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INTRODUCING PRE-CUTTING & CLEARANCE TECHNOLOGY: THE FUTURE OF CABLE BURIAL

A Thesis on How Disruptive Technology Tackles the Challenges of Hard Soils

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1. Executive summary

The offshore wind industry has witnessed unprecedented growth in recent years, driven by the global push towards renewable energy. As a result, the number of offshore wind farms has surged, with installed capacities increasing significantly. However, this rapid expansion brings new challenges, amongst others in the installation of subsea power cables, which are critical for the operation of these wind farms. The industry's traditional methods for cable burial, such as jetting and chain cutting, are becoming increasingly inadequate, especially as wind farms are now being constructed in regions with challenging seabed conditions like boulder clays, rock, and glacial tills.

This white paper addresses these challenges by introducing a novel pre-cutting and clearance technology specifically designed to enhance the efficiency, safety, and environmental sustainability of subsea cable installation in hard soils. Traditional cable burial methods, while effective in softer seabeds, struggle to efficiently achieve the required cable protection in harder soils. These methods can lead to construction delays, higher costs, and sometimes inadequate cable protection, resulting in expensive remedial works.

This innovative pre-cutting and clearance technology is designed to pre-condition hard seabeds, making it more suitable for cable burial. This process involves the use of advanced dredging techniques to remove subsurface obstacles and loosen the soil, converting it into a state that allows for effective jet trenching. By addressing the soil challenges before the cable is laid, this technology significantly improves the efficiency of the burial process, ensuring that the cables are securely and reliably installed.

The white paper provides a comprehensive overview of the limitations of conventional cable burial techniques, particularly in hard seabeds. It also details the benefits of the proposed solution, which include:

1. Improved Cable Safety: The pre-cutting and clearance process ensures that cables can be buried to the required depth with minimal risk of damage, reducing the likelihood of cable failures during operation.

2. Minimized Construction Risks: By pre-conditioning the seabed, this technology reduces the unpredictability and risks associated with trenching in hard soil conditions, leading to more predictable and faster installation schedules.

3. Lower Total Cost of Ownership (TOTEX): The enhanced efficiency of the burial process reduces the need for expensive remedial work and allows for the use of simpler, less costly jetting equipment for the actual cable burial, resulting in significant cost savings.

4. Reduced Environmental Impact: The technology is designed to minimize the environmental footprint of cable installation operations by reducing the number of vessel days required and lowering CO_2 and NO_x emissions through more efficient processes.

The offshore wind industry is at a critical juncture, where the need for innovative solutions is more pressing than ever. As the demand for renewable energy grows, so too does the need for reliable and efficient cable installation methods that can withstand the challenges of diverse seabed conditions. The pre-cutting and clearance technology presented in this white paper offers a robust and forward-thinking solution that addresses the key issues facing the industry today. By adopting this approach, developers and contractors can ensure the successful and cost-effective installation of subsea cables, supporting the continued expansion of offshore wind energy and the global transition to a more sustainable future.

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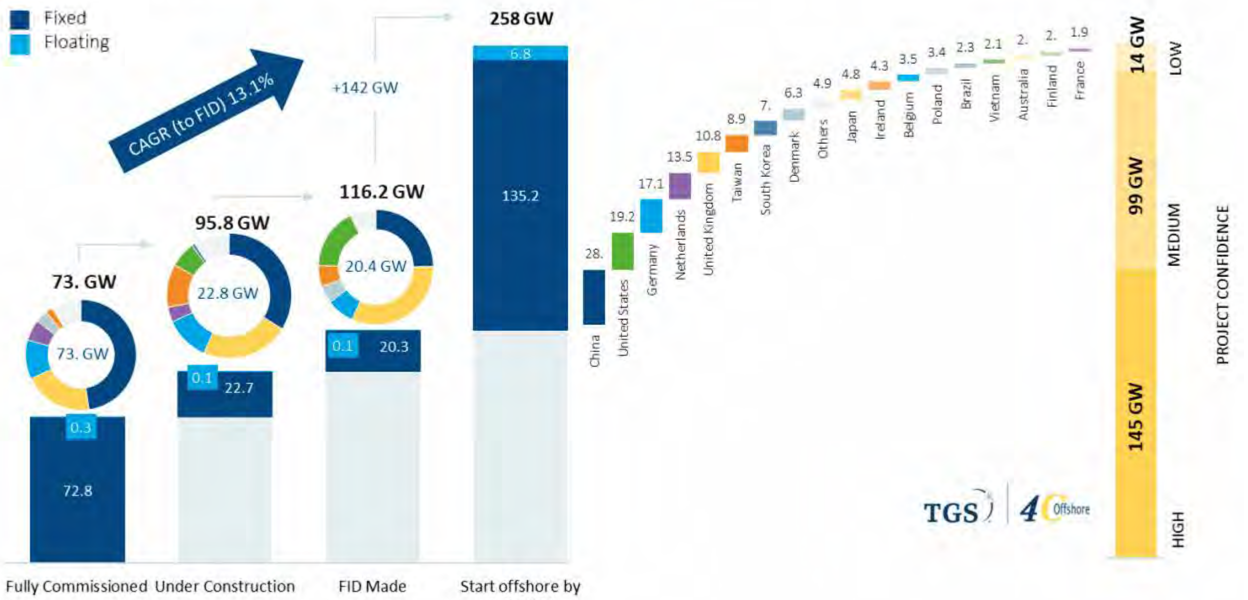
2. Introduction

Growth of the Offshore Wind Industry

The offshore wind industry has undergone remarkable growth in recent years, largely fueled by the global transition towards renewable energy sources. This expansion is clearly reflected in the surging number of offshore wind farms being developed around the world, leading to a significant rise in installed capacity. Industry data reveals that the global installed capacity of offshore wind power has more than tripled over the past decade, surpassing 70 GW in 2023. Looking ahead, this growth trajectory appears poised to persist, with forecasts suggesting that global offshore wind capacity may exceed 200 GW by 2030, underscoring the sector's accelerating momentum and its pivotal role in the future of clean energy.

Journey to 2030

Country pipeline by project status and confidence.



Source: 4C Offshore – Global market overview Q1 2024.

Projected Growth and Supply Chain Challenges

The future of offshore wind energy appears promising, but the rapid expansion of the industry presents significant challenges for the installation-related supply chain. Achieving the ambitious targets set by governments worldwide will require substantial enhancements in installation capacity. This potential bottleneck could severely hinder efforts to meet global renewable energy goals. For example, research from Spinergie suggests that by 2030, over 50% of the cable installation demand might go unmet due to capacity shortages. Scaling up the supply chain is no simple task, with significant obstacles such as workforce availability and the limited number of advanced installation vessels. Therefore, boosting productivity through more efficient installation methods and innovative, productivity-enhancing technologies will be crucial for overcoming these challenges and meeting future demands.

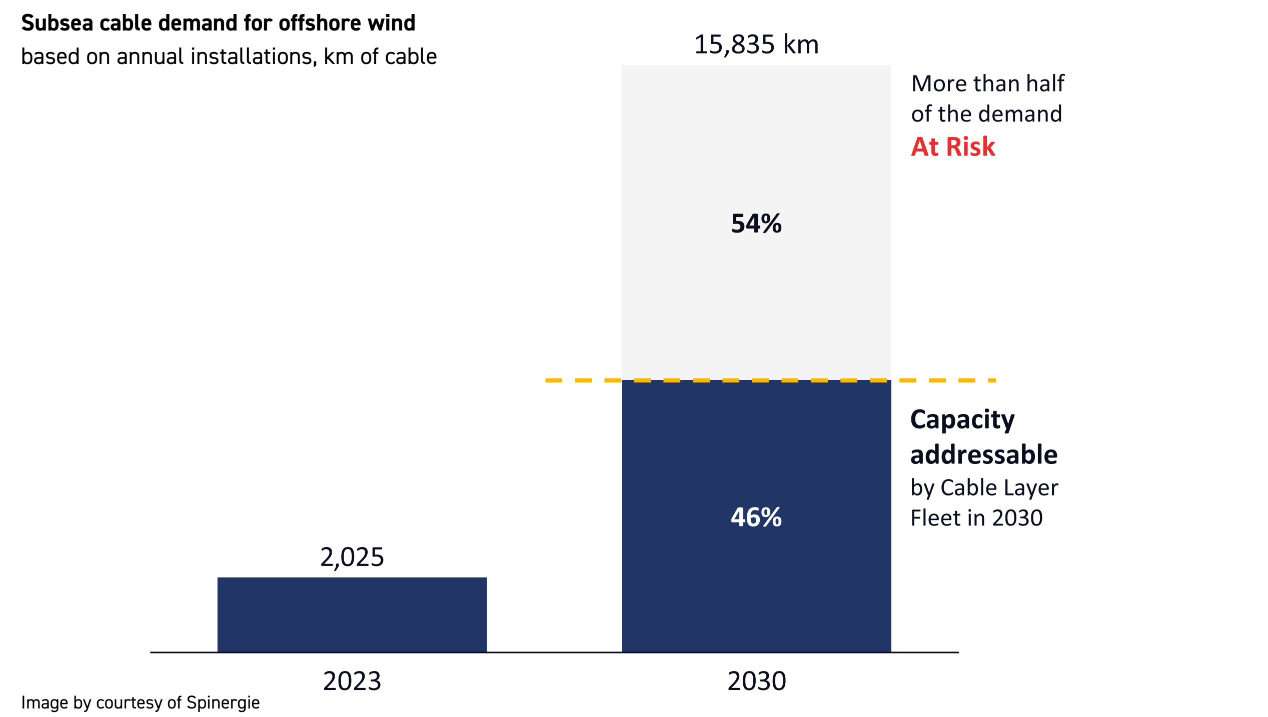


Image by courtesy of Spinergie

Global map highlighting coastal areas where governments have planned offshore wind farms and where some degree of hard soil is expected.

Shifting Towards More Challenging Seabed Conditions

Another critical trend in the offshore wind industry is the increasing construction of wind farms in locations with less favorable seabed conditions, characterized by soils like boulder clays, dense sands, cemented sands, rocks, and glacial tills. These challenging conditions are prevalent in key regions with significant offshore wind ambitions, including the UK, the US, Japan, and Scandinavian countries. Such hard soil conditions pose serious challenges for installation methodologies, necessitating advanced technologies to ensure successful installation operations.

The Need for Improved Installation Technologies

These dual pressures — the need for greater productivity to meet renewable energy targets and the shift towards more challenging soil conditions — highlight the urgent need for improved installation technologies. While recent years have seen significant advancements in offshore foundation installation technologies, such as active heave compensated monopile grippers and the introduction of drilling techniques for rocky seabeds, innovation in subsea cable burial technology has been notably limited. This is particularly true for burial techniques in hard soil conditions. The dominant methods, such as chain cutters, were introduced over 50 years ago and have seen little innovation since. This is particularly striking given their relatively low performance: they offer limited productivity, incur high overall costs, and sometimes fail to achieve required burial depths.

Importance of Effective Cable Burial

The inadequacy of current burial methods is particularly concerning given the critical importance of protecting subsea cables. Subsea power cables are highly vulnerable to mechanical loads during installation and operation, with nearly 49% of failures attributed to mechanical stresses. Effective burial is essential to protect these cables from external threats such as fishing activities, anchoring, and even sabotage. Moreover, a single cable failure can result in societal costs of around €100 million, including repair expenses and electricity losses. Therefore, ensuring effective burial, especially in challenging soil conditions, is not just a technical necessity but an economic imperative.

Proposed Solution: Innovative Pre-Cutting and Clearance Technology

Given the pressing need for improved productivity and the

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shift towards more difficult soil conditions, enhanced burial methods and technologies will become increasingly vital in the coming years. This white paper introduces a new approach and technology for the effective and efficient burial of submarine cables in hard soil conditions. The solution leverages rugged and powerful dredging technologies to pre-condition the seabed by removing subsurface objects and by loosening the soil. This ensures that subsequent cable laying and burial can be performed with high efficiency and effectiveness. This approach offers numerous benefits, including improved cable safety, minimized construction risks, and significant cost reductions.

Overview of the White Paper

This white paper provides an in-depth exploration of the challenges and solutions associated with the burial of submarine cables in hard soil conditions. It begins by examining the limitations of conventional cable burial methods and the increasing demand for more effective techniques as wind farms are constructed in more challenging seabeds. The document then introduces an innovative pre-cutting and clearance technology designed to address these challenges, offering a detailed explanation of its working principles, benefits, and impact on the overall cable installation process. Additionally, the white paper outlines the potential value creation and benefits of adopting this new approach, including enhanced cable safety, reduced installation risks, cost savings, and environmental benefits. The paper concludes with a discussion on the limitations and considerations of implementing this technology, providing a comprehensive guide for industry professionals seeking to improve cable installation outcomes in difficult seabed environments.


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3. Current Approach and Challenges

The majority of challenges encountered during subsea cable installation can be traced back to two primary issues: incomplete soil data and inappropriate trenching technology. These problems are often closely interrelated, with one exacerbating the other. In this section, the focus will be on delving deeper into these issues, particularly the limitations of current chain cutting technology.

3.1 Incomplete Soil Data

Uncertainty in Soil Conditions

Despite extensive geotechnical surveys, modeling, and route clearance efforts during the early stages of offshore wind farm construction, a significant portion of the soil data and potential obstructions remain unknown until actual cable burial takes place. This uncertainty, often referred to as “soil risk,” arises from incomplete knowledge of soil types and strengths, particularly in deeper layers. Soil risk is particularly pronounced in offshore wind developments, where cable routes span long distances. Often, soil conditions can vary greatly along cable routes and within offshore wind farm sites, sometimes changing abruptly. While many trajectories consist largely of sand, which is typically best suited for jetting as the burial method, soil profiles can quickly transition to sand-clay mixtures, sand-clay with boulders, or sand on top of glacial till. Moreover, soft top layers with low bearing capacity can create traction issues, especially when the underlying layers consist of hard clay, as is common in areas like the Baltic Sea.

