MARITIME SOLUTIONS FOR A CHANGING WORLD

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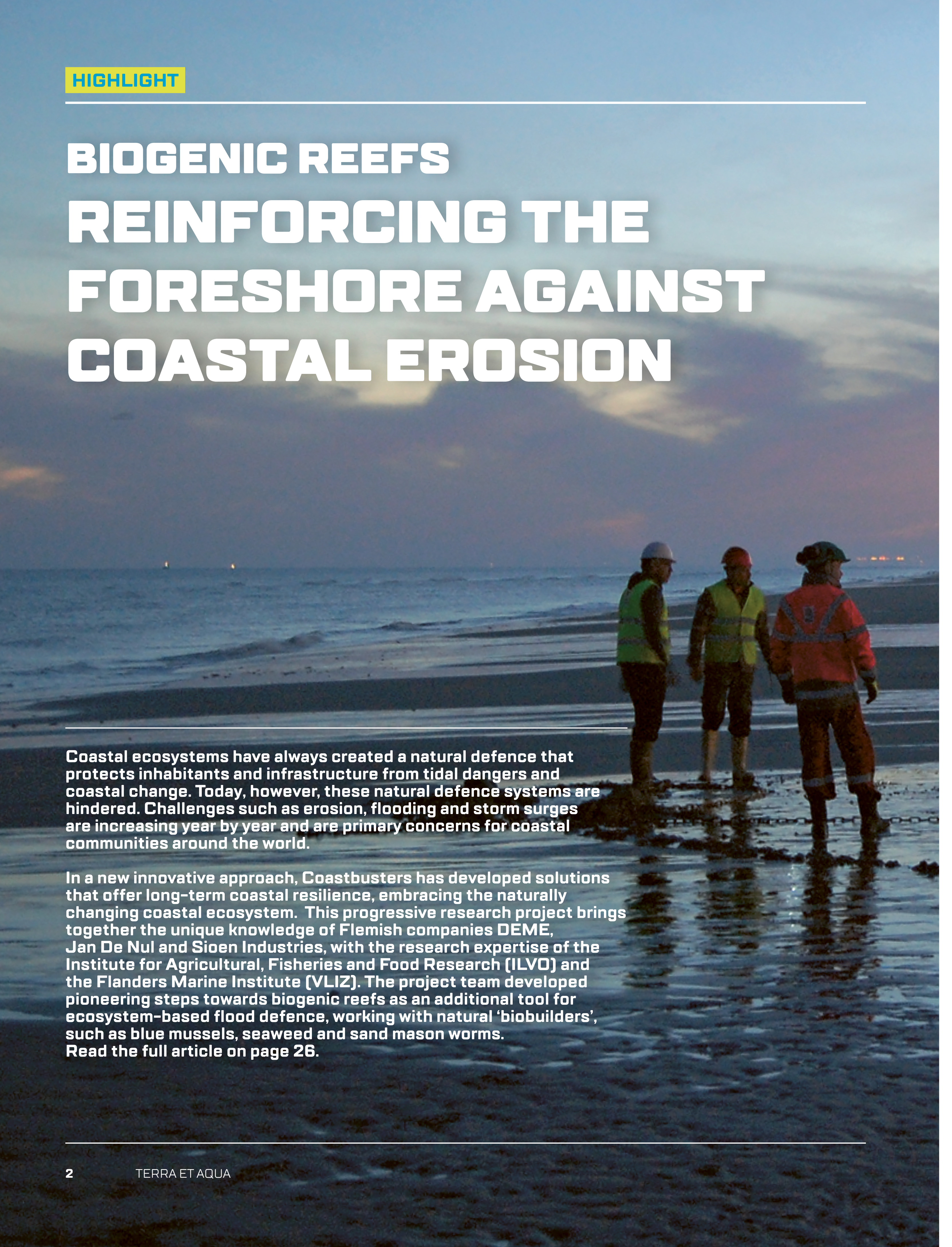
TERRA ET AQUA

ENGINEERING WITH NATURE
Dr Todd Bridges reflects on creating future value from the human-nature connection

ADHESION FACTOR OF CLAY
Experimental study examines the relationship between adhesion and undrained shear strength

COASTBUSTERS

BUILDING BIOGENIC REEFS FOR ECOSYSTEM-BASED COASTAL MANAGEMENT



HIGHLIGHT

BIOGENIC REEFS
REINFORCING THE FORESHORE AGAINST COASTAL EROSION

Coastal ecosystems have always created a natural defence that protects inhabitants and infrastructure from tidal dangers and coastal change. Today, however, these natural defence systems are hindered. Challenges such as erosion, flooding and storm surges are increasing year by year and are primary concerns for coastal communities around the world.

In a new innovative approach, Coastbusters has developed solutions that offer long-term coastal resilience, embracing the naturally changing coastal ecosystem. This progressive research project brings together the unique knowledge of Flemish companies DEME, Jan De Nul and Sioen Industries, with the research expertise of the Institute for Agricultural, Fisheries and Food Research (ILVO) and the Flanders Marine Institute (VLIZ). The project team developed pioneering steps towards biogenic reefs as an additional tool for ecosystem-based flood defence, working with natural 'biobuilders', such as blue mussels, seaweed and sand mason worms.
Read the full article on page 26.

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WHEN THE WHEELS OF COMMERCE LITERALLY RUN AGROUND

Frank Verhoeven
President, IADC

On 29 March, SMIT Salvage and Boskalis successfully refloated the Ever Given in a challenging operation conducted under the watchful eye of the world. For nearly a week, the colossal container ship blocked the Suez Canal halting billions of dollars a day in maritime commerce. Around 12% of global trade passes through the 120-mile waterway, which provides the shortest sea link between Asia and Europe.

The socio-economic impact of the incident was immense. The unprecedented shutdown of one of the world's most vital trade routes led to raising concerns over extended delays, goods shortages and rising costs for consumers. Goods like food, fuel, vital medical equipment and PPE were caught in a backlog of more than 420 vessels waiting to enter the canal. All of which added strain on the shipping industry already under pressure from the COVID-19 pandemic.

The incident cast a spotlight on the importance of global shipping to daily life and the delicate nature of the global supply chain it underpins.

As the world continues to battle the crisis, there is an opportunity for nature-based solutions to support post-pandemic recovery efforts. The World Bank is making an estimated US$ 1 billion in annual investments in projects applying nature-based solutions. At IADC, we're working on a joint report to explore the role that investors can play in sustainable waterborne infrastructure projects. From a societal point of view, there is no alternative to green infrastructure if we want to tackle the challenges of climate adaptation, mitigation and biodiversity decline. From a financial point of view, investors are increasingly conscious of, and concerned about, the predictability of the future value of their assets.

The World Bank's approach to using natural infrastructure solutions to address climate change challenges shares a synergy with Engineering With Nature's approach of using nature-based solutions. Dr Todd Bridges, National Lead for the Engineering With Nature® initiative for the past 10 years, talks about the opportunity of incorporating nature into engineering in a more tangible and substantive way in the interview on page 18.

In April and May, IADC organised two webinars as part of the 'Meet the Expert' series. Each webinar invited an expert(s) from the dredging sector to speak on a particular topic and focused on a high-profile dredging project. To register for forthcoming events in the series as well as view past webinars on demand, visit https://www.iadc-dredging.com/webinars.

Also in this issue, articles on a pioneering coastal management approach that induces a self-sustaining stabilisation of the foreshore, as well as a study into the adhesion factor of clay.

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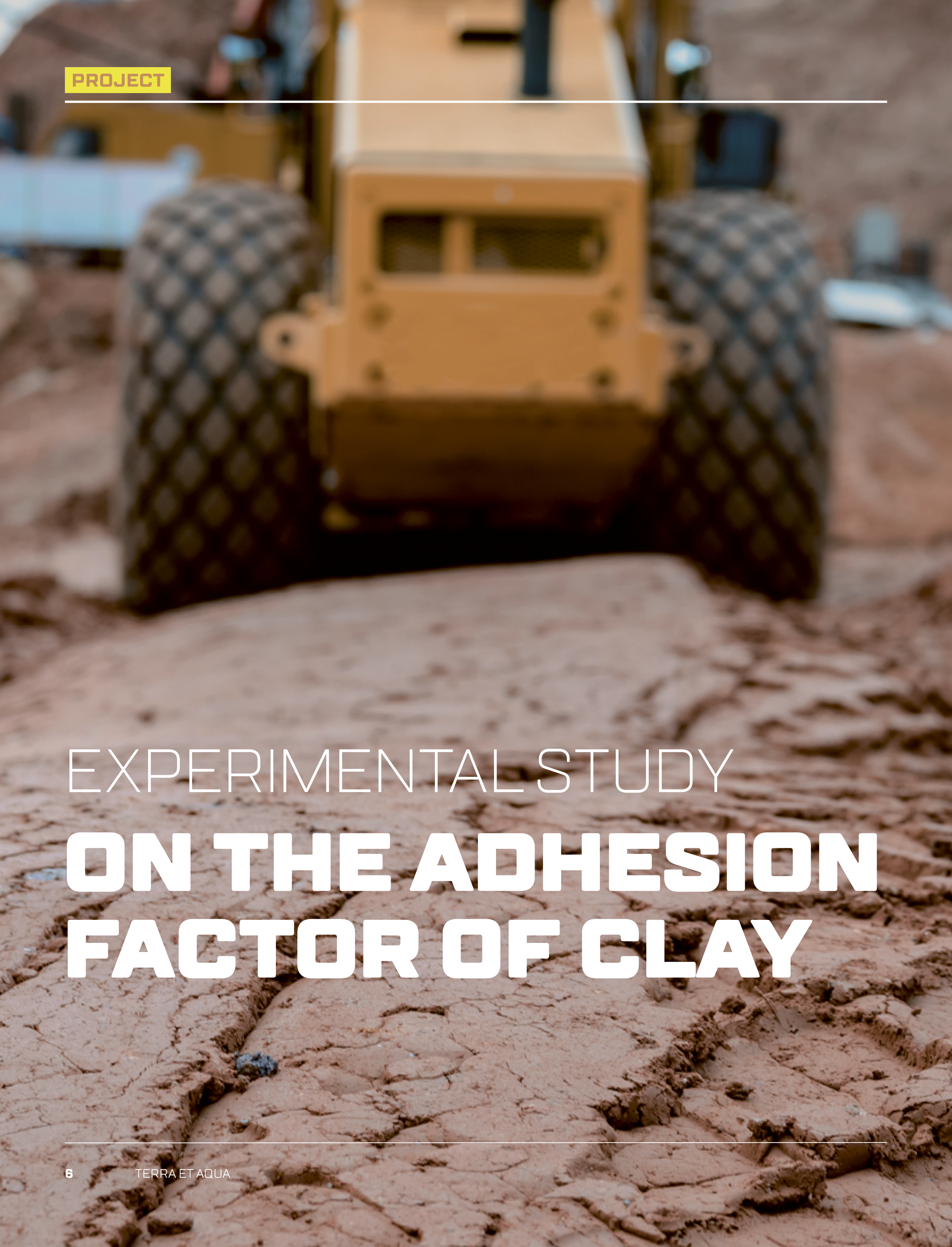


PROJECT

EXPERIMENTAL STUDY ON THE ADHESION FACTOR OF CLAY

Clay is one of the three most commonly encountered soil types in riverbed and seabed, other than sand and silt. A major mechanical property of clay is the adhesion factor that reflects the ratio between its cohesive and adhesive strength under different water content. Currently, this adhesion factor is not exactly known. It is important however, to get a better understanding of the relationship between cohesive and adhesive forces, since large surfaces on dredging tools can generate a lot of resistance, therefore slowing production. In this study, experiments were undertaken to determine the actual relation between adhesion and cohesion. The results can help the implementation of analytical cutting models, in turn, allowing the optimal cutting angle in dredging practice to be calculated.

Efforts were made to determine the adhesion factor by investigating literature research and conducting laboratory experiments.

In the last two decades, the global economy and population have been growing steadily. The already densely populated coastal areas are becoming even more crowded, calling for new artificial islands to provide additional space for housing and recreational areas, etc. As global trade increases, there is greater demand for dredging activities to keep ports and waterways navigable. Due to these global trends, the demand for dredging, trenching and deep-sea mining activities have grown dramatically.

To be able to optimise these activities and increase overall production, understanding the physics and the analytical or numerical build-up of these cutting processes becomes key. In these engineering practices, underwater excavation is one of the major procedures, which involves complicated physics. In dredging, the cutting process is required to obtain the soil from the river/seabed. In offshore wind farm installation, the vulnerable power cables transporting the generated energy must be buried a few metres under the seabed for their protection, so trenching becomes indispensable. In deep-sea mining, underwater excavation is one of the major ways in which to retrieve the highly concentrated minerals from the seabed.

To reasonably estimate the cutting force and cutting energy needed for underwater excavation on cohesive soil, Miedema (2014, 2017) has developed a model, 'The Delft Sand, Clay and Rock Cutting Model', in which several sets of equations are derived for each type of seabed soil. In these equations, the cutting depth, the cutting angle, the cutting speed and the soil properties are used as input parameters, while the cutting forces and the specific energy are the output results.

In the case of clay, the adhesion factor, defined as the ratio between the cohesive strength and the adhesive strength of the cohesive soil, should be known as one of the input parameters. However, this factor is not well studied or recorded. In this research project, efforts were made to determine the adhesion factor by investigating literature research and conducting laboratory experiments. Details on this research can be found further in this article.

Adhesion factor and its significance

Clay is the collective noun for a fine-grained natural soil material consisting of clay minerals combined with metal oxides. The soil material properties change with the amount of water the clay contains, thus it is difficult to give definitive values of the properties of clay. In dredging practice, Miedema, (2014, 2017) summarised the clay cutting into the

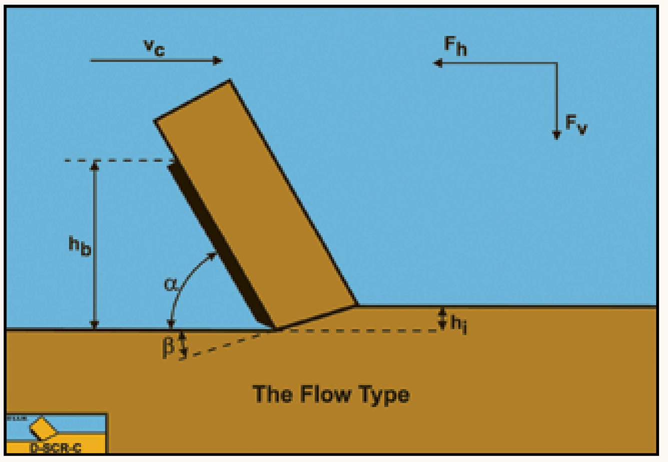


FIGURE 1

The flow type encountered during the clay cutting process (Miedema, 2014 and 2017).

