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.
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Dredging for a new port complex in a remarkable, protected marine environment required adherence to very specific thresholds and an intensive Environmental Management Plan (EMP) that included mobile monitoring as well as daily visual observations of turbidity levels around the dredging works and the disposal zone.

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Environmental Aspects of Dredging Training Course in April, WEDA 32 in June, PIANC DREDGING 2012 in October, and several Calls For Papers for 2012-13.
Care for the environment remains one of the most urgent issues of our times. And it cannot be said often enough: Environmental preservation and remediation is a top priority for the dredging industry as well. For those of us in the dredging industry, that is a given. But for those outside of the industry – for stakeholders, port authorities and government officials – the connection between dredging and the environment is not always so obvious.

To demonstrate the numerous ways that dredging supports sound environmental policies, IADC often joins forces with other organisations which share its concerns. Recently, in December 2011, at the request of the National Marine Dredging Company (NMDC), the CEDA-IADC Environmental Aspects of Dredging Training Course was successfully presented at the Higher Colleges of Technology in Abu Dhabi. This course will again be offered at the PAO-Delft (Postgraduate Academic Programme, Delft University of Technology) at the end of April (see page 34).

Other support can be seen in the presentation of the IADC Award to the Best Paper by a Young Author at selected conferences. In this issue of Terra et Aqua, the Award presented at CEDA Dredging Days in November is published. The article focuses on the threat to flora and fauna which provide coastal protection, as tidal flats worldwide decrease as a result of sea level rise, subsidence by gas extraction and erosion initiated by human interventions such as construction projects. It describes the lessons learnt from a pilot nourishment executed at the Gageplaat tidal flat in 2008 (Eastern Scheldt, The Netherlands) which is part of the “Building with Nature” programme, a joint project of dredging companies, research institutes and the Netherlands government.

Another project with a vital environmental component is that of the port expansion project in the Voh region of New Caledonia, an area that needs dredging for economic development and yet is guardian of an incredibly unique UNESCO World Heritage site. The remarkable efforts of the dredging company to validate the Environmental Management Plan (EMP) requirements included extensive monitoring campaigns, which are described here in detail.

The dredging community is also committed to the intensive research conducted in by third parties, which involve safety as well as environment. An example of this is the article on calculations for trench ploughing in sandy soil. With the growing demand for offshore wind energy, the number of submarine cables required to export the energy from wind farms to shore has also increased. Since these cables can be damaged when exposed on the sea bed, adequate protection is a critical factor in cable installation and thus the demand for detailed knowledge of actual burial capacities of the plough has increased. The article in Terra provides a calculation method to predict the towing forces required to pull the plough through sandy soil types.

The international dredging industry’s concern for and commitment to the environment – and to state-of-the-art solutions in general – is evident in the ongoing interaction between the industry and researchers at universities, knowledge institutes and engineering companies, as well as their own in-house R&D.

For an industry as dynamic as dredging, remaining on the cutting edge of technology is a challenge that is taken very seriously. Finding and working with experts and colleagues who share this enthusiasm and dedication to a sound environmental future is key to the continued advances in the industry.

Koos van Oord
President, IADC
Tidal flats are valuable habitats for different plants and animals. However, the total area of tidal flats is decreasing worldwide caused by various problems like sea level rise, subsidence by gas extraction and erosion initiated by manmade constructions. Nourishing tidal flats might be a promising solution, but the impact both on the physical processes and the ecological system are unknown.

This article describes the lessons learnt from a pilot nourishment executed at the Galgeplaat tidal flat in 2008 (Eastern Scheldt, The Netherlands) with a total volume of 130,000 m³ over a total area of 150,000 m². The hypothesis is that as a result of the natural dynamics, i.e., the combined effect of currents and waves, the nourishment will gradually spread out and heighten the flat. To become a valuable habitat, the nourished area has to recolonise after the nourishment has buried all benthic fauna. To optimise nourishment strategies in the future with respect to shape, size and frequency, both the recolonisation of benthic fauna as well as the physical processes are monitored, modelled and analysed. After two years, only minor morphological changes of the nourishment occurred, but the overall change in sediment volume is approximately only 2%.

The nourishment killed all benthic macrofauna when buried. The recovery started directly after the nourishment was put in place. On the nourishment the recolonisation of the benthic macrofauna was very patchy, with some sites having a relatively rich fauna, whereas at other sites hardly any macrofauna was observed. The latter are mainly situated on the higher parts of the nourishment, where sediments dry out more during low tide compared to lower sites on the nourishment. The shape and nourishing method appear to be important factors influencing benthic recolonisation. Model results confirm the (small) morphodynamic changes and reveal the influence of currents and locally generated waves on the degradation of the flats. Combining the monitoring and modelling results shows that the biogeomorphological interactions (morphological changes driving recolonisation and vice versa) play a role and should be taken into account to come to successful nourishment strategies for tidal flats.

This article was first published in the Proceedings of the CEDA Dredging Days, Rotterdam, November 2011 and is reproduced with slight revisions with permission.

Bas Borsje was the lead author and received the IADC Young Authors award for his work. Other contributing authors are Katherine Cronin and Harriette Holzhauer of Deltares, Isel de Mesel and Tom Ysebaert of IMARES – Institute for Marine Resources & Ecosystem Studies and Anneke Hibma of Van Oord, all of whom are also members of the EcoShape I Building with Nature team.

The work was carried out as part of the innovation programme “Building with Nature”, which is funded from several sources including the Subsidieregeling Innovatieketen Water (SIW, Staatscourant nrs 953 and 17009) sponsored by the Dutch Ministry of Transport, Public Works and Water Management and partner contributions of the participants to the Foundation EcoShape. The programme receives co-funding from the European Fund for Regional Development EFRO and the Municipality of Dordrecht. The monitoring programme of the Galgeplaat is established by

Above: Aerial photo of the construction of the nourishment (24-09-2008). As a possible solution to the global problem of receding tidal flats, a pilot nourishment project at Galgeplaat was started in 2008. Tidal flats are an important habitat for plants and animals as well helping to maintain the coastal defense.
the Dutch Ministry of Transport, Public Works and Water Management. The field measurements are carried out by the Dutch Ministry of Transport, Public Works and Water Management. Previous model work was carried out under the ANT (Autonome Neerwaardse Trend) Oosterschelde study commissioned by the Dutch Ministry of Transport, Public Works and Water Management.

**INTRODUCTION**

Globally, tidal flats disappear at a fast rate as a result of intense human activities, sea level rise subsidence by gas extraction and erosion initiated by manmade constructions. Reduction in tidal flat area and elevation result in the loss of valuable habitats both for plants and animals and undermine the coastal defense as dikes become less protected from waves and currents. In the Netherlands, the Eastern Scheldt is suffering from sand shortage as a result of the construction of the Eastern Scheldt storm surge barrier. Consequently, the tidal volume and current speed within the estuary decreased considerably and the dynamic balance between the accretion and erosion of tidal flats, salt marshes and mudflats has been disturbed. The tidal channels are now too large relative to the reduced tide and are infilling. With very little sediment transport through the storm surge barrier, the majority of this sediment demand comes from the adjacent tidal flats, a process that mainly takes place during storm events. Because of lower current speeds less suspended sediment can be moved back onto the tidal flats. As a result of the changes in sediment dynamics, the elevation of the tidal flat is continuously lowered and the size of tidal flats is diminishing.

At the moment 50 hectares of mudflats and tidal flats are disappearing irrevocably under water each year in the Eastern Scheldt. It is expected that this will increase to 100 hectares per year (Jacobse et al., 2008). This means that in the future valuable intertidal habitat, which is foraging ground for tens of thousands of birds, will disappear. The Oosterschelde is of international importance for many wader species. In addition, the tidal flats form a barrier against waves running up the dikes.

When these areas disappear, the wave exposure on the dikes along the Eastern Scheldt will increase and additional strengthening of the dikes will be required. To deal with these threats, innovative, cost-efficient and sustainable methods are required (Van Raalte et al., 2008). Within the Dutch innovation programme “Building with Nature”, in cooperation with Rijkswaterstaat Zeeland, ecodynamic solutions to mitigate tidal flat degradation in the Eastern Scheldt were investigated. One of these solutions consists of nourishing tidal flats. As a pilot the Galgeplaat tidal flat was chosen (Figure 1).

The Galgeplaat is subject to erosion, with an average erosion rate of about 0.01 m/year (Van Zanten & Adriaanse, 2008). Herein, all areas between +1 and –1 m NAP are eroding. The higher areas on the west of the Galgeplaat are flattening, spreading the sediment over the tidal flat. In order to mitigate the erosion, Rijkswaterstaat Zeeland executed a pilot nourishment in the period of August-September 2008 using sand recovered during dredging activities for the shipping access channel next to the Galgeplaat.

During the construction, a sand wall was first built approximately 1m high, forming a ring with a diameter of 450 m. The ring was filled in with sand during the flood phase of the tidal cycle and spread by bulldozers during the ebb phase. This allowed for a controlled construction of the nourishment, as an increase in suspended matter concentration had to be avoided because of nearby commercial mussel beds. The total volume of the nourishment is 130,000 m³ and the

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Figure 1. Overview map of the Galgeplaat tidal flat located in the Eastern Scheldt (The Netherlands).
Biogeomorphological Interactions on a Nourished Tidal Flat: Lessons Learnt from Building With Nature

Total area is 150,000 m². In order to give recommendations about future nourishment strategies an extensive monitoring campaign and a modelling study were set up.

The hypothesis is that as a result of the natural dynamics, i.e., the combined effect of tidal currents and waves, the nourishment will spread over the tidal flat and heighten the tidal flat in the surrounding area. On a time scale of a couple of years the nourishment will balance the erosion of the tidal flat. Balancing the erosion will keep the tidal flat above low water and therefore birds will be able to forage long enough during low tide. Keeping the tidal flat above low water however is not enough for the birds; there has to be food to forage. The nourishment buries all benthic fauna. After some time the benthic fauna is expected to have recolonised the area.

The volume of the pilot nourishment is not sufficient to heighten the entire tidal flat, since this is the first nourishment put on a tidal flat in The Netherlands and the effects of the nourishment on the tidal flat and the surrounding area are not known.

Field measurements are carried out by the Dutch Ministry of Transport, Public Works and Water Management and Building with Nature to study the morphological and ecological developments. The main questions are:
- does the sediment spread over the tidal flat,
- how does it spread, and
- how long does it take the benthic fauna to recolonise the nourished area.

The processes of sediment spreading and benthic recolonisation are coupled and interact with each other. Therefore integrated measurements and data analyses are needed.

The aim of this research is:
(1) to quantify the impact of the nourished area on both the biotic and abiotic system of the tidal flat and
(2) to give recommendations for successful nourishment practice in intertidal areas.

To achieve these objectives an overview of the results of the monitoring campaign executed around the nourishment (see Monitoring) is given, and the results of the process-based model (see Modelling). Subsequently the nourishment is modelled at another location to assess the morphological changes (see Discussion). Finally, the main conclusions are given.

MONITORING
Galgeplaat nourishment monitoring
A detailed monitoring programme was set up to follow the morphological and ecological development of the nourishment on the Galgeplaat in space and time (Figure 2). Morphological developments were monitored monthly in the first year and later on every third month through visual inspections at the edge of the nourishment, sedimentation-erosion plots at 14 locations along three transects and elevation measurements with RTK-DGPS with a spatial resolution of 25 m. Hydrodynamic measurements of waves and currents are being done with ADCP shortly after the construction of the nourishment, for a period of a month, to better understand the sediment dynamics in the area.

Additionally, a Waverider was installed 200 m southwest of the Galgeplaat in order to measure the dominant wave climate.
continuously. During the construction phase suspended matter concentration was measured in the channels around the tidal flat. Ecological measurements include regular sampling of benthic macrofauna, sediment characteristics (grain size) and chlorophyll-a (i.e., measurements for the presence of algae) to track the benthic recolonisation in time.

Sampling sites on the nourishment (n = 10) are compared with reference stations (n = 6) in nearby undisturbed sediments. Macrofauna samples consisted of three cores (3 × 0.005 m²) pushed 30 cm into the sediment within a 1-m radius of the sample site. Sediment samples for grain size and chlorophyll-a concentrations were taken with a 1-cm diameter tube pushed 3 cm and 1 cm into the sediment respectively. Samples were taken in June 2008 (before the nourishment took place), and shortly after the completion of the nourishment (September and October 2008). In 2009 and 2010 sampling was done in April, July and October. In July and October 2009 and 2010 additional samples (n = 25 in total) were taken of the nourishment to get a better picture of the spatial patterns of recolonisation on the nourishment.

