Fall Pipe ROV Trenching Conversion

Conceptual design of an ROV trenching tool and the development of a mathematical model to predict trenching performances

MSc Thesis Report
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Section of Dredging Engineering

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Under the authority of:
TIDEWAY OFFSHORE SOLUTIONS
Abstract

This version of the thesis only covers the non-confidential part of the report.

Tideway, as an offshore contractor, is often involved during the construction of an offshore wind farm to carry out cable burial and/or rock placement operations. The process of burying a cable, by means of a trencher, is until now executed by subcontractors. Tideway considers conducting the cable burial proceedings themselves, rather than hire a subcontractor. The goal of this research is to identify whether it is feasible to integrate burial equipment into the fall pipe ROV of the Flintstone, such that Tideway can carry out both burial and rock placement operations, as separate activities, using a single vessel.

A literature study is performed in order to produce a qualitative analysis of the existing jet trenching theory, and revealed that both the relationship between jet-production and total momentum flux of a jet system (Vlasblom, 2003) and the mathematical relationships for moving jets (Yeh et al., 2008), can serve as the basis for a computational model. Furthermore, an overview of the main components of an ROV jet trencher is added to the report.

A mathematical model is built in order predict the trench performances on the basis of the available hydraulic power. This model contains three different calculations methods, which are based on the collected theory, and provides a range of achievable burial depth versus ROV transit velocity, within which the actual trench performances are expected.
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Nomenclature

ABBREVIATIONS
AHC  Active Heave Compensation
DP   Dynamically Positioned
DSV  Diving Support Vessel
E-pod  Electronics-pod
LARS Launch and Recovery Systems
LTP  Lower Telescope Pipe
MFE  Mass Flow Excavator
ROV  Remotely Operated Vehicle

NOTATIONS

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<td>A_trench</td>
<td>Cross-sectional area trench</td>
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<td>b</td>
<td>Effective width of the turbulent layer</td>
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Chapter 1 Introduction

The offshore industry consists of a wide variety of projects and activities. In the early days, the offshore industry main activity was the search for oil and gas. From the 1920s mankind went offshore in their quest for oil and gas and it was Kerr-McGee in 1947 who drilled the first well out of sight of land. Nowadays the offshore activities range from drilling and pipelaying to the installation of offshore wind farms, rock placement operations and creating artificial islands by means of dredging. Often some kind of protection is required, varying from scour protection of offshore structures to cable protection by means of cable burial to prevent damage by fishing trawlers, trailing anchors, buckling and lost cargo. If circumstances indicate cable burial is not possible or inadequate, cable protection by rock dumping may offer a solution.

Projects executed in the past (for instance at the Thornton Bank Offshore Wind Farm, 30 km from the Belgium coast line) show that burying a cable in the seabed is a reliable and cost effective method to protect a cable against external threats. Various techniques can be used to bury the cable, such as mechanical trenching, ploughing and jet trenchers. During the last years, cable burial by utilizing an ROV trencher fitted with jet swords to fluidize the seabed gained increasing importance. Instead of performing the burial in two separate activities of excavation and backfilling, the jet trencher temporary liquefies the seabed, which allows the cable to sink into the seabed before being covered with settling sand particles.

Rock dumping is also a well-known technology, usually applied in areas where it is difficult to provide sufficient protection for the cables by conventional methods. Areas with a rough seabed or strong currents can prevent the deployability of cable burial equipment. Also a hard seabed can prevent the effectiveness of cable burial equipment. In such environment, creating a rock berm by continuously rock dumping through a fall pipe provides an effective alternative of cable protection. For rock placement operations, Tideway employs fall pipe vessels, equipped with centrally mounted vertical fall pipe with a special Remotely Operated Vehicle (ROV) at the lower end, for accurate positioning.

Often protection of a cable is achieved by partial burial, and completed by rock placement where burial is not feasible or only partially successful.

The objective of this study is to develop a concept to combine burial and rock placement operations, such that they can be carried out, as separate activities, using a single vessel by integrating the burial equipment into the fall pipe ROV. A feasibility study will determine whether integrating burial equipment into the fall pipe ROV is feasible.