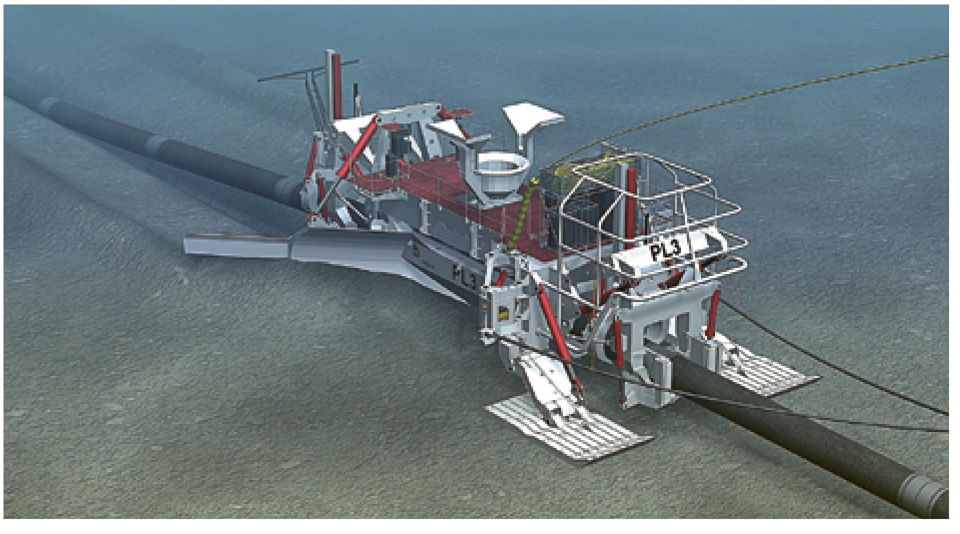


FIGURE 2

The PL3 v-shaped pipe burial plough designed by Royal IHC for Saipem UK Ltd Ltd. Photo courtesy of IHC 2009.

following three types: the flow type, the tear type and the curling type, in which the flow type is the most commonly seen failure mechanism in clay (as shown in Figure 1).

Analytical solutions are derived to calculate the cutting forces on the blade in both horizontal and vertical directions:

$$F_h = \lambda \cdot c \cdot h_i \cdot w \cdot \frac{\frac{\sin(\alpha)}{\sin(\beta)} + r \cdot \frac{\sin(\beta)}{\sin(\alpha)}}{\sin(\alpha+\beta)} \quad (1)$$

$$F_v = \lambda \cdot c \cdot h_i \cdot w \cdot \frac{\frac{\cos(\alpha)}{\sin(\beta)} - r \cdot \frac{\cos(\beta)}{\sin(\alpha)}}{\sin(\alpha+\beta)} \quad (2)$$

$$r = \frac{a \cdot h_b}{c \cdot h_i} = \alpha \cdot \frac{h_b}{h_i} \quad (3)$$

Where Fh is the horizontal cutting force that is aligned with the direction of the cutting blade *[N]* while Fv is the vertical cutting force *[N]*, α is the cutting angle *[-]*, β is the angle of the shear plane with the direction of the cutting velocity *[-]*, λ is the strengthening factor, which follows the fact that when the cutting velocity increases, the clay gets stronger. c is the cohesive shear stress *[Pa]* while a is the adhesive shear stress *[Pa]*, hi is the cutting depth *[m]* and hb is the blade height *[m]*, w is the width of the blade *[m]*, and r is the ratio between adhesion and cohesion *[-]*.

Figure 1 describes the working mechanism in dredging, while in trenching, cutting into clay is also often discussed, for example, in the form of subsea ploughing. Subsea ploughing is a common engineering practice for subsea cable protection. Ploughs are capable of working in a wide range of soils and are capable of operating in water depths up to 1500 metres. An example of a v-shaped plough used to bury pipe is depicted in Figure 2. For the operation of this type of machine, the analytical model to calculate the pulling force F_{pull} is given in Equation 4, in which c_u is the undrained shear strength of a cohesive soil *[kPa]*, N_c is a dimensionless coefficient depending on the plough geometry *[-]*, d the ploughing depth *[m]*, b the ploughing width *[m]*, α the adhesion coefficient defined as *(a/c) [-]* and l_a the adhesion length *[m]* (depending on the plough geometry).

$$F_{pull} = c_u \cdot N_c \cdot d \cdot b + 2 \cdot \alpha \cdot c_u \cdot d \cdot l_a \quad (4)$$

In Equation 3 and 4, the adhesion factor α is an unknown parameter, which reflects one of the fundamental mechanical properties of the clay soil: the ratio between adhesion and cohesion. Without this factor, it becomes almost impossible to calculate the cutting force and pulling force on the mechanical tools.

Literature study on the adhesion factor

In the past, researchers have carried out a series of research activities to investigate the mechanical behaviour of clay with respect to cohesion, adhesion and the relation between them. The adhesion factor is studied based on the two following perspectives**:** the total shear resistance and the adhesive resistance.

In geotechnical engineering, and in particular foundation engineering, the α–method is a commonly used total shear stress analysis for the capacity of the side resistance of the shaft foundations in cohesive soils. In this method, the side resistance capacity is related to the soil's undrained shear strength by an empirical coefficient denoted as α, which is, as mentioned earlier, the adhesion factor. With the adhesion factor, the side resistance of a pile foundation in cohesive soil is calculated using Equation 5 (Chen et al., 2011).

$$Q_s(\alpha) = \pi B \sum_{n=1}^{N} \alpha c_u t \quad (5)$$

$$\alpha = \frac{Q_s(L)}{\pi B c_u t} \quad (6)$$

Where Q_s is the side resistance capacity of the pile foundation *[kPa]*, α the adhesion factor *[-]*, c_u the undrained shear strength of the soil *[kPa]*, B the foundation width *[m]* and t the thickness *[m]*. Based on Equation 5, Equation 6 is derived to calculate the adhesion factor, where L is the contacting length of pile *[m]*. It should be noted that the total skin shear resistance consists of both adhesion and friction. Therefore, this empirical coefficient, which is based on the total shear resistance for a given undrained shear strength, is typically higher than the adhesion factor based on the true adhesion of the soil.

Another type of model is based on the ratio between the adhesive resistance and the undrained shear strength. A considerable amount of experimental data has been published supporting this concept. Littleton (1976) measured the adhesion factor, which is around 0.84 for very soft clay. Kooistra et al. (1998) measured for relatively firm river clay that the adhesion factor is around 0.07. Recently, van der Wielen (2014) conducted measurements on soft river clay where he found the adhesion factor to be 0.58.

With the concept that the total shear resistance consisting of the adhesive resistance and the external friction force, Zimnik et al. (2000) further separate the adhesive strength of a soil into:

- an adhesive strength in the normal direction, called the adhesive tensile strength *at [Pa]*; and
- an adhesive strength in the tangential direction, which is called as the adhesive shear strength *a [Pa]* as depicted in Figure 3.

The soil material properties change with the amount of water the clay contains, thus it is difficult to give definitive values of the properties of clay.

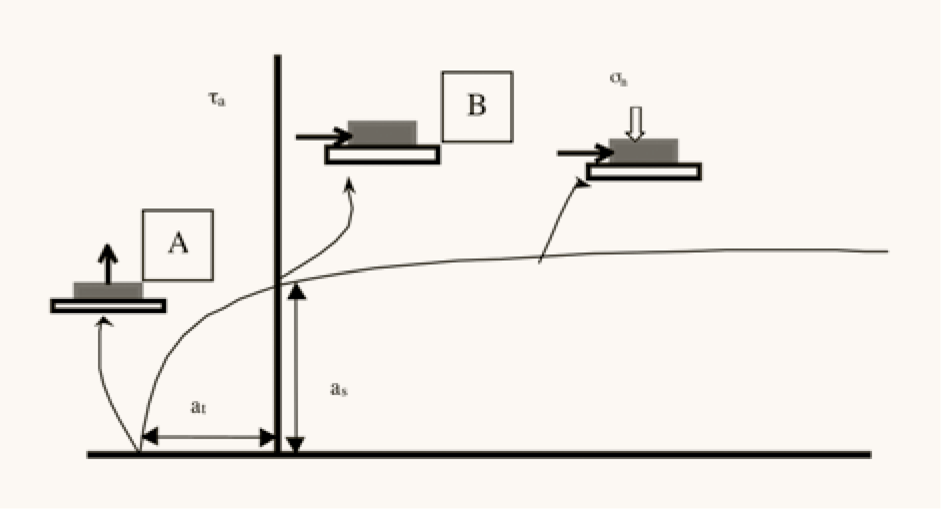


FIGURE 3

The adhesive tensile strength (normal pull) and the adhesive shear strength (tangential pull). Zimnik et al. (2000).

Both the internal tangential resistance and the external tangential resistance of the soil follow a linear Mohr-Coulomb type expression.

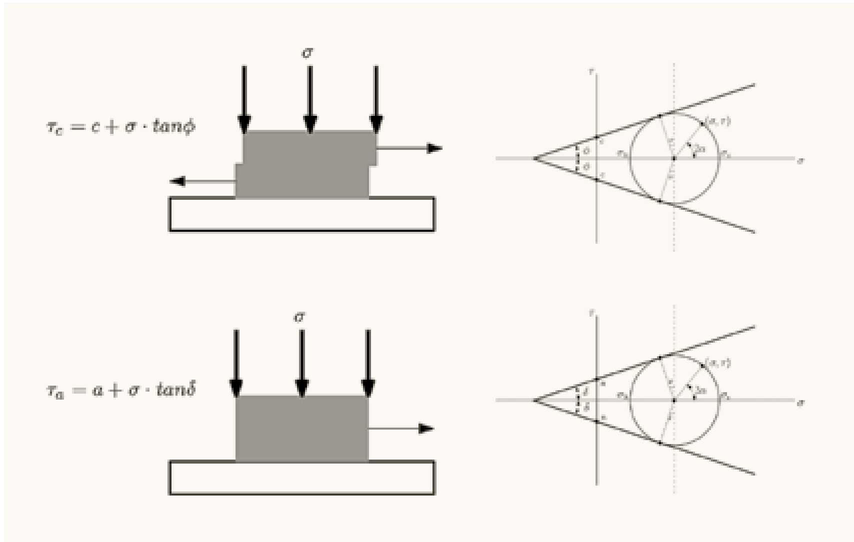


FIGURE 4
The Mohr-Coulomb failure criterion for both internal and external shear strength.

When pulling a foreign body from an adhesive soil in normal direction, the adhesive tensile strength a_t is simply given by Equation 7. On the other hand, when dredging or trenching tools, for example a pipelay trencher, are moving through an adhesive soil, the trencher is subjected to a tangential sliding resistance consisting of an adhesive and a frictional part. This sliding resistance τa *[Pa]* is described by Stafford and Tanner (1977) and follows the Mohr-Coulomb type expression give in Equation 8.

$$a_t = \frac{F}{A_s} \tag{7}$$

$$\tau_a = a + \sigma \tan(\delta) \tag{8}$$

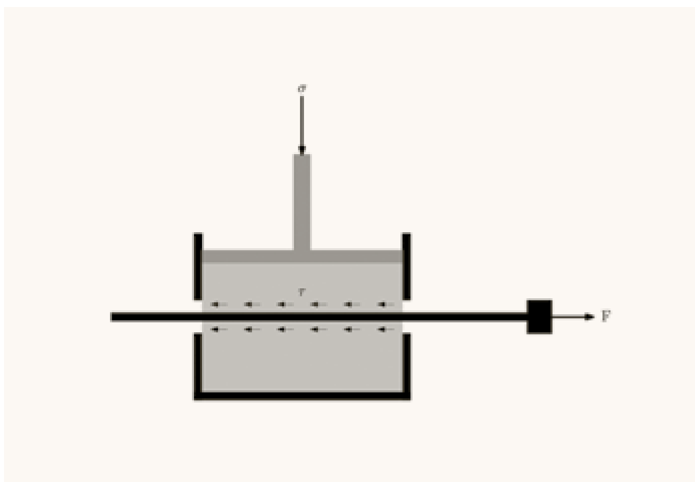


FIGURE 5
Conceptual design of the setup for measuring the external tangential resistance.

Where a_t is the adhesive tensile strength *[Pa]*, *F* is the required pulling force *[N]* and *As* is the effective soil-body contact area *[m²]*, *a* is the adhesive shear strength *[Pa]*, σ is the normal stress at the contact surface *[Pa]* and δ the external friction angle *[-]* of the clay or the soil to the metal blade. Combe and Miedema (2015) investigated the influence of adhesion on cutting processes typically encountered in dredging practice. A custom adhesive test setup was designed and tangential adhesive strength tests were performed. It was concluded that with an increasing cohesive strength of the clay, there is a decrease to zero for the adhesive strength. Furthermore, in addition to the decreasing adhesion there is an increase in the internal friction angle φ.

Experimental study on the adhesion factor

To investigate and analyse the relation between cohesion and adhesion in clayey soils, a series of tests were performed. Both the internal tangential resistance and the external tangential resistance of the soil follow a linear Mohr-Coulomb type expression. Measurements of the tangential resistance at a range of normal stresses σ are used to build up this linear relationship, which can be used to determine:

- the internal shear strength (cohesion) *c*;
- the internal friction angle φ;
- the external shear strength (adhesion) *a*; and
- the external friction angle δ of the soil as depicted in Figure 4.

The internal shear strength, or often just referred to as the 'cohesion', and the internal friction angle φ, are the two properties mostly used to characterise a cohesive soil. For these two properties, the direct shear testing equipment applying to the ASTM-standards is already available. However, this does not apply

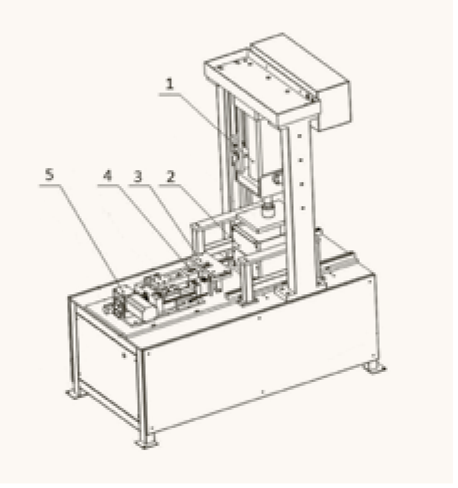


FIGURE 6
A schematic overview of the experimental setup measuring soil-metal contacting shear force.

TABLE 1
The main soil properties of the used soils.

Soil types	Density in dry condition [kg/m³]	Mineralogy analysis	Plastic limit Liquid limit [w/w/%]
Wuhan clay	2180	Quartz, Calcite, Graphite, Kyanite, Albite, Cordierite, Orthoclase, Anorthite, Anatase, Almadine	14.2 23.4
Lianyungang clay	1950	Quartz, Graphite, Sylvite, Spinel, Sodalite, Siderite, Rutile, Magnetite, Magnesite, Hematite, Calcite	12.2 25.7

for external shear strength and external friction angle of soils. Therefore, a dedicated test setup was designed (Figure 5).

In this setup, the cohesive soil is contained in a slotted container with a blade between the two blocks of the cohesive soil. While a normal stress is applied to the top plate and distributed to the clay, the blade is pulled out and the pull-out force is recorded. Dividing this steady-state pull-out force F by the contact area A between the blade and the soil gives the overall tangential resistance τ_a between the blade and the soil. By conducting this test for a series of normal stresses, a Mohr-Coulomb failure diagram (as in Figure 4) can be created and the external shear strength a and the external friction angle δ can be obtained.

Experimental setup

Machine for the pull-out tests

To enable the measurement of interface shear strength properties, a new experimental setup according to the concept depicted in Figure 5 was designed. The design was a collaboration between Delft University of Technology in the Netherlands and The National Engineering Research Center for Dredging Technology and Equipment located in Shanghai, China. The test equipment was constructed by the Shanghai Leao Test Instrument Company and complies with the Chinese T1129-2006 and T1130-2006 specifications in the JTG E50-2006 Test Procedure for Geo-synthetics for Highway Engineering. A schematic overview is given in Figure 6.