Additional high frequency monitoring by means of the Argus-Bio station is carried out to map the nourishment and wet areas, track the foraging behaviour of birds and track the development of algae, oysters and sandworms on the nourishment. The Argus-Bio station is a station with four fixed Argus-cameras and one movable monitoring camera on a pole in a protective housing at a platform at +17 m NAP. The station has been operational since 31 July 2009. The system is programmed such that the nourishment is monitored during low tide and there is sufficient light.

Abiotic development
After two years the nourishment is still clearly visible at the Galgeplaat. Initially the bed level had been raised by the nourishment from −0.5 m NAP to +0.5 NAP on average. The morphological development is minor. The field measurements showed that the nourished volume decreased circa 2% (Figure 3). The nourishment is not constructed entirely flat. The northern part is higher than the south-western part (Figure 4).

Field measurements show that the erosion is greatest at the high northern part of the nourishment (> +0.25 m NAP). Most of the eroded sediment is transported in a north-eastern direction and accreted along the edge of the nourishment (Figure 3).

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Sediment from maintenance dredging work in the adjacent channels of the Galgeplaat was used for the nourishment. The median grain size observed on the nourishment was coarser compared to the surrounding undisturbed sediment (206 ± 3.6 μm and 166 ± 7.7 μm, respectively) and hardly changed over time.

Ecological development
A sampling just before the start of the nourishment (June 2008) at sites on the nourishment area and at reference sites in the surrounding

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Ecological development
A sampling just before the start of the nourishment (June 2008) at sites on the nourishment area and at reference sites in the surrounding
area revealed similar chlorophyll-a concentration and similar total density, biomass and species richness (i.e., total number of species present) of benthic macrofauna (Figure 5). Chlorophyll-a concentration dropped drastically after the nourishment and recovery to pre-nourishment values is still ongoing after 2 years.

The nourishment killed almost all benthic macrofauna. Shortly after the nourishment, in September and October 2008, only a few organisms were observed in the samples, mainly being adult mud snails (*Hydrobia ulvae*) which migrated from the surrounding undisturbed area. This species was very common in the summer of 2008 and is capable of travelling over large distances by floating. In 2009 further recolonisation of the nourishment by benthic macrofauna was observed. In July and October 2009, one year after nourishment, densities were similar between the nourishment and the reference sites, but both biomass and species richness was still lower on the nourishment.

The second year, in July and October 2010, both biomass and species richness were similar to the reference area. The much lower density observed in the reference stations in 2009 and 2010 was a result of the almost complete absence of *Hydrobia ulvae*, by far the dominant species in the summer of 2008. *Hydrobia ulvae* is known to show great year-to-year variation in the whole Eastern Scheldt and therefore these fluctuations are not abnormal (Troost and Ysebaert 2011).

On the nourishment the recolonisation by benthic macrofauna was very patchy. This is most likely a result of topographical differences on the nourishment, as the northern part is more elevated compared to the southern part (Figure 5). As a consequence the higher areas dry out more quickly during low tide, whereas in the lower area wet areas remain. Based on the Argus Bio-camera images a link was observed between the occurrence of wet and dry areas and the position of the sampling locations for the benthic macrofauna. In the wet areas, recovery of the benthic macrofauna was better compared to the dry areas. More particularly, the number of species, biomass and total density of the macrofauna recolonising the nourishment was higher on the wet areas compared to the dry areas (Figure 6).
MODELLING

As part of the work of Das (2010) a depth-averaged, two-dimensional horizontal (2DH) Delft3D-FLOW hydrodynamic model was set up for the Galgeplaat with a horizontal grid resolution of 25-45 m. Delft3D-WAVE (SWAN) was used to simulate waves on the Galgeplaat grid (coupled with the hydrodynamic model) which was nested in a larger wave domain (Figure 7).

Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation programme which calculates non-steady flow and transport phenomena, including sediment transport that results from tidal and meteorological forcing on a rectilinear or curvilinear, boundary fitted grid, including the robust simulation of drying and flooding of inter-tidal flats (Deltares, 2010). When coupled with Delft3D-WAVE, current-wave interactions are included (see Deltares, 2010 for a description of these models). This coupled model was in turn nested in the KustZuid model. This larger model simulates the hydrodynamics (including waves) of the southern part of the North Sea, Western Scheldt and Eastern Scheldt (Figure 8).

This work was continued as part of the ANT project where a series of sensitivity tests were carried out in order to understand the processes responsible for (non-cohesive) sediment transport on Galgeplaat (2001 bathymetry) and to examine the influence of meteorological forcing on morphological development.

In this work the hydrodynamics and sediment transport in the Eastern Scheldt were simulated for a November spring/neap cycle (winter) and an April spring/neap cycle (spring) in order to assess the effect of these processes on the nourishment. The bathymetry in the model was updated using the latest available echo-soundings (2007 bathymetry) and the nourishment was included at two locations – the present location and another more dynamic location further north where transport rates are higher – in order to investigate the behaviour in a more dynamic location.

KustZuid Model

The offshore boundary conditions for the KustZuid model are astronomic water level constituents. The model timer was kept the same in all scenarios (28 October 2009 – 15 November 2009) to avoid differences resulting from nodal correction of the astronomical tide. A time-step of 0.5 minutes was used and bathymetry from 2001 and 2004 as it was the most complete dataset for the entire model. Wave and winds from the wave buoy Europlatform (51.9N 3.3E) were used to force the model. A Manning coefficient of 0.025 was applied. Boundary conditions were generated for the Galgeplaat model with an offline nesting procedure.

Galgeplaat Model

The Galgeplaat model has three open boundaries, to the north-west (NW), north-east (NO) and south-east (Zo). The north-west is a mixture of current and water level boundary segments, the south-east and north-east are current boundaries. Simulations were set up to examine the effect of wind and wave forcing on morphological development over the tidal flats. The outer domain of the Galgeplaat wave model was also forced by waves from Europlatform with winds from Stavenisse Station. Winds were predominately from the south-west in November 2009 (average 6 m/s; maximum 15 m/s) and from multiple directions in April, but a large proportion from the north-east (average 4.5 m/s; maximum 11.5 m/s).

Runs with and without wind or waves, for both the winter and spring scenarios were set up to examine the effect of tide only and different meteorological conditions on the morphological development of the Galgeplaat. These simulations were repeated with the presence of the nourishment to examine the behaviour of both the nourishment under different conditions and on erosion rates of the flats. Two additional runs were set up with the nourishment in a more dynamic location further north. Winter and spring forcing conditions were again used. An overview of simulations is given in Table I.

A time step of 0.5 minutes was applied and a uniform non-cohesive sediment diameter of 200μm. This sediment diameter was chosen as it best represented the nourishment grain size. A Chézy coefficient of 65 m$^{1/2}$/s was used in all
were repeated as part of the ANT study (Cronin, K., 2011) with double the tidal currents at the boundary of the Galgeplaat model. With a doubling of currents the Galgeplaat still experienced spatially averaged erosion of –0.008 m for the November scenario showing the dominance of wind and wave forcing, albeit the erosion was less. For the calmer April scenario, a spatially averaged deposition of +0.001 m was simulated. This shows that accretion of the tidal flats is possible under calm conditions but that the current velocities since the construction of the barriers are reduced to such an extent that overall accretion is rare or impossible.

Including the nourishment in the model resulted in slightly less erosion in the winter scenario (–0.016 m) as a result of the supply from the nourishment (G03) (Figure 11) and no significant difference in the spring scenario, where there was much less sedimentation and erosion on and around the nourishment.

Moving the nourishment to a more dynamic area of the flats, in the northern half, results in the same level of erosion for the winter forcing (G07) (Figure 12) as the winter reference scenario (Figure 10b). More erosion of the nourishment occurred and sand was transported in greater amounts to the

Figure 10a shows the Galgeplaat spring simulation (G02) with a spatially averaged erosion of –0.002 m. Figure 10b shows the winter scenario (G01) with much more erosion of –0.018 m – an order of magnitude difference. The south-westerly wind and wave conditions during the simulation period are also reflected in the dominant direction of the transport vectors. Prior to the construction of the storm surge barrier, calm weather generally resulted in an overall trend towards slight vertical accretion. Under storm conditions however substantial amounts of sediment were stirred up by wave action and picked up by the current.

To examine the effect of stronger currents in the model, the spring and winter simulations runs. In the morphological parameterisation, bed updating was switched on and a morphological factor of 6 was applied with an initial spin-up period of 12 hours before bed-updating began. Therefore results of the morphological simulations represent 6 spring-neap tides. This should be borne in mind when looking at the cumulative sedimentation/erosion rates of the winter simulations. The sediment transport formula of van Rijn (1993) is used by default.

Validation and Results
A comparison was made between waves at Keeten and the closest model observation point (~300m NW) (Figure 9). Significant wave height was predicted correctly for most of the simulation period, with the exception that lower wave heights around 9 November 2009 were overestimated. Current velocities were also compared with measurements done on the flats in 2008. A run with 2008 wind and wave forcing was set-up for this purpose. Velocity magnitudes compare well at some stations in the field and are slightly underestimated in others. The direction of the flow velocities over the flats vary throughout the tidal cycle. Kohsiek et al. (1988) found during field measurements in the adjacent western tidal channel of the Galgeplaat that the current direction near the bottom is along the edge of the shoal, but that the current direction near the surface is shifted 20 degrees and is directed onto the shoal. This occurs around the maximum flood velocities.

Although the model is 2D, the vectors do appear to curve inwards towards the flats mid-way through the flood (11:00) and around high water (13:00) on the western side. During ebb, large current velocities are directed off the flats.
In order to understand and better predict these impacts, a monitoring study and a modelling study are underway. The morphological development of the nourishment was remarkably small: the nourished volume hardly eroded and the redistribution of sediment from the nourishment to the surrounding tidal flat was minor in the two-year period after placement. The ecological development is still on-going after 2 years. Interestingly, the recolonisation on the nourishment showed clear spatial differences related to the differences in topography of the system. In an attempt to reduce this degradation a nourishment was placed on the flat in 2008.

**DISCUSSION**

The Galgeplaat has been experiencing erosion rates of 0.01 m/year from 1985-2001 (Zanten & Adriaanse, 2008) with up to 0.02 – 0.05 m/year locally. This loss of tidal flats has a detrimental effect on the ecology of the system. In an attempt to reduce this degradation a nourishment was placed on the flat in 2008.

The impact of the nourishment is two-fold: next to short-term negative impact on the disturbed biota, over the longer term the nourishment will supply sand to the surrounding area, thus compensating the erosion of the valuable tidal flat for biota such as birds that use these areas as foraging grounds.

In order to understand and better predict these impacts, a monitoring study and a modelling study are underway. The morphological development of the nourishment was remarkably small: the nourished volume hardly eroded and the redistribution of sediment from the nourishment to the surrounding tidal flat was minor in the two-year period after placement.

The ecological development is still on-going after 2 years. Interestingly, the recolonisation on the nourishment showed clear spatial differences related to the differences in topography of the system. In the analysis, wet areas, which remain covered with water for a longer time period during low tide, were distinguished from dry areas which dry up quickly. In terms of total densities, the nourishment site is comparable.

**Figure 10a.** Cumulative sedimentation/erosion for the spring scenario with no nourishment (G02).

**Figure 10b.** Cumulative sedimentation/erosion for the winter scenario with no nourishment (G01).

surrounding area. Similarly for the spring scenario, more sand was transported from the nourishment to the surroundings.

Regarding the locations of erosion and deposition, the morphological patterns are partly in agreement with observations that show the western edge eroding and the sediment building up on the eastern channel edge. Louters et al. (1998) found that between 1987 and 1994 most of the sediment eroding from the Galgeplaat was deposited along the banks of the eastern channel, indicating the importance of westerly storms in this process. However these simulations show infilling of the main gully on the western side of the flats. This may also be caused by incorrect simulation of currents and transport around this area. In reality there is a large area of oyster beds around this gully and flow patterns would therefore be affected.
to the reference site the second year after nourishing and spatial differences between wet areas and dry areas are small. Recolonisation was slower though in the dry than in the wet areas, as was clear from the observations in 2009.

For the biomass, however, overall averages indicate similar values in the nourishment and the reference site reached in 2010, but the spatial difference is high. After two years, biomass was much higher in the wet area compared to the dry sites. The number of species was initially higher in the wet areas than in the dry areas, but these differences are getting smaller as time goes on. It is foreseen that it will take several years to get a fully recovered benthic community. Also the recovery trajectory might be different depending on the initial conditions of the nourishment compared to the original conditions (Defeo et al., 2009). Although not constructed intentionally, the elevation differences allowed for a different recolonisation rate, probably as a result of different drainage patterns which affect the moisture of the sediment. This should be taken into account when designing nourishments on tidal flats. Instead of completely flat surfaces, probably a design with troughs or a gentle slope is more favourable for the biological recovery of the system.