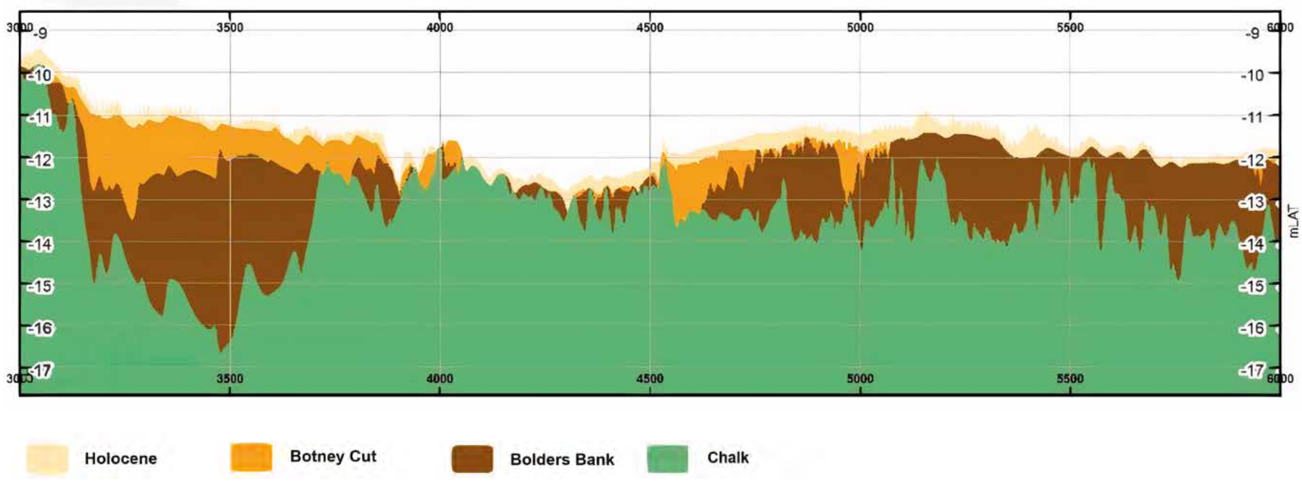
Challenges of Adapting Burial Tools

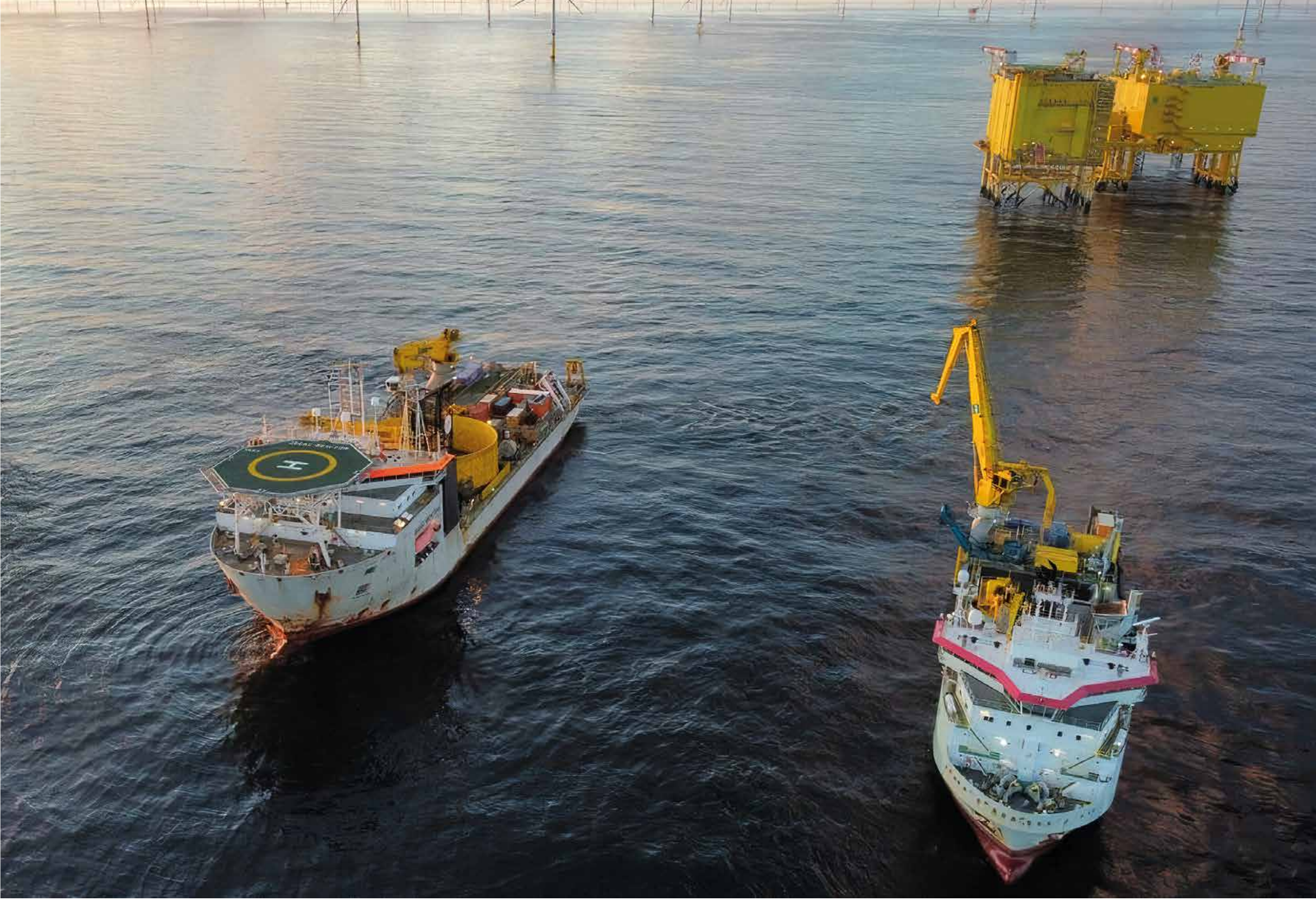
The variability of soil conditions requires the use of multiple burial tools to adapt to local conditions and achieve the required burial depth while maintaining acceptable progress rates. When mixed soil compositions are known in advance, contractors can develop an appropriate burial plan and select the necessary tools. Although this approach is costly, requiring the mobilization of multiple tools, it is currently the only reliable method to ensure acceptable burial performance. Problems arise, however, when soil conditions are more challenging than anticipated. If the available tools, typically jetting tools, are unable to cope with the encountered soil, burial performance can suffer significantly, impacting progress rates and the percentage of cable buried to the required depth. In such situations, remedial measures, such as subsea rock installation, may be necessary to protect the cable from external mechanical threats. These measures are not only expensive but can also lead to delays in the construction schedule.

Risks from Sub-Surface Obstructions

Significant risks during cable installation arise not only from incomplete soil knowledge but also from sub-surface obstructions. While surface obstructions are typically addressed through boulder removal campaigns or Pre-lay Grapple Runs (PLGR), slightly deeper sub-surface objects, such as unregistered old telecom cables, sometimes go undetected. When these obstructions are encountered, options for immediate remediation are limited. For example, if a boulder is encountered, the cable must be unloaded, the trencher repositioned, and

Fragment of ground model containing hard soils





the cable reloaded before trenching can resume. These interruptions can lead to substantial additional costs for remedial work, delays in the construction schedule, and an increased risk of cable damage due to the extra handling and exposure during the period between the incident and the completion of remedial measures.

Limitations of Current Technology

The incomplete knowledge of soil conditions and potential obstructions wouldn't be as problematic if cable burial techniques were more capable of handling varying or unexpected conditions. Unfortunately, experience indicates that today's technology isn't capable of this. While hybrid trenchers provide the advantage of both cutting and jetting capabilities, theoretically enabling them to better adapt to local soil conditions, they are unable to switch from jetting to cutting mode mid-operation if non-jettable soils are encountered and the cable is not positioned in the cable highway. As a result, if there is a possibility of encountering non-jettable soils along the trajectory, operators must choose the slower mechanical mode, which is typically chain cutting. This approach diminishes much of the potential benefit of having dual burial methods available. Additionally, hybrid trenchers often rely on chain cutters, which, as will be discussed in the next section, frequently perform poorly in harder soils and are ineffective at handling sub-surface obstructions.

3.2 Inadequate Trenching Technology

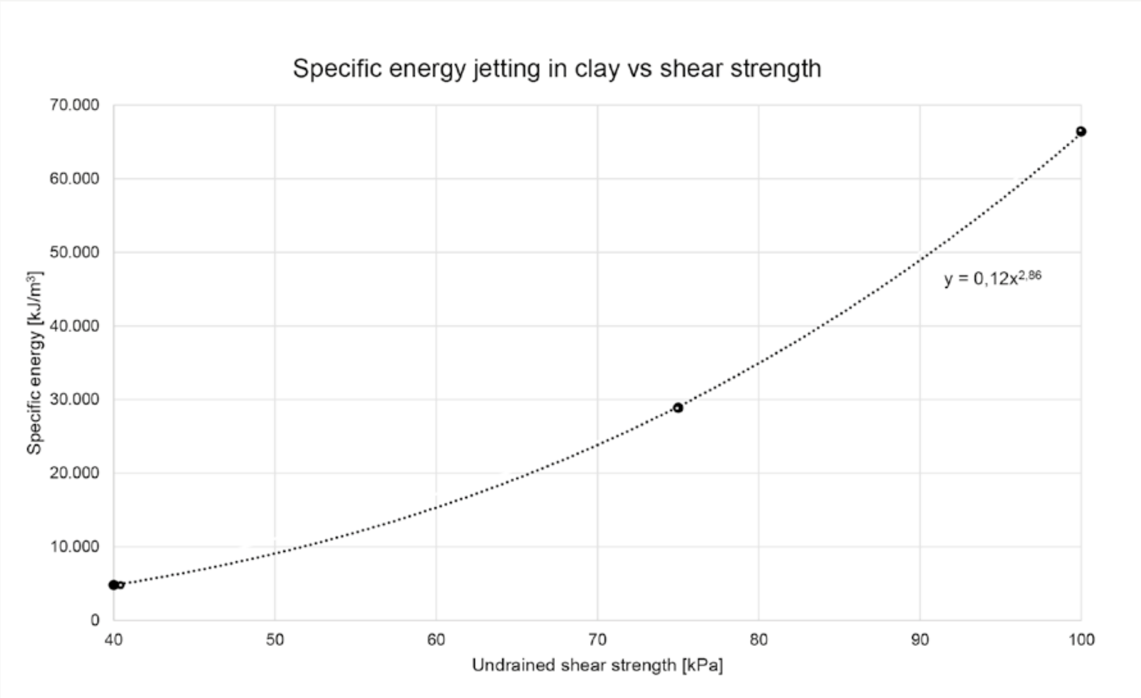
Inefficiency of Jetting in Cohesive Soils

In offshore cable installation, jetting is the preferred method when dealing with non-cohesive soils such as sands and silts. By using high-pressure water jets, the pore water pressure in the soil is increased, temporarily transforming it into a fluid-like state. This fluidization allows the cable to sink into the seabed. Jetting is efficient and effective in these conditions, making it the preferred technique in many offshore projects.

Jetting however becomes significantly less efficient and more challenging when applied to cohesive soils such as clays. These soils are characterized by high plasticity and cohesion, which makes them resistant to fluidization — a key process in jetting where the soil temporarily transforms into a fluid-like state to allow cable burial. To overcome the shear strength of cohesive soils, much greater energy is required. In the offshore wind industry, soils with an undrained shear strength of up to 80–100 kPa are still considered jettable, but the energy cost is substantial, and easily require more than ten times more in comparison to mechanical cutting. Despite these inefficiencies, jetting remains a widely used method, raising questions about the industry's continued reliance on this approach even as mechanical cutting offers a far more energy-efficient alternative.

Research Insights: Jetting Inefficiency in Clays

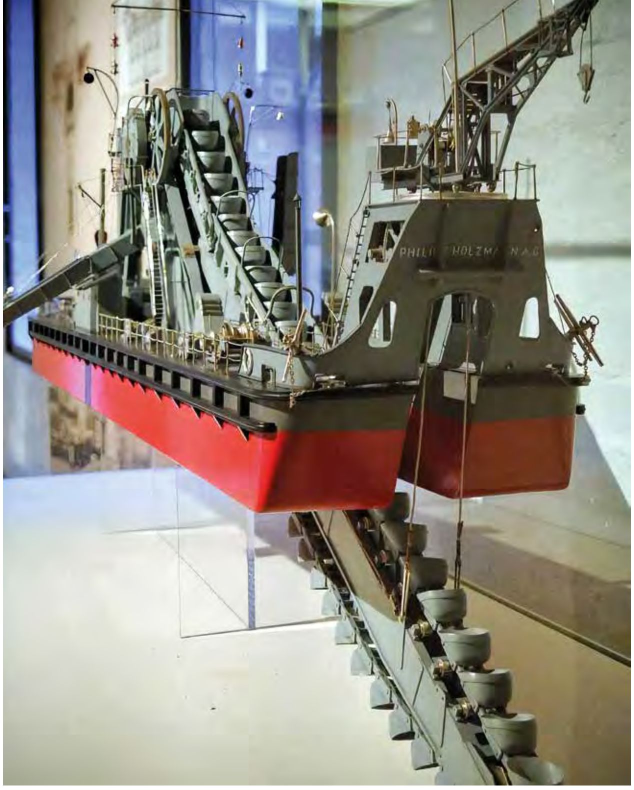
Fundamental experimental research by Deltares on jetting of clay has demonstrated that as the undrained shear strength increases from 40 to 100 kPa, the specific energy required for jetting rises dramatically — almost to the third power — making jetting increasingly inefficient as soil strength increases. To make a more specific comparison, this research shows that jetting clay with a shear strength of 70 kPa requires between 25.000 and 35.000 kJ/m³, compared to only 800 – 1.600 kJ/m³ needed for mechanical cutting, for example. Although this energy comparison is incomplete, as jet water is also required for soil transport, this data and experience from the dredging industry indicate that mechanical cutting is significantly more efficient than jetting in clay materials.



The Persistence of Jetting: Limitations of Mechanical Cutting

The continued reliance on jetting can be attributed to the limitations of current mechanical trenching methods. Chain cutting, the dominant mechanical method, was originally adapted from agriculture in the 1970s for subsea pipeline protection. Although widely used, chain cutting has frequently proven to be less reliable and efficient, and it lacks the robustness found in other dredging technologies. No alternative has emerged that meets all the necessary criteria for subsea cable burial, leading the industry to stick with jetting despite its inefficiencies in cohesive soils and other hard soils. However, as the offshore wind industry grows, developing better solutions for cable burial will be essential to meet future demands while minimizing energy consumption and environmental impact.

> **The dredging industry faced similar challenges in the previous century when bucket dredgers, which share many design similarities with chain cutters, were widely used. Due to these inefficiencies, bucket dredgers were phased out in the 1980s in favor of more productive, robust, and efficient technologies like cutter suction dredgers.**



3.2.1 Diagnosis of Core Problems

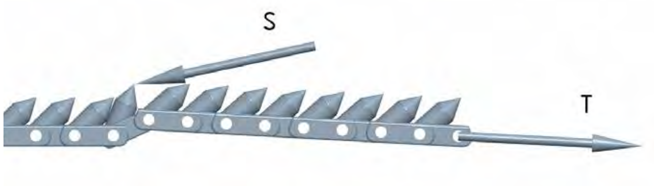
Common problems encountered when using chain cutting technology for subsea trenching include:

- (Very) low production rates
- (Very) high wear and tear rates
- Frequent clogging
- Inability to handle boulders

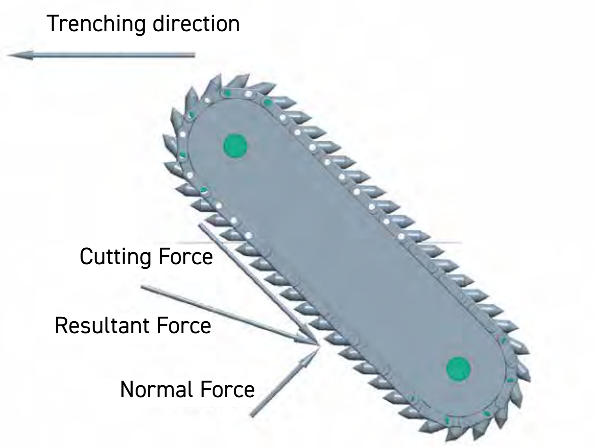
Unfit for Purpose: Chain Cutting Technology in Dredging
Many of the encountered problems stem from the fact that chain cutting technology is not inherently robust for dredging applications. Modern dredging equipment, such as Cutter Suction Dredgers (CSDs) and Trailing Suction Hopper Dredgers (THSDs), are designed on principles of geometric simplicity, robustness, and minimal moving parts. In contrast, chain cutters are characterized by complex geometries, numerous moving parts, friction points, and multiple weak points, which lead to a range of operational challenges when exposed to a hostile environment like dredging. The dredging industry faced similar challenges in the previous century when bucket dredgers, which share many design similarities with chain cutters, were widely used. Due to these inefficiencies, bucket dredgers were phased out in the 1980s in favor of more productive, robust, and efficient technologies like cutter suction dredgers. This historical precedent suggests that a similar transition away from chain cutting technology may be necessary to meet the demands of modern trenching.

One significant challenge is that exposing a chain with numerous links to seawater and abrasive materials generates high friction and accelerates wear, particularly in the pins and links. This friction is not limited to the links and pins but also occurs between the chain and the cutting boom, as well as between the links and the sprocket. These internal frictions, intensified by the harsh environment, result in substantial energy losses and excessive wear rates. An even more critical drawback of the fragile chain cutter design is its vulnerability to catastrophic failure, particularly chain breakage. Such failures have occurred multiple times, often requiring complex recovery operations.

Challenges Posed by Unfavorable Forces
The effectiveness of the chain cutter is compromised by both internal and external forces that work against it. Internally, the eccentric forces acting on the cutting tool introduce additional tension in the chain, particularly when trenching in soils with obstructions like boulder clays. These obstructions can cause high impact loads on the cutting tools and chain, limiting the height of cutting tools that can be safely used. As a result, operators must be very cautious when applying power. The restricted cutting tool height, in turn, reduces soil transport capacity, which slows down the overall progress rate.



Externally, the reaction forces generated by the chain cutter present significant challenges that directly oppose the machine's intended progress. To overcome these forces, the tractive force must be sufficiently strong, which often requires a machine of substantial weight. This is particularly true when working in dense soils, rock, or boulder-laden ground, where the normal force component is especially high, making traction the limiting factor for progress. However, this issue is not confined to hard or dense soils; it also arises in softer soils like sticky clays, which can cause the chains to partially clog. In such conditions, the operation effectively becomes a struggle of pushing clay against clay, and the lack of sufficient traction from the soft soil further hinders progress.