The experimental rig depicted in Figure 6 is comprised of five main elements: (1) is a pneumatic cylinder capable of applying and maintaining a vertical pressure and (2) indicates the metal container that holds the cohesive soil. The constant speed linear pulling mechanism is made out of a bolted clamping mechanism (3) to ensure the metal blade is securely attached to the rig. (4) is a force sensor and (5) indicates an electrical drive system, consisting of an electrical stepper motor, an encoder and a reduction gearbox to provide a constant pulling speed.

Preparation work and cohesive soil samples

Two types of soils were used in the cohesion-adhesion experiments. Both soils were obtained from real-time dredging projects in China: soil 1 originates from Wuhan and soil 2 originates from Lianyungang. Immediately after dredging, both soils were packed and sent to the research facility where they were stored in a humidified cabinet. Furthermore, part of the two soils were prepared using air-drying, crushing and sieving (1 mm), and then mixed with water to certain water contents to conduct the Atterberg Limit tests. Finally, X-ray diffraction tests were performed by the Shanghai OKanalysis Center to determine the mineralogy of the soils. An overview of the main properties of the soils is presented in Table 1.

The experimental protocol

1. To ensure full saturation, the soil is placed in a large container filled with water for at least 3 days. Subsequently, the soil is put in the metal soil container (see (2) Figure 6), separated in the middle by a plastic film; in this way the soil is split in two halves, which makes for easier blade placement. The container holding the soil is placed on the test equipment and a constant vertical pressure is applied for a predetermined period to ensure the consolidation of the soil up to the desired shear strength.

2. After consolidation, the plastic film and the top half of the consolidated clay are removed from the container. First, both surfaces are rolled to ensure a smooth surface and then the blade is placed in the correct position on the bottom half of the soil. Subsequently, the top half of the soil is put on the top of the blade so that the blade is clamped to the test equipment using the bolted clamping mechanism (see (3) Figure 6).

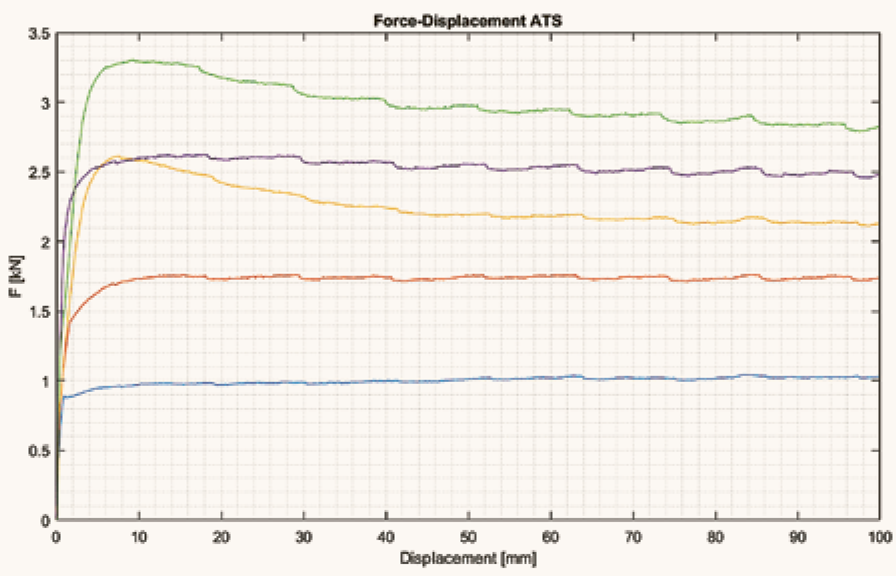


FIGURE 7

Example of results for soil 1 obtained in the blade pull-out tests.

3. Compression on top of the soil is applied and after the pressure is maintained at a constant value for 30 seconds, the blade pull-out test is commenced. For each consolidated soil sample, five blade pull-out tests are performed at normal pressures ranging from 40 kPa to 200 kPa, at an incremental steps of 40 kPa. Between each two tests, the top half of the consolidated soil and the blade are removed from the test setup. The blade is cleaned to remove any residual soil and the consolidated soil is rolled again to have equally smooth surfaces between tests. The tests are performed at a constant speed of 1 mm/s and recorded for a distance of 100 mm.

4. After the blade pull-out tests, four samples are taken from both the top and bottom half of the consolidated soil to conduct the undrained direct shear tests according to the ASTM-D6528 standard (2007) for undrained direct shear tests. Direct shear tests are performed at four normal pressures and a constant speed of 0.8 mm/min. Furthermore, two samples are taken to determine the water content for each consolidated soil specimen.

Preliminary results of the experiments

In total, tests were performed on 10 consolidated soil samples: five blade pull-out tests and four direct shear tests for each soil sample. The blade pull-out force was recorded with sampling frequency of 10Hz. The pull-out force F was plotted versus the pull-out displacement. An example is shown in Figure 7.

The direct shear tests were recorded with a sampling frequency of 6 data points per sheared millimetre. For each test, the internal tangential resistance τc was plotted versus

In total, tests were performed on 10 consolidated soil samples: five blade pull-out tests and four direct shear tests for each soil sample.

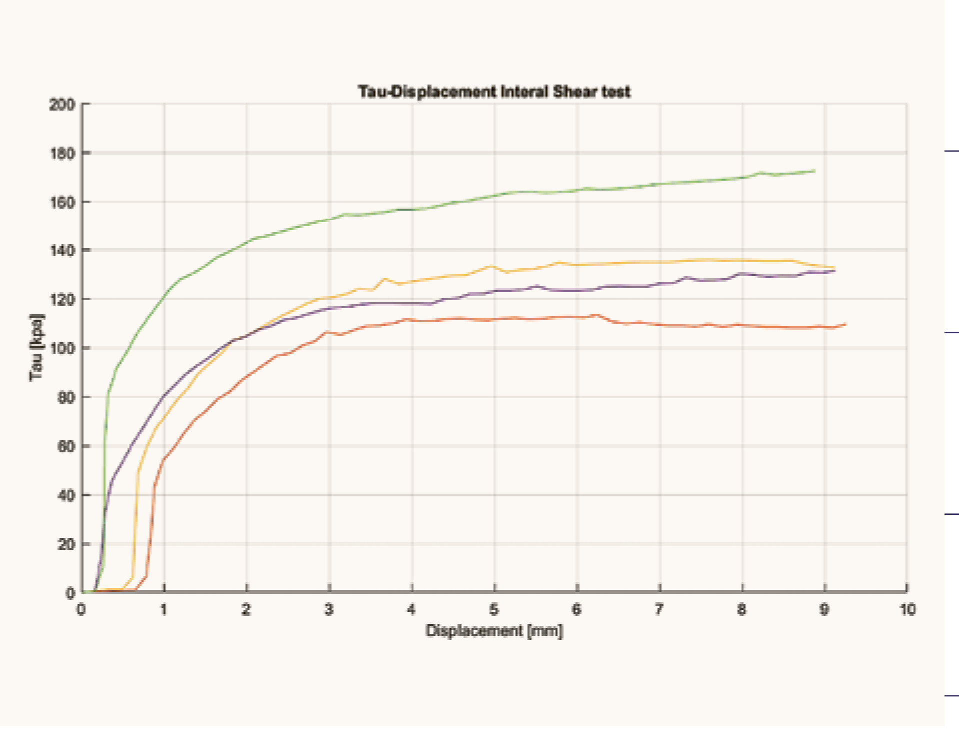


FIGURE 8

Example of results for soil 1 obtained in the undrained direct shear tests.

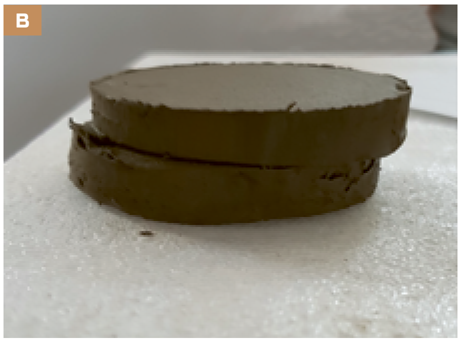


FIGURE 9

Four metal rings are inserted simultaneously into the same soil pile to obtain clay samples for the direct shear tests [A]. The obtained clay samples are flat cylinders [B].

the shearing displacement. An example of these direct shear results for soil 1 is shown in Figure 8.

For both the undrained direct shear and the blade pull-out tests, the average steady-state value for the internal tangential resistance τc and blade pull-out force F were scattered in a Mohr-Coulomb diagram showing normal stress versus shear stress.

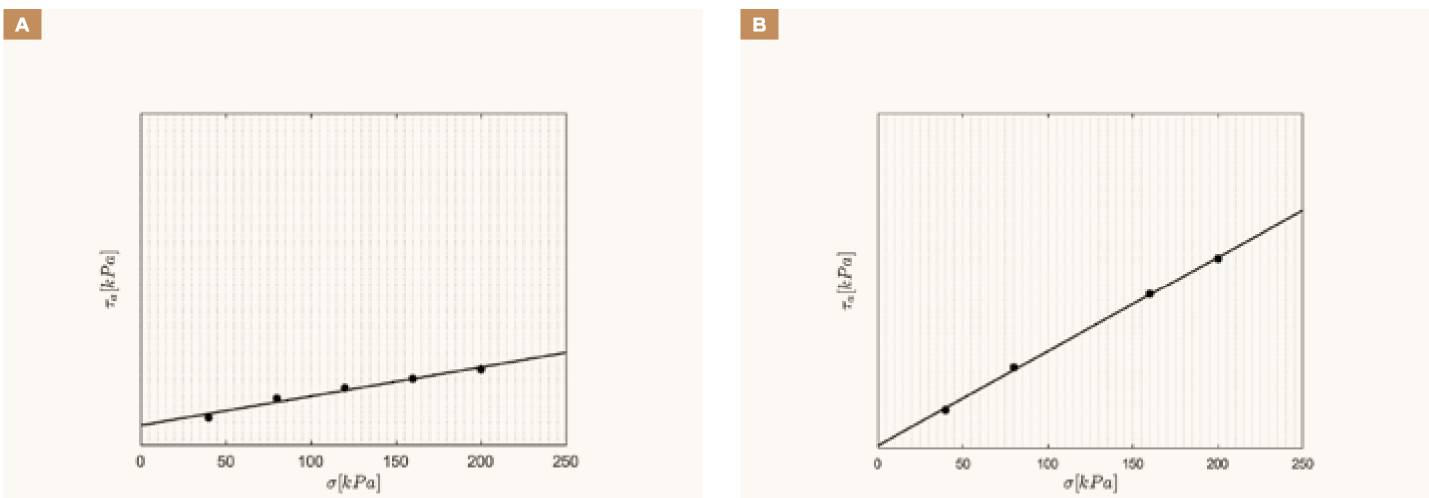
Linear regressions were made according to the Mohr-Coulomb failure criterion (Figure 4) to obtain the internal and external shear strength at zero normal stress (cohesion and adhesion), and the internal and external friction angles. Statistical analysis showed a significant linear regression between the normal stress σ and shear stress τ for both the direct shear results and the blade pull-out test results. Examples for showing this linear regression on the pull-out test data for both soil 1 and 2 are illustrated in Figure 10.

The experimentally obtained internal and external shear strength data was analysed and used to create an empirical model shown in Figure 11, where the dimensionless cohesion c^* is plotted against the adhesion factor, defined as a/c. The dimensionless cohesion is the nominalised cohesion based on the gravitational force. The filled dots represent data obtained in tests on soil 1 (Wuhan) and the circles represent data obtained in tests on soil 2 (Lianyangang). The black line represents the best exponential fit according to the least-square method.

Preliminary analysis of the results

Efforts have been made on interpreting the adhesion and cohesion of cohesive soils. Actually, the adhesion and cohesion can be interpreted in both the mechanical and non-mechanical manners. From the mechanical perspective, the adhesion and cohesion are generated as a result of the pore water pressure change. This concept is supported and well explained by Mitchell et al. (2005).

The non-mechanical perspective tends to emphasise the impact of the



A: Soil 1: 15.9 % [w/w] – Normal stress versus shear stress with a linear fit according to the Mohr-Coulomb failure criterion.

B: Soil 2: 12.0 % [w/w] – Normal stress versus shear stress with a linear fit according to the Mohr-Coulomb failure criterion.

FIGURE 10

Example of normal stress versus shear stress with a linear fit according to the Mohr-Coulomb failure criterion for both soil 1 and soil 2.

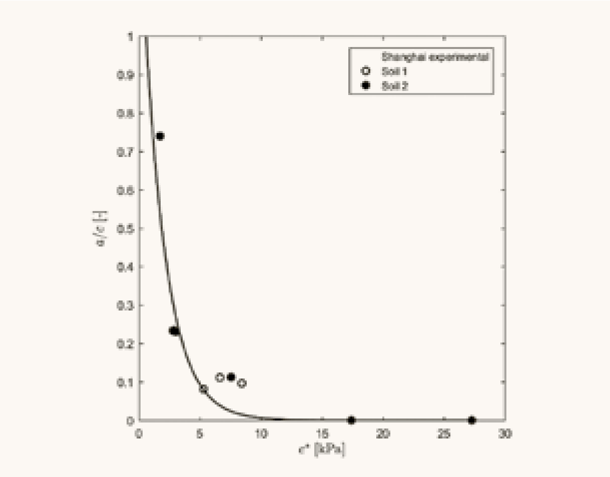


FIGURE 11

Dimensionless cohesion versus the adhesion factor. The filled dots represent the data obtained in tests on soil 1 and the circles represent data obtained in tests on soil 2. The black line represents the best polynomial fit according to the least-square method.

micro-electrochemical reactions that happen inside the clay soil and between the clay soil and the foreign bodies, especially when the clay contains organic compositions. Preliminary results show that although these two types of soil are comprised of different minerals, they still show the same trend that the adhesion factor drops logarithmically to zero with increasing cohesion. It shows that the adhesion factor has a positive correlation with the water content of the clay, which corresponds with the qualitative empirical relation.

In the undrained shear tests of the fully saturated clay, it appears that the external load is transmitted to the pore water, thus increasing the pore pressure. In this way, the effective stress of the solids does not need to change as a result of the frictional forces. Both the internal and external friction remain unchanged. If the cohesive shear strength and the adhesive shear strength of the clay can be seen as constant for a fixed soil type (i.e. soil 1 or soil 2) with fixed water content, then increasing the external compression can hardly affect the apparent shear stress of the soil samples. However, Figure 10, on the contrary, tells that the apparent shear stress increases proportionally to the normal stress. Possible reasons for that might be the local effects on the contacting boundary.

On the contacting surface between the clay sample and the pull-out blade, it is found that in order to ensure the sufficient contact between the soil and the blade, the soil sample is not completely sealed. Therefore, during the pull-out tests, there is inevitably always a small amount of drainage that occurs near the moving blade. That means the load from the upper part of the soil cannot be fully borne by the pore water, so that the local effective stress will increase.

Apart from that, when the blade is being pulled out, in the boundary layer of the soil sample near the blade, a local dilatation in the solid skeleton is expected to occur due to the shearing. Therefore, it is possible that locally the pore volumes will change and most likely increase, considering that the clay samples hold very low porosities and permeability; the surrounding water can hardly flow into the expanded pores and the pore water can hardly flow out of the shrunken pores. Hence, the water under pressure will form up in the boundary layer, which is the part of the clay sample near the blade. For the solid grains in this layer, it means an extra pressure gradient force acting on them, thus locally the effective stress in vertical direction will increase. All these possible reasons lead to an increasing apparent shear resistance against the increasing external compressive load.