Regarding the modelling, further work is needed on both the nested Galgeplaat model and the KustZuid model in order to improve understanding of the physical processes dominating the morphological changes in nature and within the model. In this study only a relatively short period was simulated and the morphological patterns are still rather patchy. For a better understanding of these patterns a longer period needs to be simulated with a wider range of representative conditions.

These simulations showed that locally generated waves play an important role in the transport of sediments around and on the tidal flats. This transport should be investigated further by looking at the resuspension processes involved as a result of both currents, waves and wave-current interaction. The inclusion of biological features, such as oyster and mussel beds will also have an impact on the simulation of current magnitudes over the tidal flats and hence patterns of sedimentation/erosion.
Nonetheless, the model is already a useful tool to assess the behaviour of the nourishment under different conditions and at different locations. Simulating the present nourishment location, results show a similar pattern of deposition around the north and north-east of the nourishment as in reality. Currently, monitoring shows that the nourishment has remained quite intact with only a minor spreading of sediment.

The observed bed level changes over the nourishment cannot yet be compared to the modelled bed level changes. To do this a longer term simulation with realistic wave and wind forcing will be done. However, the model does show that little is happening to the nourishment under calm conditions and it is much more morphologically active under higher wind and wave conditions. The model is also useful to test the behaviour of the nourishment in another location, as much more morphological change occurred on and around the nourishment in a location further north-west.

Linking the simulated morphological change of different nourishment scenarios with the impact on biota and vice versa is, as of yet, complicated by both temporal and spatial scale issues. Further model work is under way to include the effects of the oyster and mussel beds on the morphological development of the Galgeplaat.

**REFERENCES**


Morphological and ecological developments, 15 months after the construction. Deltares, Delft.


**CONCLUSIONS**

In order to (temporarily) stop the loss of intertidal area, a pilot nourishment was executed at the Galgenplaat, a tidal flat in the Eastern Scheldt, The Netherlands. The morphological changes of the nourishment appear to be small. A detailed monitoring programme revealed that biological recovery at the nourishment site was highest at locations which were wet during a longer period of the tidal cycle. Two years after implementation, the overall average biomass reached similar values at the nourishment and the reference site.

The numerical morphological model of the Galgeplaat forms a useful tool to study the wind and wave conditions that have most impact on the spreading of the nourishment and to examine different nourishment strategies, both in terms of nourishment location and nourishment design (shape and size). More analysis is needed to connect the morphological patterns observed in the model and its effects on the biota since the nourishment has been put in place. The interaction between the abiotic and biotic field measurements and the model is essential in understanding the impact of the nourishment. Field measurements are used to validate the model and model results will be used to pinpoint locations for more detailed field measurements like the wet areas.

Given the lessons learnt in this pilot project, the nourishment strategy can be improved and a nourishment is proposed:

1. on a more dynamic location, in order to spread the sediment over the tidal flat by currents and waves,
2. with topographical differences in order to speed up recolonisation and
3. to minimise the impact on other user functions in the area like commercial mussel beds.

Through the improved knowledge on the abiotic-biotic interactions, recommendations on the frequency as part of the nourishment strategy can also be given.
ABSTRACT

With the ever-growing demand for offshore wind energy, the number of submarine cables required to export the energy from wind farms to shore has also increased in recent times. These cables can be damaged when exposed on the sea bed, and thus need proper protection. Burial of these cables by use of a cable trench plough is one key technique to achieving such protection. A submarine cable trench plough can be used in various soil types, from hard boulder clay to loose sand. Because providing adequate protection is a critical factor in cable installation and the current calculation methods and theory used for submarine ploughing are mostly empirically extrapolated, the demand for fundamental and detailed knowledge of actual burial capacities of the plough has increased.

This article provides a calculation method to predict the towing forces required to pull the plough through sandy soil types.

The calculation algorithm developed for this research divides the tow force on a submarine plough into a cutting force component and a friction force component on the share, heel and skids. The total cutting force can be calculated by summation of the force components of separate cutting tooth. The methods to calculate the cutting force originated from the “2-D saturated soil cutting theory” Adaptations have been included to correct for three-dimensional effects and the education process of the sand.

The whole process of saturated soil cutting is dominated by the pore pressure development as a result of dilatancy – the phenomenon whereby a viscous substance solidifies under pressure – during shearing.

Therefore an extensive algorithm, called the parallel resistor method, is used to calculate pore pressures on a finite number of elements on the shear plane in front of the cutting tooth. When the water pore pressure reaches vapour pressure, cavitation will occur.

INTRODUCTION

As a result of the increasing demand for electrical energy transportation from offshore wind farms, many subsea power cables will be installed during the coming decades. Wind farms have been built up till now in relatively shallow water. Therefore the cables transporting the electrical energy are vulnerable to various kinds of threats.

Sometimes export cables transporting the energy from the wind farm to shore cross busy shipping routes, fishing areas or river deltas, where the sea bottom is regularly disturbed by anchoring, dredging, trawling and such. Usually in these areas a great number of cable and pipeline crossings have already been installed, and both the new cable, as well as the existing asset, must be protected during and after installation. Besides that, dropped objects from shipping and complete shipwrecks can put a cable at risk.

Thus, to reduce the risk of damaging the cable by ensuring effective protection of the cable, meticulous engineering and careful execution of cable laying and burial operations are required. Protection of submarine power cables can basically be arranged in three major ways:
For practicality and for financial reasons, burial of the cable is the preferred way to protect the cables against impacts. With the use of trenching machines or ploughs, a trench is excavated in order to install the cable several metres below the sea bed. Different types of trenching equipment are used in various types of soil. Four main burial methods are used:

- Mass flow excavation: fluidisation of the soil/jetting (cable sinks in)(high flow)
- Water-jet cutting (high pressure)
- Mechanical trenching
- Ploughing

Depending on the type of tool used, the trench has to be backfilled or, if the trench is sufficiently narrow, the surrounding soil will collapse into the trench. In case of narrow trench ploughing (also called trenched ploughing) the cable is laid down and has to be fed through the machine, called simultaneous laying and burial. Usually the cable is forced into the trench by the depressor, ensuring that it touches down at the bottom of the trench.

Depth of burial is always an issue for cable exploitation companies, insurance companies and contractors. One can imagine that soil with a high strength will provide more protection at the same depth than a weaker soil. However, no international classification rules and regulations have been developed to accurately measure the precise protection level provided by specific burial depths are stated so far.

Interest and research in this industry first started to blossom during the 1980s driven by the increase in demand of marine telecommunications and power cable installations. In 1997 the concept of a Burial Protection Index (BPI) was first induced in Mole, Featherstone and Winter (1997).

Three levels of required protection have been stated:

- **BPI 1.** Depth of burial consistent with protecting a cable from normal fishing gear only. This would be appropriate to water depths greater than say 50 to 100 m where anchoring ships is unlikely.
- **BPI 2.** Depth of burial will give protection from vessels with anchors up to approximately 2 tonnes (light anchors). This would be adequate for normal fishing activity but would not be adequate for larger ships.
- **BPI 3.** Depth of burial sufficient to protect from anchors of all but the largest ships.

The required burial depth can be determined based on the soil type, strength and the BPI. Mole, Featherstone and Winter (1997) produced a series of charts to select the appropriate burial depth to provide a certain protection level in the applicable soils.

Visser & Smit Marine Contracting (VSMC), a cable installation company, part of the Volker Wessels group, owns a cable trenching plough, the Sea Stallion 4, that has been operational for several years now (Figure 1). Unfortunately low performance is experienced in several soil types as impermeable dense sand and stiff clay. When the performance of a burial tool in a specific soil can be assessed prior to the operation, money and effort can be saved. Today’s prediction models to calculate forces on the plough turn out to be too optimistic. The demand for a proper calculation model has thus arisen.

Except for the research on mouldboard plough, executed by Reece and Grinsted (1986) and Palmer (1979), not much information can be found in the public domain, especially not for narrow single share cable trench ploughs (or trenched ploughs).

For this article, a calculation method to predict the required tow force-velocity relation, for different burial depths in different soil types (only cohesionless soils) is described. The method is based on the 2-D saturated sand cutting theories for dredging excavation (van Os, 1977; Miedema, 1984 and others). What is new to this approach is the calculation of pore pressure forces with an adapted version of the parallel resistor method.

**FAILURE MECHANISM OF SAND**

During this research only plough force-velocity calculations for saturated sand cutting have been investigated. The failure principles and the friction development of the soil are different for cohesive (left out of consideration) and non-cohesive soils. It is of major importance to understand the actual failure mechanism when one wants to establish force-velocity-soil predictions.

In sandy soil the friction force acting on the shear plane in front of the cutting blade is originated from normal force (or stress) against the soil and the friction angle of the soil. Because the normal force and thus the resistance against deformation are dependent on the dilatant volume increase of the soil caused by shearing, the rate of dilatancy is an important parameter in all subsea soil excavation processes (see Figure 2) (van Os, 1977; Joanknecht, 1974; Miedema, 1984, 2001).

When the plough is cleaving through the soil, first the soil encounters the cutting blades.
Calculations on Forces and Velocities of a Submarine Narrow Trench Plough in Sandy Soil

RUUD BEINDORFF
graduated in autumn 2011 with an MSc in Offshore Engineering and Dredging from the Delft University of Technology, the Netherlands (DUT) on the subject of submarine cable ploughing. He is currently a project engineer working at the R&D department of the Dutch submarine power cable installation company Visser & Smit Marine Contracting (VSMC), part of the Volker Wessels Group.

SAPE A. MIEDEMA
obtained his MSc in Mechanical Engineering with honours at the Delft University of Technology (DUT) in 1983 and his PhD in 1987. From 1987 to the present he has been at DUT, first as assistant, and then associate, professor at the Chair of Dredging Technology, then as a member of the management board of Mechanical Engineering and Marine Technology. From 1996 to 2001 he was simultaneously educational director of Mechanical Engineering and Marine Technology at DUT. In 2005, in addition to his other functions, he was appointed educational director of the MSc programme of Offshore Engineering and Dredging.

LENNART R. VAN BAALEN
is currently working as Manager, Research Development & Support at Visser & Smit Marine Contracting, which is part of the Volker Wessels group. VSMC specialises in cable installation and burial for offshore wind mill parks. Van Baalen studied Engineering Geology at Delft University of Technology, faculty of Civil Engineering and Geosciences (previously Mining and Petroleum Engineering). He then worked in Namibia for an offshore diamond mining company. He has also worked on offshore pipeline installation and burial in the North Sea and the Gulf of Mexico.

(at the front of the cutting teeth). Such a blade has an inclination relative to the horizontal called the blade angle $\alpha$. The blade has a width $b$ and has an inclined length of $h b \cos(\alpha)$, where $h_b$ is the vertical height of the cutting blade and $h$ is the height of the cutted soil layer. The plough evaluated for this research has 3 teeth located at a height of 0, 1.15 and 2.30 m above the bottom of trench (BoT).

While the inclined blade ($\alpha$) penetrates the soil, a slice of soil is cleaved and pushed upwards. In front of the blade tip, a shear plane occurs where the soil is sheared by the cutting mechanism. This shear plane runs all the way from the blade tip to the surface. This process is extensively elaborated in the theory of van Os (1977), Joanknecht (1974) and Miedema (1984). An equilibrium between gravitational, inertial, frictional and pore pressure forces is described for a two-dimensional situation in the 2-D saturated sand cutting theory.

The important adaptation to the 2-D soil cutting calculation is the inclusion of 3-dimensional edge effects owing to the narrow width of the trench excavation. The 3-dimensional components (edge effects) are much more important for a narrow blade plough than for conventional dredging blade calculations. Transversal stowing of soil cannot be neglected anymore, because transportation of the excavated soil is hindered.

Although the trenching velocity is relatively low compared to the conventional dredging excavation, cavitation might occur in lower parts of the trench. The resistance of the soil against water flow is so high that the hydrostatic pore pressure reaches the vapour pressure limit. Cavitation will only occur partially at the cutting tooth, depending on the velocity. The calculation algorithm described here uses the method of minimum resistance or Coulomb theory to evaluate whether cavitation would occur. Besides a cutting force component on the teeth of the plough, there will also be frictional forces acting on the plough share, heel and the skids.

OFFSHORE SOIL MECHANICS
For the installation of the cable, special attention has to be paid to the soil characteristics along the cable route.