Chained to Inefficiency

Another major challenge with chain cutting technology is its low and often unpredictable progress rates, which not only hinder productivity but also introduce significant risks to construction schedules. Improving this aspect is difficult because production is constrained by a range of factors, any one of which can become the limiting factor depending on the actual conditions. The main factors that inhibit production include:

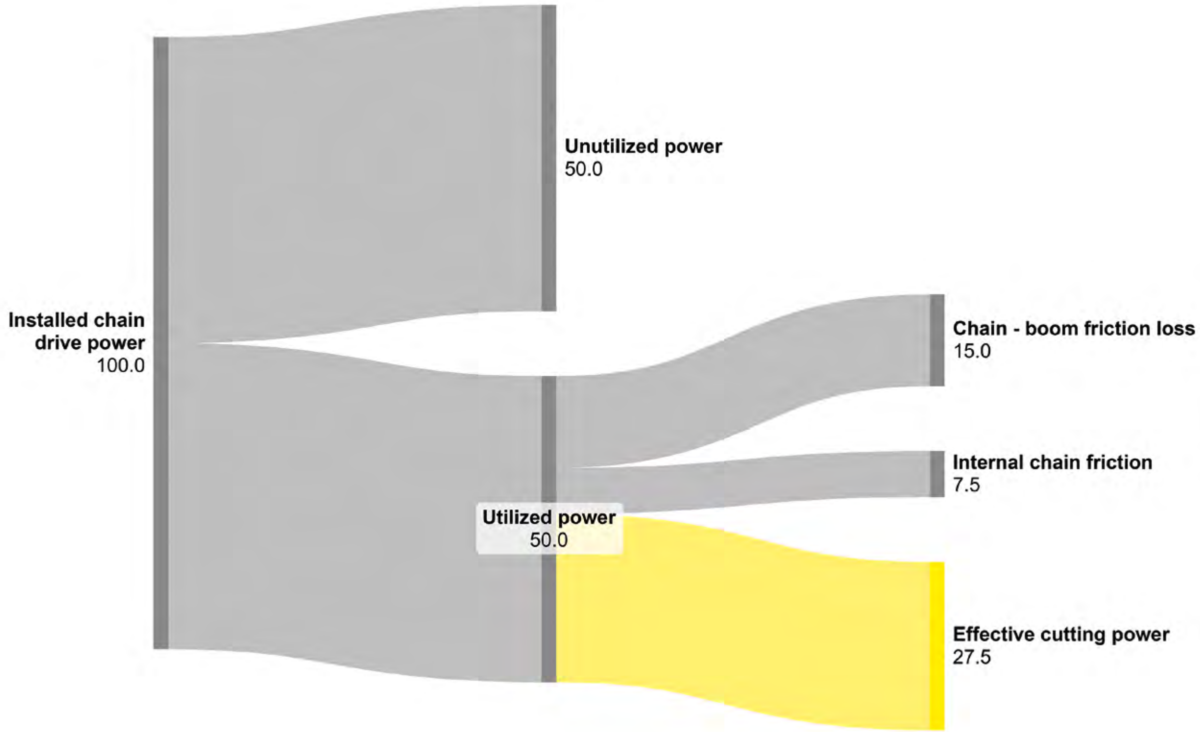
- Low available cutting energy
- Low hydraulic transport capacity
- Restricted transport capacity of the chain itself
- Insufficient traction
- Indirect factors like interruptions due to boulders, chain clogging, or maintenance

Field experiments on the energy efficiency of chain cutters have revealed that only about 55% of the mechanical energy fed into the chain sprocket is actually available at the cutting tools for soil cutting. Friction between the chain and the boom accounts for 30% of energy loss, while internal chain friction contributes an additional 15%. This substantial loss is not surprising, given the significant friction force between the chain and the boom, with abrasive soils further exacerbating the problem. In extremely hard soils, such as when cutting through rock, these figures deteriorate further as the normal forces intensify.

However, the situation is even more problematic than these figures suggest. As discussed in the previous section, operators must avoid chain breakage at all costs, leading them to exercise extreme caution when applying full power, particularly in soils where obstructions may cause peak loads on the chain. As a result, operators typically utilize only about 50% of the

Sankey diagram chain cutting operation

Sankey diagram illustrating the energy flow in a chain cutter, derived from field data.

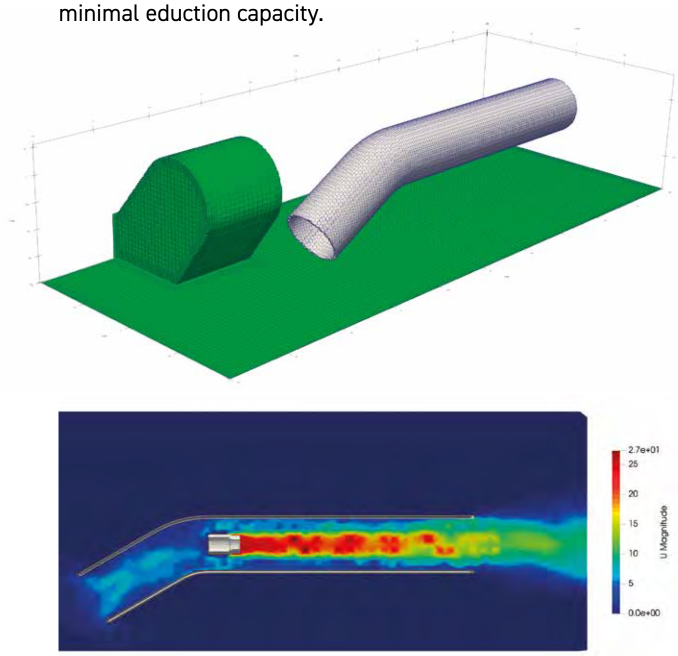


> Only 25 to 30% of the installed power is actually transferred into the soil — an exceptionally low figure, especially considering that a costly trenching support spread relies on this process.

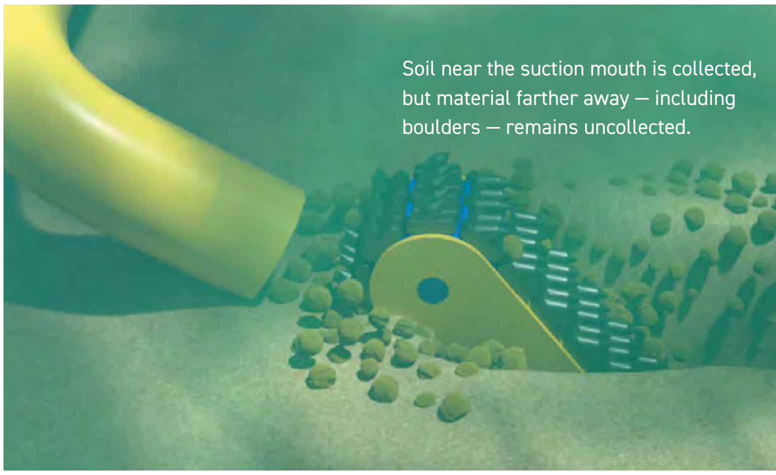
available power, meaning that only 25 to 30% of the installed power is actually transferred into the soil — an exceptionally low figure, especially considering that a costly trenching support spread relies on this process.

Despite the low cutting power, it is not always the limiting factor in production. Often, the limiting factors are related to transport capacities, either of the chain itself or the hydraulic transport system. The chain's transport capacity is restricted due to the limited height of the cutting tools and frequent chain clogging, especially in sticky clays. Chain clogging is a well-known issue caused by the chain's complex and closed structure, which provides a large adhesion area with many dead corners and angles where soil can easily stick. Although attempts have been made to mitigate this problem by introducing jets at various points, the issue persists because the chain's design inherently includes areas that are difficult to clean.

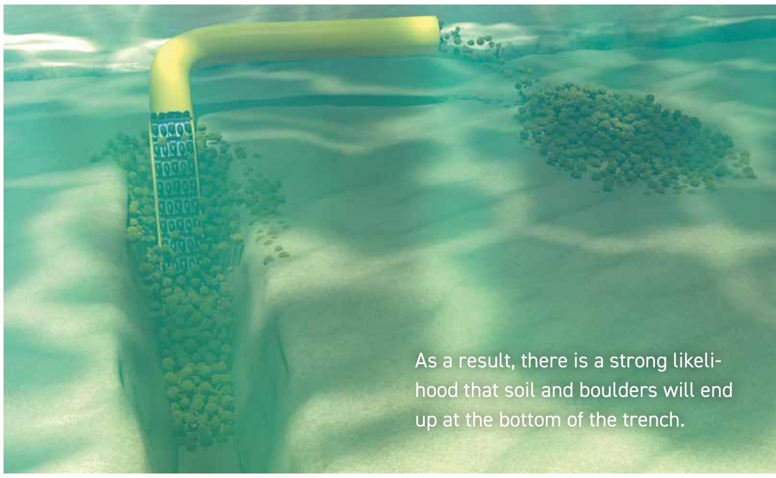
Transport capacity is also influenced by the efficiency of moving the material from the trench face to its ultimate location. Typically, a suction mouth is placed in front of the chain cutter to collect and transport the excavated material. However, this setup is problematic for two main reasons. First, a significant portion of the material often remains uncollected, due in part to the considerable distance between the cutting tool and the suction mouth, which reduces the effectiveness of the suction process. Additionally, unlike the draghead of a hopper dredger, there is no enclosed compartment to generate the necessary turbulence and pressure differences required to pick up the cut material. The second problem arises from the inefficiency of the eductor pumps used to minimize the risk of clogging in the slurry transport ducts and pump. These eductor pumps are are notoriously inefficient, with efficiencies in the range of 25-30%, requiring a substantial amount of power to achieve even minimal eduction capacity.



CFD simulations have demonstrated that slurry transport via suction in an open environment is highly ineffective and energy-intensive.



Soil near the suction mouth is collected, but material farther away — including boulders — remains uncollected.

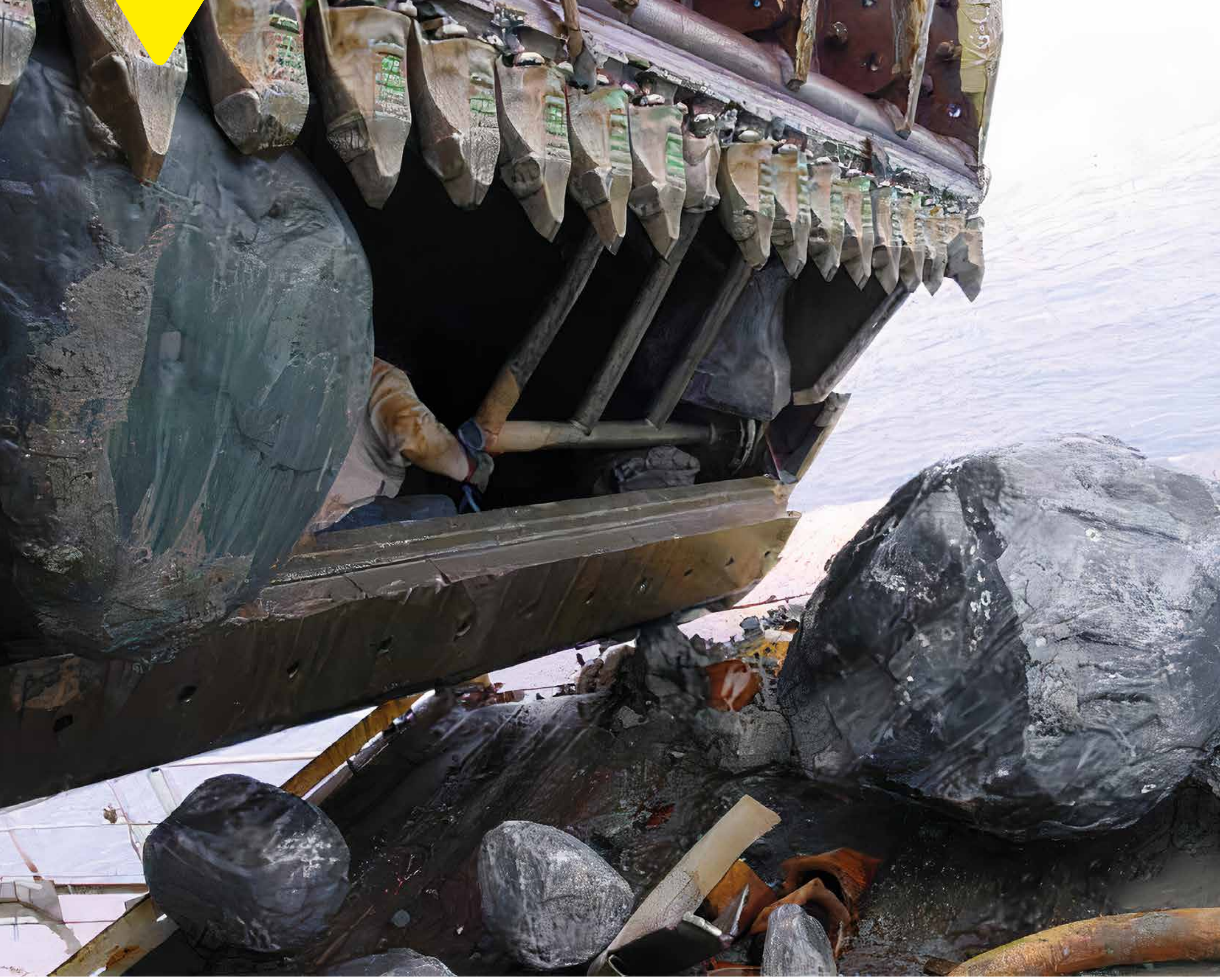


As a result, there is a strong likelihood that soil and boulders will end up at the bottom of the trench.

When eduction is ineffective and some of the cut soil remains near the trench in the form of soil heaps, there is a high likelihood that this soil will fall back into the trench, especially if the sandy top layers of the trench walls collapse. While this issue can be partially addressed by using closed depressors, a hybrid trencher configuration, or additional eduction systems within the trench, each of these solutions introduces significant downsides, all stemming from the fundamental problem of ineffective hydraulic soil transport.

Chains vs. Boulders

In dredging operations, boulders present a significant challenge, particularly when using a fragile and enclosed cutting arrangement like a chain cutter against hard boulders, often firmly embedded in a clay matrix. The primary issue is that the restricted height of the cutting tools creates limited space within the chain's structure, making it difficult to grab, hold, and effectively transport larger boulders, thus preventing their easy removal. Additionally, dragging these boulders through the clay matrix requires substantial force, with the required force increasing as the depth of the boulder increases. Consequently, operators are left with the time-consuming task of either attempting to cut through the boulder or working it out of the clay through repeated impacts. Both approaches are slow, primarily due to the limited cutting power and typically



Top: Even the most robust dredging equipment faces difficulties with boulders, let alone delicate chain cutters.

Bottom: Boulders challenge chain cutters due to the limited height of cutting tools, which restricts the space needed to grasp and transport larger boulders, complicating their removal.

low available traction force. Moreover, these efforts place significant stress on the chain, increasing the risk of breakage. To avoid this risk, contractors often choose to retrieve the cutting unit and bypass the boulder, a process that is also very time-consuming. In addition, this approach leaves the cable exposed, necessitating further remedial work to ensure proper cable protection.

Another issue with boulder fields is that boulders and cobbles can fall into the trench between the trench face and the cable touchdown point, often due to collapsing trench walls. Once these boulders are in the trench, they cannot be removed by methods such as jetting, which typically results in the cable being unable to reach the required burial depth — especially when the trench width is just large enough to accommodate the cutting boom, or in the case of a hybrid trencher, both the cutting boom and jetting lances. One solution that has been implemented is the use of a closed depressor, which essentially fills the space between the trench face and the touchdown points. However, this approach has several drawbacks and may not be feasible in certain situations.

Chains: A Costly Consumable in Cable Burial

In most cable trajectories where a mechanical cutting method like chain cutting is required, the top layer typically consists of sand. When combined with seawater, this sandy top layer leads to extremely high wear and tear rates on the chains. Although chains are considered consumables, they are quite expensive and have a limited lifespan of only 2 to 8 kilometers. This means that after every one or two inter-array cables, the chain needs to be replaced. In practice, chains are often replaced even earlier than their expected lifespan, as contractors are keen to avoid the catastrophic consequences of chain breakage. The high direct costs of replacing the chain are compounded by significant indirect costs, including the downtime of 4 to 8 hours required for chain replacement, which further disrupts operations.

Cable Laying Challenges and Integrity Impacts

The chain cutter not only influences the effectiveness of the burial operation but also has a significant direct and indirect impact on the cable laying process. Unlike twin sword jetting trenchers, where the cable is routed through the jetting swords during burial, mechanical trenchers require the cable to be loaded into a cable highway and guided either over or alongside the cutting boom before being laid into the seabed. Typically, the cable is guided over the cutting boom rather than beside the chain cutter, as routing it alongside would necessitate bending the cable in two planes within a short distance, introducing unfavorable stresses. To avoid these stresses, the cable is usually lifted over the cutting boom to a height of 1.5 to 2 meters, and in some cases, even up to 3 meters. However, this loading height is disadvantageous as it reduces flexibility in the cable burial operation. To accommodate the loading height, the cable must be laid with additional slack, which restricts the ability to start the trenching operation to specific slack points along the cable route. If trenching is unsuccessful at a particular location for any reason, the installer is forced to move to the next designated loading point, leaving a significant portion of the cable exposed and vulnerable.