Conclusions

An often neglected, while very important mechanical property of clay soils, the adhesion factor has been discussed and studied. The two types of adhesion factor, the ratio between the overall external shear resistance versus the undrained shear strength, and ratio between the actual adhesive resistance versus the undrained shear strength, have been explained. The former is mainly used in the agricultural applications, on which a set of empirical equations have been introduced, and the later is the term needed in dredging applications, on which the experimental study in the past has been introduced.

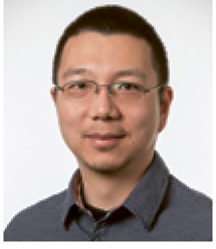
This study shows that the adhesion factor varies heavily with the cohesive strength of the clay, while the cohesive strength relies heavily on the water content. While in dredging operation, the clay encountered can all been seen as fully saturated, thus for the clay in the specific field, the adhesion

This study shows that the adhesion factor varies heavily with the cohesive strength of the clay, while the cohesive strength relies heavily on the water content.

factor should be seen as constant. The discovered adhesion factor can be brought into Equation 3 and 4 for calculating the cutting forces on clay in dredging and trenching operations. Another discovery lays in the magnitude of the friction. The internal and external friction of clay is frequently neglected since they are considered to be significantly smaller than the cohesion and adhesion. This study found that if the loading process is not fully undrained, then there is an apparent internal and external friction angle which could lead to non-negligible frictional forces. If the two parts are correctly combined, then the cutting force and the specific cutting energy can be calculated in the right order.

The results presented in this article are based on the preliminary post-analysis.

It is recommended to conduct further post-analysis on the obtained experimental data to quantitatively obtain all the adhesion factor and friction coefficients of the clay samples. It is also recommended to conduct experiments on more types of soils with different water contents. Only by conducting a large number of tests will it be possible to generate a material database so that a sound empirical relation can be established. In the end, it is expected that with a comprehensive database, a set of empirical equations can be used to calculate the adhesion and external friction coefficient when the clay soil type is known.



Xiuhan Chen
Xiuhan is a scientist working for the Offshore and Dredging Engineering department of Delft University of Technology in the Netherlands. He specialises in seabed processes (e.g. dredging and trenching) and has established a framework of 3D dynamic numerical models that simulates the underwater excavation process. Xiuhan is actively involved in both CEDA and WODA, and is General Secretary of the WODA Technical Orientation Committee and Reservoir Dredging Working Group.

Jan van den Broecke
Jan graduated in 2018 with an MSc in Offshore and Dredging Engineering at the Delft University of Technology, focussing on Discrete Element Modelling (DEM) and the experimental research of the cohesion-adhesion relation. For the past two and a half years, he has worked as a R&D Engineer for DEME's activity line dredging, working on CSD related topics with the focus on cutter heads. As of May 2021, he will be one of the dedicated production engineers for DEME's CSD Spartacus.

Gongxun Liu
Liu is a Senior Engineer and holds a doctorate in Geotechnical Engineering. His areas of research include engineering characteristics of dredged soil, reduction and resource utilisation of dredged soil, soil cutting, dam construction and mold soft soil construction technology and equipment. He has published more than 20 academic papers and filed more than 10 patent applications. In 2017, he was selected to join the Technical Expert Committee of China Dredging.

Guojun Hong
Guojun is a Senior Engineer. His research work includes aspects of geotechnical cutting, the development of large-scale high-performance mud pump, environmental dredging and treatment of contaminated sediment. He has completed more than 10 provincial and ministerial scientific research projects, and has received many awards, including the National Science and Technology Progress Award. He has obtained more than 40 patents, including 10 invention patents and published more than 30 papers, including 12 SCI/EI retrieval papers.

Sape Miedema
Sape obtained both his MSc in Mechanical Engineering and PhD in Dredging at Delft University of Technology. Since 1987, he has been an assistant, then associate, professor at the Chair of Dredging Technology, then as a member of the management board of Mechanical Engineering and Marine Technology. He was appointed Educational Director of the MSc programme in Offshore Engineering in 2005 and since 2013, he is also Educational Director of the MSc programme in Marine Technology.

Summary

Clay or cohesive soil is one of the three most commonly encountered soil types in riverbed and seabed, other than sand and silt. Excavation into clay is an important engineering practice in dredging, trenching and drilling practice. One of the major mechanical properties of clay is the adhesion factor that reflects the ratio between the cohesive and adhesive strength of clay under different water content. This factor plays a key role in determining the cutting force for the excavation process, either on a clamshell tooth or on a plough. In this research project, efforts were made to determine the adhesion factor by conducting both literature research and laboratory experiments. In conclusion, the adhesion factor for a certain type of clay should not be taken as a fixed value, which is common practice nowadays. On the contrary, this factor varies heavily dependent on the local water content. It is also shown that the adhesion factor holds an exponential decrease correlation with the undrained shear strength of the clay.

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INTERVIEW

NATIONAL LEAD FOR USACE ENGINEERING WITH NATURE INITIATIVE DR TODD BRIDGES

‘THERE ARE JUST SO MANY WAYS IN WHICH **NATURE IS THE SOLUTION TO THE PROBLEMS THAT AIL US**’

> There is a fantastic opportunity, I believe, worldwide to incorporate nature into engineering in a more tangible and substantive way.

From an early fascination in oceanography, nature has played a defining role in the career of Dr Todd Bridges. With a decade's investment in the Engineering With Nature® initiative, he has seen that sustainability and engineering can go hand-in-hand providing economic, environmental and social benefits. His focus now is to build on that foundation – to encourage and facilitate collaboration across sectors, public and private, to advance and accelerate Engineering With Nature practice.

How and why did the Engineering With Nature initiative begin?
The U.S. Army Corps of Engineers (USACE) formally started the Engineering With Nature (EWN) initiative in 2010. The short answer to why we started EWN was that it was time. In the 1960s, there were several ideas beginning and maturing. For example, Howard Odum, started the idea of ecological engineering, combining ecosystems with society and human need. Ian McHarg, a landscape architect, published his seminal work *Design with Nature* in 1969, combining natural systems and approaches with the practice of landscape architecture. Over the decades, those approaches have matured and grown. When we consider the challenges and opportunities that present themselves to the world in the 21st century, we need to apply these ideas as we pursue infrastructure development. In the 20th century, we built a lot of infrastructure with steel, concrete, rock and asphalt. In the 21st century, how will we pursue investment and development of infrastructure? There is a fantastic opportunity, I believe, worldwide to incorporate nature into engineering in a more tangible and substantive way – to diversify and really expand as well as increase the value that can be generated from such projects.

Your career with USACE spans nearly 30 years. How did your background spark your interest to work on the initiative?
It all began when I was a boy. When I was growing up, I watched Jacques Cousteau on television. I was completely captivated and fascinated by the ocean and in particular, the biology of the ocean. I consciously remember at the age of 10 or 11 deciding that this was what I was going to do. I went to college and got my bachelor's and master's in biology, and then did my doctoral work in oceanography. So, I had a natural sciences background with a focus on the ocean and marine systems, and then I came to work for an engineering organisation, the U.S. Army Corps of Engineers. It was here that I benefited from daily interaction and collaboration with engineers. They have a different educational foundation and a different way of thinking about their work, problems and solutions that I've come to really appreciate. When scientists and engineers work together, it can be a very powerful combination that is complimentary in so many regards. Over the years, with my education and professional experience, Engineering With Nature came together in my thinking in terms of what a solution could look like. A solution being something that combines engineering and nature together.

Not everyone can say their passion turned into their work.
No, to be able to combine what you do many hours a day with work that provides you with personal satisfaction and fulfilment, I mean, that's the ideal. There's nothing that compares.

There have been so many USACE projects over the past decade. Is there one that stands out for you and why?
It's so difficult to choose. With the publication of both volumes one and two of the *Engineering With Nature Atlas*, there are a total of 118 projects from around the world described in those books. 50 of those projects are USACE projects that go back many years. We started the Engineering With Nature initiative formally in 2010, but we did

so recognising that there are decades of prior practice we could look to for examples. We're working to elevate this approach to solution development and, as I've said many times, to make the exceptional projects of the past commonplace in the future.

What has been accomplished over the last several years is not contained in one project, more a network of activities. In coastal New Jersey, we have worked for several years with many organisations, including our Philadelphia District of the Corps of Engineers, state agencies, the non-profit world, the private sector and academia. Through that collaboration, an initiative called the Seven Mile Island Innovation Laboratory (SMIIL) was formed. This group is building first of their kind projects, drawing from the principles and practices of Engineering With Nature. It's a beautiful thing to behold when alignment occurs across organisational boundaries and mandates to really deliver nature-based solutions.

I'd also like to mention another more recent example, where Engineering With Nature has been working closely with the U.S. Air Force. At Tyndall Air Force Base on the Gulf Coast of Florida, Hurricane Michael did a huge amount of damage when it struck in 2018. Right now, the U.S. Department of Defense is investing nearly US$ 5 billion to rebuild this 30,000-acre military base in a way that is resilient with respect to future conditions, climate change and future storms. Part of the approach that we're taking there through Engineering With Nature is to make investments in the natural landscape. There's a beautifully complex, natural landscape there that includes islands and beaches, dunes and back bay environments, reefs and wetlands. Our aim is to invest in those natural landscapes to provide resilience to the mission. It's a prime example of the connection between nature-based solutions and national security infrastructure.

There must be many opportunities and challenges in undertaking projects within an organisation such as USACE. Can you share some of them?

There certainly are. USACE, like the Rijkswaterstaat in the Netherlands, has a long history stretching back more than 200 years. It's interesting to look at the comparisons between the two organisations. We maintained our connection to the military, within the U.S. Army and the U.S. Department of Defense, whereas the Rijkswaterstaat evolved out of that structure. I think one of the chief advantages of working for the Corps is the

Meet Dr Todd Bridges

Dr Todd Bridges is the U.S. Army's Senior Research Scientist for Environmental Science. He leads research and applications for the U.S. Army and U.S. Army Corps of Engineers in the areas of sustainable infrastructure and environmental management. Todd is the National Lead for the USACE Engineering With Nature initiative, which includes a network of research projects, field-scale projects and communication activities to promote sustainable, resilient systems. He led the focus on Natural and Nature-Based Features (NNBF) within USACE's North Atlantic Coast Comprehensive Study from 2013–2015 following Hurricane Sandy and currently leads an international collaboration to develop guidelines on the use of NNBF for coastal and fluvial systems. Todd is also the Programme Manager for the Dredging Operations Environmental Research programme, one of the Corps' largest civil works R&D programmes, where he directs the execution of more than US$ 6 million in research annually. He has chaired international working groups and guidance development for the United Nations' International Maritime Organisation and the World Association for Waterborne Transport Infrastructure, where he currently serves as Chairman of the Environmental Commission.

We have the possibility to deliver for future generations, something that is very different from what infrastructure looked like in the 20th century.

sheer scope of our programme and our engineering for the nation. Over the last two years, our total programme equates to a US$ 60 billion portfolio of work.

With a programme that size, there is clearly an opportunity to be involved with and to deliver projects on a significant and large scale. There is also so much to be done to prepare ourselves for and to really support our society for the remainder of the 21st century. When you consider the types of infrastructure investments that are needed and the reinvestment that's going to be made in infrastructure, there's so much possibility. Then the excitement comes from thinking what is that infrastructure going to look like? How is it going to work and how is it going to incorporate nature? We have the possibility to deliver for future generations, something that is very different from what infrastructure looked like in the 20th century.

Can you touch on some of the challenges?

Like anything that involves people, change can pose a challenge for large organisations, whether public or private. Government organisations have a reputation for being very averse to change, but I think any large organisation struggles with change management. For an engineering organisation, the standards of practice can become very established, even calcified. There can be resistance to change, which creates a tension.

Within the Corps we recognise the need to innovate. With that in mind, USACE organised and conducted its first Innovation Summit in 2019. It brought together representatives from government, industry and academia to talk specifically about innovation. The second Innovation Summit will be held virtually this October. So, we are trying to be purposeful about it within the Corps to address this issue of change, but it is a challenge.

I also think there might be a bit of a blind spot in organisations where technical matters, i.e. engineering and science, are so dominant in the culture. What can sometimes be left out is the social element of the equation. It is not necessarily the case that the best technical argument wins. If you have not set the social conditions for change, it doesn't matter if you have a better way of slicing bread. It's not going to get implemented if you didn't give proper attention to the social science of your problem.

The COVID-19 pandemic has had considerable impact on world trade. What impact has it had on USACE, its work and the type of projects currently undertaken?

It has certainly been a roller coaster for everyone. At a personal level, I spent several months last year nearly exclusively focused on COVID-19. USACE had a US$ 2 billion mission related to the response to the pandemic and engineering related to supporting what we call 'Alternative Care Facilities'. I led a technical team of scientists, mathematicians, engineers and public health professionals within USACE to develop modelling tools, including an epidemiological model that we built more or less from scratch. This model enabled us to project the dynamics of the disease and anticipate the kind of logistics issues we were going to face. It was quite consuming and some of that work continues today.

What will be the learnings we take away from the pandemic in relation to Engineering With Nature?

I feel there are some very important lessons and takeaways from the pandemic that are certainly related to Engineering With Nature. Something that everyone would recognise, if they pause for a moment and think about it, is that humanity is connected to nature. In respect to something like a pandemic you're talking about the downside of being connected, i.e. the origin of the virus. The other point of this is that because we are connected to nature in this way, there are common vulnerabilities. Rich or poor, we can all get sick, we are all vulnerable. However, some populations and groups within our countries, within our societies, are particularly vulnerable. I think there is a renewed interest in these topics, of social equity and vulnerabilities that exist, that are variable across our society. Infrastructure development in particular needs to be attentive to that. Who are we serving and who is the infrastructure serving? Is it serving people and different groups of people adequately? These are important questions. Engineering With Nature and nature-based solutions are very important because people benefit, whether they consciously realise it or not, from nature.

People need more nature in their lives, not less. There is a great deal of science documenting the importance of this, both in terms of physical and mental health. People need to be connected to nature. When I think about that, I'm excited about the idea that while we've had this reminder on a grand scale that we as humans are connected to nature, we need to look for ways to create benefit and value from that connection. Infrastructure development should be a vehicle for providing that connection to nature, because concrete doesn't satisfy every human need.

In the recently published volume 2 of the *Engineering With Nature Atlas*, there is a wonderful Chinese proverb quoted that says, 'One generation plants a tree, another gets the shade.' In thinking about the future, what do you consider are the key elements to advancing engineering practice with Engineering With Nature?

Yes, I was struck by that proverb. It tells us that we need to look ahead, which isn't always easy to do, but we must plan for the long term. One of the conversations I've been having with my colleagues involves asking them, What are your big ideas? What should, for example, our coasts and our rivers look like by the end of the century? By 2100, how should these systems work? What kinds of services and functions do we want them to deliver? With respect to our

On 7 April 2021, USACE held a virtual book launch for the release of *Engineering With Nature, An Atlas, Volume 2*. The event included speakers from a range of US and international partner organisations.

work within the Army Corps of Engineers, what projects need to get built for them to operate that way? We have to ask questions that get us to think about the future, especially when you consider that by the end of the century there are going to be 10 billion or more people on the planet, which increases the demand for services provided by infrastructure. And when you add climate change on top of that – there are some big challenges ahead.

