a new institute “EcoShape” (www.ecoshape.nl) was founded in 2007-08. This private-public innovation programme has given a new impetus to researching the interface of nature and maritime infrastructure construction, with sustainable coastal development as the key motivating factor.

At about the same time a project in Belgium was launched known as “Flanders Bay 2100” (www.vlaamsebaaien.com/flanders-bay-2100) in which ten specific cities and sites along the Flemish coastline have been targeted for applying the principles of Building with Nature to ensure the success of long-term coastal planning.

Since, clearly, dredging and maritime construction operations are an essential element in improving global economic and social welfare, it is incumbent upon us all to find an understanding and balance between development and nature. Facts About Building with Nature presents an introduction to the concept and principles, to its application in specific situations, why and when it should be implemented and how this can be done by cooperation between engineers, ecologists, regulators, project developers and all other stakeholders. Working within the structure of Building with Nature can often mean the difference between a long-term, well-accepted project and no project at all.


All Facts About are downloadable in PDF form at the IADC website: www.iadc-dredging.com. Printed copies can be ordered by contacting the IADC Secretariat: info@iadc-dredging.com.
One-day Pre-conference Workshop on Dredging Techniques and Environment  
APRIL 12 2011  
SINGAPORE

In connection with the MTEC 2011 in Singapore from 13-15 April 2011, a one-day pre-conference workshop on the environmental aspects of dredging and state of the art dredging techniques will be presented by IADC. The fee for the workshop including lunch is EUR 450. The course is based upon the IADC-CEDA publication, *Environmental Aspects of Dredging*, published in 2008. The price of this publication is normally EUR 90.- (SGD 150), but will be included free of charge to those attending this pre-conference workshop to the MTEC 2011.

The lecturer will be Frans Uelman who was the engineering manager at the Channel Deepening Project in Melbourne, Australia for 5 years. As such, he was involved in the environmental approval process and responsible for ensuring environmental compliance during the execution phase of the project. He was also the environmental and quarantine manager at the Gorgon Project in Western Australia.

The Workshop will takes place from 9:00 hrs until 17:00 hrs (lunch will be served) and will be held at the Grand Captaine Waterfront Hotel, Waterfront room 1, level 2. Participants at this one-day workshop will receive a certificate of attendance. To register, please download and complete the registration form at the IADC website www.iadc-dredging.com and return it to the IADC Secretariat by e-mail: info@iadc-dredging.com or fax: + 31 (0)70 351 26 54. Details for payment will then be forwarded to you.

For further information please contact:  
Mr. René Kolman  
• E-mail: info@iadc-dredging.com  
Tel: +31 70 352 3334, Fax: +3170 351 2654, www.iadc-dredging.com

ESPO 2011 Conference -  
Optimising Port Performance  
MAY 5-6 2011  
FOUR SEASONS HOTEL, LIMASSOL, CYPRUS

The ESPO 2011 Conference, organised with Cyprus Port Authority, will explore the complex but fundamental theme, “Optimising Port Performance: Measuring and improving the competitiveness of the European port system”, with the help of port practitioners, (port) community stakeholders as well as policy and academic experts. ESPO is currently coordinating the EC co-funded project ‘PPRISM,’ ‘Port Performance Indicators – Selection and Measurement’.

The project involves five academic partners and aims to identify a key list of sustainable and feasible indicators to monitor the overall performance of the EU port system and assess its impact on the society, environment and the economy. The interim results of this project, which will form the basis of a European Port Observatory, will be presented.

The programme will include an update on relevant EU policy as well as an appraisal of the economic climate in which European ports operate. Finally, continuing the series of regional seminars held in Marseilles (2009) and Helsinki (2010), a special interest seminar will be held on port development in the East Mediterranean and Black Sea.