A larger challenge arises from the resistance generated when loading and running the cable through the trencher vehicle. Even with a well-designed cable highway, resistance is inevitable, especially with greater lifting heights and tighter curvatures. This resistance complicates the management of slack in the cable, often resulting in a running bight in front of the trencher, which can lead to excess cable length — particularly challenging to manage when approaching the second end of the inter-array cable. Additionally, the beginning of the cable presents its own challenges, as the chain cutter cannot reach the starting point for burial, leaving the cable exposed until remedial work is completed.

Resistance-related problems are likely to worsen in the coming years as DC cable bundles become increasingly popular. These bundles are larger and stiffer than conventional export cables, presenting additional challenges. Extensive research has been conducted on guiding these cable bundles through a trencher highway and depressor to gain a deeper understanding of how they behave under these conditions. As the bundle moves through the machine, it can twist, become stuck, or cause a cable tie to unravel. Various failure mechanisms can occur, with the likelihood of failure increasing with the number and sharpness of bends in the pathway. Therefore, minimizing or even eliminating cable loading height — and thereby reducing cable friction — is crucial to safeguarding the integrity of the cable.

DC cable bundles become increasingly popular. These bundles are larger and stiffer than conventional export cables, presenting additional challenges during burial campaigns.

3.3 Other Hard Soil Techniques

In addition to chain cutters, various other methods and technologies are often used for trenching in hard soil conditions, such as cable burial ploughs, pre-trenching ploughs, and wheel cutters.

Wheel Cutters

Wheel cutters offer a relatively robust cutting mechanism compared to chain cutters, but they come with significant limitations that have hindered their widespread adoption. One of the main drawbacks is the limited burial depth, often restricted to 1.5 meters due to the small diameter of the cutting wheel. This limitation reduces the suitability of wheel cutters for projects requiring deeper trenches.

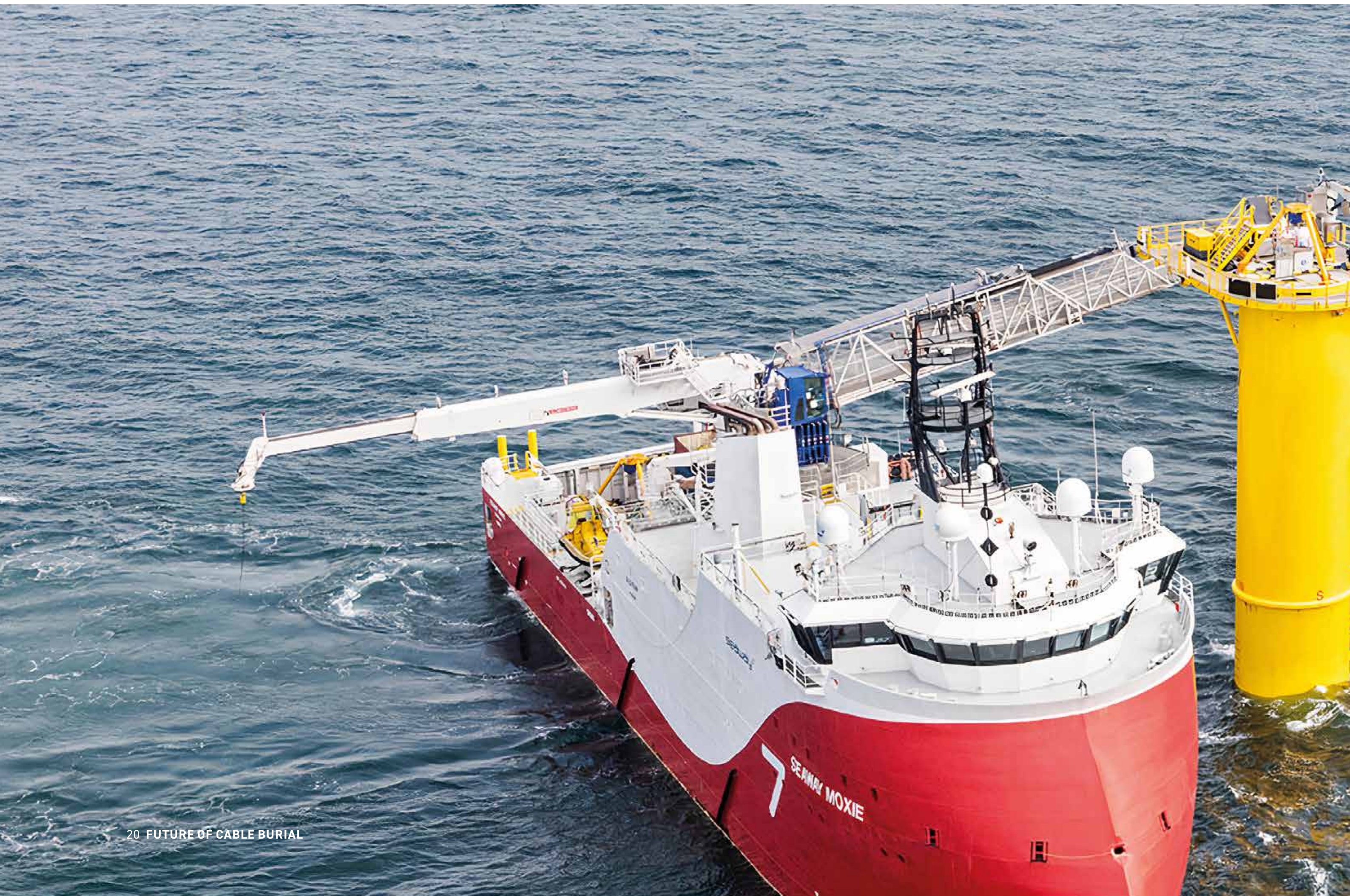
In addition to depth constraints, wheel cutters present challenges in cable handling. The design often necessitates a high cable loading height, particularly if two-plane bending of the cable is not permitted. This increased height introduces mechanical stresses to the cable and complicates the preceding cable-laying process. Furthermore, the soil transportation mechanism in wheel cutter trenchers, which relies on principles similar to those in chain cutters, often leaves significant soil deposits along the trench sides. To achieve the necessary burial depth despite these deposits, which often fall back into the trench and reduce its depth, cables must pass through a closed depressor, introducing additional forces and resistance between the cable and the trencher. This can result in running bights in front of the trencher, further complicating the burial process.

Moreover, the design of the wheel cutter itself, particularly the complex geometry of the cutting wheel's circumference where the cutting tools are mounted, poses a high risk of clogging, especially in sticky soil conditions like soft clays and chalk. These factors collectively make wheel cutters suitable and attractive only for a limited range of trenching applications.

Cable Ploughs

Cable ploughs, available in various designs, have been widely used for burying cables in challenging soil conditions. Unlike mechanical trenchers that use active cutting mechanisms like chain or wheel cutters, cable ploughs are mechanically simpler and more robust. This simplicity enhances their reliability, increases uptime, and reduces maintenance needs.

However, cable ploughs do have limitations. They struggle with very hard soils, uneven terrains, and obstacles like boulders, and their maneuverability is restricted. While they are well-suited for long, straight trajectories like export cables, they are less effective for shorter runs, such as inter-array cables. The requirement for a certain distance between the vessel and the plough often limits their use in confined areas. Additionally, applying significant back tension to a cable connected to a foun-



dation is undesirable, further restricting their applicability. Despite these challenges, subsea cable ploughs have proven to be effective within specific conditions and environments, with generally positive outcomes in their deployment.

Pre-Lay Ploughs

Pre-lay ploughs are a specific type of plough designed to create an open V-trench, where a cable can be laid and buried in a subsequent campaign. While this approach might initially seem straightforward and effective, practical experiences have revealed several challenges and limitations. This is partly due to the inherent limitations and disadvantages that pre-lay ploughs share with traditional cable ploughs, as outlined in the previous section, since they exhibit similar shortcomings. However, their limited adoption is more directly attributed to their low success rate in achieving the required burial depth.

Several factors contribute to the difficulty in reaching the necessary burial depth. Primarily, the time gap between the trenching campaign and the subsequent cable burial allows the trench to partially fill with soil, reducing the trench depth and, consequently, the final cable cover. While attempting to estimate the amount of infill and compensating by trenching deeper is possible, predicting the exact amount of infill is challenging. Overestimating the required depth could result in excessive burial, which can lead to thermal issues due to the insulating properties of the surrounding soil.

Another significant challenge is ensuring that the cable is laid precisely at the bottom of the V-trench. In previous campaigns using this method, cables often ended up resting on the trench flanks due to lay tolerance, leading to insufficient soil cover and inadequate protection, much like the infill issue.

Additional complications arise when dealing with soft soils or very hard soils with obstructions such as large boulders. Pre-lay ploughs, designed to withstand significant towing forces, are typically very heavy, which can lead to bearing capacity problems in soft soils like clays, preventing the plough from achieving the desired V-trench dimensions. Similarly, in very hard soils or soils with obstructions like firmly embedded boulders, the plough can be forced out of the seabed when too much resistance is encountered, resulting in insufficient burial depth. In such cases, there is little that can be done except to accept the reduced burial depth or undertake costly remedial work, such as subsea rock installation.

In conclusion, while various technologies and methods exist for cable burial in hard soil conditions, each approach comes with significant disadvantages or limitations. These challenges often result in high costs, failure to meet burial requirements, and considerable uncertainty in the construction schedule.

4. An Alternate Solution for Hard Soil Cable Burial

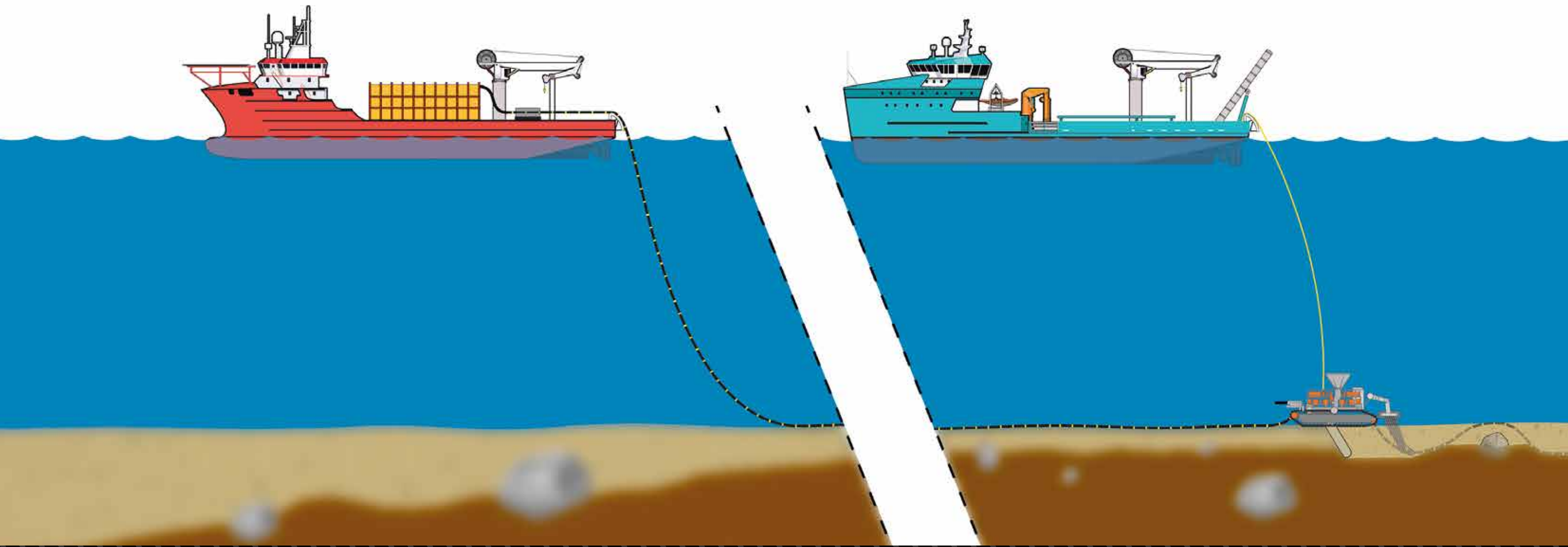
To address the issues outlined in the previous section, it's essential to first gain comprehensive knowledge of seabed conditions along the entire cable route, ensuring appropriate burial methods and tools are used. Second, improved trenching technology is needed for hard soils. This section proposes an alternative approach, involving an early pre-cutting and clearance campaign using an innovative seabed preparation tool.

4.1 Pre-Cutting and Clearance: A Revised Approach

During offshore wind farm construction, geotechnical and geophysical surveys assess seabed conditions, identifying hazards and obstructions. While surface obstacles are cleared during seabed preparation campaigns, deeper buried obstacles, such as UXOs and boulders, may go undetected or be left untouched, posing risks during the burial phase. Addressing these sub-surface obstructions and gaining comprehensive knowledge of the seabed is crucial to avoiding complications in later operations.

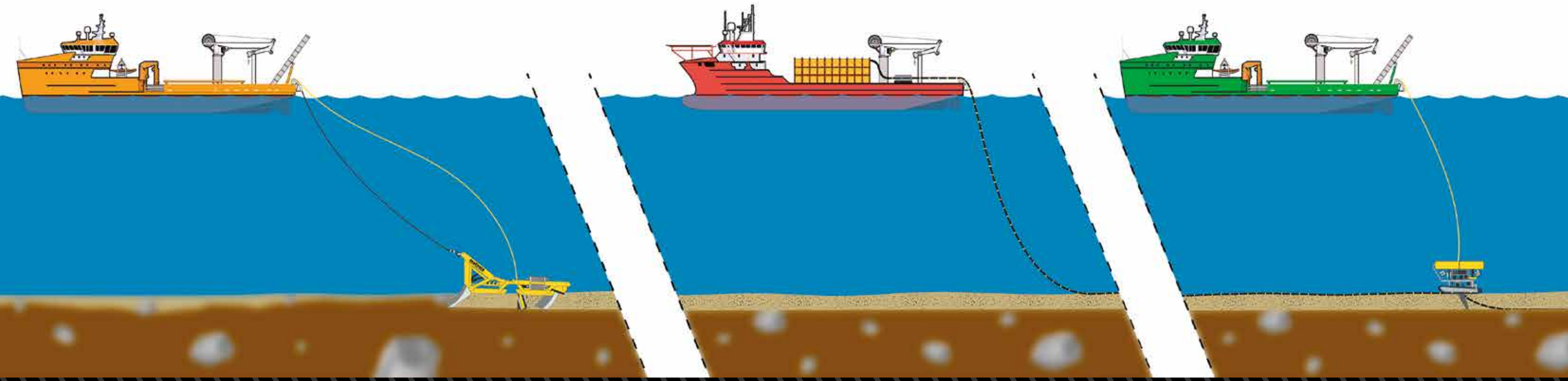
We therefore propose a new approach that extends the scope of seabed preparation by incorporating a pre-cutting and clearance operation. This enhanced process would involve more thorough preparation by removing all sub-surface obstructions and pre-cutting the seabed. By doing so, many common challenges encountered during subsequent cable laying and burial campaigns can be effectively mitigated.

In addition to clearing the seabed from obstructions, the objective of the operation is also to loosen the seabed such that it becomes jettable. For cohesive soils like clay, this involves cutting the seabed into small clay fragments. For non-cohesive soils like dense sands, it means reducing the sand's relative density through jetting. The ultimate goal of this conditioning



The conventional approach, which carries significant uncertainty and risk.

> The ultimate goal of this conditioning step is to facilitate easy cable burial, allowing the installation contractor to use a single jetting-based tool, leading to more efficient, predictable, and successful burial operations.



The revised approach, which ultimately aims to eliminate soil and obstacle risks.

step is to facilitate easy cable burial, allowing the installation contractor to use a single jetting-based tool, leading to more efficient, predictable, and successful burial operations.

It is important to note that this approach differs from the pre-ploughing method described earlier. In the pre-ploughing approach, the goal is to create an open V-trench where the cable can be laid in a subsequent phase, after which the trench is backfilled with soil. However, this method is fundamentally different. Instead of creating an open V-trench, the tool will clear and pre-cut the seabed over a width of approximately 3 to 4 meters, while leaving the soil in place. As previously mentioned, creating open trenches can lead to uncertainty in the final cable burial depth due to soil infill, especially with V-shaped trenches.

Unlocking Full Jet Trenching Potential via Seabed Conditioning

The conditioned soil must be prepared in such a way that it allows for cable burial using jet trenching machines, such as jetting sleds or ROV jet trenchers, regardless of the original soil type and condition. There are various trenchers available in the market within this category that are relatively simple in design, compact, and lightweight. This contrasts with most mechanical and hybrid trenchers, which tend to be heavy, bulky, and complex. Using these straightforward jet trenching machines offers several advantages, including improved workability under various weather conditions and soil bearing capacities, suitability for short cable trajectories like inter-array cables, higher productivity, and increased safety for the cable due to minimal cable interference.

Example jet trencher that can operate effectively on pre-conditioned seabeds consisting of hard soils.