The other side of this is that we spend too much time and give too much consideration to the boxes that we build for ourselves. By that I mean the mental boxes that we build for ourselves using concepts or business practices, or even technical approaches, that we employ to develop projects. We construct these boxes and they represent constraints for how we will do things and of how we will think. It's a cliché, but we really need to think outside the box, but that has to be a deliberate choice on our part. When you're turning the crank really fast to deliver a project, that time to think outside the box might be minimised or set aside for a while. There's a real danger there because if you don't give yourself, or your organisation doesn't give itself, time to think outside the box, it's unlikely you'll be able to innovate and to deliver solutions you will need in the long term.

Countries around the world are facing the challenges of climate adaptation. When it comes to nature-based approaches to protecting urban shorelines, what have been the most important lessons that you have learned since launching the initiative?
I think there is growing recognition of the realities that we face. For example, I mentioned the Tyndall Air Force Base case. When you have such an important facility and military installation that suffers damage to the extent that it did, that's very real.

What's encouraging to me is how robust the dialogue is internationally about the role of nature-based solutions as a part of climate adaptation. The solution set that we need to draw from must be diverse. It's clear that the solutions that we employed in our approach to engineering in the 20th century are not aging well and the statistics bear this out. Since 1980, there have been 285 weather or climate disasters in the United States, which produced at least US$ 1 billion of damage. If you look at the cumulative costs, the total damage for those 285 events exceeds US$ 1.8 trillion dollars. In addition, 14,000 people lost their lives.

So, when you have a problem on that kind of scale, arguably our approaches are not aging well. Not at all. The question is how do we reduce those kinds of impacts? We must have a diversified solution set in which nature is a part of the solution. There's no doubt in my mind – and there's no doubt in the minds of many people around the world – that nature will be part of the long-term solution.

Sustainability has become an important concept in engineering over the last two decades. What is the key to sustainability for you?
That's a good question because there has been a lot written about sustainability and there are a lot of nuanced definitions. Some people get a bit concerned about a term as 'flexible' as sustainability. I don't find that a problem. I think it's actually advantageous because it can lead to some very good dialogue and conversation about what we're trying to achieve.

To me, sustainability is about the distribution of costs and benefits across the three legs of the stool – the economic, environmental and social domains of our system. We recognise that there are costs, but we also need to recognise that solutions have to carry benefits with them. That's why we're putting them in place. What's the return on our investment in a particular solution? There's certainly much renewed interest in the United States and within the Army Corps of Engineers to understand more about this distribution across the three legs of the sustainability stool, and in particular the benefits.

I believe there are benefits being generated by infrastructure projects now that we have not described or maybe don't understand, because in the past there's been more focus on economic benefits. However, the environmental and the social benefits, whether they are monetised or not, need to be understood as well because they're real. You may not be able to put a dollar symbol next to it, but that does not make the benefit less real. What I think, in regards to sustainability, is how to decrease the costs and increase and diversify the benefits, over the long term, across those three categories of economic, environmental and social outcome. That's what sustainability is for me.

How do you think the dredging industry as a whole is addressing the task of sustainability and innovation?
Without sounding overly critical, I think there's work to do. We've been dredging in 'mechanical' ways for 150 plus years and dredging has been such a vital approach to economic development. That has been its primary role across countries and still is even today. It supports port infrastructure and coastal and riverine infrastructure related to navigation, as well as flood risk management. I think it's generally understood what the relationship is between dredging and the dredging industry, and economic development. Less well captured, I believe, is how dredging, whether it's the equipment that we're using or how we operate that equipment, can be used to support more directly the other two categories of environmental and social benefits. More attention needs to be given to how dredging practice and the industry itself can support, modify and innovate to deliver more diversified and combinations of benefits.

There is of course innovation within the industry. However, if you were to look at photographs of dredgers from 100 years ago and compared them to dredgers of today, they look a lot alike. Yes, there are differences in the energy systems being used, the technology and how the machinery operates, but in large measure, it looks very similar. I think the timing is more than ripe, I would say overly ripe, to have a broad discussion about innovation within the dredging industry.

There is an obvious partnership between green financing and sustainable waterborne infrastructure projects, but work is needed. What do you see are the challenges and the potential solutions to making Engineering With Nature projects viable and interesting to investors?
Yes, I think this is also a source of hope. When we think about 20th century practice with respect to infrastructure and especially infrastructure associated with water systems, it's been dominated by public investment, i.e. government agencies and public investment. However, what we've seen emerge in recent years is interest in the private sector, including that portion of the private sector that actually owns and needs to protect its own assets, such as the chemical industry.

> **It's clear that the solutions that we employed in our approach to engineering in the 20th century are not aging well.**

For example, Dow made a very substantial internal commitment to generate US$ 1 billion of value in nature as a part of its business practice. This is business value it's generating, which might take the form of building a wetland to provide water treatment value. In fact, Dow has projects in the second volume of the *Engineering With Nature Atlas* that illustrate part of its approach to this.

Now we're seeing this interest in the private sector, the next question is how does the private sector and the public sector collaborate and work together to deliver nature-based solutions? Which brings us to financing. There are also very positive developments in the insurance sector with respect to nature-based solutions and in companies giving attention to and trying to understand the role of nature. There's a coral reef off the coast of Mexico that's now insured because of the protection value it provides to the coastline. So, there are many positive developments. This is an issue where innovation in the area of financing will be needed because it involves policies and laws at a public level that can be difficult to change.

The value that can be delivered to society and humanity as a whole through these approaches is just tremendous.

Do the Engineering With Nature, Working with Nature and Building with Nature organisations share ideas, experiences, successes and failures?

Yes very much so. There's been sharing since the beginning of these formalised initiatives. There are Building with Nature projects in the *Engineering With Nature Atlas*, volumes one and two. I've served on panels and advisory groups for Building with Nature. So, it's definitely a collaborative engagement and there's a lot to be gained by all concerned in terms of sharing.

Experience and ideas are vital to accelerating the innovation that is needed in this space, as well as the implementation of these practices on the ground. It comes back to what I mentioned earlier about the challenges of change. While you want to put newer approaches into practice, there are naturally going to be some obstacles to doing that.

To share experiences, case examples and practice can often help provide the evidence that you need in order to move forward. I've personally benefited, in so many ways, by being able to travel around the world (back when we could do that) to engage with other organisations. Even though an organisation or project is located on the other side of the planet from where you sit, you will see, more or less, the same set of problems, the same challenges, the same context that you experience. So, when you can see and experience that, it brings a clarity to what the key factors are in that problem and also what the key elements are to the solutions. It really brings a clarity that you only get by seeing projects in different places and making these kinds of comparisons.

People using the ESII field app to collect site-specific data. Mercy Corps' Transform Project, Semarang, Indonesia. Photo © Morgan Erhardt, EcoMetrix Solutions Group.

Incorporating the value of nature into decision making

The Ecosystem Services Identification and Inventory (ESII) tool allows users to better understand the benefits that nature provides and informs decisions to protect, restore or monitor specific natural assets. Developed in collaboration by Dow, The Nature Conservancy and EcoMetrix Solutions Group, the tool is a free application available online and as an iPad-based app. It can advise a broad spectrum of stakeholders (including non-ecologists) as they make decisions on various land-use alternatives with corresponding quantified ecosystem services. Understanding how various designs impact the ecological performance of a piece of land helps drive adoption of nature-based solutions. As in many of its projects, Dow has incorporated the ESII tool into its land management strategy.

What are your future ambitions and plans for the Engineering With Nature initiative to evolve?

I could say more of the same, but it's not really more of the same. This past year we started the Network for Engineering With Nature (N-EWN). We established a virtual space where organisations can come together with the idea of collaborating with each other to advance and accelerate Engineering With Nature practice. It started last year with the Army Corps of Engineers and the University of Georgia, and now other organisations are joining the Network. It's a way of encouraging and facilitating collaboration across sectors, public and private. Those sectors are able to come together and to share not only their interests, but also to contribute to this enterprise that is engineering with nature. That's the kind of the future that we're looking to build upon.

In fact, I'm currently at the University of Oklahoma in Norman, Oklahoma, meeting with professors and university leadership about their engagement with Engineering With Nature. While there are a lot opportunities and needs in our coastal systems, we also need to think about the middle of the country, including the portion we call the Great Plains. The University of Oklahoma is located in that part of the country. We want to discover and deliver solutions for engineering with nature across the Great Plains and understand what these kinds of solutions look like. For example, what can we accomplish with a large and significant commitment to reforestation? How does that provide value in the form of restored hydrology and reduced risk to flooding and even enhanced drought resilience? There are just so many ways in which nature is the solution to the problems that ail us.

After 10 years as National Lead, what inspires and motivates you to keep moving forward with the initiative?

Well, there are many sources of inspiration. I'll describe one of them at a personal level. Walter Andersen was a Mississippi artist and writer. He was born in 1903 and he spent most of his life on the Gulf Coast and called Ocean Springs, Mississippi, his home. He was a wonderful artist. I have a print of one of his watercolour paintings of blue crabs in my office. Anderson spent a considerable amount of time during his life being alone in nature and contemplating nature. At one point he said, "I wonder how long it will be before nature and man accept each other again." When I look at that painting on the wall in my office, I think Engineering With Nature is a step on that path. Simply put, the potential is huge. That's the drive for me.

The future is bright for Engineering With Nature. I truly believe that. The value that can be delivered to society and humanity as a whole through these approaches is just tremendous. When you know what's possible and you think about future generations that will benefit from the shade of the tree you planted, that's inspiring and motivating. It creates a sense of urgency within me that simply says, let's get on with it. But you have to pair a sense of urgency with a sense of patience, because you don't get to snap your fingers and just make it all happen immediately. It requires investment and commitment. Now that we've entered the promise of our second decade of Engineering With Nature, I can reflect back on the first decade of investment and say that it's all been worth it.

Resumé

United States Army Corps of Engineers (USACE)

2006–Present
Senior Research Scientist, Environmental Science
Leads research, development and environmental initiatives for the U.S. Army and USACE supporting resilience, sustainability and environmental management. Areas of research and application include: 1) science and engineering of sustainable infrastructure development; 2) risk and decision analysis methods applied to infrastructure and environmental systems; 3) management of sediment and environmental contaminants; and 4) natural systems engineering.

2010–Present
National Lead, USACE Engineering With Nature initiative
Leads a network of multi-organisation collaboration, research and development, field-scale application and communication activities to advance sustainable, resilient infrastructure systems through nature-based solutions.

2006–Present
Programme Manager, Dredging Operations Environmental Research Programme
Leads research, development and application in infrastructure science and engineering, dredging, and sediment management for USACE's US$ 2+ billion navigation programme.

1992–2006
Research Biologist and Team Leader
Led research, development and application in ecotoxicology, environmental assessment and sediment assessment and management.

COASTBUSTERS

A NATURE-BASED SOLUTIONS COASTAL MANAGEMENT ALTERNATIVE

Photo © Daan Delbare

Today's challenges of erosion, flooding and storm surges are primary concerns for coastal communities around the world. Traditional coastal engineering solutions, such as concrete seawalls or rock breakwaters however, will become unsustainable due to their limited resilience, higher costs, societal impacts and unwanted ecological side effects. In response to these challenges, Coastbusters developed a nature-based solutions approach to sustainable coastal management. These solutions will create new habitats based on known 'biobuilder species' in the form of biogenic coastal reefs. The purpose of the reefs is to induce natural accretion of sand, attenuate storm waves and reinforce the foreshore against coastal erosion, thus adding to coastal protection.

Three key biobuilding concepts were identified and tested to develop ecosystem-based coastal engineering.

Coastal zones are under duress of climate change (e.g. sea level rise, intensification of storms, increasing beach erosion) and enhanced anthropogenic pressure (e.g. demographic evolution, loss of habitats, economic expansion). Both hard and soft conventional coastal protection measures, such as sea walls, dykes, embankments and beach reclamations, are increasingly required to combat flood risks (Malherbe et al., 2013).

Conventional coastal protection measures however, are currently challenged by stakeholders because they are seen as unsustainable and carry high installation and structural maintenance costs. Hard structures are designed for current sea levels and are incapable of adapting to increasing flood risks. Soft measures will suffer from storm events and require additional maintenance afterwards. As a consequence, current civil engineering approaches can fall short in efficiently and cost effectively protecting the coast (Syvitski et al. 2009). This often results in negative or unforeseen impacts on local ecology and surrounding ecosystems on larger scales, reducing the resilience of the coast.

Resilient coastal protection

Innovative, sustainable and perennial approaches for a resilient coastal protection are therefore crucial to safeguard economic, environmental and societal assets of the coast. In recent decades, sustainable coastal management approaches have emerged within the nature-based solutions (NBS) philosophy (European Commission, 2015; IUCN, 2016; Nesshöver et al., 2017). In this context, the application of ecosystem engineering species for achieving civil engineering objectives is not new. From a coastal protection point of view, these species need to have the ability to modify the local physical environment by their structures or activities to trap sediments and attenuate waves (Borsje et al., 2011; Emmerman et al., 2013). Examples of coastal ecosystem engineers are numerous, with the most tangible being dune vegetation, seagrasses, corals and mangroves.

An ecosystem-based coastal flood protection can only be brought into large-scale practice as a regional solution, on condition that:

1. sufficient space is present to accommodate the creation and development of (additional) ecosystems;
2. key engineering species and its habitat naturally occur; and
3. local stakeholders support development of ecosystem services.

Once these conditions are met, solutions can be designed to translate the desired ecosystem engineering functionality into coastal management measures. On the one hand, such development requires a generic framework to select the appropriate measures based on the spatial and temporal scale of coastal protection. On the other, it requires knowledge (and broad dissemination thereof) on the ecology, engineering and ecosystem services delivered by the reef-forming ecosystem.

The core of Coastbusters is to understand and validate the underlying processes that drives this natural biostabilisation. To translate the optimal conditions for the development of biogenic reefs into an engineered design will generate a new business model for coastal

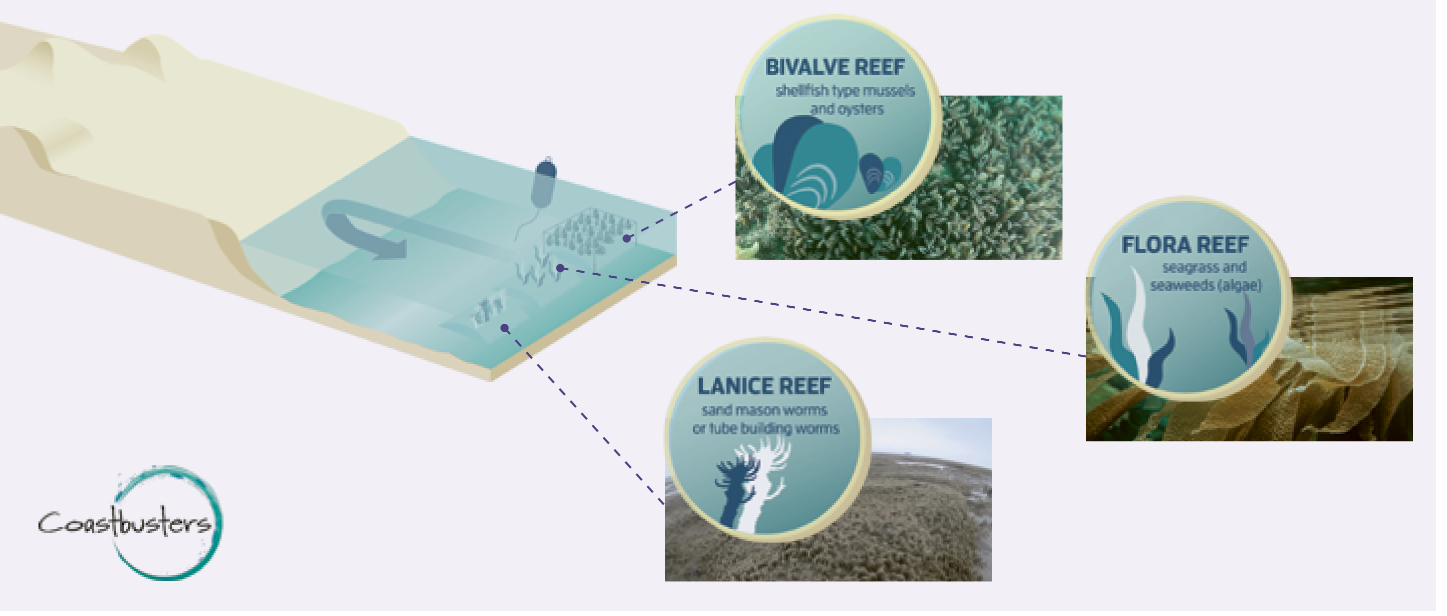

FIGURE 1

Illustration of the three different reef types at the test site off the Belgian coast of De Panne.

management (Sterckx et al., 2019). To unravel this dynamic interaction between traditional technical and ecological engineering requires diverse expertise and multidisciplinary collaboration. Therefore, an exceptional public-private partnership was created. The Coastbusters consortium is currently composed of three companies, Dredging International (part of the DEME group), Jan de Nul and Sioen industries, together with two research institutes, the Institute for Agricultural, Fisheries and Food Research (ILVO) and the Flanders Marine Institute (VLIZ). The Coastbusters research projects are facilitated by the Blue Cluster (DBC) and supported by the Flemish agency for Innovation and Entrepreneurship (VLAIO).