In Western Europe, sand mostly consists of quartz. The chemical formula of this mineral is $\text{SiO}_2$. Sand has a grain size diameter from about 0.06 mm up to 2 mm. Smaller grain sized materials are called silt (very fine Quartz) or clay (Western Europe: $(\text{Si}_4\text{O}_{10})^4^\text{f}_6$ and $\text{Al}_2/\text{Mg}_3(\text{OH})_6$).

Usually in an offshore environment soil characteristics are obtained using offshore Cone Penetration Tests (CPTs) and Vibro Core (VC) tests including laboratory tests like Particle Size Distribution (PSD) analysis. From a CPT the relative density of the soil is indicated. An additional microscopic photograph of the individual grains of the soil could provide information on the shape, the roughness and material of the grains.

Usually the sand type is characterised by:
- The smallest 10% fraction diameter, $D_{10}$
- The smallest 30% fraction diameter, $D_{30}$
- The mean diameter ($D_5$) and,
- The smallest 60% fraction diameter, $D_{60}$.

The relation of these parameters can be written as constants of uniformity and curvature:

$$c_{\text{curv}} = \frac{D_{30}^2}{D_{10} \cdot D_{60}}$$  \hspace{1cm} \text{[Eq. 1]}

$$c_{\text{uni}} = \frac{D_{60}}{D_{10}}$$  \hspace{1cm} \text{[Eq. 2]}

From these correlations, together with the relative density, most parameters as permeability, friction angle and dilatancy rate can be determined empirically.

Porosity of sand
Soil is not a continuum material but consists of individual sand grains, water and air. In offshore conditions, only water is present in the pores between the particles.

The commonly used parameter to quantify the amount of pore space is the porosity:

$$n = \frac{V_{\text{pore}}}{V}$$  \hspace{1cm} \text{[Eq. 3]}

Where:
- $n$ = Porosity $[-]$
- $V_{\text{pore}}$ = Pore Volume $[m^3]$
- $V_{\text{soil}}$ = Soil Volume $[m^3]$
In most of the in-situ soils the porosity \( n \) has a value between 0.3 and 0.45. The smaller the porosity, the denser the soil will be. Other parameters to identify the pore space are void ratio and density.

**Relative density**

The relative density \( RD \) is used to describe the compactness of the in-situ soil, with respect to the loosest and the densest state of the soil. The relative density can be expressed based on the porosity (min, in-situ and max), or by using the densities.

\[
I_d = \frac{\rho_{\text{max}} - (\rho_{\text{insitu}} - \rho_{\text{min}})}{\rho_{\text{insitu}} - (\rho_{\text{max}} - \rho_{\text{min}})} \quad \text{[Eq. 4]}
\]

Where:

- \( \rho_{\text{insitu}} = \text{in-situ density} \) \( \frac{\text{kg}}{\text{m}^3} \)
- \( \rho_{\text{min}} = \text{minimum density} \) \( \frac{\text{kg}}{\text{m}^3} \)
- \( \rho_{\text{max}} = \text{maximum density} \) \( \frac{\text{kg}}{\text{m}^3} \)

**Particle shape**

Sand grains may have very different shapes caused by the weathering and erosion which the grains have experienced throughout their ‘life’. These shape parameters affect strength of the material and so the ability of the excavation.

Three classifications will be used to describe the particle shape of the sand.

- The roundness of the particle can be described by a roundness factor \( R \).
- The Form factor, particles can be relatively cubic in volume or more flat or elongated.
- The surface texture factor. Basically this is a factor ranging from rough to smooth.

**List of Symbols Used**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
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<td>( \alpha )</td>
<td>Blade cutting angle</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Shear zone angle</td>
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<tr>
<td>( \xi )</td>
<td>Plough share cutting angle</td>
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<tr>
<td>( \varphi )</td>
<td>Internal friction angle</td>
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<tr>
<td>( \delta )</td>
<td>External friction angle</td>
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<td>Minimum density</td>
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<td>Maximum density</td>
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<tr>
<td>( \rho_w )</td>
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<td>Coefficient of permeability</td>
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<td>( C_v )</td>
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<td>Gravitational acceleration</td>
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<td>Pore pressure force (shear zone)</td>
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<td>( WD )</td>
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<td>( z )</td>
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Table I. The British Standard density classification.

<table>
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<tr>
<th>Term</th>
<th>Relative density (%)</th>
<th>SPT (blows/feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very loose</td>
<td>0-15</td>
<td>0-3</td>
</tr>
<tr>
<td>Loose</td>
<td>15-35</td>
<td>3-8</td>
</tr>
<tr>
<td>Medium dense</td>
<td>35-65</td>
<td>8-25</td>
</tr>
<tr>
<td>Dense</td>
<td>65-85</td>
<td>25-42</td>
</tr>
<tr>
<td>Very Dense</td>
<td>85-100</td>
<td>42-58</td>
</tr>
</tbody>
</table>

**Friction angle**

The internal friction angle can be used for calculating friction forces on a sand-sand interaction shear plane. Friction angles increase if:

- Particles are more angular
- Amount of coarse particles is larger
- Relative density is larger
- Sand is better graded (large $(C_u)$)

For making a first estimation of the internal friction angle from CPT and PSD data, the following correlation from CROW is proposed:

$$\phi = 33^\circ - \frac{3}{D_{60}^2} + 15 - \frac{4}{D_{10}^2} \cdot RD$$  \[Eq. 5\]

For the presence of silt the following corrections can be included:

- 10% silt = $-2^\circ$ reduction of friction angle.
- 20% silt = $-5^\circ$ reduction of friction angle.
- Very well rounded particles = $-3^\circ$ reduction of friction angle.

Marine sand is usually characterised by its uniform gradation (especially in coastal regions), their relative rounded shape. Often a percentage of silt is present as well (depending on the location). The external friction angle is used to calculate friction between sand and other material (external interface angle). According to literature the external and internal friction angles have a certain relation to each other depending on size, particle shape and relative density. In this article, a simple indicative relationship is often used in dredging engineering.

$$\delta = \frac{2}{3} \phi$$  \[Eq. 6\]

Where:

\( \delta \) = external friction angle [$^\circ$]

**Permeability**

Permeability in soil mechanics is a measure of the ability of a porous soil to allow fluids to pass through. When excavating saturated dense sand, for example during dredging or trenching work, the pore volume increases by shearing of particles. One of the most common correlations for estimating the permeability is the Hazen’s relationship (Beyer, 1964).

$$k_i = C_{\mu} \cdot D_{10}^2$$  \[Eq. 7\]

Where:

- $C_{\mu} = coefficient for permeability [m^{-1} s^{-1}]$
- $C_{\mu} = 0.006 - 0.015$

can be selected from charts based on relative density and $D_{10}$, diameter.

The CROW (2004) provides another formula which provides more accurate results in sands with different compaction levels.

$$k_i = C_{\mu} \cdot D_{10}^2 \cdot C_{\text{uni}} \cdot e_{\text{curv}}$$  \[Eq. 8\]

**Dilatancy**

As mentioned, soil deformation is accompanied by volume changes caused by shearing called dilatancy. Densely packed sand can only deform when it is loosened at the same time (Figure 2). In water saturated sand, water flows through the pore spaces and tends to fill the gaps between the grains.

The soil stress inside the subsurface soil is constant, regardless of the type of deformation. The soil stress can be formulated as the summation of grain stress and pore pressure. When, during deformation, the pore pressure drops, the grain force has to increase.

That is the reason for strengthening of soil when the pore pressure drops as a result of dilatancy.

$$\sigma_{soil} = \sigma' + u_{pore}$$  \[Eq. 9\]

Where:

- $\sigma_{soil} = Total soil stress [kPa]$
- $\sigma' = effective soil stress, grain stress [kPa]$
- $u_{pore} = water pore pressure [kPa]$

Dilatancy is a time-dependent process (owing to permeability term) and therefore it is seldom mentioned in civil foundation theory. During sand excavating processes this dilatancy process does have a major impact on the excavating forces (Figure 2).

The amount of dilatancy is expressed as a “dilatancy potential”, or in dredging engineering literature often referred to as “dilatancy rate” or “volume strain”.

The volume strain can be calculated via the initial porosity of the sand and the maximum porosity of the remoulded sand after shearing.

\begin{align*}
i_n &< n_i \\
i_n &> n_i
\end{align*}
In sand excavating processes, cavitation is rather pleasant because stresses will no longer increase further with increasing deformation velocity. This phenomenon is also observed in the drag head of a trailing hopper dredger above a certain dredging velocity.

Forces on the plough
Pulling forces to pull a submarine narrow trench plough comprise multiple components:
- Cutting force on teeth
- Friction force on skids
- Friction force on the share.

In the next section cutting of water saturated sand, the cutting force mechanism components are extensively elaborated.

Calculations on the friction force are elaborated below; there is no fundamental difference between the friction force on the skids and the friction force on the share, except that the normal force is calculated differently.

Friction on the skids and the heel
During sand ploughing the friction force is calculated as a normal force multiplied by the tangent of the external (soil-steel) friction angle. The horizontal friction force on the skids and the heel of the plough is determined by the vertical load and a friction factor:

\[ F_{\text{skids}} = \tan(\delta) \cdot F_v \]  \hspace{1cm} [Eq. 11]

Where:
- \( F_{\text{skids}} \) = friction force on the skids [kN]
- \( F_v \) = vertical force components of cutting blades, and weight of the plough [kN]

The vertical force \( F_v \) originates from:
- The weight of the plough
- The vertical component of the cutting force

Friction on the plough share
Normal load against the share is dependent on:
- The average soil stress level aside the share (depending on the density and depth)
- The area of the sides of the plough share.

\[ F_{\text{share}} = \frac{\tan(\delta) \cdot K_p \cdot Z}{A_{\text{sides}} \cdot \rho_{\text{sub}}} \]  \hspace{1cm} [Eq. 12]

This is caused by increasing interaction forces between the grains. At a certain shearing velocity the pore pressure in the shear zone(s) reaches the vapour pressure limit and the water starts to vapourise (boil) in the pores.

From this point on, the pressure cannot drop further, the stresses and resistance forces will not increase any more while the velocity is still increasing.

Hence, it can be stated that "tow force is limited by cavitation".

In seawater of 10º Celsius the vapour pressure is equal to 1.18kPa and with a sea temperature of 20ºC vaporisation occurs at 2.27kPa.

Cavitation
When the velocity of deformation is increased, the pore pressure decreases and the resistant force against deformation will increase.

\[ \varepsilon = \frac{n_{\text{max}} - n_i}{1 - n_{\text{max}}} \]  \hspace{1cm} [Eq. 10]

Where:
- \( n_{\text{max}} \) = max. porosity [-]
- \( n_i \) = initial porosity [-]
- \( \varepsilon \) = volume strain or dilatancy potential [-]

The higher the in-situ density, the more dilatancy can occur during shearing. So the more pore space is induced, the more hardening will occur.
The cutting of water saturated sand with a straight blade

The 2-D cutting theory of cutting saturated sand is based on the calculation of the pore pressure force over the blade and over the shear plane. From the pore pressure force, an internal grain force can be deducted, and the horizontal and vertical resultant grain stress integrated over the blade can be seen as the forces (horizontal and vertical) required to excavate a wedge shape soil slice in front of the blade.

In the case of cutting water saturated sand, the cutting force can be divided in five components acting on soil wedge in front of the blade, inducing reactional grain force:

- Gravity force (G)
- Inertia force (I)
- Pore Pressure force (W)
- Adhesion force (A)
- Cohesion force (C)

Inertia (I) and Gravity (G) forces are very small compared to Pore Pressure (W) force and therefore are usually neglected. In sandy soil there are no Adhesive (A) and Cohesive (C) forces between the grains or the grains and the machines, so these terms will be left out of the cutting equations as well.

Parallel resistor theory

When cutting sand, a proper estimation of pore pressure forces is important for calculation of the cutting forces. The parallel resistor theory is a pragmatic method providing an estimation. This theory is computed for a 2-dimensional situation. However, with some adaptations, it is assumed to be suitable for solving equations for a 3-dimensional flow situation (Figure 6).

As long as water can flow to the pore spaces in the shear zone (without pore pressure dropping below the vapour pressure) the pore pressure is depending on the dilatancy potential ($\epsilon$), permeability ($k$), length of the water flow path to the shear zone (see $S1,S2,S3$ and $S4$ in Figure 6) and, of course, velocity of the plough.

In the theory of parallel resistors in pore water flow, by Miedema (2001), a method for calculating the resistance against deformation, as a result of water flow to the shear zone, is provided. In this theory the flow of water to a finite number of elements on the shear zone is calculated via certain (most favourable) flow paths.