Inspired by Snip, Liefferink, and Bentvelsen: Evolving the Survey Plough Idea for Hard Seabeds

The concept of adding an additional seabed preparation operation to minimize soil and obstacle risks is not entirely new. In their presentation, "The Development of a Route Survey Plough for Subsea Power Cable Routes," Wino Snip, Daniel Liefferink, and Barend Bentvelsen from TSO TenneT introduced the idea of using a survey plough to gather geotechnical data, such as soil strength and thermal conductivity, along the entire route while simultaneously loosening the seabed and removing obstacles. Although this approach shares similarities with our proposal, there is a significant difference in its application. Their focus is on conditioning the Dutch and German nearshore seabed, which mainly consists of sands with no boulders, whereas our interest lies in addressing harder seabeds that are not suitable for jetting and hence require active mechanical methods for effective soil loosening in a single pass. This distinction underscores the need for tailored technological solutions that address the diverse seabed conditions across the various geographical regions where offshore wind farms are being developed.

Given our focus on conditioning unjettable seabeds, the success of this approach ultimately hinges on the effectiveness of the active cutting mechanism for soil loosening. Relying on traditional chain-cutting methods would simply transfer the associated challenges from the cable burial phase to the seabed preparation phase. Therefore, there is a need for innovative dredging technology capable of cutting a rectangular-shaped slot in hard seabeds — without removing the soil — across a range of challenging materials, including boulder clays, dense sands, peat, cemented sands, rock, and glacial tills.

Disruptive Technology: Iron Bull – Pre-Cutting and Clearance Tool

Ensure reliable cable burial with the Iron Bull: loosened soil, no obstructions, and 100% soil knowledge.

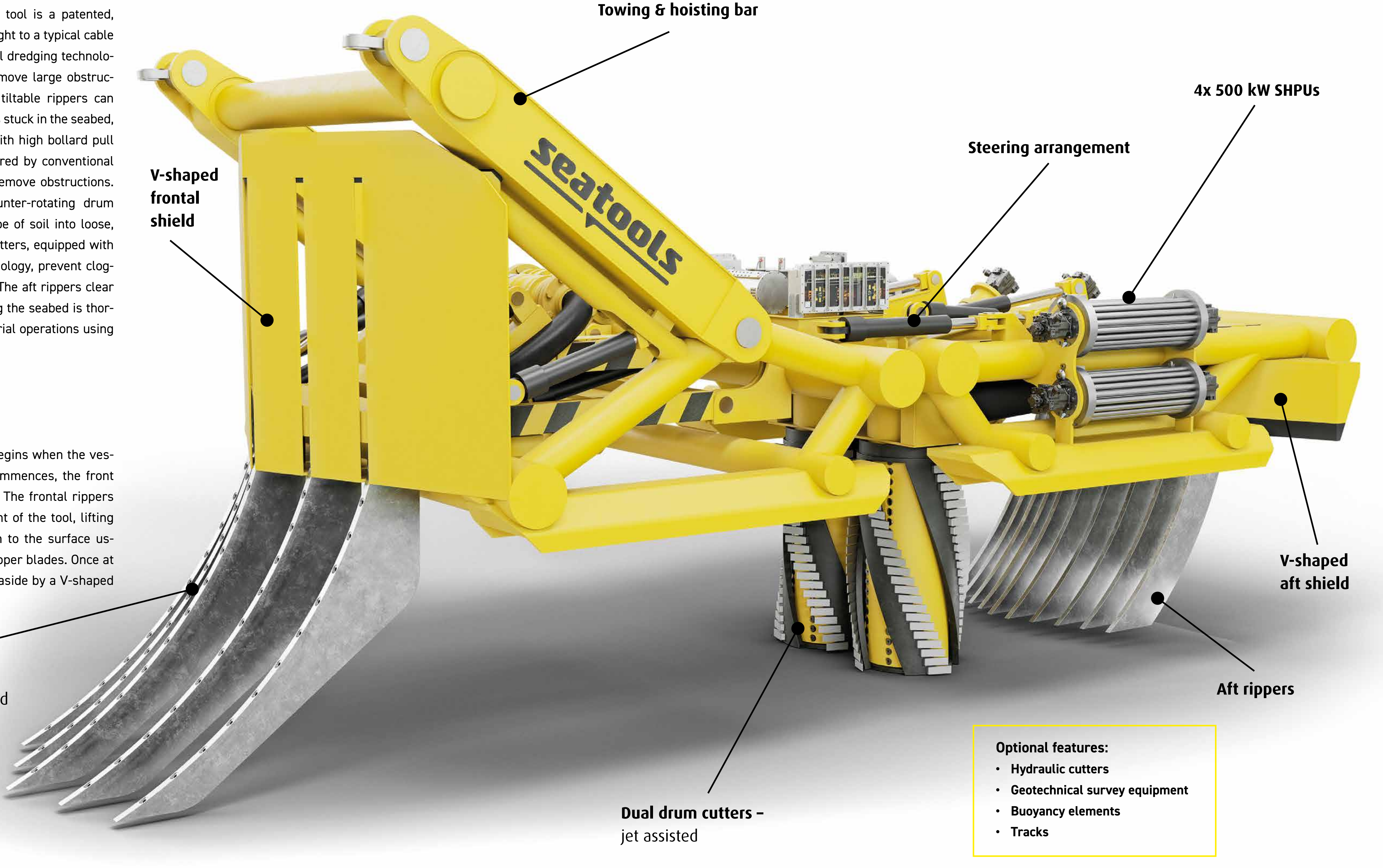
Indicative key specifications

Estimated weight	65 [mT]
Size	L = 13.0, W = 6.5, H = 4.8 m
Continuous tow force	150 [Mt]
Installed power	2 MW
Cutting depth	2.5 m
Cutting width	3 m
Typical progress rate	200 m/hr

The Iron Bull Pre-cutting and Clearance tool is a patented, towed sledge, comparable in size and weight to a typical cable plough, incorporating robust and powerful dredging technologies. Jet-assisted rippers at the front remove large obstructions like boulders. These hydraulically tiltable rippers can exert immense break-out forces on objects stuck in the seabed, eliminating the need for costly vessels with high bollard pull capacities that would otherwise be required by conventional tools relying solely on towing forces to remove obstructions. Additionally, the tool features twin counter-rotating drum cutters for transforming virtually any type of soil into loose, eventually jet-able material. The drum cutters, equipped with Seatools' proprietary jet assistance technology, prevent clogging even in the stickiest clay materials. The aft rippers clear any remaining oversized objects, ensuring the seabed is thoroughly prepared for subsequent cable burial operations using simple and effective jet trenchers.

Working principles

The pre-cutting and clearance process begins when the vessel starts towing the tool. As towing commences, the front and aft rippers engage with the seabed. The frontal rippers cut or jet through the seabed at the front of the tool, lifting any obstacles too large to pass through to the surface using the upward force generated by the ripper blades. Once at the surface, these obstacles are pushed aside by a V-shaped

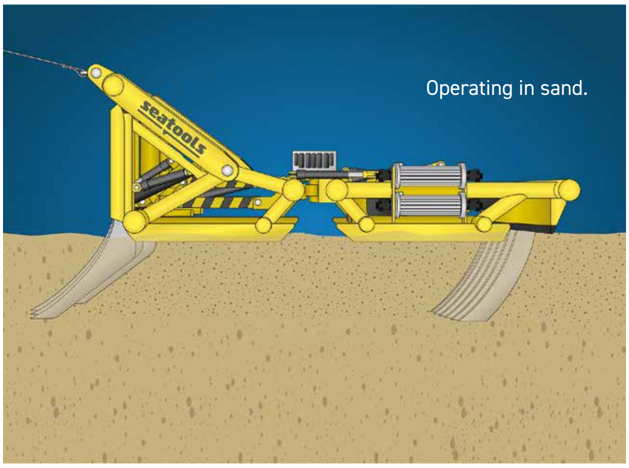


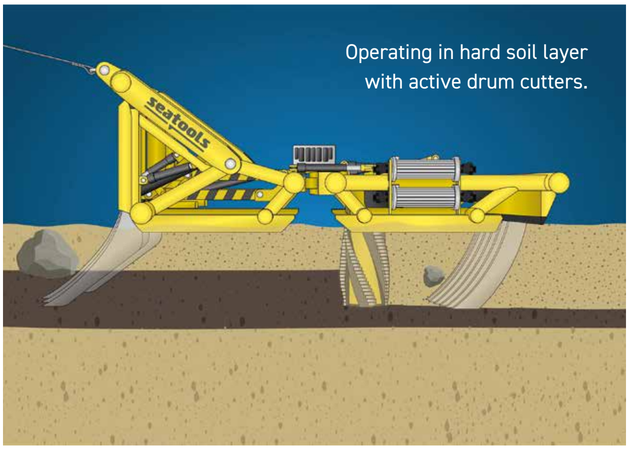
Optional features:

- Hydraulic cutters
- Geotechnical survey equipment
- Buoyancy elements
- Tracks

frontal shield. Smaller obstacles, such as small boulders, that pass through the front rippers but are unsuitable for the subsequent cable burial process (via jet trenching) are filtered out by the aft rippers. The aft rippers operate similarly to the frontal ones: when encountering an obstacle, the upward force lifts it to the surface, where it is then directed to the side by the V-shaped aft shield.

If hard soil layers, such as clay, are encountered and the towing force exceeds a pre-specified threshold, the drum cutters are activated and engage with the seabed. The two Ø1.5 m drum cutter units cut the hard seabed layers into fine pieces, making them suitable for jetting. This cutting process reduces the towing forces, which is monitored by force sensors on both the frontal and aft ripper teeth.





Boulder tilting

Innovative Principles for Boulder Clearance in Hard Seabeds

Most obstructions, primarily boulders, can be removed using the towing forces exerted on the tool. However, experience from dredging indicates that some larger boulders, especially those in hard clay, can be firmly stuck within the clay matrix. In such cases, the vessel's towing force might be insufficient to dislodge the boulder. The tool is designed to handle this scenario. If the towing force becomes too high, the constant tension (CT) towing winch will start to pay out, bringing the tool and vessel to a stop. At this point, the rippers can be tilted using the ripper tilting mechanism. Powered by hydraulic cylinders, this mechanism exerts immense forces on the boulder to tear it out, generated internally by the tool without relying on external forces such as vessel pulling. This approach is expected to deal with even the largest boulders effectively. However, in the unlikely event that this method fails, the rippers can be retracted, allowing the tool to move slightly forward and employ the drum cutters with point-attack picks to cut the boulder apart. This backup strategy is feasible due to the robust drum cutters, which possess sufficient power and pressure to mill the boulder into pieces — something that would be unachievable with a conventional track-driven trencher.

Overcoming Boulder Blockages

An obstruction, such as a boulder, can become wedged between two rippers, creating a blockage that hinders the speed of seabed preparation by increasing resistance. The V-shaped frontal shield is designed to effectively address such blockages. When the rippers are retracted, the obstructing boulder is guided towards the frontal shield positioned between the rip-

> **Powered by hydraulic cylinders, this mechanism exerts immense forces on the boulder to tear it out, generated internally by the tool without relying on external forces such as vessel pulling.**

pers where the blockage occurred. The contact with the frontal shield, combined with the retraction of the rippers, dislodges the boulder, clearing the blockage and allowing the tool to continue its operation efficiently.

Trench Strategies and Soil Management

For seabed conditioning, a closed trench is generally preferred over an open trench, as an open trench can lead to not meeting the specified burial depths. However, there may be instances where an open trench is desired. For example, the seabed preparation campaign may also involve removing thermally insulating soil, such as peat, to ensure sufficient heat transfer during the operation of the offshore wind farm. Soil removal might also be required to compensate for excessive soil bulking during clay cutting, thereby preventing the drum cutters from clogging. While the frontal rippers help reduce soil bulking by removing thin strips of clay and directing them to either side of the tool, additional soil removal may still be necessary to prevent the drum cutters from clogging.

The drum cutters can be adapted to meet these requirements and are capable of side-casting all cut material, leaving an open trench. The drum cutter units can be equipped with soil evacuation channels that use low-pressure, high-volume flow nozzles to blow the expelled soil from the bottom of the trench upwards and then sideways. This innovative method of soil eduction is far more energy-efficient and less prone to clogging compared to conventional soil eduction techniques, which typically rely on suction.

Accurate Path Tracking

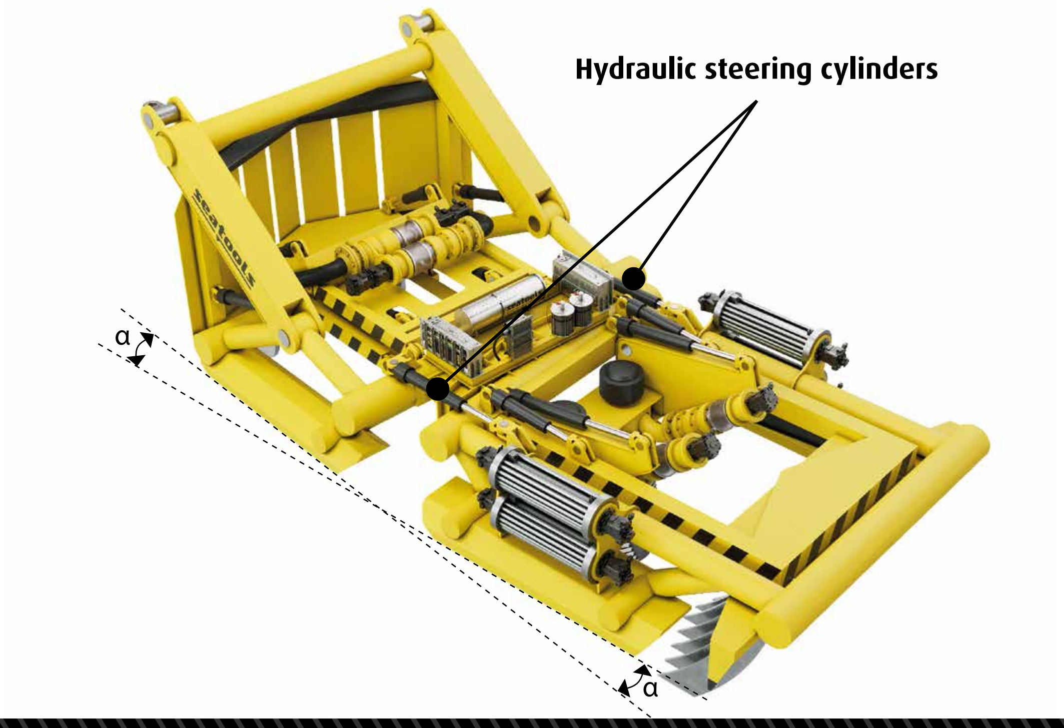
The tool's main frame is divided into two sections: a front frame and a rear frame. These sections are connected by a hinge mechanism, allowing the rear frame to pivot relative to the front. This pivoting action, facilitated by a hydraulically actuated steering mechanism, minimizes the tool's turning radius, provides direct control over its heading, and enables it to closely follow a predetermined cable path.