Ecosystem engineers

The implementation of nature-based solutions (NBS) in the marine environment necessitates in-depth knowledge and insights on the driving parameters and natural processes. Moreover, integrating this fundamental expertise of the natural processes into the traditional technical engineering of coastal management tools (i.e. design, installation, operational management and maintenance) is key. To acquire the required knowledge and skills, a chain of dedicated research and innovation lines are introduced.

The original Coastbusters research and innovation lines focus on three ecosystem engineers present in Belgian coastal waters: seaweed (*Saccharina latissima*); tube-building sand mason worms (*Lanice conchilega*); and blue mussels (*Mytilus edulis*). Respectively referred to here as flora reef, lanice reef and bivalve reef.

An ecosystem engineer is defined as an organism that directly or indirectly modulates the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In doing so, it modifies, maintains and creates habitats. The reef-building capacity of ecosystem engineers is important for marine management as the recognition as reef builder is key for both regulators and offshore industry. To classify as reefs however, ecosystem engineering activities need to significantly alter several habitat characteristics (i.e. elevation, sediment consolidation, spatial extent, patchiness, reef-builder density, biodiversity, community structure, longevity and stability) as defined in EU habitat directive guidelines (Hendrick and Foster-Smith, 2006). This foundation is the rationale for selection behind the original three coastal Coastbusters reefs.

Owing to their functional characteristics, these biobuilders can exert a strong influence on the surrounding system properties that exceeds what may be expected based on their relative abundances alone. Therefore, following the cascading effects on the wider ecosystem, it is crucial to consider this group of common, but functionally important, species beyond a mere conservation point of view. They are the natural tools for a resilient coastline and our best allies to cope with sea level rise.

Flora reef

Seaweed beds are critical for the recruitment and protection of many commercially important fish species. Seaweeds that attach to the substrate by means of a holdfast are structurally important components of the marine environment and support high biodiversity by providing habitat, shelter and food, as well as affecting wave flow and energy. The French Atlantic coast and Californian coast are famous examples where kelp forests thrive in the coastal ecosystem. Additionally, seaweed beds play a significant role in the removal of nutrients and organic materials, especially from eutrophicated water, serving as buffers of coastal water quality.

For the flora-reef field setup, the consortium installed bags and frames with innovative spore impregnated (geo)textiles. Such techniques are commonly used on land applications such as grass seeds in cellulose fabrics. For the purpose of Coastbusters, the substrates have been re-engineered to advanced textile seaweed cultivation substrates. A second flora-reef research line investigated the use of biodegradable material as potential impregnation substrate. Unfortunately, the seaweed tests proved unsuccessful due to the aggressive local hydro- and morphodynamics, and competition with other organisms for a settling substrate. As a response, Coastbusters developed a third flora-reef research line for another ecosystem engineering species that traps sediments and dampens wave action: seagrasses. As currently no seagrass meadows naturally occur at the Belgian coast test site, a Coastbusters spin-off project called 'PLANT ME' has been initiated (see reference box).

FIGURE 2

The advanced textiles for seaweed cultivation (AlgaeTex©) being impregnated with seaweed spores before being lowered into the sea.

Lanice reef

Aggregations of tube-building polychaetes, here *Lanice conchilega* (commonly known as the sand mason worm or tube worm) stabilise the intertidal sediment bed of sandy shorelines. The bay of Mont Saint-Michel in France is a famous example of such a natural biogenic reef. The harder aggregations within soft sandy sediments provide refuge from predation, competition and physical as well as chemical stresses. The formed reef also represents an important food resource and critical nursery or spawning habitats

PLANT ME project

Plant a million seagrasses is an ambitious Coastbusters spin-off project focussing on the further development of the flora reef, more specifically for seagrasses. The project aims to restore these important ecosystems. A large-scale restoration planting technique, which will stabilise the seabed and reduce coastal erosion, will be developed. Based on natural biodegradable substrates overgrown with seagrass plants, this new method is relatively low cost to produce. Thus, allowing the quick and easy planting of seagrass beds in shallow coastal ecosystems.

Coordinated by DEME (Belgium) and co-promoted by Jan de Nul (Belgium), a public-private partnership has been established combining scientific expertise and hydraulic engineering, comprising Ghent University (Belgium) and Centro de Ciências do Mar (Portugal).

FIGURE 3

Sand mason worms (Lanice conchilega) on an intertidal sandy beach.

for a diversity of organisms. Therefore, this filter-feeding polychaete is considered an interesting target species in the search for nature-based solutions for coastal management.

In contrast with tidal marsh plants and mangroves, *L. conchilega* aggregations cannot be planted. Tube worms undergo a pelagic larval phase prior to settling. This settlement process is facilitated by the presence of small hard structures on the sandy seabed (e.g. shells or tubes of adult conspecifics). The presence of other sand mason worms in the area indicate favourable conditions. Thus, to induce and enhance adult aggregation, larval settling needs to be facilitated.

Coastbusters investigated two lanice-reef research lines:

1. The cultivation of larvae and settlement process on different substrates through laboratory trials; and
2. The facilitation of natural larval settlement using artificial substrates in small-scale field pilots.

During the laboratory trials, different designs of substrates (geo-textile and bio-based) were investigated. The biological and mechanical properties of the different substrates to attract larvae were tested under controlled conditions. These revealed a number of potentially interesting engineered substrates to attract larvae (Wyns et al., 2020).

Following the laboratory trial results, small-scale field pilots were conducted to optimise the design and installation of the chosen substrates in natural conditions. Prior to the start of the field tests and in the control reference site, no sand mason worms were found in large numbers, nor in aggregations. The field pilot and the associated scientifically underpinned monitoring revealed a positive effect on the settlement (i.e. presence of *L. conchilega* and slight sand elevation) of certain substrates. A significantly higher number of sand mason worms were observed in and under substrates having a stiffer but open three-dimensional matrix structure.

In conclusion, the substrate 3D matrix generated favourable local stable conditions to facilitate larvae settlement. The physical structure (thickness and density of the 3D matrix) seems likely to determine the effectiveness of the holdfast structure during the settlement process. The open structure allowed growth of the larvae to adult specimens without hampering exchange with the environment (e.g. food, water and oxygen). In turn, the settled worms seemed to slow down the passing water flow, which locally causes sand to pile up and the sediment bed to stabilise. Additionally, the newly formed biogenic reef is oxygenated due to tube irrigation activity of the worms, which benefits creation of distinct microhabitats in an otherwise uniform landscape.

In other words, the Coastbusters engineered reef-facilitation textiles successfully attracted larvae of the sand mason worm and enhanced its settlement. Over time, the induced natural reef will further stabilise the sandy shore and generate a local biodiversity hotspot. Whilst promising, this low-cost deployment of stabilising textile mats in the intertidal sandy shoreline has several upscaling shortcomings. The three main hurdles encompass:

1. The anchoring of the substrates in a dynamic intertidal environment;
2. Coping with the temporary (biodegradable) function of the facilitation substrates; and

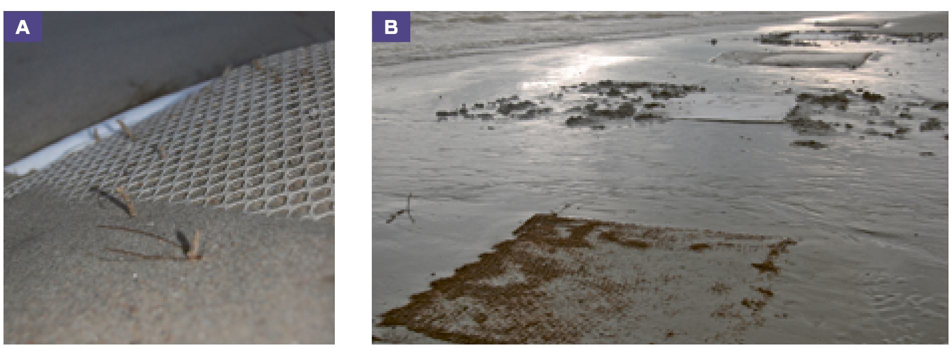

FIGURE 4

(A) A sand mason worm colonised substrate after a few weeks of deployment. (B) Small-scale field pilot installation of different biofacilitating substrates.

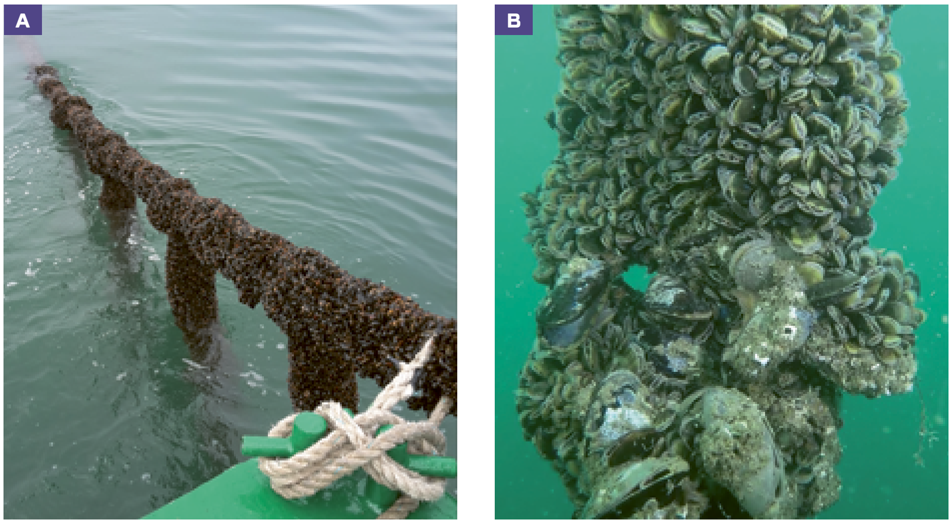

FIGURE 5

(A) Floating linear longline with mussel-grown droppers during maintenance survey. (B) Under-water picture of a dropper colonised by blue mussels and associated fouling community. Photo © Sven Van Haelst, VLIZ.

3. The interface with other users and stakeholders of the shoreline.

To conclude, the aggregation-inducing process of the lanice reef works but needs to be refined and requires further research steps before it is operational for large-scale and industrial use.

Bivalve reef

Mussel beds are biogenic reefs that can serve for bio-stabilisation of the sediment in a high-energy environment (e.g. high turbidity, high current velocity, strong wave action). Coastbusters investigated the use of a mussel bed as a third possible nature-based solution for coastal protection and biodiversity enhancement. In order to initiate such a mussel bed, Coastbusters relied on aquaculture techniques to capture mussel spat (*Mytilus edulis*). By using a modified mussel longline system and dropper lines, the setup enabled an efficient attachment of mussels' larvae. When the mussels have grown large and dense enough, they detach in clumps and fall to the seabed beneath the lines. These mussel clumps then form a mussel bed on the seabed under the facilitating structure.

A proof-of-concept test in sheltered conditions provided a first solid knowledge base on the technical requirements of a longline system in a high-energy coastal environment. This gave an initial insight into the efficiency of different (non-) biodegradable materials (e.g. dropper lines). The project also generated knowledge on the safe deployment and decommissioning for such an installation. In addition, light was shed on the biological diversity development of the newly formed mussel biogenic reef as new habitat. In conclusion, Coastbusters was able to build a dense mussel bed under the mussel longline facilitation system for two consecutive seasons.

Over time, the induced natural reef will further stabilise the sandy shore and generate a local biodiversity hotspot.

This very successful proof-of-concept test obviously yielded more dedicated questions and challenges than direct operational answers. For instance, what is the impact on the underlying sediment in terms of compaction and composition? Is the Coastbusters biogenic reef producing a more cohesive and less erodible sediment? Does the evolution of a soft sand surface to a protruding 3D mussel carpet structure significantly alter the hydrodynamics and enhance sediment stabilisation? Are the partial disappearance of reef patches in winter related to the presence of predators like common starfishes (*Asterias rubens*) and netted dogwhelks (*Tritia reticulata*) or are the physical forces of winter storms overcoming the reef's cohesive forces? Does the increase in local biodiversity influence the adjacent sand banks biodiversity? Which factors influence the density distribution of the reef? How can Coastbusters configure the facilitating infrastructure to be more modular and better fitting the mussel distribution? From which (bio)material should each element of the facilitating structure be? Etcetera.

To answer these questions and to prepare to scale up the proof-of-concept, fine-tuning through advanced research and innovative adaptation was needed. Moreover, the Coastbusters bivalve reef is adapting a commercial aquaculture system to a completely different objective than seafood harvesting, which it was originally designed for. It should be clear, that the commercial value at hand is the biogenic reef that contributes to coastal protection and boosts ecosystem services. It is not the adapted aquaculture system, which is merely a tool to facilitate the reef formation.
The current approach has not been attempted before and therefore a significant amount of novel research still has to be conducted to make this tool fit for the purpose at hand (i.e. installation of a biogenic reef). Subsequently, a Coastbusters bivalve reef 2.0 project to implement significant improvements to the complex offshore facilitation system was started.