1.1 Problem description

Upon installation of a cable on the seabed it requires protection usually through burial into the seabed. If conventional burial methods are inadequate, rock placement maybe applied to provide the cover required.
In general, burial of cables is carried out using a diving support vessel, whilst rock placements are conducted by a fall pipe vessel. Mobilizing a second vessel, if it turns out cable burial is inadequate on a certain part of the scope, is an expensive resolution. By integrating burial equipment into the fall pipe ROV, a single vessel is capable to carry out either cable burial as rock placement operations and consequently reduces the project cost.

1.2 Tideway Offshore Solutions

Tideway Offshore Solutions is a company specialized in offshore dredging, landfall construction, pipeline stabilization and rock placement operations. It is based in Breda in the Netherlands and part of the Belgium based company DEME. Since the establishment in 1991, Tideway is characterized by both its youth and experience.

As a precision rock placement contractor, Tideway works for oil, gas and renewable operations all over the world. Pipeline-related services include scour protection, pipeline protection/stabilization against anchor damage or trawlers boards, upheaval buckling prevention and insulation of pipelines.

Tideway is the owner and operator of four Dynamically Positioned (D.P.) rock placement vessels: the side stone dumping vessel Pompei with a loading capacity of approximately 1,500 tons and fall pipe vessels Seahorse, with a loading capacity of approximately 18,500 tons, Rollingstone, with a loading capacity of approximately 11,500 , and the newest ice-class vessel Flintstone with a loading capacity of approximately 20,000 tons.

1.3 Rock placement vessels

Fall pipe vessels are developed for rock placement operations in deeper water. Side stone dumping methods, where large amounts of stones are simply pushed over the side of the ship, are primarily used in water depths up to 50 metres, because the accuracy of rock placement from the water surface is limited. On the contrary, fall pipe vessels are designed to place rocks in deeper water with great precision. The vessels are equipped with centrally mounted vertical fall pipes with a special ROV attached at the lower end, for accurate positioning. Besides positioning equipment, the ROV has a sophisticated range of technologies such as camera’s and survey equipment.

![Figure 1.1: Rock dumping methods](image-url)
1.4 Thesis goal

The main goal of this Master thesis is to develop a concept to combine burial and rock placement operations such that they can be carried out, as separate activities, using a single vessel by integrating the burial equipment into the fall pipe ROV.

The main goal will be achieved through the following sub goals:

- A literature study will be performed in order to produce a qualitative analysis of the existing jet trenching theory.
- Subsequently, the trench performances will be predicted based on the theory in the literature report. The theory will also be used to create a computational model.

The main research questions are:

1. Based on the available hydraulic power of the fall pipe ROV, is it feasible to utilize the ROV as a trencher?
2. How can the fall pipe ROV be converted, such that it can operate as a trencher as well?

1.5 Boundary conditions

1.6 Structure Report

Chapter 2 is confidential.

An overview of the main components of an ROV jet trencher is given in chapter 3.

In chapter 4 the collected theory, ranging from the fundamental principles of submerged jets to sophisticated jet trench models, is described.

In chapter 5, three different calculation methods, used to predict the trench performances, are explained. Additionally, a number of general calculations are explained that are applicable to all three of the calculation methods.

Chapter 6 and 7 are confidential.

This thesis report is concluded in chapter 8, which contains the conclusions and recommendations for future research.
Chapter 2  D.P. fall pipe vessel ‘Flintstone’

*The content of this chapter is confidential*
Chapter 3  Description ROV jet trenchers

Jetting is widely used for burial of cables near crossings of existing pipelines and cables, as well as in very soft clays which not may be able to support a plow. Jet plows have an ability to bury a cable already laid on the seabed and able to operate close to existing installations with minimum risk of damage.

Jet trencher ROVs of the type shown in Figure 3.1 are often equipped with 400-1000hp installed power, can provide 80-600 l/s at a jetting pressure of 6-15 bar and can be propelled at approximately 0.5 m/s. These systems have been designed to offer burial in soils up to an undrained shear strength of 100 kPa and trench depths of up to 3 meters in non-cohesive seabed conditions. Although primarily tracked trenchers, these vehicles are capable of operating in free-fly mode to carry out trenching.

The jetting tool has twin legged parallel jet swords, fitted with water nozzles, and uses pressurized sea water to fluidize sediment long enough to deposit the cable which sinks down through a slot. The water nozzles are directed to maximize the trench depth. The cable settles into the trench to the planned burial depth under its own weight.