4.3 Technical Breakdown and Design Rationale

Active Cutting: The Preferred Over Passive Cutting

The pre-cutting and clearance tool incorporates a novel combination of passive and active cutting systems, utilizing rippers and drum cutters, respectively. This configuration differs from traditional pre-cutting ploughs, which rely solely on passive cutting. While the conventional approach offers simplicity and robustness with its minimal moving parts, there is a compelling reason why the inclusion of an active system is preferable, and possibly essential, for meeting the demands of this seabed conditioning application

A key consideration is the preference for performing pre-cutting and clearance operations in a single pass, rather than multiple passes. To accommodate a soil preparation depth of 2.5 meters and a preparation width of 3 meters — necessary for flexibility in subsequent cable laying — the tool must handle a cross-section of 7.5 m² in one go. This goes far beyond the capabilities of typical cable ploughs, for example, which usually handle a seabed cross-section of around 1 m². Detailed analysis based on theoretical plow force models, calibrated with extensive field data from subsea ploughing operations, suggests that achieving this in practice is barely feasible. The required towing forces for a seabed composed of soft to medium-strength clay with a sandy top layer are in the order

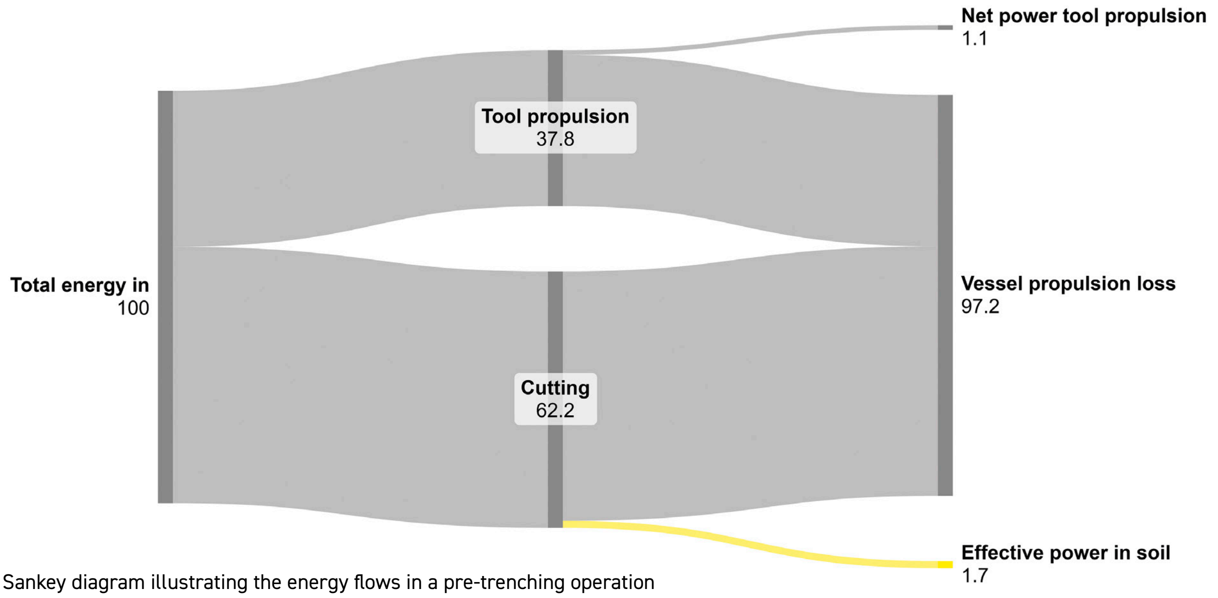


of 150 tons. In stiff clay, the required pulling force increases to approximately 375 tons, not accounting for additional forces that may be introduced by boulders. Consequently, multi-passing is unavoidable, though it introduces significant challenges and often fails to achieve the desired trench geometry. Hence, a single-pass process with greater control over the trench geometry is highly desirable.

It could be argued that a 2.5-meter burial depth might be excessive, particularly in harder soils where a 1.5-meter depth could be sufficient. While this may hold true in some cases, making the required bollard pull forces more manageable, the real question lies in the efficiency and level of control that can be achieved with this approach.

Theoretically, from a soil mechanics perspective, ploughing is a highly efficient process. When considering specific energy consumption, passive cutting of clay using a plough is more efficient than active cutting methods like drum cutting, as active cutting causes greater soil fragmentation, requiring more energy per unit of soil volume. However, this is not the whole picture. The key difference is that, with passive ploughing, the cutting force must be generated entirely by the vessel, and generating towing force at very low speeds through vessel propulsion is extremely inefficient. Specifically, each metric ton of towing force requires approximately 55 to 65 kW of vessel propulsion power. In practical terms, this means that, for instance, generating a towing force of 130 tons for a 1.5-meter trench depth requires about 8 MW of propulsion power. When compared to the actual cutting power applied by the plough to the seabed, around 140 kW, the efficiency is shockingly low, at less than 2%. Therefore, from an energy perspective, it is crucial to minimize the extent of passive cutting in favor of active cutting. This shift not only optimizes overall energy efficiency and environmental impact, but also significantly reduces the size and bollard pull requirements of the towing vessel, leading to more effective and economically viable operations.

Sankey diagram of passive pre-cutting



Sankey diagram illustrating the energy flows in a pre-trenching operation with a passive plough, highlighting that less than 1% of the total energy input is effectively utilized for soil cutting.

> **Generating 130 tons of towing force needs about 8 MW of propulsion power, yet only around 140 kW reaches the seabed, yielding an efficiency of less than 2%. To improve energy efficiency, it's crucial to minimize passive cutting and focus on active cutting.**

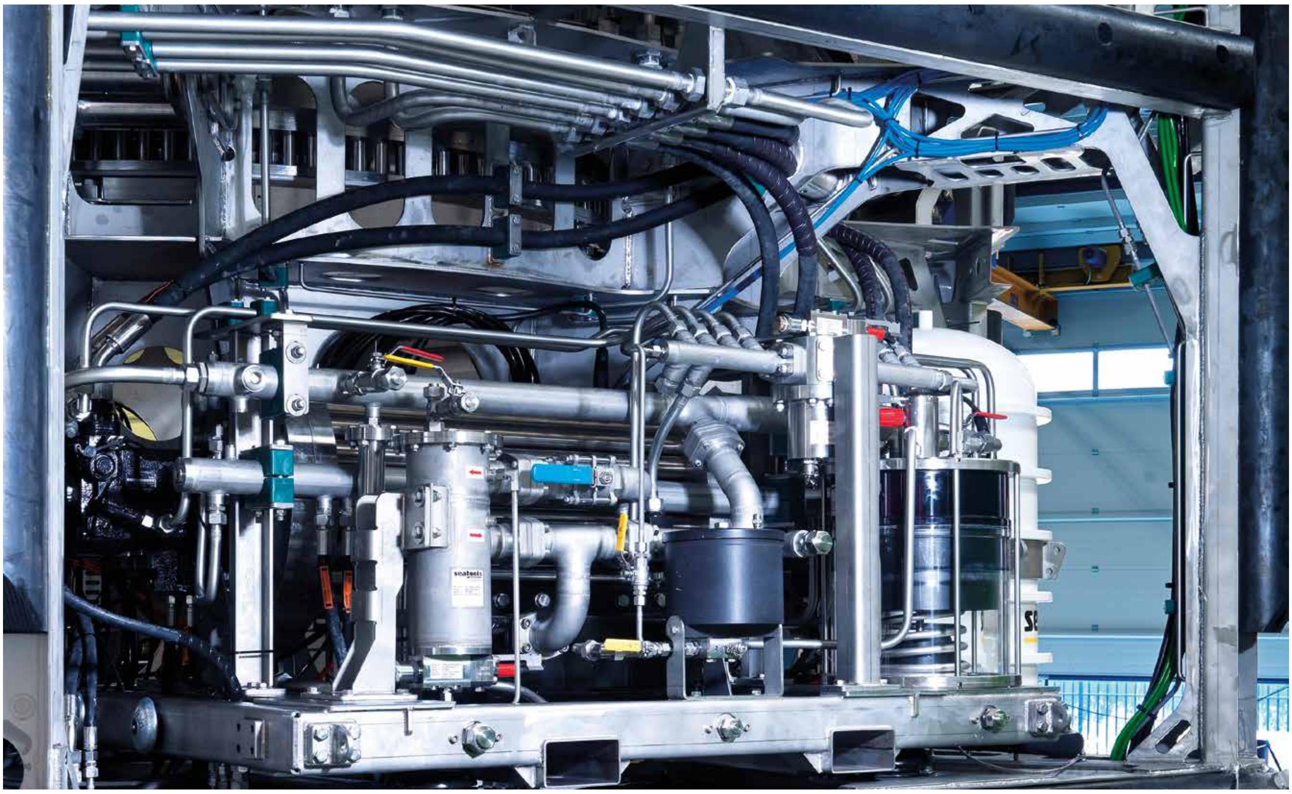
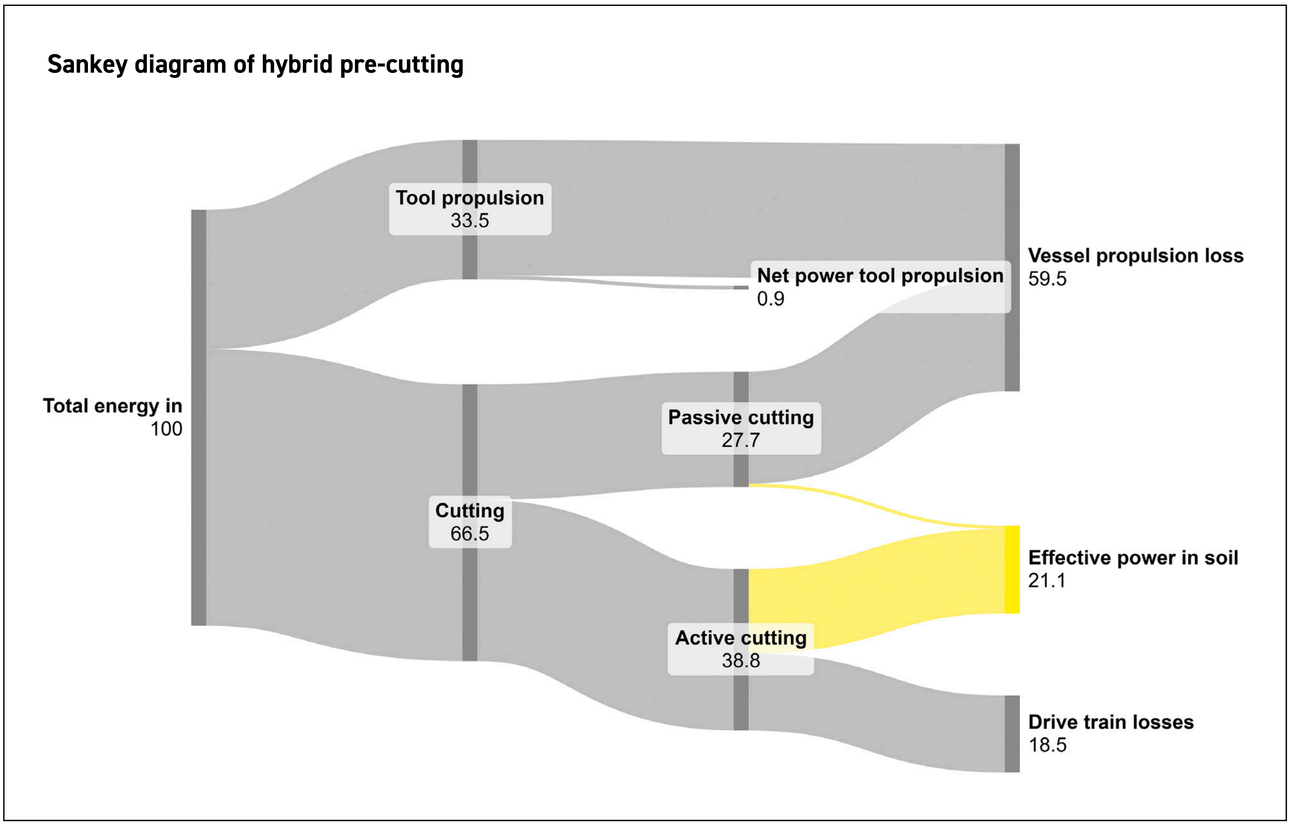


Image of a Seatools' subsea electro-hydraulic drive system.

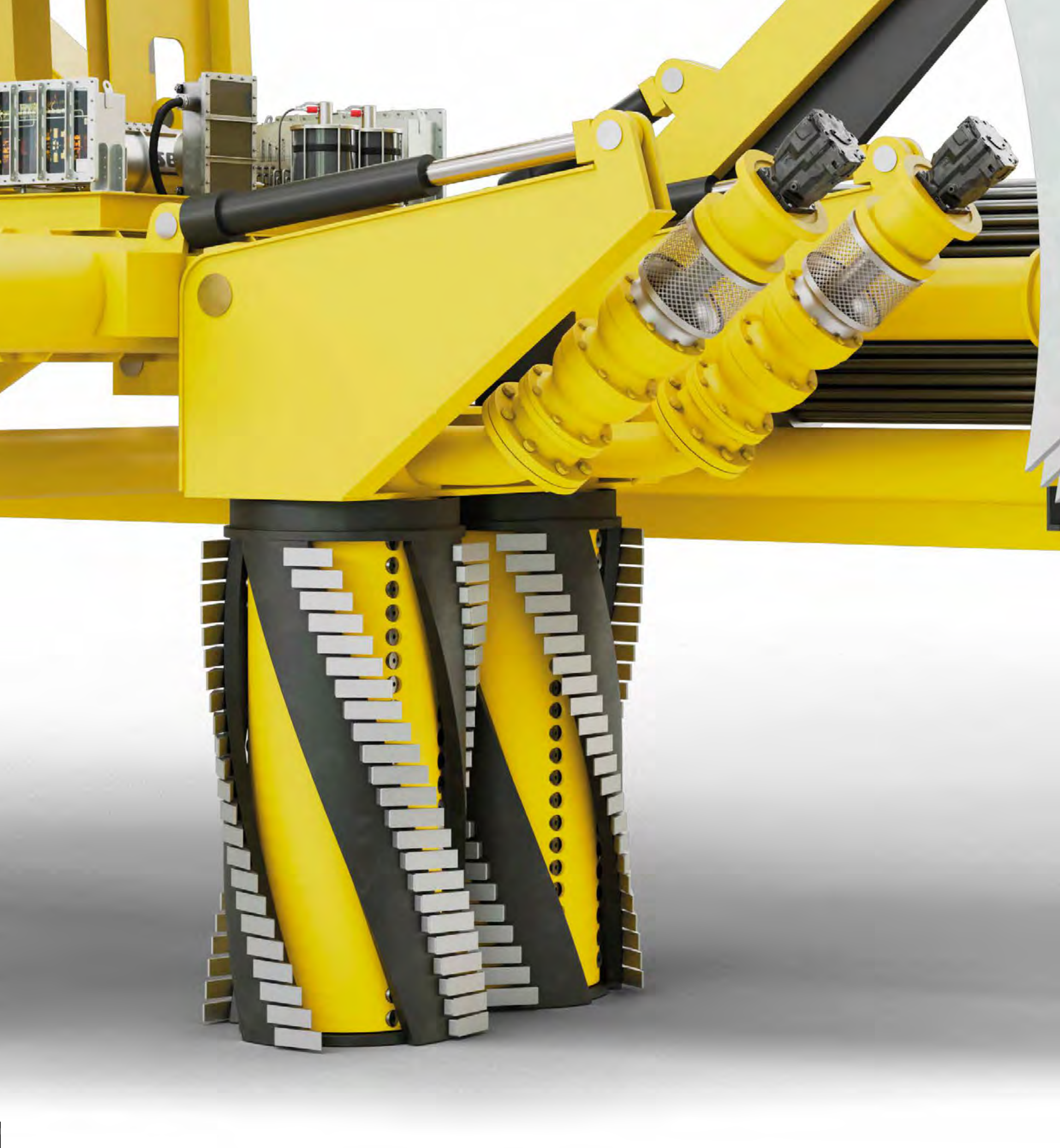
Switching to active cutting significantly alters the energy dynamics. However, in that case, while less towing force is required, the inclusion of an electro-hydraulic drivetrain from the vessel to the actuators on the subsea tool introduces its own energy losses. To understand how these losses compare to those of a passive system, a comparative energy assessment was conducted across three configurations: entirely passive cutting, entirely active cutting, and a hybrid setup combining both, as proposed in the Iron Bull pre-cutting and clearance tool. This assessment is a like-for-like comparison, with all configurations powered by the same shaft power available on the vessel. In the passive cutting scenario, all available power is directed toward vessel propulsion. In contrast, the active cutting scenario channels power into the electro-hydraulic drive train, starting with the conversion of mechanical energy to electrical energy via an alternator. In the hybrid setup, part of the power is allocated to vessel propulsion, while the remainder powers the electro-hydraulic drive system. All energy losses in the electro-hydraulic drive system are based on Seatools' experience. The active cutting mechanism itself is based on drum cutting technology, which includes jetting for soil disposal, with its energy consumption factored into the analysis.



Sankey diagram illustrating the energy flows in a pre-trenching operation using a hybrid cutting configuration. The hybrid setup increases energy chain efficiency by 7 to 12 times, from vessel power to cutting power in the soil, ultimately resulting in a 1.5 to 2.5 times reduction in overall energy consumption.

The analysis revealed that in a hybrid configuration, such as the setup of the Iron Bull tool, which combines passive rippers with active drum cutters, the efficiency gain over a fully passive system ranges from 14 to 17 times, depending on soil type. This significant efficiency improvement is primarily due to a substantial reduction in required towing forces, which eliminates the inefficient conversion of propulsion power to towing power. However, the absolute power input is not reduced by the same factor, as the specific energy demand of the active cutting process is considerably higher due to the increased level of soil fragmentation and the need for jet water. Accounting for these differences in specific energy, the overall absolute energy gain is between 1.5 to 2.5 times, which still marks a significant advancement over a fully passive system. Active cutting not only reduces power consumption but also substantially lowers the required vessel size and bollard pull capabilities, which is likely the most significant advantage. In a passive cutting scenario, the required bollard pull is around 250 tons, whereas the hybrid setup requires approximately 70 tons. This reduction in bollard pull requirements greatly improves vessel availability and reduces day rates, thereby enhancing the overall economics of the operation. Additionally, the increased control over the trenching process provided by active cutting systems makes them the preferred choice for pre-cutting operations.