Inertia ($I$) and Gravity ($G$) forces are very small compared to Pore Pressure ($W$) force and therefore are usually neglected. In sandy soil there are no Adhesive ($A$) and Cohesive ($C$) forces between the grains or the grains and the machines, so these terms will be left out of the cutting equations as well.

The Grain force ($K$) is the reaction force of the grains coming owing to Gravity and Pore Pressure. An equilibrium of forces in the vertical and horizontal direction can be formulated in order to find these grain forces. First the Pore Pressure has to be calculated; Miedema (1984) proposes the following formulas, in the case of a non-cavitating process:

$$W_1 = \frac{\left(p_{zm} \cdot \rho_w \cdot g \cdot v_c \cdot \epsilon \cdot h_f^2\right)}{k_m \cdot \sin(\beta)}$$  \[Eq. 13\]

$$W_2 = \frac{\left(p_{zm} \cdot \rho_w \cdot g \cdot v_c \cdot \epsilon \cdot h_f^2\right)}{k_m \cdot \sin(\alpha)}$$  \[Eq. 14\]

Where $k_m$ is an average permeability because the permeability of the surrounding sand is not equal to permeability inside the soil slice.

$$k_m = \frac{k_i + k_{max}}{2}$$  \[Eq. 15\]

Where:

- $k_m = \text{average permeability [m/s]}$
- $k_{max} = \text{max. permeability [m/s]}$
- $k_i = \text{initial permeability [m/s]}$

$p_{zm}$ and $p_{zm}$ represent the average dimensionless pressures along the shear zone, respectively the blade surface. These values have been calculated with numerical potential flow calculation, by Miedema (1984). They could also be computed with the use of the parallel resistor theory, as elaborated by Miedema (2001).

For calculation it is crucial to know the pore volume increase by dilatancy per unit blade width ($\Delta V$):

$$\Delta V = \epsilon \cdot \frac{dx}{dt} \cdot \Delta h_l \cdot b$$  \[Eq. 16\]
At each element on the shear plane the pore pressure can be calculated by:

\[ \text{Eq. 29} \]

\[ \text{Eq. 30} \]

Where:

\[ \text{Eq. 31} \]

Average pore pressure in the shear zone can be determined by summation of pore pressures at each element.

\[ \text{Eq. 32} \]

In order to be able to calculate pore pressures at the blade surface. Relations between the average pore pressures on the blade (\( p_{2,\text{avg}} \)) and the pore pressures in the shear zone (\( p_{1,\text{avg}} \)) have been established. It is assumed that the pressure on the blade is half the pressure at the blade tip, corrected with a certain factor \( f \).

\[ \text{Eq. 23} \]

\[ \text{Eq. 24} \]

\[ \text{Eq. 25} \]

\[ \text{Eq. 26} \]

The angles \( \theta_1 \) till \( \theta_4 \) depend on the blade angle (\( \alpha \)) and the shear angle (\( \beta \)) as illustrated in Figures 5 and 6.

\[ \theta_1 = \alpha + \beta \]  
[Eq. 23]

\[ \theta_2 = \pi - \beta \]  
[Eq. 24]

\[ \theta_3 = \pi + \beta \]  
[Eq. 25]

\[ \theta_4 = \frac{\pi}{2} \]  
[Eq. 26]

When the geometrical angles are determined (Eq. 23 to Eq. 26) and the flow path lengths are calculated (Eq. 19 to Eq. 22), the resistance of water through every flow path can be calculated:

\[ R_1 = \frac{S_x}{k} \]  
[Eq. 27]

Where:

\( R_x = \text{resistance of water, path } x [1/\text{s}] \)

\( S_x = \text{length of flow path, path } x [\text{m}] \) (Figure 6)

According to the parallel resistor theory of Miedema (2001), the total water flow resistance to a certain element of soil can be calculated via parallel summation.

\[ \frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \]  
[Eq. 28]

Where:

\[ R_{\text{tot}} = \text{total resistance of water flow} [1/\text{s}] \]

When the total resistances of all elements are summed over the total shear plane (height, width), a total pore pressure resistance can be obtained. Verification of these calculation results of pore pressure flow might be done with potential flow finite element modelling.

When the total resistances of all elements are summed over the total shear plane (height, width), a total pore pressure resistance can be obtained. Verification of these calculation results of pore pressure flow might be done with potential flow finite element modelling.

\[ \text{Eq. 27} \]

\[ \text{Eq. 28} \]

\[ \text{Eq. 29} \]

\[ \text{Eq. 30} \]

Where:

\[ P_{ij} = \text{pore pressure at element } i,j [\text{kPa}] \]

Average pore pressure in the shear zone can be determined by summation of pore pressures at each element.

\[ P_{1,\text{avg}} = \frac{1}{x \cdot y} \sum_{i=0}^{x} \sum_{j=0}^{y} \Delta R_{ij} \]  
[Eq. 31]

Where:

\[ P_{1,\text{avg}} = \text{Average pressure in shear zone} [\text{kPa}] \]

In order to be able to calculate pore pressures at the blade surface. Relations between the average pore pressures on the blade (\( p_{2,\text{avg}} \)) and the pore pressures in the shear zone (\( p_{1,\text{avg}} \)) have been established. It is assumed that the pressure on the blade is half the pressure at the blade tip, corrected with a certain factor \( f \).

\[ P_{2,\text{avg}} = \frac{P_{\text{tip}} + f}{2} \]  
[Eq. 32]

\[ P_{2,\text{avg}} = \text{Average pressure at blade} [\text{kPa}] \]

\[ P_{\text{tip}} = \text{pressure at tip of blade, bottom of shear zone} [\text{kPa}] \]

\[ f = \text{correction factor} [-] \]

For calculating the pore pressures on the blade and the share of the plough, the correlations have been chosen pragmatically. The same motivation is used: The pore pressure distribution from blade tip to surface is assumed linearly. Figure 4 illustrates the assumptions on the pore pressure distribution. With the following equations the pore pressure at the blade tip is related to the pore pressures at the shear zone and at the blade surface:

\[ P_{2,\text{avg}} = \frac{P_{\text{tip}} + P_{\text{tip}}}{2} = 0,75 \cdot P_{\text{tip}} \]  
[Eq. 33]

and figure

\[ P_{3,\text{avg}} = \frac{P_{\text{tip}}}{2} + 0 = 0,25 \cdot P_{\text{tip}} \]  
[Eq. 34]
Calculations on Forces and Velocities of a Submarine Narrow Trench Plough in Sandy Soil

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It is assumed that the average normal stresses (indicated \( \sigma_1, \sigma_2, \sigma_3 \)) can be calculated by dividing the forces by the areas of the shear plane, the blade respectively the plough share.

\[
W_1 = \frac{(p_w \cdot g \cdot (WD + 10) \cdot h_1 \cdot b)}{\sin(\beta)} \quad [\text{Eq. 37}]
\]

\[
W_2 = \frac{(p_w \cdot g \cdot (WD + 10) \cdot h_b \cdot b)}{\sin(\alpha)} \quad [\text{Eq. 38}]
\]

Where:

\( WD = \) water depth [m]

\( h_b = \) blade height [m]

When pore pressure reaches the vapour pressure, the pressure cannot decrease further with an increase of velocity. The tow force will therefore not increase either with a velocity increase. There will be a transition zone between non-cavitating and full cavitating behaviour, where certain elements reach vapour pressure and other elements do not. This phenomena can be seen in Figure 9.

**Grain forces inside the soil slice**

When the pore pressure forces are calculated, it is possible to solve the horizontal and vertical force equilibriums on the soil slice, in order to calculate the cutting force on the blade and the ploughshare. First the normal forces on shear zone (\( N_1 \)), the normal force component on the blade (\( N_2 \)) and the normal force on the plough share (\( N_3 \)) can be defined by:

\[
N_1 = \frac{K_1}{\sin(\beta)} \quad [\text{Eq. 39}]
\]

\[
N_2 = \frac{K_2}{\sin(\alpha)} \quad [\text{Eq. 40}]
\]

\[
N_3 = \frac{K_3}{\sin(\zeta)} \quad [\text{Eq. 41}]
\]

Now, when the average pore pressures at the shear zone and the blade are determined, the pore pressure force at the shear zone and the blade can be calculated by multiplying with the shear and blade areas.

**Non cavitating:**

\[
W_1 = \frac{(p_{1,\text{avg}} \cdot h_1 \cdot b)}{\sin(\beta)} \quad [\text{Eq. 35}]
\]

\[
W_2 = \frac{(p_{2,\text{avg}} \cdot h_b \cdot b)}{\sin(\alpha)} \quad [\text{Eq. 36}]
\]

Where:

\( b = \) blade width [m]

The equations are equivalent to Eq. 8 and Eq. 10, based on the dimensionless pressures \( p_{1\text{m}}, p_{2\text{m}} \) determined using FEM software.

When cavitation occurs in the shear zone when deforming the sand, the parallel resistor theory is no longer of use. The pore pressure is no longer depending on the resistance of the water to the shear zone. Velocity is not of influence anymore. It is assumed that pressure in the pores is nearly zero (vacuum).

**Cavitating:**

The maximum pore pressure difference can be calculated only from the surrounding pressure at the sea bed level relative to the vapour pressure. Pore pressure force is the multiplication of: hydrostatic pressure times the area of the shear plane (\( h_b \cdot \sin(\beta) \)) or blade area (\( h_b \cdot b \)):

\[
\sigma_1 = \frac{(N_1)}{h_1 \cdot b} \quad [\text{Eq. 42}]
\]

\[
\sigma_2 = \frac{(N_2)}{h_b \cdot b} \quad [\text{Eq. 43}]
\]

\[
\sigma_3 = \frac{(N_3)}{h_b \cdot b} \quad [\text{Eq. 44}]
\]

Where:

\( \sigma_1 = \) average grain stress in shear zone [kPa]

\( \sigma_2 = \) average grain stress at blade area [kPa]

\( \sigma_3 = \) average grain stress at plough share [kPa]

The average grain stress (\( \sigma_{\text{avg}} \)) inside the soil slice is pragmatically assumed to be:

\[
\sigma_{\text{avg}} = \frac{|\sigma_1| + |\sigma_2| + |\sigma_3|}{3} \quad [\text{Eq. 45}]
\]

Where:

\( \sigma_{\text{avg}} = \) average grain stress inside soil slice [kPa]
Where:

With the calculated pore pressure forces, and an expression for the dozing force it is possible to write a horizontal and vertical equilibrium of all the forces on a soil slice.

Horizontal:
\[ \sum F_{\text{horizontal}} = 0 = -W_1 \cdot \sin(\beta) \cos(\beta + \varphi) + W_2 \cdot \sin(\alpha) \cos(\beta + \varphi) + W_3 \cdot \sin(\zeta) \cos(\beta + \varphi) + K_1 \sin(\beta + \varphi) \cos(\beta + \varphi) - K_2 \cdot \sin(\alpha + \delta) \cos(\beta + \varphi) + K_3 \cdot \sin(\delta + \xi) \cos(\beta + \varphi) + 2 \cdot k_4 \cdot d \cdot \tan(\varphi) \cdot \cos(\beta + \varphi) \]  

Vertical:
\[ \sum F_{\text{vertical}} = 0 = +W_1 \cdot \cos(\beta) \sin(\beta + \varphi) + W_2 \cdot \cos(\alpha) \sin(\beta + \varphi) - W_3 \cdot \cos(\zeta) \sin(\beta + \varphi) - K_1 \cos(\beta + \varphi) \sin(\beta + \varphi) - K_2 \cdot \cos(\alpha + \delta) \sin(\beta + \varphi) - K_3 \cdot \cos(\delta + \xi) \sin(\beta + \varphi) + G \cdot \sin(\beta + \varphi) \]  

Both, the distribution of the grain stress and the level mobilisation of lateral pressure are not exactly known. Therefore a factor to incorporate these uncertainties is put into the model. This factor \( K_{\text{lat}} \) can be quantified by comparing empirical results (model experiments or real scale) with the result of the calculation.

Possibly this lateral factor itself is dependent on soil characteristics and cutting depth. Long-term data logging and extensive model experiments are necessary to indicate correlations and prove a consistency in the magnitude of this lateral stress factor.