For further information please visit:  
www.espo.be and/ or www.espo-conference.com

Coastal Engineering and Management Asia 2011  
MAY 11-12 2011  
AMARA HOTEL, SINGAPORE

This is a two-day conference on Planning, Designing, Engineering, Constructing and Maintaining Sustainable Coastal and Marine Structures in Asia for government authorities and the private sector who need to tackle these relevant issues. Expert speakers include: Ian Muir, Maritime Sector Director (Asia Pacific) Scott Wilson; Gildas Colleter, Executive, Lead Coastal Engineer at Aurecon; Peyman Moazzen, Senior Design Engineer at Penta Ocean Construction; Dr. Mark Yong, Associate Director, BMT Asia Pacific; Lucien Halleux, Managing Director, G-TEC and many other distinguished experts.

The conference will be followed by a Masterclass on May 13, 2011 from 9.00-15.00 on “Handling your Marine Projects: Initiating Expansion and Redevelopment Plans to Delivering the Results”.

For further information contact:  
• Email: enquiry@iqpc.com.sg  
Tel: +65 6722 9388, Fax: +65 6720 3804  
www.coastalengineeringasia.com
IAPH 27th World Ports Conference  
MAY 23-27, 2011  
BUSAN, KOREA  

The conference theme “Embracing Our Future - Expanding Our Scope” was chosen because 2011 will be a time when the port industry will be undergoing many changes brought on by the economic crisis. It is important that the industry find new strategies to prosper in this newly developing economic climate. It is also time to face imperative global concerns, particularly climate change and the role of ports in climate action. As such, it is vital that the port industry explore all possibilities and not be limited to only advancing current technological practices. World Ports Conference 2011 will explore ways in which ports can improve efficiency and lower their environmental footprint.

For further information visit:  
www.iaph2011.kr

WEDA 31/TAMU 42 Annual Meeting  
JUNE 5-8, 2011  
GAYLORD OPRYLAND CONVENTION CENTER  
NASHVILLE, TENNESEE, U.S.A.

The Western Dredging Association (WEDA) and Texas A & M University will host their Annual Western Hemisphere Dredging Conference, with the conference theme “Enhancing the Economy Through Dredging”. The conference will focus on dredging and environmental issues associated with dredging programmes that create a strong economy and enhance the marine environment. This conference will be a forum for discussions between North, Central and South American Dredging Contractors, Port Authorities, Other Government Agencies, Environmentalists, Consultants, Academicians, Civil/Ocean Engineers throughout the Western Hemisphere who work in the fields of dredging, navigation, marine engineering and construction and the enhancement of the marine environment. The International Association of Dredging Companies (IADC) will present its Best Paper Award for a Young Author 35 years of age or under. Authors who wish to be considered are requested to indicate their birth date.

For further information contact:  
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• Email: weda@comcast.net  
http://westerndredging.org/weda_31.php

Forum on Early Contractor Involvement  
JUNE 23-24 2011  
HILTON DOCKLANDS LONDON, UK

An interactive forum and networking event for project owners, financiers, insurers, contractors, construction lawyers, regulators, government agencies and NGOs, advisors to decision makers in the maritime infrastructure construction industry. This two-day forum with the theme Partnering Creates Possibilities will bring together top-level experts and advisors responsible for construction projects for an in-depth exchange of knowledge. With well-known keynote speakers setting the tone for the forum the participants will explore the benefits of “contractual partnering” – that is, a co-operation amongst all the contractual players from the very early stages of project development. Early Contractor Involvement can help identify risks and responsibilities and obstacles to co-operation, as well as possible methods to deal with, eliminate or minimize them. The aim of conference is to explore the practical and legal possibilities of utilising better and more intelligently the resources associated with “the early involvement of contractors” in order to bring benefits to society in the form of faster and more cost-effective solutions.

By examining four successful recent projects from different parts of the world, this free-spirited event aims to disseminate existing knowledge and to stimulate new, creative ideas for achieving solutions for Best for the Project (win-win). A hypothetical case study will challenge the participating professionals to think out of the box and confront their own doubts and preconceptions. Whilst the event’s primary focus will be maritime infrastructure construction projects, experience and lessons learned in other industries will also be sought. The target audience comprises but is not limited to experts involved in maritime infrastructure projects: project principles/project owners (both experienced and less
experienced), development agencies; dredging contractors; consulting engineers; construction lawyers and legal counsels; project financiers; and decision makers and their advisors.