> In a passive cutting scenario, the required bollard pull is around 250 tons, whereas the hybrid setup requires approximately 70 tons. This reduction in bollard pull requirements greatly improves vessel availability and reduces day rates, thereby enhancing the overall economics of the operation.

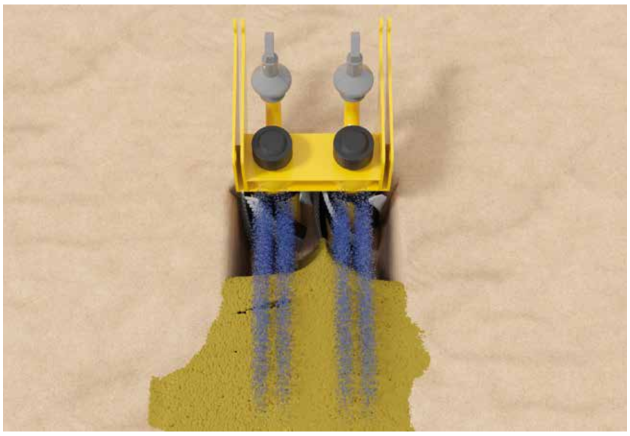


The Obvious Choice for Drum Cutting Technology

In the previous section, the introduction of active cutting was highlighted as a method to significantly enhance overall energy efficiency while providing greater control over trench geometry. However, this is contingent upon the active cutting configuration being both efficient and highly reliable. The commonly used active cutting systems fail to meet these requirements, leading to the development of a new trenching arrangement: the jet-assisted drum cutting concept.

Drum cutters are not a new technology; they have been widely utilized across various industries, including construction, quarrying, and mining. Drum cutters are valued for their simplicity, robustness, high energy efficiency, and versatility in handling a broad range of materials. These attributes made the drum cutter an ideal foundation for developing a new active cutting mechanism. However, the straightforward application of a drum cutter in dredging is not sufficient, particularly when operating in subsea conditions with potentially sticky soil

Seatools has gained valuable experience with drum cutting technology through its implementation in the Arthropod hard soil pipeline trencher.



At the front of the drum cutter, soil is cut and, as the drum rotates, moved to the aft, where high-pressure jets flush it out.

and varying soil conditions. To address these specific dredging challenges, the drum cutter was chosen as a basis, and new principles for soil slurrification and transportation were incorporated, drawing on past experience and lessons learned.

This new design features an open drum cutter, similar to a cutter head used in CSD dredgers but with a longitudinal shape, where the cutting tools are mounted on spokes rather than on a solid drum. This open design enables the integration of an inside-out jet flow to flush away the cut soil from the drum cutter. The working principles are as follows: at the front half of the drum cutter, soil is cut by the array of cutting tools. As the drum rotates, the cut soil is transported to the aft half, where it is flushed out by high-pressure jets fed by a static jet feed pipe, situated along the center of the drum. During pre-trenching, where retaining the soil within the trench is desired, the soil-water mixture is left behind the drum cutter. Alternatively, the mixture can be transported away from the trench using an additional evacuation chamber.

The open cutter design, combined with the principle of blowing rather than suction for soil removal, significantly reduces the risk of clogging. Its simple, open structure with minimal surface area offers few opportunities for soil to adhere, especially under the influence of the high-energy jets directed at the cut soil.

Maximizing Rock and Boulder Excavation with Open Drum Design

An open drum design is not only crucial for efficient soil transport but also for handling boulders. As noted in the chain cutter evaluation, one limitation in dealing with boulders is the lack of space within the chain to grip and transport them. The large spokes in the open drum design provide space for boulders to be captured at the front and expelled at the back of the drum cutter. In scenarios where a boulder is firmly embedded in the clay matrix, the robust drum cutters are capable of cutting through it. The drum cutter's design allows for the addition of significant inertia to the system, or the use of electric motors to drive the drums, similar to the cutter heads of modern high-power CSD dredgers. This not only enhances efficiency but also reduces the risk of stalling when encountering boulders, thanks to the high inertia provided by the electric motor and gearbox.

The open drum design plays a crucial role not only in handling boulders but also in excavating certain rock types like limestone and sandstone, especially when they are discontinuous.

The open drum's large internal volume allows for capturing and transporting boulders.

Frontal jets can be activated to enhance production while minimizing wear and tear.

In such cases, a ripping excavation method can be employed. Ripping occurs when the cutting tool (bit or pick point) loosens the blocks of rock bound by the natural discontinuities within the rock mass. In this mode, the cutting tools primarily function to dislodge these rock blocks, which are then transported out of the trench.

However, this excavation mode is only effective when the block size is sufficiently small relative to the drum. If the blocks are too large, milling of the rock will occur to fragment the blocks into smaller sizes for removal from the trench. However, ripping is a significantly more productive excavation process, making it essential to have an open drum design with the maximum possible transport volume in these discontinuous rocky soils to ensure optimal efficiency.

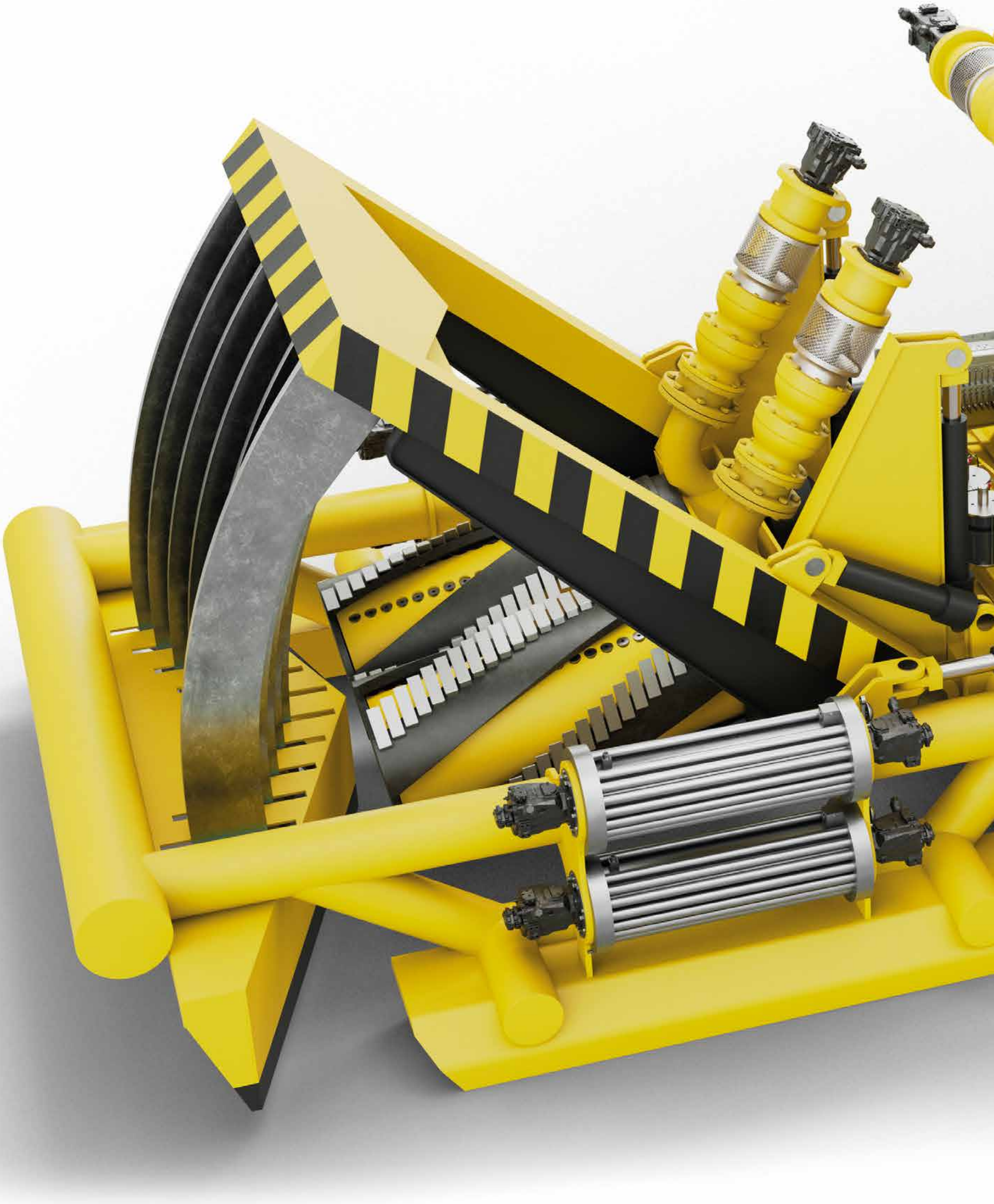
Drum Cutter Versatility Across Soil Types

Trenching often involves encountering hard seabeds with a sandy top layer. While the drum cutter is capable of mechanically cutting through this layer, hydraulic jetting is more efficient and reduces wear and tear. To optimize sand handling, nozzles can be activated at the front of the jetting pipe. The jet streams from these frontal jets protrude through the open drum cutter, allowing the sandy soil layer to be jetted rather than mechanically cut.

As mentioned in the previous section, the drum cutter can be equipped to handle harder rocky soils. By fitting the appropriate cutting tools, such as point-attack picks, rocky seabeds with strengths up to 20 MPa can be cut effectively. In some cases, a combination of cutting tool types is beneficial. For example, in boulder clays, a point-attack pick can be combined with a flared chisel. The point-attack pick, designed to cut through boulders, can be set up with a slightly greater circumferential cutting path than the flared chisels. This setup maximizes production in clay while effectively handling boulders.

Efficient Soil Evacuation Principles

During pre-trenching, the soil may be left within the trench, but it is also possible to transport the soil out of the trench. The drum cutter unit can be extended with soil evacuation channels that use low-pressure, high-volume flow nozzles to blow the soil flushed out of the drum cutters upward, where it is guided through a channel to the side of the trencher. For short-distance transport of a soil-water slurry, blowing is far more effective than suction. This approach minimizes the risk of clogging in the evacuation channel while keeping energy requirements low. This energy efficiency is further enhanced by utilizing part of the jet water from the cleaning nozzles, effectively repurposing the kinetic energy of this water for soil transportation.




seatools

5. Benefits and Impact Analysis

The pre-cutting and clearance method in subsea cable installation revolutionizes how hard soils and complex seabeds are managed. It boosts cable burial efficiency, enhances cable safety, reduces total costs, and lowers environmental impact, making offshore wind projects more sustainable and aligned with cleaner energy goals.

5.1 Improved Cable Safety

The pre-cutting and clearing of the seabed, which enables the use of a jet trencher in hard soil conditions, represents a significant advancement in cable protection by offering superior burial performance compared to traditional methods in these challenging environments. Superior burial performance, particularly in consistently meeting the specified burial depth, is achieved because the burial process is highly unlikely to be hindered by obstructions. Additionally, well-understood soil conditions and fully jettable seabed allow for the effective use of a single jetting tool along most, if not the entire, cable route.

The jet trencher further enhances burial performance by eliminating the need for cable loading and unloading, as required with mechanical trenchers. This reduces the occurrence of short cable sections being left unburied, which would otherwise require remedial work. The reduction in cable manipula-

Replacing a mechanical trencher with a jet trencher significantly enhances cable safety.

tion not only improves burial performance but also significantly decreases the risk of cable damage. Cable damage becomes a significant risk when cable parameters are exceeded, especially when the cable is locked into tools like mechanical trenchers and ploughs, where pulling forces can be transferred to the cable, potentially leading to mechanical damage. Minimizing cable manipulation is particularly important for the increasingly popular export cable bundles, which are heavier and stiffer than conventional export cables. These stiffer bundles generate more resistance when running through a cable highway, and this increased resistance can lead to running bights ahead of the trencher, complicating the process of achieving the required burial depths.

In contrast, a jet trencher eliminates the need to significantly raise, load, or lock the cable into the tool, as is necessary with mechanical trenchers and ploughs. Essentially, a jet trencher can operate with little to no contact or manipulation of the cable. While it may sometimes be beneficial to use a depressor for cable localization or guidance, when properly designed and operated, this should pose no risk to the cable.

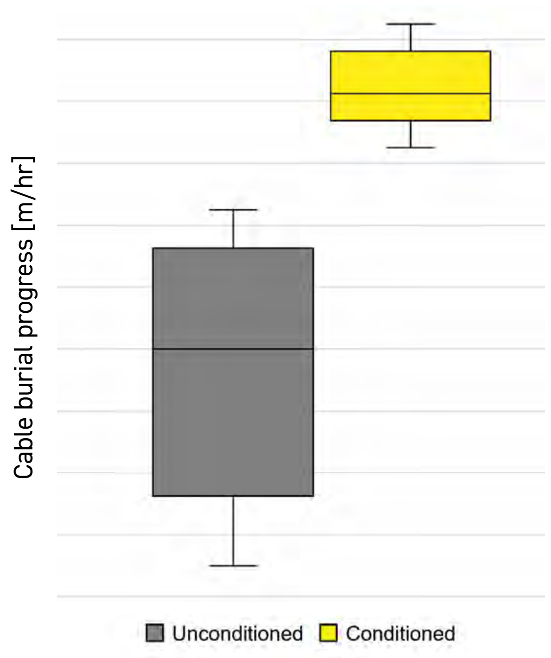
5.2 Minimizing Construction Risk

The installation of inter-array and export cables in offshore wind farms is a critical phase that can be significantly impacted by adverse soil conditions, such as hard seabeds or large boulders. These conditions can complicate cable laying and burial, leading to increased risks of damage, delays, and costly remedial works. Developers invest heavily in geotechnical surveys, advanced modeling, and contingency planning to mitigate these risks, recognizing that cable installation is typically on the critical path of the project schedule. Delays in this phase can cascade into broader project delays, resulting in substantial daily costs that can reach up to €1 million, along with severe financial repercussions, including missed first power dates, penalties, lost revenue, and potential damage to the developer's financial standing and market reputation.

The newly developed pre-cutting and clearance tool has been specifically designed to address these risks. It effectively mitigates soil and obstacle risks by loosening the soil, fully pre-cutting the seabed, and removing obstacles along the entire cable trajectory. Additionally, the tool provides soil resistance data along the entire path, both before and after the cutting and clearing pass. By comparing the towing force of the tool with the soil resistance measured by the aft ripper frame, it verifies that the soil resistance has been reduced to a sufficiently low level for successful cable burial via jetting.

In addition to addressing soil and obstacle-related risks, the tool also reduces weather-related risks. Jetting pre-conditioned soils, whether sandy, clay, or any other type, allows for significantly higher trenching speeds compared to unconditioned seabeds. A shorter burial campaign reduces exposure to adverse weather conditions, thereby lowering the "Waiting on Weather" risk. Moreover, the conditioned seabed enables the use of simpler jet trenchers, which are typically smaller and lighter than mechanical or hybrid trenchers, thus expanding the launch and recovery windows and further minimizing weather-related risks.

Cable burial progress - unconditioned vs conditioned seabed



"The tool provides soil resistance data along the entire path, both before and after the cutting and clearing pass.

Furthermore, by reducing uncertainties associated with soil conditions, this tool allows for a smaller risk mark-up in the project, whether on the developer's side or for the installation contractor. This reduction in risk ultimately leads to a more favorable business case for all stakeholders involved.

This innovative approach and technology are crucial for ensuring seamless cable installation while safeguarding the project's schedule and budget. The accompanying box plot illustrates this by comparing the anticipated progress rates and their variability between two methods: traditional cable burial in hard soil using current trenching technologies in an unconditioned seabed with partially unknown soil conditions, and jet trenching in a pre-conditioned seabed with fully known soil conditions. The latter method allows for significantly higher average progress speeds and considerably lower variability, resulting in shorter construction times and more reliable offshore construction schedules.

5.3 Improved Cable TOTEX

The use of a pre-cutting and clearance tool in subsea cable installation has the potential to significantly reduce the cost in various ways. One way is by enabling higher burial speeds during the cable lay and burial operations. This efficiency is particularly pronounced in clay soils, but even in typically jettable soils, pre-conditioning the seabed through jetting with rippers can provide substantial benefits. Field data shows that jet production in dense sand can be up to four times less efficient than in loose sand, due to the higher shear strength and lower permeability of dense sand, which make it resistant to jetting. However, by conducting a pre-conditioning pass with a less advanced and more cost-effective vessel, such as an anchor handler, these challenges can be mitigated at a lower cost compared to using a more expensive cable lay vessel (CLV) or trenching support vessel (TSV). This approach not only reduces the need for costly vessels but also allows for a more predictable and tightly scheduled operation, avoiding delays and rescheduling that could drive up costs.

Furthermore, pre-cutting and clearance tools contribute to cost savings by ensuring that a higher percentage of the cable is laid at the required burial depth, thereby minimizing the need for expensive remedial work, such as subsea rock installation. The method also allows for the cable burial campaign to be executed with a single jet trenching spread, rather than multiple spreads, reducing the number of mobilizations required. This reduction in mobilizations not only lowers costs but also shortens the overall duration of the burial campaign.