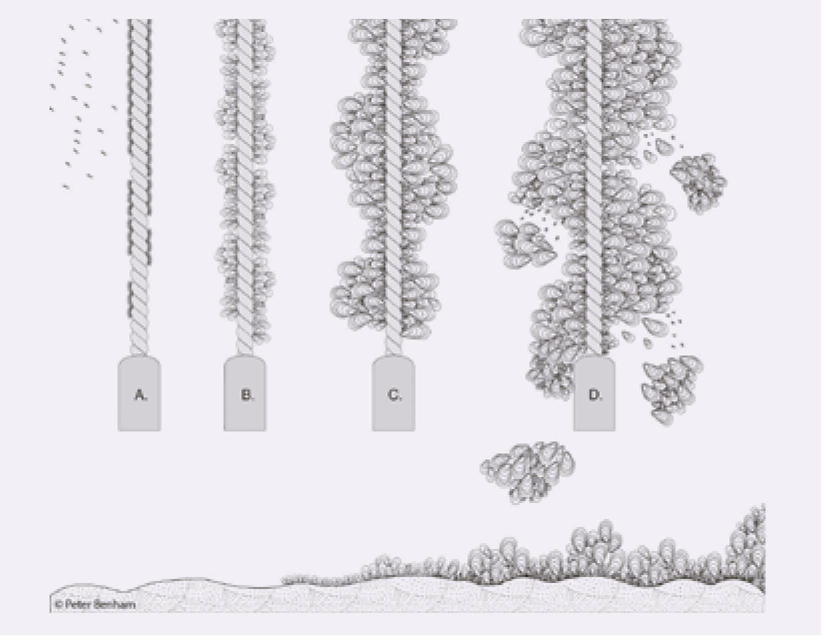

FIGURE 6

Bivalve reef formation sequence: (A) Mussel larvae attach to the suspended substrate. (B) Mussels begin to grow in size. (C) Competition for space forces some mussels away from the surface of the substrate, forming clumps. (D) Clumps of mussels break off from the dropper line and fall to the seabed to form a mussel reef.

Coastbusters off-the-shelf engineered textiles and materials withstood the offshore harsh conditions perfectly and fulfilled their purpose in the formation of the biogenic reef. However, improving the material type (of the floating and the seabed-based elements) would enable Coastbusters to achieve an innovative tuneable design and improve the reef in two ways: (1) to increase the resilience of the formed reef and (2) enhance the biodiversity associated to it. Moreover, judicious material selection could reduce the carbon footprint and general impact of the production. Therefore, under the lead of the industrial Coastbusters partners, innovative bio-based, biodegradable materials will replace some key elements within the reef-facilitating structure. In addition to the composition, the selected materials will have to attract a specific assemblage of organisms.

Evidently, only materials that do not adversely affect the adjacent environment as a result of weathering or leaching processes should be used. Biodegradable materials are often presented as the least impacting solution because they 'biodegrade'. However, the certification of the biodegradation process is often achieved in environments that are far from the natural conditions of coastal waters (e.g. high temperatures, non-saline and low oxygen). Hence, some biodegradable materials tend to first break down into potentially harmful pieces, such as microplastics, before truly biodegrading, if ever completely (Fojt et al., 2020). Coastbusters will thus create and monitor colonisable materials taking into account the timescale of degradation and composition

Bivalve reef 2.0

The sequel installation was planned with various scientifically underpinned research trajectories. By bringing together expertise and experience on both technical and ecological engineering, Coastbusters coordinated to achieve a further elaboration of the bivalve concept first developed. More specifically, trying to get an answer to the following elementary research questions:

- Can tuneable (controlled over time) bio-based/biodegradable materials be used to replace conventional off-the-shelf materials as building components of an offshore reef-facilitating setup?;
- What is the most appropriate technical, spatial and temporal design of the offshore setup stimulating efficient biogenic-reef forming and survival under different hydrodynamic conditions?;
- Which advanced environmental observation techniques are necessary to scientifically underpin the development, the evolution and overall resilience of the newly formed reef?; and
- What are the boundary conditions (e.g. biology, safety and survivability) and added ecosystem values and services of such a mussel reef?

Tuneable bio-based materials

The mussel biogenic-reef facilitation structures are based on modified aquaculture techniques and materials. The current

FIGURE 7

Underwater picture of a successfully newly formed bivalve reef and its associated benthic community. Photo © Sven Van Haelst, VLIZ.

Deployment of the mussel shaker and biofacilitating anchor prototypes.

Mussel Shaker and Biofacilitating Anchor

As part of the optimised modular configuration of the facilitating structures and in search of environmentally friendly alternative materials (compared to classical linear aquaculture longline setup), Coastbusters developed the 'Mussel Shaker' and 'Biofacilitating Anchor'. The shaker places the dropper lines in a circular configuration to yield a denser mussel reef. The anchor, made from low-carbon emission cement (CEM III/C), gives mussels a hard substrate to kick-start the reef. To investigate the preferred attachment surface of mussel larvae, three sides of the pyramid were applied with (1) smooth concrete, (2) brushed rough concrete and (3) oyster shells. Researchers of ILVO and VLIZ will monitor the settling organisms on the anchor. In order to be able to do so and to track biodiversity, a fixed ARMS (Autonomous Reef Monitoring Structure) has been attached to the fourth side of the anchor, which will be sampled and analysed by VLIZ within the framework of the European Lifewatch biodiversity programme.

to understand the impact of these novel materials in offshore deployment conditions.

Complementary to the composition, surface micro-relief or roughness of the material is known to influence fouling communities. Substantial research is still needed on coatings and surface treatments to attract species-specific assemblage of marine organisms. This applies to the floating structures, such as longlines and droppers, but also to the anchors that keep them in place as these will, over time, become part of the reef. Coastbusters is testing an environmentally friendly concrete composition compared to standard Portland cement and several surface treatments, to assure the attractiveness of blue mussel spat and even flat oyster larvae (*Ostrea edulis*) in time (see reference box: Mussel Shaker and Biofacilitation Anchor).

Modular configuration and design

The conventional linear longline prototype with modified dropper lines has proven to resist offshore conditions off the Belgian coast of De Panne (on the sheltered leeward side of the Broersbank) and successfully facilitated initial biogenic-reef formation. However, the modularity and scalability of the coastal protection design is very important. The design should be generally applicable across an extended coastal zone in different locations around the globe and adaptable to local conditions, such as currents, depth, type of seabed, etc. To check if the envisaged innovations can withstand more exposed hydrodynamic conditions, a twin setup was deployed on the seaward side of the Broersbank. This means that the bivalve reef 2.0 facilitating infrastructure is being tested in a sheltered zone (representing a less erosive foreshore) and in an exposed zone (representing a more erosive foreshore). The performance of the twin setup in the erosive zones (due to several factors such as increased seabed instability for instance), will be the key for the global operational deployment of Coastbusters.

For a number of benthic ecosystems such as mussel beds, studies suggest that the spatial distribution within the bed is self-organised (e.g. behaviour amongst mussels or external predation pressure) and not per-se imposed by underlying landscape features (e.g. shape and height of sand ripples under the reef). Scientists concluded that the spatial distribution and density of the reef influences the resilience of the reef (De Paoli et al. 2017). For instance, an area of reef with a low density of mussels is more sensitive to predation. In addition, suspended mussels on vertical substrates, compared to naturally occurring horizontal seabed mussels, develop a significantly firmer attachment to the substrate and a closer aggregated structure. This gives suspended mussels a better resistance to predators, such as the shore crab (*Carcinus maenas L.*) and hydrodynamic stress. Therefore, the configuration and design of the facilitating structure yielding the falling mussel clumps, will impact the persistence to wave action of the newly formed reef.

Thus, Coastbusters is in search of the optimal configuration of floating facilitation structures. This research will reduce deployment costs and improve both technical and environmental performance. One of the alternative configuration prototypes is currently being tested (see reference box: Mussel Shaker and Biofacilitating Anchor).

Advanced environmental monitoring

The monitoring programme evaluates the success of the reef-facilitation structure and the production of an early stage natural biogenic mussel reef under the floating structure. Nonetheless, to understand the underlying processes of reef development, a specialised environmental monitoring strategy needs to be developed. As such, the main objectives of the monitoring is

FIGURE 8
Coastbusters scientists monitoring the mussel growth on the dropper lines.

twofold: (1) develop an integrated scientifically underpinned monitoring strategy and (2) detail the ecological and morphological evolution of the reef.

Using advanced and dedicated monitoring techniques such as Unmanned Surface Vehicles (USV), will allow the consortium to cover the key parameters of reef development over a wide spatial-temporal scale. One of the major advantages using marine robotics is the ability to measure various parameters at the same time. The multi-sensor deployment of the Coastbusters monitoring approach (e.g. side-scan sonar, sub-bottom profiler, wave motion sensors), the advanced processing of multi-beam water column and backscatter data and vicinity to the seabed/infrastructures, adds to the resolution and magnitude of the yielded data. Coastbusters is thus taking a leading role in the development of automatic monitoring alternatives for the often risk-bearing and costly diving and vessel bound surveys. This will result in better and more data at lower cost, whilst improving safety.

Coastbusters is in search of the optimal configuration of floating facilitation structures.

Ecosystem values and services

Coastbusters also aims to unravel the boundary conditions and feedback mechanisms of the sheltered and exposed test sites. This knowledge will define the parameters that are essential to evaluate the status and success of the mussel reef. In other words, is it possible to strengthen or partly replace conventional engineering constructions for coastal protection by ecological elements such as biogenic reefs?

To answer this question, an ecosystem service assessment is proposed. This approach is increasingly being advocated to ensure sustainable use of the environment, through a set of defined indicators incorporated in an ecosystem services tool. The ecosystem services concept offers a framework to make the linkages between ecological and socio-economic properties. Coastbusters identifies the ecosystem service provision in terms of the biogenic reef impact (e.g. sediment stabilisation, reduction of wave energy and changing shoreline), the creation of valuable habitat (e.g. a reef in comparison to bare sand) and changes in biodiversity levels (e.g. within and adjacent to the reef).

The seasonal aspect of working with biology is one of the challenges faced by nature-based solutions. If we look at dunes and wetlands for instance, their growth is known to be dynamically complex: A period of steady growth, leading to stabilisation, may be followed by a period of discrete and major decline, inducing a temporary erosion and protection failure. The same applies to mussel reefs as shown by the partial disappearance during the winter period. Consequently, depending on chosen ecosystem engineering species, a hybrid coastal defence model seems to prevail as ecological components follow a biological window with its boundary conditions. However, the residual indirect effects (e.g. the consolidation of sediment under the reef, change of underwater seabed profile and increased biodiversity and ecosystem services) generate a clear benefit for the coastal zone over a longer period. As a result, an integrated nature-based solutions coastal management alternative seems to be the way forward.

Nature-based solutions business model

The trademarked Coastbusters brand represents a broader philosophy of nature-based solutions (NBS) projects. As such, the first projects should be regarded as part of a chain of various research and innovation projects, tackling different aspects of the broader technical, ecological and social engineering topics at hand.

The benefits of NBS have been found to outweigh the costs of implementation and maintenance in a range of conventional grey coastal risk reduction measures (Fordeyn et al. 2019; Seddon et al. 2020). Multiple examples corroborate the evidence that NBS can be more cost-effective than conventional engineered alternatives, at least when it comes to less extreme hazard scenarios. In other words, the absolute level of protection provided by the NBS strategy depends on many factors. For example, efficacy can vary with intensity and frequency of storm events and the resilience of the ecosystem engineer to withstand impacts will depend on intrinsic biological cycles.

Hence, attention must be paid when comparing NBS to conventional solutions. Focus on one service solely (e.g. absolute coastal protection) will underestimate the NBS potential to deliver a wide range of benefits at both local and global scale, especially over the long term.

FIGURE 9

VLIZ's unmanned surface vehicle, Adhemar, surveying the Coastbusters test site. Photo © Kobus Langedock, VLIZ.

Implementing nature-based solutions requires a new business model approach in economic thinking.

For instance, benefits of higher fisheries catch, carbon sequestration and space for recreation are not accounted for. Conventional solutions are usually implemented with relative certainty about the type and timescale of benefits, whereas NBS generally offers more flexible long-term solutions with benefits that might not be directly felt by stakeholders. As a result, the response of ecosystems is much harder to value and cost than conventional grey infrastructures.

Therefore, Coastbusters is of the opinion that, in areas where relatively little space is available, the combination of nature-based solutions and (existing) grey infrastructure is the best coastal management solution. Such hybrid-integrated solutions are capable to address a range of climatic impacts, provide additional ecosystem services and can be managed over the long term.

The question at hand is how to finance this integrated solution to reconcile economic development with the stewardship of ecosystems. Currently, most funding comes from public funds (e.g. green climate fund, green deal) or private funds from the voluntary market such as financial institutions. However, these rarely cover the large-scale implementation/installation costs. In addition, the short-term nature of the financing sector decision-making hampers the longer-term planning and maintenance required for the provisioning of NBS benefits. Moreover, many of the benefits associated with NBS cannot be capitalised by one specific stakeholder only, making ownership almost impossible. Therefore, conventional finance where the risks are mainly carried by the project owner is not viable. The return benefits are not solely measured in material and financial capital, but mostly as human, social and natural capital.

Future coastal management business models will therefore have to take into account the valuation of ecosystems and biodiversity within the economic system, and the added value it provides to society as a whole. This new nature-positive business solution will have to frame nature as an asset ('capital') and mark biodiversity as a characteristic of those assets that enables them to be more productive and resilient. Concepts such as Ecosystem Services and Natural Capital Accounting can create an extension of the global project valorisation, including the 'sustainable economics' and the 'whole life cycle cost' of these nature-based solutions. Monetising co-benefits or revenues generated by ecosystem elements (i.e. framing the value of natural capital within the context of economic prosperity and human well-being) will form a key enabler.

More fundamentally, implementing nature-based solutions requires a new business model approach in economic thinking. Shifting from a focus on infinite economic growth to a systemic thinking framework that accounts for multiple ecosystem services and goods from the perspectives of different stakeholders.

Conclusions

Nature-based solutions (NBS) offer huge potential to address climate change whilst supporting biodiversity and generating ecosystem services on which human socio-economic well-being depends. In this framework, the Coastbusters public-private consortium deployed three biogenic-reef facilitating pilots in Belgian coastal waters.

Each pilot targeted a specific ecosystem engineering species: (1) sugar kelp (*Saccharina latissima*), (2) sand mason worm (*Lanice conchilega*) and (3) blue mussel (*Mytilus edulis*). The survivability and biogenic-reef building capacity have been monitored and each reef yielded distinct outcomes. The flora-reef arrangement has not been able to germinate, due to unfavourable local conditions. The lanice-reef field test demonstrated successful colonisation by naturally occurring larvae forming an elevated consolidated reef. The bivalve-reef setup proved to be the most successful biogenic-reef facilitator. It generated a natural diverse reef ecosystem for consecutive seasons with a reduction of the reef extent during storm periods. The bivalve reef became the Coastbusters nature-based solutions flagship. A newly started 2.0 pilot in more exposed waters will prove the resilience of the Coastbusters biofacilitating structures. Together with novel tuneable bio-based materials, advanced observation techniques (i.e. marine robotics) and revolutionary designs, Coastbusters will benchmark the future of NBS projects.

Incorporating NBS as a crucial element into (future) coastal zone management, results in a more sustainable, ecosystem-based and cost-effective management approach. Developing such NBS alternatives will lift up coastal engineering towards a more integrated and multidisciplinary future.

However, NBS cannot always be seen as a stand-alone coastal management answer as ecosystem conditions, sufficient space and local stakeholder support is required. Subsequently, under certain local conditions NBS should be integrated with conventional coastal management. In addition, NBS requires a new approach in economic thinking valuing the natural capital through ecosystem services assessments. Therefore, Coastbusters is of the opinion that the synergy of scientifically underpinned and stakeholder-wide supported nature-based solutions and where necessary in combination with (existing) grey infrastructure is the best coastal management solution. Such Coastbusters integrated solutions are capable to address a range of climatic impacts, provide additional ecosystem services and can be feasibly implemented and managed over the long term.

Summary

Conventional coastal protection solutions, such as dykes, embankments and beach reclamations, are being challenged in terms of life expectancy and maintenance cost by climate change and sea level rise. The Coastbusters brand stands for innovative nature-based solution (NBS) alternatives for a more sustainable and resilient coast. Through engineered facilitation of biogenic-reef formation, this integrated coastal management approach induces a self-sustaining stabilisation of the foreshore that enriches the ecosystem in place, yielding supplementary ecosystem services.