Registration: Fees: CEDA/IADC Members: £ 595 excl. VAT; Non-Members: £ 655 excl. VAT. Register online at: www.dcm-conference.org or contact Richard Hart at Event Logistics (richard.hart@event-logistics.co.uk).

Accommodation: A limited number of rooms are available at the Hilton London Docklands (the conference venue) at a reduced rate, £ 169 excl VAT. These are available on a first come, first served basis and will only be available at the special rate until 22nd April 2011. Online booking at http://www.hilton.com/en/hvi/groups/personalized/LYLONDDHI-GINTB-20110622/index.jhtml.

For further information please contact:
Anna Csíki, CEDA Secretariat
Tel: +31 15 268 2575, • Email: ceda@dredging.org or
René Kolman, IADC Secretariat
Tel: +31 70 352 3334, • Email: info@iadc-dredging.com).
or visit: www.dcm-conference.org

Smart Rivers 2011 Conference
SEPTEMBER 13-16, 2011
WESTIN CANAL PLACE
NEW ORLEANS, LOUISIANA, USA

The next installment of the outstanding Smart Rivers Conference series, a biennial forum bringing together an international professionals involved in inland/river transport will take place in September 2011. This 3-day technical conference is organised by PIANC USA, with more than twenty partnering organisations. The concept of “Smart Rivers” sprang from a group started in 2004 called SmartRivers21, an international coalition intent on realising “Strategic Maritime Asset Research and Transformation for 21st Century River Systems”. It began with a cooperation agreement between American and European partners and was followed by the organisation of Smart Rivers Conferences in Pittsburgh (2005), Brussels (2006), Louisville (2007), and Vienna (2009). The overarching theme of the 2011 Conference is “Systems Thinking,” with a particular emphasis on making this a global conference.

For further information contact:
PIANC USA
Tel: +1-703-428-9090, • Email: pianc@usace.army.mil
www.pianc.us or www.smartrivers.org

Europort 2011
NOVEMBER 8-11 2011,
AHOY ROTTERDAM, THE NETHERLANDS

Europort 2011 is one of the largest exhibition for the international maritime and dredging industry. The theme in 2011 will be “Advanced Technology: Your access to the future”. Presenting the newest technologies which aim at keeping pace with increasingly demanding maritime markets. Since the Netherlands is home to a wide variety of maritime disciplines, from world-class shipyards to innovative suppliers, and excels in complex shipbuilding, high-quality technologies and engineering, Europort, situated in the heart of the port of Rotterdam, is the ultimate venue for a maritime exhibition.

CEDA Dredging Days 2011
NOVEMBER 10-11 2011,
AHOY ROTTERDAM, THE NETHERLANDS

The theme of CEDA Dredging Days 2011, “Dredging and Beyond”, reflects the insight that dredging is no longer a stand-alone exercise, but is part of a broader, more integrated project realisation process. The dredging industry is increasingly confronted by projects involving environmental protection, nature development, offshore energy production and mineral mining on the sea floor. CEDA Dredging Days provide an important forum for presenting and debating new ways of thinking, innovative approaches, and cutting-edge dredging tools and technology. The focus will therefore be on two main areas where an integrated dredging approach is emerging:
• Dredging and rock dumping for the offshore oil and gas industry and deep-sea mining
• Building with nature for soft and hard dredging solutions (coastal and inland)

In the framework of CEDA’s support of the industry’s younger members, papers by students and young professionals will be presented as part of the new Academic Session - an integral, and popular, part of the technical programme. The International Association of Dredging Companies (IADC) will present its Best Paper Award for a Young Author 35 years of age or under.

A technical exhibition will be located in the area adjacent to the technical session room providing organisations with an opportunity to present their products and services to a focused group of international experts. CEDA Dredging Days will be held in conjunction with Europort 2011.