Cable installation vessels are increasingly vital assets for the industry, with their efficient deployment becoming ever more crucial for future operations.

5.4 Reduced Environmental Impact

The environmental impact of cable burial in offshore wind farm projects is increasingly critical, driven by the need to meet Environmental Impact Assessments (EIA) and permitting requirements. These assessments, which evaluate potential impacts like vessel emissions, are essential for securing regulatory approvals. The introduction of a pre-cutting and clearance tool offers a significant opportunity to reduce NOx and CO2 emissions from the cable installation process. While this approach requires an additional campaign during the construction phase, it is expected to result in a net reduction in vessel days. Additionally, the burial process becomes much more efficient, with energy gains from combining active and passive cutting estimated to be 2 to 4 times greater. Given the MegaWatt-scale of these operations, this improvement leads to a considerable reduction in emissions. Ultimately, these advancements not only help in minimizing the project's environmental footprint but also align with broader sustainability goals and regulatory demands, supporting the transition to cleaner energy.

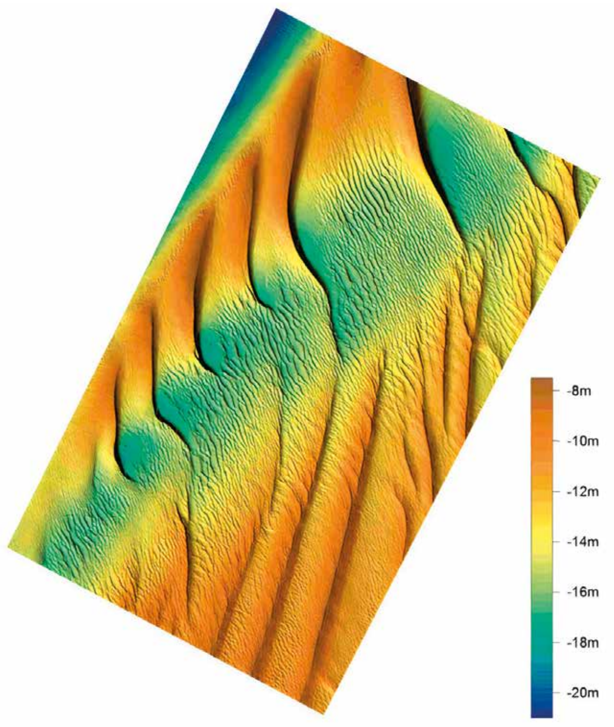
> **This approach not only reduces the need for costly vessels but also allows for a more predictable and tightly scheduled operation, avoiding delays and rescheduling that could drive up costs.**

6. Limitations and Challenges

While the pre-cutting and clearance technology offers significant advantages in cable burial for offshore wind farm projects, it is not without its limitations and challenges. Understanding these constraints is essential for optimizing its application and integrating it effectively into the broader construction process.

Trench Depth Limitations

One of the primary limitations of the pre-cutting tool is its capacity to achieve significant trench depths. Although, in theory, the design of the tool can be scaled to achieve burial depths of for instance up to 5 meters, practical considerations make this less feasible. A tool capable of such depth would be exceedingly large and difficult to handle, posing operational challenges. Moreover, excessive burial depths are typically required only for short distances, such as in sandwave areas, surf zones, or shipping lanes. In these cases, conventional trenching methods may still be necessary, or sandwaves may need to be removed before the pre-conditioning campaign can commence.



Leveling of sandwave areas is essential before initiating pre-conditioning operations.

Boulder Management Challenges

Another limitation of the pre-cutting tool is its management of boulders extracted from the seabed. After being ripped out, the tool pushes these boulders to either side of the vehicle, potentially leaving a trail of boulders along the seabed. In many cases, particularly when larger trenchers are used for the actual cable burial, these displaced boulders will still need to be removed to create an obstacle-free cable corridor. This necessitates additional boulder clearance efforts to ensure that the cable burial can be performed without obstruction.

Typically, boulder clearance campaigns are already conducted where surface boulders are present. Integrating the removal of unburied boulders from the subsurface during this phase can be cost-effective, as it prevents the need for additional mobilizations. However, this requires careful planning and coordination to ensure that all obstacles are adequately addressed.

The Importance of Early Pre-Conditioning Execution

Timing is a critical factor in the effective use of the pre-cutting and clearance tool. Performing this pre-conditioning phase early in the construction process, before the installation of offshore wind foundations, seems to be crucial. Maneuvering the towed tool between installed foundations for pre-conditioning inter-array cable trajectories becomes significantly more challenging and less efficient. Conducting this campaign early, before foundations are in place, ensures smoother execution and minimizes the risk of delays or complications later in the construction timeline.

Adapting the Jetting Process to Address Altered Soil Dynamics

It is important to note that the jetting process may need to be adapted to the conditioned soil in certain cases. For example, in a seabed composed of clay that has been cut into smaller clay fragments, these clay particles have a significantly shorter settling time after fluidization by jetting compared to, for instance, sand particles. If this short settling time is not accounted for in the jetting configuration design, there is a potential risk that the soil could settle before the cable reaches the required burial depth. Therefore, this factor must be considered through proper soil mechanical analysis. As a result, the jetting configuration might need to include two or three jetting swords (front, mid, and aft) to keep the relatively heavy clay particles elevated until the cable reaches the desired burial depth.

However, the short settling time also has its advantages. In some cases, the cable tends to move upwards after the trencher has passed, for instance due to tension in the cable. In cases where jetting occurs in soils with a long settling time, such as fine sand, the soil can remain fluid for an extended period, increasing the risk of the cable moving upwards, even with the use of depressors. A shorter settling time means the soil settles more quickly after the jet swords pass, reducing the chances of the cable movement and ensuring a greater depth of burial.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7. Conclusion

In conclusion, the introduction of pre-cutting and clearance technology marks a significant advancement in the field of subsea cable installation. By addressing the shortcomings of traditional methods and offering a more efficient, reliable, and environmentally friendly solution, this technology is poised to play a critical role in the future of offshore wind farm development. As the industry continues to grow and expand into more challenging environments, the adoption of such innovative approaches will be essential to meeting global renewable energy targets and ensuring the long-term success of offshore wind projects. The benefits of this technology, from improved safety and reduced risks to lower costs and environmental impacts, make it a valuable addition to the toolkit of offshore wind developers and contractors alike.

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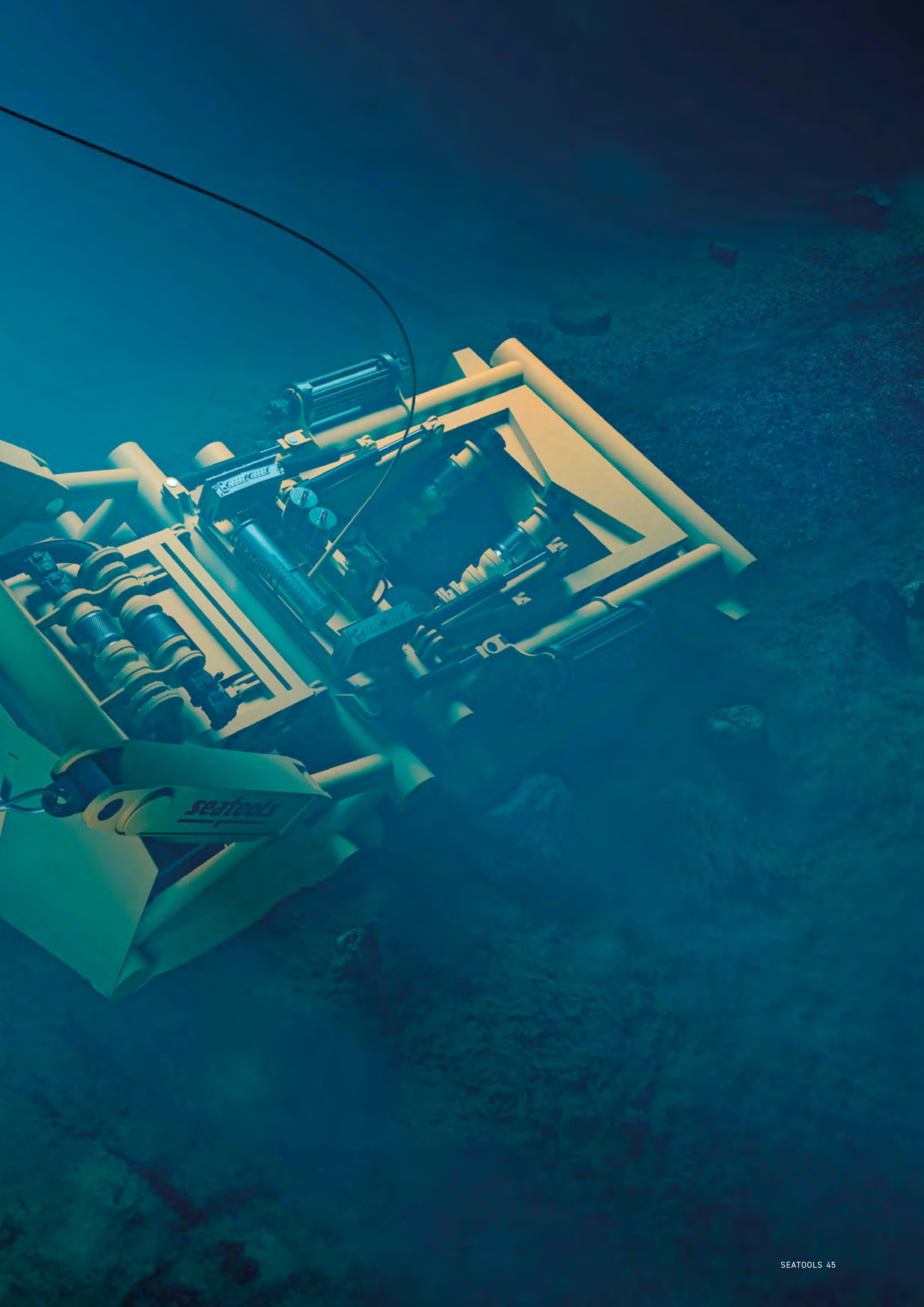

seatools

8. About Seatools

A Team of Specialists

Founded in 1999, Seatools was established by a team of specialists with a wealth of experience in underwater technology. From the outset, Seatools' core activity lies in the design and manufacturing of industrial-quality subsea equipment. This ranges from individual sensors to sizable subsea equipment, including Remote Operated Vehicle (ROV) spreads.

Based in the Netherlands, Seatools serves the following worldwide markets:

- Offshore renewables
- Dredging
- Deep-sea mining
- Offshore oil and gas
- Civil underwater

Approach

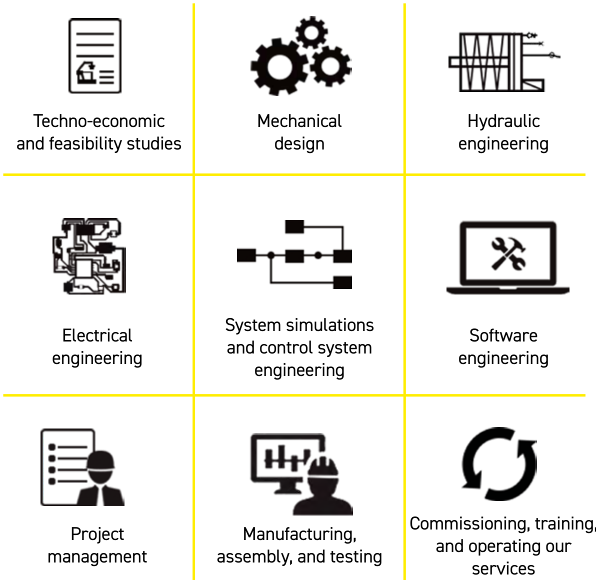
Generally, the markets that we serve are characterized by a high capital intensity, challenging conditions, and 24/7 operations at remote locations. To align with these conditions, our approach is based on two fundamental principles: multidisciplinary and first-time-right.

Multidisciplinary

We believe that only a multidisciplinary engineering approach will deliver innovative and high-quality, custom-made solutions in a time frame that serves our clients. This means we accommodate all required engineering disciplines in house. We are able to combine disciplines in an effective way and provide customers with one-stop subsea solutions.

First-time-right

In the capital intensive industries that our clients operate in, elaborate on-site testing or experimenting is out of the question. To ensure proper functioning, rapid commissioning, and quick start-up of our subsea equipment solutions, Seatools adopts a first-time-right philosophy which relates to a variety of deeply-routed principles and routines which guarantee our solutions are first-time-right.



Clients

Equipping industry leaders

Allseas

BAUER

Boskalis

BW Offshore

CDWE
台船環海風電工程公司

DB

DEME

H
MARINE CONTRACTORS

Jan De Nul
GROUP

OCEAN INFINITY

subsea 7

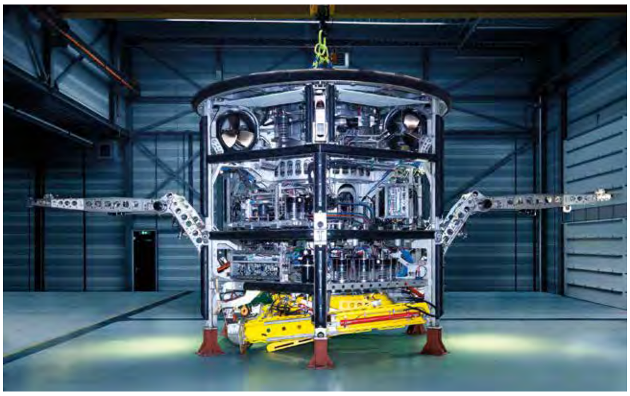
Van Oord
Marine ingenuity

Track record

Some highlights from our relatively short existence

Pre-piling template
Heerema Marine Contractors

Seatools provided metrology, controls, and hydraulic systems for this pre-piling template, ensuring precise installation of pin piles for jacket foundations.



Fall pipe ROV
DEME

Highly automated fall pipe ROV with highly redundant system architecture.

Remote offshore monitoring system
The Ocean Cleanup

Remote offshore monitoring system for the first-ever ocean cleanup system.

Fall pipe ROV
Boskalis

Highly innovative fall pipe ROV for precision rock installation. Executed with integrated survey ROV which features full DP functionalities, and can dock and undock fully automatically.

Nodule collector vehicle
Allseas

Pioneering nodule collector vehicle. Seatools carried out the engineering, manufacturing, and qualification of the electronics, controls, and hydraulics.

Nodule collector vehicle
GSR

Prototype nodule collector designed to verify the effectiveness of the collection process. Design and delivery of the vehicle's electronics, instrumentation, and hydraulics.

All-electric diamond wire saw
1Diamond

All-electric subsea diamond wire saw designed as a emergency response tool for use in water depths of up to 3000 meters

Pipeline trencher
MRTS

Revolutionary subsea pipeline trencher suitable for both pre- and post-lay subsea trenching in hard soil conditions.

Pre-piling template
CDWE

Seatools provided metrology, controls, and hydraulic systems for this pre-piling template, ensuring precise installation of pin piles for jacket foundations

Deep water excavation grab
Boskalis / DEME

Innovate deep-water excavation system with high level of automation. Seatools designed and built the grab-positioning ROV and its control system, including full 3D motion compensation.

Remote cleaning machines
DCN

Remote cleaning machines for cleaning of power plant cooling water intakes.

AHC gangway
Offshore solutions

The first heave-compensated gangway in the offshore industry, ensuring the secure transfer of personnel to and from offshore structures.

9. About the Authors

Bruno Tack

Bruno Tack, the founder of Innovate2dredge, has over 30 years of experience in dredging technology, specializing in addressing challenging soil conditions such as stiff clay, compact soils, and rock formations. Over the course of his career, he has worked on improving dredging operations by developing and implementing tools and techniques designed to handle difficult conditions in the industry.
Bruno has played a key role in developing various patented dragheads and cutting heads, which have been successfully deployed in major dredging projects around the world. These inventions have improved production efficiency and established new standards within the industry. His experience in both the design and practical application of these technologies has made him a recognized expert in the field of dredging.

Johan Sol

Johan Sol is an experienced business development professional with over a decade of experience in the subsea technology and renewable energy sectors. As the Business Development Manager at Seatools, he focuses on market research, client engagement, and driving the development of innovative technologies. Johan has contributed significantly to the development of advanced subsea trenching technologies designed to enhance the cost efficiency of cable installation. In addition to his management role, Johan serves on the Supervisory Board at Seatools, where he provides strategic oversight, supports key decisions, and helps guide the company toward sustainable growth and innovation. He holds a Master of Science in Business Studies and a Bachelor of Science in Mechanical Engineering.

Version 1.0

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