For now:
\[ D = \sigma_{\text{avg}} \cdot \text{Area}_{\text{side}} \cdot K_D \]  

\[ D = \sigma_{\text{avg}} \cdot \text{Area}_{\text{side}} \cdot K_{\text{lat}} \cdot K_P \]  

Where:
- \( D \): dozing force \([\text{kN}]\)
- \( K_D \): Lateral dozing force coefficient \([-\text{]}\)
- \( K_{\text{lat}} \): lateral coefficient \([-\text{]}\)
- \( \sigma_{\text{avg}} \): average stress \([\text{MPa}]\)
- \( \text{Area}_{\text{side}} \): area of soil slice \([\text{m}^2]\)

The dozing force in that case can be calculated by:
\[ D_{\text{max}} = \sigma_{\text{avg}} \cdot \text{Area}_{\text{side} \cdot \text{slice}} \cdot k_p \]  

Where:
- \( D_{\text{max}} \): maximum dozing force \([\text{kN}]\)
- \( \text{Area}_{\text{side} \cdot \text{slice}} \): area of soil slice \([\text{m}^2]\)

In direction of velocity also induces a stress lateral to the running direction onto the walls of the trench. This stress component will be used to incorporate edge effects of the cutting process.

Since sand has no isotropic behaviour, as for example a fluid has, this stress in lateral direction is not equal to the stress in running direction. The resultant force caused by the lateral stress to the walls of the trench is called the Dozing force \(D\) in this research (see Figure 8). It interacts between the shear zones along the sides of the soil slice in front of the blade and the walls of the trench. The lateral stress can be calculated with the multiplication between the average stress in running direction, and the lateral passive soil failure factor: \( k_p \).

In case the lateral stresses caused by the longitudinal stresses are fully mobilised, the relation between stress in lateral and stress in longitudinal direction \( k_p \) can be obtained by:
\[ k_p = \frac{1 + \sin(\varphi)}{1 - \sin(\varphi)} \]  

The dozing force in that case can be calculated by:
\[ D_{\text{max}} = \sigma_{\text{avg}} \cdot \text{Area}_{\text{side} \cdot \text{slice}} \cdot k_p \]  

Where:
- \( \sigma_{\text{avg}} \): average stress \([\text{MPa}]\)
- \( \text{Area}_{\text{side} \cdot \text{slice}} \): area of soil slice \([\text{m}^2]\)
- \( k_p \): lateral passive soil failure factor

The horizontal contribution of this dozing force to the equilibrium of forces is implicated by force \( S \). This force \( S \) can simply be calculated by multiplication of the tangent of the internal (sand-sand) friction angle \((\tan(\varphi))\) with the outward dozing force.

Keep in mind that this term has to be multiplied by 2 as well because there are dozing forces acting on both sides of the soil slice.

\[ S = D \cdot \tan(\varphi) \text{(per side)} \]  

Where:

\[ S = \text{Shear resistance owing to dozing force} \ [\text{kN}] \]

With the calculated pore pressure forces, and an expression for the dozing force it is possible to write a horizontal and vertical equilibrium of all the forces on a soil slice.
Calculations on Forces and Velocities of a Submarine Narrow Trench Plough in Sandy Soil

The total force on the plough can be calculated by summation of the individual cutting forces on all three teeth.

**The total Tow force**

If the friction forces on the skids, heel, and cutting teeth are calculated, and the total towing force can be calculated via summation of the individual components. The total towing force to pull the plough through saturated soil can be calculated with:

\[
F_{\text{tow}} = F_{H\text{t1}} + F_{H\text{t2}} + F_{H\text{t3}} + F_{\text{Skids}} + F_{\text{Share}}
\]

In the following section the results of individual parameters on the total towing force are elaborated.

**RESULTS OF THE CALCULATION**

**Effect of permeability and cavitation**

As long as during the cutting process no cavitation occurs, the permeability of the sand is the most important parameter for cutting force. The permeability has a direct relation to the pore pressure development, and the ability of water to flow to the shear zone (Figure 9). Unfortunately permeability is hard to determine.

From calculations, it turned out that ploughing with a reasonable Burial Depth (BD) and a reasonable velocity (>100 m/hr), in soils with a very low permeability tow forces are rapidly increasing, almost regardless of the plough shape and width. If cavitation does start to occur, the water depth is also of importance limiting the maximum pore pressure development (Figure 10).

**Influence of friction angle**

With an increase of the friction angle the towing forces will increase given a certain velocity. The increase of friction angle will also have its influence on lateral earth pressure mobilisation to the sides of the soil wedge. Besides an increase on frictional shear in the shear zone, the geometry of the soil wedge itself will also change because the shear zone from blade tip to the surface changes with a changing friction angle.
CONCLUSIONS

Because a subsea plough will operate in fully saturated soil, it can be concluded that the cutting forces during sand cutting are dominated by pore pressure stresses caused by dilatancy of sand grains. Only in loose sand friction of sand-machine interaction plays a more significant role.

The parallel resistor method provides very reasonable results on the pore pressures, when compared to the potential flow FEM calculations as done for 2-D cutting blades by Miedema, (1987, 2001). In order to verify the exact 3-dimensional flow of water to the shear zone of a submarine plough, a potential flow calculation might provide more understanding.

The 2-Dimensional cutting theory does not include 3-dimensional edge effects on both sides of the excavated soil wedge. Hence, grain force inside the soil wedge will mobilise a stress component lateral to the running direction of the plough (Y-Z). The lateral outward stress will induce a shear stress (X-Y) between both sides of the soil wedge and the walls of the trench. The lateral stress component can be included in the equilibrium of forces as proposed in Eq. 56. It is not possible to exactly measure force components from real-scale measurements or model experiments. However, pragmatic coefficients to match the final result of the tow force calculation best to reality have been determined. Perhaps a DEM (discrete element calculation) best to reality have been to match the final result of the tow force experiments. However, pragmatic coefficients from real-scale measurements or model experiments might provide more understanding.

The applicability of the tow force calculation algorithm will increase if these different soil types are taken into account. More research on this topic is required.

REFERENCES


INTRODUCTION

New Caledonia is renowned for its nickel reserves, but also for its aquatic fauna and flora. Therefore, the Koniambo Project in the Voh region (Northern Province of New Caledonia) was carried out with utmost care for the surrounding environment. As part of the project, Koniambo Nickel SAS needed to construct a new port complex in support of its nickel processing plant. The port will be used to import consumable commodities such as coal, fuels and maintenance stores and will export refined product in 20-foot shipping containers. Dredging works were carried out by Jan De Nul Succursale NC.

The TSHD Le Bougainville, the backhoe dredge BHD Mimar Sinan and several split-hopper barges (Concepción, L’Étoile, Le Sphinx and Le Guerrier) were involved in the dredging of a 4,500 m long navigation channel and turning basin, to a design depth of –12.0 m CD. The dredging and disposal areas were surrounded by vulnerable ecosystems like coral reefs and seagrass meadows (Figure 1).

Before the project started, key points of attention had to be identified and adequate responses to these had to be defined. An Environmental Management Plan (EMP)
was prepared, which contained the main environmental concerns and the monitoring and mitigation actions. This document was the main guideline for environmental protection on the project. Several local and international companies took part in the implementation of the EMP.

Several years before dredging started, biological and physico-chemical studies were conducted to take inventory of the initial state of the marine environment in order to evaluate possible future impacts. In the months before dredging started, coral transplantation was done by a local company to rescue and relocate the most important species and formations to nearby less-impacted areas.

During dredging, continuous monitoring of the suspended sediments arising from the dredging activities was needed in order to respond rapidly in case of possible negative impacts on the local ecosystem.

For this purpose, the Marine Environmental Department (MARED) of Jan De Nul was asked to install, maintain and follow up a telemetry system. When dredging activities finished in April 2010, Koniambo Nickel SAS continued the physico-chemical and biological monitoring in order to evaluate the possible impacts of the port activities and the nickel processing plant. This article focuses on the turbidity monitoring done by Jan De Nul during the dredging works.

**ENVIRONMENTAL CONSIDERATIONS**

In 2008, a large part of the lagoons surrounding New Caledonia were inscribed on the list of UNESCO-IUCN World Heritage sites. Sensitive areas (coral reefs, sea grass habitats) surrounded the area where the entrance channel and turning basin had to be dredged for the development of the new harbour. According to the IUCN (International Union for Conservation of Nature and Natural Resources), the tropical lagoons and coral reefs of New Caledonia are examples of high diversity coral reef ecosystems and form one of the three most extensive reef systems in the world. They are the location for the world’s most diverse concentration of reef structures, with an exceptional diversity of coral and fish.
Dredging in New Caledonia at a UNESCO-IUCN World Heritage Site with Care for Nature

Several impacts on the marine environment were considered as possible results of the implementation of the project. The removal of sediments, coral, and sea grass areas by dredging has a direct impact on the marine flora and fauna in that area, but a substantial impact was also expected in the areas adjacent to the dredge area as a result of the high sedimentation and turbidity.

This was expected up to approximately 300 metres from the dredge works. Sessile species (e.g., corals, seagrass) were most at risk, but increased marine traffic could also present a risk to marine mammals (dolphins, whales, dugongs) and sea turtles.

The disposal site was located more than 5 km from the outer reef in order to minimise the possible effects of suspended sediment.

Stratification of the water column might affect the settlement of the discharged sediment (Figure 4): The descending plume of fine material might partially spread laterally as it impacts the region of rapidly changing density (the pycnocline). This part of the plume could most likely affect the outer reef.

Therefore, monitoring was carried out at several stations along the reef to detect possible changes in turbidity.

The Environmental Management Plan (EMP) considered the following areas within the vicinity of the dredging works to have the highest priority for protection:

- Outer barrier reef coral habitats (including the Passe du Duroc) and associated water quality.
- Seagrass habitats south of the predicted high impact zone.
- Mid-lagoon reticulated reef systems south of the Passe du Ronfleur and west of the predicted high impact zone.
- Near shore fringing reef.
ENVIRONMENTAL CRITERIA

Regarding turbidity, two types of monitoring sites were specified in the Environmental Management Plan (EMP) – an investigation site and an action site.

Investigation sites were located in the proximity of the zones of operation (dredge channel and offshore disposal area) and were used to gain a better understanding of the way dredging activities affect sediment resuspension and turbidity. Their purpose was also to identify turbidity values above a specified “investigation value”, which were different for the lagoon and the offshore sites (Table I).

To each investigation site belonged an action site. These were located closer to the sensitive areas in order to monitor whether an increase of the turbidity was reaching the various sensitive habitats. Threshold investigation values and action values as well as corresponding actions to be implemented, were defined for these action sites.

When an investigation value was exceeded, the source had to be sought and the frequency of monitoring had to increase. If action values were exceeded an action had to be taken in accordance with the EMP.

ENVIRONMENTAL MONITORING

Turbidity Monitoring

Besides the environmental monitoring by local and international companies, part of the marine environmental programme was carried out by the Marine Environmental Department (MARED) of Jan De Nul. This ensured a quicker response time by engineers who are closely involved with the dredging process (Figure 5).

In order to check compliance with the thresholds outlined in the EMP and ensure continuous monitoring, telemetry buoys were used at most of the action sites. These telemetry buoys (Figure 6) were equipped with a multi-parameter probe. On site verifications, calibrations and maintenance were conducted regularly to ensure reliable measurements and proper functioning of the equipment.

All the data collected from these buoys was transmitted by a radio modem inside the buoys and sent to a receiver station near the office where data was automatically processed by the Environmental Monitoring System (EMS). The EMS is a computer interfaced programme that can receive data strings sent out by various devices, such as buoys, weather stations, … It automatically analyses the data strings and subsequently puts it on the dedicated project website where it becomes available for any involved party.

Besides posting the data on a website, the EMS software also sent alert messages by means of SMS (text message) in case turbidity exceeded the threshold levels or when a problem occurred with one of the buoys. In this way, turbidity levels could be followed up continuously. Furthermore, the telemetry system enhanced the reliability of the data acquisition, because it allowed a rapid intervention in case of technical problems (e.g., malfunctioning sensor, biofouling, …).

Table I. Threshold values in NTU (Nephelometric Turbidity Unit) as stated in the EMP.

<table>
<thead>
<tr>
<th>Site type</th>
<th>Threshold value</th>
<th>Required action</th>
</tr>
</thead>
<tbody>
<tr>
<td>INVESTIGATION</td>
<td>Investigation value Lagoon - &gt; 70NTU Offshore - &gt; 10NTU</td>
<td>When this value is exceeded, an investigation is required to determine the source of the elevated value.</td>
</tr>
<tr>
<td>ACTION</td>
<td>Investigation value Lagoon - &gt; 30NTU</td>
<td>This is the value above which investigation and more frequent monitoring is required. The source of the value is also checked.</td>
</tr>
<tr>
<td></td>
<td>Action value Lagoon - &gt;30NTU for 3 days or &gt; 70NTU Offshore - &gt; 10NTU</td>
<td>When this value is exceeded an action is required. If it is found to result from dredging activities then the management responses specified in the EMP must be implemented.</td>
</tr>
</tbody>
</table>
Dredging in New Caledonia at a UNESCO-IUCN World Heritage Site with Care for Nature

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used to plan dredging operations and to justify weather delays.