For further up-to-date information see:
CEDA Secretariat
Tel: +31 15 268 2575
• Email: ceda@dredging.org
www.cedaconferences.org/dredgingdays2011

For further information please visit:
www.europort.nl
MEMBERSHIP LIST IADC 2011

Through their regional branches or through representatives, members of IADC operate directly at all locations worldwide

**AFRICA**
- Boskalis International Egypt, Cairo, Egypt
- Dredging and Reclamation Jan De Nul Ltd., Lagos, Nigeria
- Dredging International Services Nigeria Ltd, Ikoyi Lagos, Nigeria
- Nigerian Westminster Dredging and Marine Ltd., Lagos, Nigeria
- Van Oord Nigeria Ltd., Victoria Island, Nigeria

**ASIA**
- Beijing Boskalis Dredging Technology Co. Ltd., Beijing, P.R. China
- Van Oord (Shanghai) Dredging Co. Ltd., Shanghai, P.R. China
- Van Oord Dredging and Marine Contractors bv Hong Kong Branch, P.R. China
- Boskalis Dredging India Pvt Ltd., Mumbai, India
- International Seaport Dredging Private Ltd., New Delhi, India
- Jan De Nul Dredging India Pvt. Ltd., India
- Van Oord India Pte Ltd, Mumbai, India
- P.T. Boskalis International Indonesia, Jakarta, Indonesia
- PT Penkonindo LLC, Jakarta, Indonesia
- Penta-Ocean Construction Co. Ltd., Tokyo, Japan
- Toa Corporation, Tokyo, Japan
- Hyundai Engineering & Construction Co. Ltd., Seoul, Korea
- Van Oord Dredging and Marine Contractors bv Korea Branch, Busan, Republic of Korea
- Van Oord (Malaysia) Sdn Bhd, Selangor, Malaysia
- Van Oord Dredging and Marine Contractors bv Philippines Branch, Manila, Philippines
- Boskalis International Pte Ltd., Singapore
- Dredging International Asia Pacific (Pte) Ltd., Singapore
- Jan De Nul Singapore Pte. Ltd., Singapore
- Van Oord Dredging and Marine Contractors bv Singapore Branch, Singapore
- Zinkcon Marine Singapore Pte. Ltd., Singapore
- Van Oord Thai Ltd, Bangkok, Thailand

**AUSTRALIA + NEW ZEALAND**
- Boskalis Australia Pty Ltd., Sydney, Australia
- Dredeco Pty. Ltd., Brisbane, QLD, Australia
- Jan De Nul Australia Ltd
- Van Oord Australia Pty Ltd., Brisbane, QLD, Australia
- WA Shell Sands Pty Ltd, Perth, Australia
- NZ Dredging & General Works Ltd, Maunganui, New Zealand