The pioneering public-private Coastbusters consortium embraces the ecosystem approach and since 2017 has deployed multiple proof-of-concept pilots at the Belgian North Sea coast. Successful biogenic reefs of sand mason worms and blue mussels were formed in the intertidal and subtidal foreshore, respectively. Coastbusters scientifically underpinned research lines provide a first solid knowledge on the technical requirements for biofacilitating infrastructures' modularity, optimal design configuration, selection of bio-based materials, innovative environmental monitoring and delivered ecosystem services. In the near future, the consortium will implement novel spin-off projects within a broader multiple-use of space framework to push sustainable coastal management forward.

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Thibaud is Environmental Engineer Marine Ecosystems at DEME and the scientific coordinator of DEME's nature-based solutions (NBS) research projects. He obtained his doctorate in 2015 from Ghent and Liège University on the subjects of seagrass ecology and environmental management. Currently, besides his tasks within dredging and offshore activities, he empowers NBS innovation and research in the fields of beneficial sediment re-use, offshore nature-inclusive design and coastal management.

Tomas Sterckx
Tomas is an Innovation, Project and Business Development manager at DEME. He graduated at the Universities of Brussels and Antwerp before working at the Antwerp Port Authority and for Development Aid in Afrika. After working in several international units at DEME, he now specialises in nature-based solutions, ocean pollution problems, multi-use of space and renewable energy. As Coastbusters coordinator, he embraces the positive feeling towards nature-based solutions it transmitted, as a great achievement.

Dr Sophie Delerue-Ricard
Sophie is an enthusiastic Oceanographer who investigates nature-based solutions and sustainability as a Marine Environmental Engineer at Jan de Nul. She obtained her doctorate in 2019 from KU Leuven University and the Institute for Agricultural, Fisheries and Food Research (ILVO) on the subjects of marine connectivity using genetics and microchemistry.

Jan Fordeyn
Jan studied at the University of Ghent and graduated as a naval architect in 1994. Since 2007, he has helped develop projects around the world that fall outside the classic canon of marine construction and whose result relies on the symbiosis of different disciplines. As such, he maintains close relations with experts, consultants, universities and manages several innovation projects.

Dr Marc Huygens
Marc is currently working as Environmental Manager within the DEME group, focussing on implementing environmental engineering and nature-based solutions within DEME's global international marine works. He graduated MSc Civil Engineering and holds a PhD in Civil Marine works (on integrated coastal zone management) from Ghent University. After an academic start at the Hydraulics Laboratory at Ghent University, he was 10 years active on the international water consultancy forum.

DIGITAL DATES FOR THE DIARY

COVID-19

Due to the COVID-19 pandemic, events can be postponed or cancelled. IADC has been following the Dutch authorities' advisory measures with regard to limiting the spread of the virus and is keeping a close eye on the situation. We advise checking the IATA website regularly to see the COVID-19 travelling regulations for every country (https://www.iatatravelcentre.com).

Join CEDA's virtual conference to share knowledge and information.

CEDA Dredging Days 2021

28–29 September 2021
Virtual
https://www.cedaconferences.org/dredgingdays2021

CEDA Dredging Days is the flagship conference of the Central Dredging Association (CEDA). A major event on the dredging professionals' calendar in the European, Middle East and Africa (EMEA) region, it is a primary forum for leading researchers and industry experts – representing the entire cross-section of the field from project owners, consultants, to contractors and shipyards – to share ideas, discuss challenges and consider potential solutions. Presenting CEDA Dredging Days 2021 as a virtual event opens up a whole new set of options for companies to promote their products and services, and further their business development objectives.

This year's conference will have a strong focus on innovative solutions in dredging. Content will range from new technologies to the way we do business, all conceived with a clear 'sustainability stamp'.

The technical programme will feature both academic and practice-oriented presentations in a variety of formats, as well as keynotes and high-level panel discussions. Sessions will address topics such as the latest developments in dredging equipment and technology, beneficial sediment use, energy transition in the dredging industry, assessing environmental turbidity levels and financing sustainable water-based infrastructure.

In addition to the technical content, the conference programme will include a business exchange session designed to involve all participants and explore reciprocal opportunities.

CEDA's conference content will range from new technologies to the way we do business, all conceived with a clear 'sustainability stamp'.

IADC's international Dredging and Reclamation Seminar gives participants the opportunity to complete a mock tender process.


Photo © Marco Hofste

UNEP Adaptation Futures 2020

New dates: 5–8 October 2021
India Habitat Centre
New Delhi, India
http://adaptationfutures2020.in

The Energy and Resources Institute (TERI) will co-host the Adaptation Futures 2020 with the World Adaptation Science Programme (WASP) in Delhi from 4–8 October 2021. It is the sixth in the Adaptation Futures international conference series on global adaptation and the first to be held in Asia. The organisers are working towards hosting a hybrid conference to combine the best of virtual and in-person experiences for the global adaptation community.

The conference is the flagship event of the World Adaptation Science Programme, which is one of the four components of World Climate Programme (WCP) based on the World Meteorological Organisation Congress XVI Resolution 18. As a premier event in the global adaptation spectrum, Adaptation Futures is a unique platform to facilitate dialogues towards action-oriented solutions from a diverse range of stakeholders that includes academia, practitioners, scientists and policy makers from across the world.

Adaptation Futures 2020 envisages to advance the overall theme of 'accelerating adaptation action and knowledge to support action'. The conference seeks to explore this overarching need through multiple thematic tracks. Topics to be addressed include: Governance of adaption; Limits to adaption; Fairness and equity in adaption; Knowledge for action; and Financing adaption and nature-based solutions, a topic high on the agenda of the global dredging industry.

SAVE THE DATES

Dredging and Reclamation Seminar

8–12 November 2021, Delft
4–8 April 2022, Singapore
www.iadc-dredging.com

For (future) decision makers and their advisors in governments, port and harbour authorities, off-shore companies and other organisations that execute dredging projects, IADC organises its international Dredging and Reclamation Seminar in Delft and Singapore. Since 1993, this week-long seminar has been continually updated to reflect the dynamic nature of the industry and is presented in cities all over the world.

The five-day course covers a wide range of subjects, from explanations about dredging equipment and methods, rainbowing sand and placing stone to cost estimates and contracts. The in-depth lectures are given by dredging experts from IADC member companies, whose practical knowledge and experience add an extra value to the classroom lessons. Topics covered include project development from preparation to realisation and the environmental aspects of dredging.

Activities outside the classroom are equally as important. An on-site visit to the dredging yard of an IADC member is an integral element in the learning process and gives participants the opportunity to gain insight into the extent of a dredging activity.

An on-site visit to the dredging yard of an IADC member is an integral element in the learning process.

USACE Innovation Summit

25–29 October 2021
Virtual
https://www.usaceinnovationsummit.org

The second USACE Innovation Summit highlights the U.S. Army Corps of Engineers innovations from both R&D and applied practices as well as innovations in Human Capital and business processes. The theme of the summit 'Innovation to Impact: Leading from the Future' is aimed at shifting a culture that tends to be risk averse to one that will take a chance with innovative ideas.

A virtual event with national visibility, the event will kick off Monday 25 through Friday 29 October and will be filled with keynote speakers, panel discussions, presentations, virtual poster/booth sessions and virtual tours.

23rd World Dredging Congress and Exposition (WODCON XXIII)

16–20 May 2022
Copenhagen, Denmark
www.wodcon2022.org

The Central Dredging Association (CEDA) will host and organise the 23rd World Dredging Congress and Exposition in Copenhagen, Denmark from 16–20 May 2022 on behalf of the World Organisation of Dredging Associations (WODA). Through innovation, participation and a creative approach, WODCON XXIII will provide the latest knowledge regarding all aspects of dredging in the broadest sense, as well as focus on new technologies and concepts. Its main objective is to ensure international excellence in dredging.

WODA recognises and values a constructive partnership between all stakeholders within the industry. As a result, the exhibition will be an essential part of the congress. The programme is structured to optimise the opportunity for participants to visit the exhibition and interact with the exhibitors and sponsors. With a selection of speakers from around the world, cutting-edge studies, research, experiences and procedures will be presented, alongside exciting innovative sessions workshops.

The need for more cost-efficient and environmentally friendly construction practices has been a driver for innovation in dredging equipment and engineered solutions. Today, all industries are challenged with meeting the sustainability objectives detailed in the UN's 2015 Sustainable Development Goals (SDGs). These challenges have continued to drive innovation in all dredging sectors, from project proponents such as government agencies and ports, to regulators, consultants and shipyards.

WODA has been a leader in sustainability and in 2013, at WODCON XX in Brussels, Belgium, WODA members signed the '*WODA Principles for Sustainable Dredging*'. The fact that it still stands today is a testament to WODA's progressive contributions to the science of dredging. WODA continues to be committed not only to meeting current sustainability objectives but also to meeting future needs.

In addition to the scientific and technical sessions, there will be many opportunities for companies and organisations to showcase their innovative products and services, both in the exhibition and during dedicated pitch talk sessions.

The focus of presentations will be on innovative technologies and approaches, sustainable design and execution, and energy transition.

Call for abstracts

Deadline 17 September 2021

The WODA Technical Papers and Programme Committee (WTPPC) invites abstracts for contributions from scientists and practitioners representing project promoters, academia, research and knowledge institutes, engineering firms, regulators, equipment designers and manufacturers, suppliers of ancillary equipment, legal firms, financiers both on traditional areas of dredging.

The committee is interested both in research and in case studies, successes and failures so everyone can learn from each other. WTPPC is interested in but not limited to projects in traditional areas, such as: Port construction and maintenance; Navigation channel development and maintenance; River deepening; Coastal and inland flood protection; Beach nourishment; Remediation dredging; Reservoir dredging; Immersed tunnels; Land reclamation; Aggregate dredging; and Offshore oil and gas. Also projects in new emerging areas, such as: Offshore energy (renewables); Offshore pipeline and cable burial and protection; Deep-sea mining; and Energy islands.

For details on abstract submissions visit www.wodcon2022.org

BOOK REVIEW

ENGINEERING WITH NATURE
AN ATLAS, VOLUME 2

Showcasing Engineering with Nature principles and practices in action through 62 projects from around the world, these projects demonstrate what it means to partner with nature to deliver engineering solutions with triple-win benefits.

Authors: Todd Bridges, Michelle Bourne, Burton Suedel, Emily Moynihan and Jeff King.
Publisher: U.S. Army Engineer Research and Development Center
Published: April 2021
Language: English
Price: Free digital download
ISBN: Ebook 978-1-7325904-3-4

Available from
https://ewn.el.erdc.dren.mil/atlasv2.html

Humanity faces many challenges in the 21st century related to supporting a population that is expected to exceed 10 billion by the end of the century. Not least, how to reduce the increasing risks posed by natural hazards and climate change. Whether we frame the future in terms of problems to resolve or opportunities to develop, nature will figure prominently in the outcomes of our pursuits. The overarching need before us is to figure out how to discover, preserve, expand and apply nature's value.

The Engineering With Nature initiative formally began in 2010 within the U.S. Army Corps of Engineers (USACE). The initiative, with its partners and collaborators, is committed to advancing technical practice and to creating diverse, holistic value through nature-based solutions and infrastructure. In 2018, USACE published the first volume of the *Engineering With Nature Atlas*. Developed to communicate the diversity of projects, contexts and organisations advancing worldwide progress in the field, it highlighted 56 projects. It promised future volumes to present new collections of projects and on 7 April 2021, USACE launched the second volume.

Volume 2 has continued the 'seeing is believing' approach, presenting Engineering with Nature (EWN) principles and practices in action through photographs and descriptions of 62 projects from around the world. Sharing examples of EWN practice and learning from project examples is the motivation for the *EWN Atlas* series. As with the first volume, the current collection of projects illustrates a diverse portfolio of circumstances, inspirations, obstacles and achievements. All of the projects in this second volume highlight the importance of collaboration to innovating

‘The future is shaped by understanding what others have done and then considering the potential for doing even more.’

and creating diversified project value (i.e. multipurpose projects). They highlight the benefits that can be produced when engineering and natural processes are successfully integrated to support navigation, flood risk management, ecosystem restoration and other infrastructure purposes.

Co-written by authors Todd Bridges, Michelle Bourne, Burton Suedel, Emily Moynihan and Jeff King, the projects are grouped into eight chapters: beaches and dunes; wetlands; islands; reefs; riverine systems; floodplains; use of vegetation and natural materials; and environmental enhancement of infrastructure.

Within the opening pages, the book lays out the bigger picture with a view towards the future. While exploring the projects, readers are invited to consider questions such as, what lessons do they teach? How could EWN support my community? As the authors simply state: ‘The future is shaped by understanding what others have done and then considering the potential for doing even more.’

Each project example introduces unique facets of developing sustainable projects while clearly highlighting the four common elements of EWN; the efficiencies produced, the natural processes used, the project benefits provided and the collaborative partners engaged. As with the first atlas, this second volume uses these four critical elements to structure each project description and to define progress and success related to EWN.

Engineering With Nature: An Atlas, Volume 2 is more than just a collection of maps and figures. In highlighting projects around the world, the atlas provides a channel for communicating progress and potential. The collection of 62 projects illustrates that restoring nature and using nature-based solutions can efficiently yield real economic, environmental and social benefits. It is not only an important resource guide, but provides broadening understanding, consideration and acceptance of natural infrastructure as a flood risk reduction and resilience strategy.

PRODUCING EFFICIENCIES

Following a thorough investigation of the environmental systems and processes of the Lagos State coastline, the project team used state-of-the-art mathematical modeling tools to calculate the optimum placement, angle, and sand volume for the sandbar breakwater. This ensured that the structure will remain dynamically stable and that the steady eastward sand transport will continue to strengthen the breakwater. Additionally, the use of offshore sand eliminated the need to use rocks, stones, or concrete. This significantly reduced construction time, materials, and costs.

USING NATURAL PROCESSES

Any obstruction of the alongshore sediment transport, whether a conventional breakwater, groyne, or a sandbar breakwater, will inherently lead to downdrift erosion and potentially significant loss of land. The most natural way to counteract this effect is by restoring the natural sand balance of the system. Therefore, a small-scale, nature-driven sand engine has been implemented in the design to mitigate the coastal retreat downdrift. As erosion continues, this sand engine will provide local distribution of the sand to stabilize the coastline over the coming decades.

BROADENING BENEFITS

The natural shoreline growth at the west of the sandbar breakwater is already being used to enlarge the Dangote quay infrastructure. And, because sand can be moved and shaped more easily than traditional quarried rock, this new concept is flexible and allows for relatively easy future port expansion. Furthermore, the soft nature of the sandbar makes it more adaptable to climate change than conventional breakwaters are. All of these features work together so that the new breakwater keeps the Dangote loading facilities calm and safe.

PROMOTING COLLABORATION

The collaborative design efforts of the three Dutch companies, CDR International, Svašek, and Boskalis, optimized construction time, materials, and costs while retaining the natural characteristics of the coastline and design. This unique coastal zone benefits from resilient and sustainable maritime infrastructure solutions. By considering both the needs of the system and the function of the harbor, the team was able to maintain the natural aesthetics and habitats without hindering community access. The combined efforts resulted in an innovative and sustainable nature-based solution.

Inside spread showing the design of the Dangote Sandbar Breakwater project in Lekki, Lagos State, Nigeria.

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TO MEET NEW CHALLENGES
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