ENIRONMENTAL MANAGEMENT

Dredging Area

The following management actions were implemented to minimise the generation of turbidity plumes by dredging:

- Dredging in accordance to wind and wave conditions.
- All vessels needed a pre-mobilisation check of all the seals and performance checks were executed during dredging.
- No overflow or discharge from barge or dredge hoppers was allowed during the dredge operations apart from the following routine operational requirements:
  - Overflow through funnel with “anti-turbidity valve” is limited to 5 minutes at the end of each filling cycle
  - Decanting from barges alongside the Backhoe Dredger is limited to 5 minutes at the end of each filling cycle
  - Use of LMOB (Lean Mixture Overboard System) is limited to 5 minutes at the beginning of each dredge run
- Barge decks should be washed down to remove sediment before the barge leaves the dredge area
- When outside the dredge channel, vessels should navigate in a manner which minimises sediment resuspension, particularly near coral reefs or seagrass beds.

Figure 7 shows an example of turbidity data recorded at a telemetry buoy during June 2009. During most of the time, turbidity levels stayed below 10 NTU. On the 9 June 2009 some biofouling occurred around the wiper of the probe, resulting in turbidity values rising up to 70 NTU.

After cleaning, values dropped immediately below 2 NTU. On the 15 June, a few spikes were observed, probably caused by marine fauna or detritus passing in front of the sensor eye. Also on the 29 June some spikes in turbidity were registered. On site investigation revealed that these outliers were caused by a technical problem of the sensor. After maintenance of the contacts of the sensor, turbidity values returned to normal.

Disregarding the erratic values as a result of biofouling and technical problems, Figure 7 also reveals the influence of dredging on the natural turbidity pattern. Between the 15 and 24 June 2009, the BHD was dredging closer to the telemetry buoy.

The influence of this dredging operation is reflected in the higher and more variable turbidity values during that period. However, turbidity remained mostly below 10 NTU, and returned rapidly to background values from the moment that dredging stopped in that nearby area.

Besides the fixed monitoring stations, mobile monitoring was also conducted to measure turbidity at several other locations in the lagoon and near the disposal area. This enabled the environmental engineer to adjust the monitoring campaigns to the ever changing working, hydrodynamic and weather conditions. In this way the advantages of fixed and mobile monitoring were being used simultaneously.

Besides measurements, also visual monitoring of the turbidity plume was conducted on a daily basis, from all dredging equipment as well as from survey vessels, to check for migration of the plume outside the pre-defined delineated area. These observations were reported to all relevant parties on a daily basis, as plumes outside the delineated area triggered monitoring at the closest (or most likely affected) action sites.

Although not included in the contractual requirements, different plume monitoring studies were also performed during the project. This monitoring was undertaken to develop a greater understanding of the effects that individual dredging activities have on the dispersion of turbidity. Examples of the activities that were monitored are: turbidity plumes from the TSHD and the BHDs (Figures 8 and 9), propeller wash during the shifting of barges, disposal activities and the sailing to and from the disposal site. The monitoring was executed using different turbidity sensors and a current profiler while sailing different tracks in and near the generated turbidity plumes with a survey vessel.

Hydro-meteo Monitoring

Hydro-meteo conditions were monitored with a weather station, a Waverider buoy (offshore) and an AWAC current profiler (in the lagoon). Wave height was an important factor to be monitored as it was stated in the EMP that the dredgers and supporting vessels had to operate within a safe range of wave and wind conditions (as determined by the captain of each ship).

This measure helped prevent incidents which could have resulted in an environmental impact. The Waverider data were needed to validate the reliability of wave predictions by Fugro and Argoss, as these forecasts were used to plan dredging operations and to justify weather delays.

Figure 5. Map of the area with indication of monitoring locations and Plume Visual Monitoring Area (source: EMP).
All floating plant had to arrive with non-fouled hulls, and to have performed adequate hopper washing and ballast water exchanges in full accordance with New Caledonian and international requirements.

Environment awareness training (including information on marine animals) was given to all personnel and crew.

Care was taken to prevent injury to native fauna as a result of dredging and disposal activities.

Turtle deflectors (suspended chain type) were installed on the drag arms of the TSHD dredger (Figure 10).

Observations of sea mammals and turtles had to be reported to the environmental engineer and subsequently transferred to all relevant parties.

Additional Protection Measures

At the most sensitive areas, dredging operations proceeded with a backhoe dredger. For this particular project this was considered the most environmental friendly dredging method.

A few times per year, during full moon, the phenomena “coral spawning” takes place. In order to cause no disturbance to the corals, dredging operations were planned in such a way that no turbidity was produced during this period.

Periodical inspections of the vessels were

Disposal Area

Regarding the disposal of dredged material, the following requirements were specified:

- The dredged material had to be released only within the limits of the approved disposal area.
- The dredged material had to be released fast to minimise the turbidity plume.
- Vessels had to take the shortest possible safe navigable route and avoid spillage by not overloading and limiting transport to within safe operating conditions.

- Wash down of the empty dredge or barge hoppers to remove residual sediments was only allowed inside the disposal area.
- Pumping out of seawater from empty hoppers had to be ceased before the vessel came to within 1 km off the reef or 500 m off the entrance to Passe du Duroc.

Flora and Fauna

To minimise direct and indirect disturbance to marine flora and fauna, the following management actions were implemented:

- All floating plant had to arrive with non-fouled hulls, and to have performed adequate hopper washing and ballast water exchanges in full accordance with New Caledonian and international requirements.
- Environment awareness training (including information on marine animals) was given to all personnel and crew.
- Care was taken to prevent injury to native fauna as a result of dredging and disposal activities.
- Turtle deflectors (suspended chain type) were installed on the drag arms of the TSHD dredger (Figure 10).
- Observations of sea mammals and turtles had to be reported to the environmental engineer and subsequently transferred to all relevant parties.

Figure 7. Turbidity values measured at a telemetry buoy during June 2009.

Figure 6. Left, the construction of the new port facility at New Caledonia. Above, Telemetry buoy anchored near the working area.
Dredging by the TSHD without overflow resulted in sediment plumes of 100-150 m wide, with peak turbidity values above 100 NTU just after passage of the TSHD, decreasing to maximum values of 40-50 NTU after 10 minutes. Turbidity further decreased at a rate depending on particle size. Dredging by the TSHD with overflow (during 5 minutes) resulted in a similar plume width (150 m), but turbidity values were higher, especially during the first 15 minutes after dredging.

The monitoring results showed that the sediment plume generated by the BHD was rather limited. Wind and current may cause the plume to drift over a larger area, but in general, the maximum turbidity dropped below 30 NTU within 175 m from the dredging location.

However, monitoring showed that turbidity plumes generated by prop wash during shifting of barges can be much denser and larger than those generated by the dredging action of the BHD, depending on the seabed material and the keel clearance.

During sailing and maneuvering in shallow areas, the propellers caused resuspension of seabed material. Monitoring showed that this “prop wash” generated large turbidity plumes. During sailing in “deep water” (5 m between keel and seabed), a narrow

specifications, a “Rapid Visual Assessment” had to be carried out at the seagrass and coral sites to evaluate possible signs of stress. The EMP mentioned the following possible measures to reduce turbidity at the dredging area:

- Increase distance to impacted area by moving dredgers further away
- Reduce prop wash by altering dredge and/or barge movement
- Implement silt curtain
- Temporal suspension of dredging activities

Had turbidity thresholds been exceeded at the offshore stations, relocation of the disposal area further offshore was a possible option to reduce turbidity.

**RESULTS**

During the entire project, the turbidity threshold values were never exceeded as a result of dredging activities. During periods without dredging activity, however, turbidity levels were sometimes higher owing to natural causes (e.g., sediment supply by rivers, resuspension of seabed sediments).

Excessive rainfall sometimes resulted in an increased sediment supply towards the lagoon. This caused turbidity to rise above the threshold limits at some locations inside the lagoon. Nonetheless, after the rainy period, turbidity levels rapidly declined back to normal values.

Dredging by the TSHD without overflow resulted in sediment plumes of 100-150 m wide, with peak turbidity values above 100 NTU just after passage of the TSHD, decreasing to maximum values of 40-50 NTU after 10 minutes. Turbidity further decreased at a rate depending on particle size. Dredging by the TSHD with overflow (during 5 minutes) resulted in a similar plume width (150 m), but turbidity values were higher, especially during the first 15 minutes after dredging.

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During the project, several sea mammals (dolphins, porpoises and dugongs) and turtles were observed every week in the vicinity of the working area. Koniambo Nickel SAS conducted also monitoring by remote sensing. During the dredging, KBR was asked to analyse satellite images based on ground-truth data, in order to investigate the distribution and intensity of the turbidity plumes generated by the dredging activities. Although, several turbidity plumes and traces could be observed on the images, simultaneous data acquisition on site revealed that turbidity values were low (Figure 11).

Prior to mobilisation to New Caledonia, the seals of the vessels were renewed, in order to prevent leakage of sediment. Monitoring surveys showed that leakage from the TSHD and SHB was minimal: Turbidity was only slightly elevated (about 3 NTU) compared to background values. During visual monitoring, it was rarely observed that a plume did go outside the defined “plume visual monitoring area” (see Figure 5). Inside the lagoon, nine observations were made of turbidity plumes outside the delineated area. These turbidity plumes triggered monitoring at the closest (or most likely affected) action sites. Measurements at these sites never showed an exceedance of the turbidity thresholds (except for the rain event of 25/03/2009). In most cases, turbidity was less than 10 NTU. During the project, several sea mammals (dolphins, porpoises and dugongs) and turtles were observed every week in the vicinity of the working area.

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**CONCLUSIONS**

Dredging works necessary for the expansion of human activities can go hand-in-hand with nature. This was clearly demonstrated on the project in New Caledonia. During the entire project, the turbidity threshold values were never exceeded as result of a dredging activities.

Besides measurements, also visual monitoring of the turbidity plume was done on a daily basis. Although some visual plumes were observed outside the delineated area, quantitative measurements revealed that turbidity values were well below the EMP thresholds. Marine mammals and turtles were observed around the working area on a regular basis until the end of the works, indicating that the animals did not flee the area and thus did not experience a major impact from the works. Although dredging finished in April 2010, Koniambo Nickel SAS have continued physico-chemical and biological monitoring in order to follow up possible impacts of future port and plant activities.

The dredging works in New Caledonia proved that good environmental management, based on both a pro-active and re-active approach, can prevent undesired negative consequences. A pro-active approach includes a thorough knowledge of the surrounding environment, preparation of different plans and procedures, modelling studies to indicate possible impact areas and environmental induction of all personnel.

The re-active approach includes the continuous monitoring of turbidity and water quality during dredging activities and implementation of a management plan which allows changes in dredging operations whenever threshold values are exceeded.
Maritime Solutions for a Changing World: TWO NEW VIDEOS FROM IADC

The International Association of Dredging Companies (IADC) has recently released its latest corporate video, “Maritime Solutions for a Changing World”. IADC member companies provided IADC with footage of their recent projects. This material, which highlights some of the major global projects of the last decade, was used to realise a short video around the six “drivers of dredging”: World Trade & Port Development, Coastal Protection & Climate Change, Land Reclamation & Urban Development, Energy, Environment and Tourism.

Additionally the video gives a brief insight into IADC’s many activities such as its publications, the Facts About series and its quarterly journal, Terra et Aqua. Also in focus are the IADC Seminars on Dredging and Reclamation and the Environmental Aspects of Dredging Seminars, as well as the Young Authors Awards presented at selected conferences.

IADC has also produced a short video with more information about its Seminars, Workshops and Forums. The aim is to give potential participants a general idea of the high-tech knowledge provided for participants at these acclaimed Seminars.

Both videos can be found on IADC’s website www.iadc-dredging.com.

Training Set Extension for the Application of Low-technology Techniques for Assessing Dredged Material

WODA / CEDA

In 1972, the London Convention (LC) was adopted to protect the world’s oceans. It was updated in 1996 by the London Protocol (LP) that came into force in March 2006. In recognising the need for guidance in implementing Annex 2 of the LP and to assist national governments with the assessment of wastes or other material that may be considered for dumping, the Contracting Parties developed the Waste Assessment Guidelines (WAG). To make the WAG more accessible the Contracting Parties further developed a WAG Training Set (WAG TS) which comprises a set of instruction materials intended for use by national authorities responsible for regulating the ocean dumping of wastes.