**EUROPE**
- Baggenwerken Decloedt & Zoon NV, Oostende, Belgium
- DEME Building Materials NV (DBM), Zwijndrecht, Belgium
- Dredging International N.V., Zwijndrecht, Belgium
- Jan De Nul n.v., Hofstadte/Aalst, Belgium
- Boskalis Westminster Dredging & Contracting Ltd., Cyprus
- Boskalis Westminster Middle East Ltd., Limassol, Cyprus
- Van Oord Middle East Ltd, Nicosia, Cyprus
- Rohde Nielsen, Copenhagen, Denmark
- Terramare Eesti OU, Tallinn, Estonia
- Terramare Oy, Helsinki, Finland
- Atlantique Drагage Sarl, St. Germain en Laye, France
- Société de Drагage International “SD” SA, Lambersart, France
- Sodraco International S.A.S., Lille, France
- Sodranord SARL, Le Blanc-Mesnil, France
- Brebwa Wasserbaugesellschaft Bremen mbH, Bremen, Germany
- Heinrich Hirdes G.m.b.H., Hamburg, Germany
- Nordsee Nassbagger und Tieflauf GmbH, Bremen, Germany
- Van Oord Gibraltar Ltd, Gibraltar
- Irish Dredging Company, Cork, Ireland
- Van Oord Ireland Ltd, Dublin, Ireland
- Boskalis Italia, Rome, Italy
- Dravo SA, Italia, Amelia (TR), Italy
- Societa Italiana Draggeri SPA “SIDRA”, Rome, Italy
- Baltic Marine Contractors SIA, Riga, Latvia
- Dredging and Maritime Management s.a., Steinfort, Luxembourg
- Dredging International (Luxembourg) SA, Luxembourg, Luxembourg
- TOA (LUX) S.A., Luxembourg, Luxembourg
- Aannemingsbedrijf L. Paans & Zonen, Gorinchem, Netherlands
- Baggermaatschappij Boskalis B.V., Papendrecht, Netherlands
- Boskalis B.V., Rotterdam, Netherlands
- Boskalis International B.V., Papendrecht, Netherlands
- Boskalis Offshore bv, Papendrecht, Netherlands
- Dredging and Contracting Rotterdam b.v., Bergen op Zoom, Netherlands
- Mijnster zand- en grinthandel bv, Gorinchem, Netherlands
- Tideway B.V., Breda, Netherlands
- Van Oord ACZ Marine Contractors bv, Rotterdam, Netherlands
- Van Oord Nederland bv, Gorinchem, Netherlands
- Van Oord nv, Rotterdam, Netherlands
- Van Oord Offshore bv, Gorinchem, Netherlands
- Dragapor Dragagens de Portugal S.A., Alcochete, Portugal
- Dravo SA, Lisbon, Portugal
- Ballast Ham Dredging, St. Petersburg, Russia
- Dravo SA, Madrid, Spain
- Flota Proyectos Singulares S.A., Madrid, Spain
- Sociedad Española de Dragados S.A., Madrid, Spain
- Boskalis Sweden AB, Gothenburg, Sweden
- Dredging International (UK) Ltd., Weybridge, UK
- Jan De Nul (UK) Ltd., Ascot, UK
- Rock Fall Company Ltd, Aberdeen, UK
- Van Oord UK Ltd., Newbury, UK
- Westminster Dredging Co. Ltd., Fareham, UK

**MIDDLE EAST**
- Boskalis Westminster Middle East Ltd., Manama, Bahrain
- Boskalis Westminster (Oman) LLC, Muscat, Oman
- Boskalis Westminster Middle East, Doha, Qatar
- Middle East Dredging Company (MEDCO), Doha, Qatar
- Boskalis Westminster Al Rashid Co. Ltd., Al Khobar, Saudi Arabia
- Boskalis Westminster M.E. Ltd., Abu Dhabi, U.A.E.
- Van Oord Gulf FZE, Dubai, U.A.E.

**THE AMERICAS**
- Boskalis International bvSucural Argentina, Buenos Aires, Argentina
- Companhia Sud Americana de Dragados S.A, Buenos Aires, Argentina
- Jan De Nul do Brasil Dragagem Ltda
- Van Oord ACZ Marine Contractors bv Argentina Branch, Buenos Aires, Argentina
- Van Oord Dragagens do Brasil Ltda, Rio de Janeiro, Brazil
- Van Oord Curaçao nv, Willemstad, Curaçao
- Dragamex SA de CV, Coatzacoalcos, Mexico
- Dredging International Mexico SA de CV, Veracruz, Mexico
- Mexicana de Dragados S.A. de C.V., Mexico City, Mexico
- Coastal and Inland Marine Services Inc., Bethania, Panama
- Dredging International de Panama SA, Panama
- Westminster Dredging Overseas, Trinidad
- Stuyvesant Dredging Company, Louisiana, U.S.A.
- Boskalis International Uruguaya S.A., Montevideo, Uruguay
- Dravensa C.A., Caracas, Venezuela
- Dredging International NV - Sucursal Venezuela, Caracas, Venezuela

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