Whilst conducting regional workshops, the need was identified for a low-technology version of the WAG TS to focus on assessing dredged material for those countries where regulations are absent or at an

FACTS ABOUT DREDGING PLANT AND EQUIPMENT

INTERNATIONAL ASSOCIATION OF DREDGING COMPANIES


No two dredging projects are the same; each project has its own unique demands. Consequently for each project a decision must be made about what type of equipment matches the project’s needs in order to work as cost-efficiently as possible. Since no single type of dredger is suited for every project, how does one decide which plant is right? Is availability the only criterion? Or size of the project and size of the dredging vessel? How does one balance cost-efficiency and environmental concerns?

In this Facts About a brief description is given of the major types of dredging equipment – trailing suction hopper dredgers (TSHDs), cutter suction dredgers (CSDs) and backhoe dredgers (BHDs) which are the most common workhorses of the industry. It also explains the differences between hydraulic, mechanical, hydraulic/mechanical, hydrodynamic and environmental dredgers. The advantages and disadvantages of each type of plant are explained and guidance is given on matching the most suitable dredger with a particular project. The choice of equipment depends on the type of soil conditions, transport options, configuration of the dredging area, water depth and depth to be realised and placement requirements. Weather, environmental and contamination must be considered.

R&D over the last 25 years has made dredging a high-tech industry that requires a broad base of knowledge and expertise. No single type of dredger is suited for every project. This brief overview will give decision-makers a first insight into matching the proper dredging equipment to the dredging operation they may be facing.

CEDA’s quality stamp awarded for the first time

The Central Dredging Association (CEDA) has taken a first step in its new policy and granted its Quality Stamp for the first time to Facts About Dredging Plant and Equipment. The CEDA Quality Stamp on a document means that it has been reviewed and endorsed by a panel of experts from across CEDA’s diverse membership representing a wide range of expertise, disciplines and nations. Endorsement by CEDA is a guarantee for impartial, state-of-the-art information for academics, industry professionals, regulators, decision-makers and stakeholders within its fields of interest.

Facts About are published periodically by the IADC as part of a series of concise, easy-to-read executive summaries on specific dredging and maritime construction subjects.

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.
The Training Course “Environmental Aspects of Dredging” organised by the Postgraduate Academic Programme (PAO) of the Delft University of Technology, it will take place 19-20 April 2011 in Delft, the Netherlands. Advance educational credits are awarded to participants. The Training Course is based on the book Environmental Aspects of Dredging that was produced as a joint effort by the Central Dredging Association (CEDA) and the International Association of Dredging Companies (IADC) and published by Taylor and Francis in 2008. The lessons are enhanced by the up-to-date knowledge of the course leaders who are constantly revising the information to reflect the most current knowledge and thinking.

The course is intensive, compacted into two very full days, composed of lectures and working group sessions. In addition to PAO educational credits, an IADC “certificate of achievement” is awarded to participants who attended both days of the course. The uniqueness of the course is characterised by small class size and individualised attention.

The fee is € 975.- excl. VAT and includes the 386-page hardcover book, Environmental Aspects of Dredging (a € 120 value), edited by Nick Bray and published by Taylor and Francis/ IADC/CEDA, as well as lecture notes, coffee, tea, lunches and dinner on April 19. Hotel reservations (when necessary) are € 115 excl. VAT per night.

For registration and further course information please contact:
PAO Civil Engineering and Construction
P.O. Box 5048, 2600 GA Delft, The Netherlands
www.pao.tudelft.nl
Tel. +31 15 278 4618, fax +31 15 278 4619
Email: info@pao.tudelft.nl

THE FUTURE OF DREDGING IN LATIN AMERICA
AUGUST 28-29 2012
RIO DE JANEIRO, BRAZIL

Officially supported by WEDA and IADC, and produced by Quaynote Communications, this new international conference aims to bring together dredging companies and their customers, oil and gas majors, ports, land reclamation companies, offshore and wind project companies, consultants, policy-makers and industry regulators.

The conference will target senior players within the Latin American and global dredging industries and its primary emphasis will be on business development, networking and debate. The main objective is to provide a forum for delegates to meet and discuss hot issues with their peers and clients. The Future of Dredging will provide the perfect environment for exploring business opportunities, with a strong programme that features roundtables and case-studies rather than academic papers. Confirmed speakers include Rene Kolman, Secretary General of the International Association of Dredging Companies (IADC). Topics will cover a review of projects in Mexico, Argentina, and Brazil, dredging finance, exploring the demand for new vessels, early contractor involvement, environment issues and regulations, lessons to be learnt from elsewhere and the constraints on dredging projects.

For further information about participating as delegates, speakers or sponsors contact:
Lorna Titley or Alison Singhal
Tel: +44 (0) 20 8531 6464
Email: lorna@quaynote.com

DREDGING 2012
OCTOBER 22-25, 2012
SAN DIEGO, CALIFORNIA, USA

Dredging 2012 is a four-day technical specialty conference on
dredging and dredged material disposal, organised by PIANC USA and the Coasts, Oceans, Ports and Rivers Institute of American Society of Civil Engineers (COPRI ASCE). Since it has been almost 10 years since the last specialty conference was held in Orlando, Florida, in 2002, many new issues have emerged. Information will be presented regarding best practices and innovation in North and South America, Europe, and Asia. This will be an international forum bringing together professionals and practitioners from developed and developing areas of the world.

The Overarching Theme of the Conference is: “40 Years of Dredging and Environmental Innovation” and will include topics such as: State of engineering practice; Dredging contracting and management innovations; Environmental dredging (remediation/ restoration); Safety; Current engineering dredging research; Integrating dredging and dredged material reuse with environmental restoration; Working with Nature; Site characterisation and survey; Sediment resuspension/ residuals; Sustainable sediment management; Dredged material management; Ports/ navigation – case studies (coastal/inland); and Regulatory challenges and solutions.

For more information see: http://dredging12.pianc.us
La Rue Forrester
Tel: +1 410 544 6710
• Email: larue@wwsc.us or dredging@pianc.us

CALL FOR PAPERS

HYDRO12
NOVEMBER 13-15 2012
SS ROTTERDAM, PORT OF ROTTERDAM, THE NETHERLANDS

Abstracts of papers for presentation at the International Federation of Hydrographic Societies’ 17th European conference in Rotterdam from 13-15 November are invited by the organisers, Hydrographic Society Benelux.

To be held aboard SS Rotterdam, the former Holland-America liner now permanently moored at the Port of Rotterdam, in the Netherlands, the three-day event is expected to attract a wide international audience drawn from all sectors of the hydrographic and related professions. “Taking Care of the Sea” is the main theme of the conference which will be supported by a major exhibition of equipment and services as well as practical demonstrations, technical workshops and a series of social activities.

Scheduled conference sessions will variously address the economic benefits of hydrography to the world at large at a time of changing technologies and extreme budgetary pressures. Individual topics will cover Innovations in Acquisition and Processing Techniques, Subsea Positioning, Smart Data Management, Simplified Customer Access to Data & Products, Marine Planning, Cost-Effective Solutions, Geophysics, Vertical References, Accurate Hydrodynamics, Education and Professional Standards, and Key Hydrographic Projects in the Benelux.

English-language abstracts of not more than 300 words plus one illustration on any of these topics and related issues are required. These should be forwarded via either email “mailto:submissions@hydro12.com” or the main conference website containing specific author guidelines: http://www.hydro12.com

For further information contact:
David Goodfellow
• Email: dvd.goodfellow@virgin.net

WODCON XX
JUNE 3-7, 2013
SQUARE-BRUSSELS MEETING CENTRE
BRUSSELS, BELGIUM

Organised by CEDA on behalf of WODA, which incorporates WEDA, CEDA and EADA, WODCON XX will showcase some 120 technical papers over three days covering all aspects of dredging and maritime construction. All WODCON XX papers will be peer reviewed and provide up to date, relevant and high quality information. The Congress will also feature a technical exhibition and technical visits. These technical programme elements will ensure a complete learning process, while various social events will allow participants to meet fellow professionals from all over the world in a friendly and inspiring atmosphere. The 2013 conference marks the XXth edition of WODCON and coincides with the 35th anniversary of the current WODA and its three component associations.

Topics of interest include but are not limited to the following broad areas: Method, Equipment & Techniques; Management of Sediments (clean and contaminated); Environmental Issues; Regulatory Issues; Management and Economics; Alluvial and Deep Sea Mining. Abstracts presenting both research and practical applications are encouraged.

Papers must be original and should not have been published or offered for publication elsewhere. Purely promotional text will not be accepted. The Technical Papers Committee reserves the right to accept a submission as an oral or poster presentation. Authors must assign all copyright of the accepted papers to WODA. Prospective authors should submit titles and abstracts (maximum 300 words) of papers to be considered for the congress by 29 October 2012.

Interested CEDA authors (Africa, Europe and the Middle East) should submit their abstracts online on the congress website: www.wodcon.org. Please use the abstract guidelines available on the website and contact:
Interested EADA and WEDA authors should e-mail their abstracts directly to the EADA or WEDA Technical Papers Committee members (see below). The submission must include the name, affiliation, telephone number and e-mail address of each author. The corresponding authors’ name must be identified.

EADA region (Asia, Austral-Asia, Pacific). Requested document format: MS Word
John Dobson
Tel.: +61 73262 3834
• Email: dobsoncj@hotmail.com

WEDA region (Americas). Requested document format: MS Word or Portable Document Format – PDF
Dr Ram K Mohan (Chair WEDA TPC)
Tel.: +1 610 337 7601 x 35
• Email: rmohan@anchorqea.com

COASTS, MARINE STRUCTURES AND BREAKWATERS
SEPTEMBER 16-20, 2013
EICC, EDINBURGH, SCOTLAND, UK

Following on from the hugely successful 2009 event, the 2013 conference will once again be held at the EICC in Edinburgh, Scotland. In addition to the main session, the “Fringe” will give opportunities for presentations of recent news, continuing research, and developments in progress. Workshops, short courses and technical visits will also be offered as part of the event.

Prospective authors are invited to submit abstracts within any of the relevant themes or topics by June 1, 2012: Marine energy systems: offshore and nearshore; Sustainable construction, refurbishment and rehabilitation; Alternative procurement, economics and finance; Climate change and major storms: adaptation; Breakwaters, seawalls and jetties; Coastal threats, storms, tsunamis, climate change, erosion and flooding; Dredging and use of dredged materials; Environmental and social awareness; and more.

A full list of themes and topics as well as full abstract guidelines and an abstract template can be found on the conference website. All abstracts must be in English, and submitted electronically at ice-breakwaters.com.

For further information visit: ice-breakwaters.com or contact:
ICE Events Team, Institution of Civil Engineers
One Great George Street
Westminster, London SW1P 3AA, UK
Tel: +44 (0)20 7665 222, Fax: +44 (0)20 7233 1743
• Email: events@ice.org.uk

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early stage of development and where access to technical equipment and knowledge may be limited. Therefore this WAG TS Extension for the application of low-technology techniques for assessing dredged material has been developed.

The Low-tech WAG aims to assist individuals or bodies in reviewing operations and provide the tools from a simple starting point to incrementally build an assessment, management and permitting system for dredged material to be considered for disposal to sea. Accordingly, the training set provides information on low-cost sampling, testing, information gathering and documenting, low-cost monitoring and feedback surveys to improve decision making. The WAG TS Extension is based on the WAG TS and the Specific Guidelines for Assessment of Dredged Material.

The WAG TS Extension is presented as a stand-alone document but follows the same format and approach as the WAG TS but it is more directing in the sense that low-tech approaches are identified and explained to enable the user to make an informed choice. Where it has been determined that there are no low-tech alternatives, the WAG text has been amended to make it more accessible for those operating in a low-tech environment.

The Low-tech WAG was adopted by the LC/LP governing bodies in October 2011. It has now been published by the IMO to be “road-tested” by its intended audience (e.g., ports and regulatory authorities operating in low-tech environments). It is hoped that this process will enable identification of further low-tech approaches that can be incorporated in the future to increase the Low-tech WAG’s usability. Members of CEDA, EADA, WEDA and others are encouraged to participate in the road-test.

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For further information:
Interested organisations should contact the CEDA, EADA or WEDA Secretariat (CEDA: Anna Csiti, General Manager, ceda@dredging.org; EADA: Rasydan Alias, rasydan@inai.com.my; WEDA: Larry Patella, weda@comcast.com).

The document is downloadable from the WODA (www.woda.org) and CEDA (www.dredging.org) websites.
Through their regional branches or through representatives, members of IADC operate directly at all locations worldwide.