3.1 ROV frame

Most workclass ROVs have a rectangular configuration and an open Al-based frame that supports and protects the thruster for propulsion, underwater cameras for monitoring, lights and other instruments such as closed-circuit television for observation, the gyrocompass for heading detection, depth gauges for depth detection, an echo-sounding device for altitude detection, and scanning sonars for environment inspection.

3.2 Buoyancy

Often ROVs are near neutral buoyancy underwater. They do have a little buoyancy to make sure the ROVs can float to the water surface during emergency conditions or if they break. This positive buoyancy would be in the range of 23 kg for work-class vehicles. Another reason for this is to allow near-bottom manoeuvring without thrusting up, forcing water down, thus stirring up sediments. An ROV moves downwards with a vertical thruster.

Jet trenchers, on the other hand, usually have an submerged weight of 0-15 kN for trenching operations. With the aid of buoyancy tanks it is possible to achieve neutral buoyancy, where the vehicle free-swims from surface to bottom and back utilizing dedicated thrusters. Once on the work site, the system lands on the bottom and is ballasted to for example 1500 kg in-water weight. The switch is made from ‘free fly’ mode to ‘trencher’ or ‘track’ mode.
Generally, the buoyancy is provided by synthetic foam material above the Al-based ROV frame. The flotation foam should maintain its form and resistance to water pressure at the anticipated operating depth. The higher buoyancy center and lower weight of gravity ensure that the ROV provides good stability performance.

3.3 Track system

The open center track belt design, driven by a sprocket in the center of the track, consists of two flat rubber belts bolted together with cast aluminum and rubber grousers. The open center provides space for soil and debris to fall clear of the drive sprocket, thus preventing a buildup of material in the drive area which could cause excessive loading of the motor, belt stretch or wear, slippage and jumping of the sprocket.

The force to drive the track is applied directly from the sprocket teeth to the grousers. Port and starboard hydraulic drive motors are used to power the drive sprockets, with an internal speed resolver employed to monitor track speed. A framework supports the track system components and is attached to the trencher lower frame.

3.4 Thrusters

Being the main part of an ROV propulsion system in free fly mode, the underwater thrusters are arranged in several ways to allow for proper maneuverability and controllability of the vehicle through asymmetrical thrusting and varying the amount of thrust. The thrusters need to be adequately sized for countering all of the forces acting on the vehicle, including hydrodynamic and workload forces. There are a wide range of thrusters from electrically powered to hydraulically powered. In general, electrical thrusters are used for smaller vehicles, while the hydraulic ones are used for larger and workclass vehicles, like a jet trencher.

3.5 Jet sword system

The jet system (Figure 3.2) consists of four independently powered motor/pump assemblies feeding the two independently deployed jet swords. Each sword contains a high pressure waterjet supply, used to supply the high pressure cutting jets, and a low pressure waterjet supply, used to supply the clearing jets.

![Figure 3.2: Jet swords](image-url)
3.5.1 Motor sump assemblies

The low pressure pumps are single stage centrifugal turbine pumps, typically used for well pump service. Each pump is designed to operate, for example, at 2.0 bar and 180 l/s. The high pressure pumps are two stage centrifugal pumps, also used typically for well pump service. Each pump is designed to operate, for example, at 9.0 bar and 80 l/s.

3.5.2 Jet swords positioning system

The sword system is built into a frame, and consists of two sets of individual operated sword arrangements built into a common horizontal guide rail. Each sword arrangement can individually be rotated from the stowed parking position to the operating position using hydraulic cylinders. The cylinders are hydraulically locked during jetting operations, with a safety system to prevent overload due to overspeed during trenching operations.

In addition the swords can be lifted vertically in order to vary the burial depth, and also move sideways to increase the trenching width from approximately 100 mm to 1,200 mm. A set of linear sensors together with software mathematics gives the trencher pilot continuously updating information about the sword depth and swords positions.

3.5.3 Jet swords

High and low pressure pumps feed each trenching sword. The high pressure water is used to cut or fluidize the soil ahead of and between the swords, and the low pressure water is used to clear the cut of fluidized soil from the continuous trench, also called backwashing. Jetting occurs beneath, around and ahead of the previously laid pipeline or cable. As the trench is cut, the flexible pipe or cable falls into the trench in a lazy ‘S’ curve (Figure 3.3).

1) Positioning the trencher over the cable

2) Transition zone - Jet pumps are turned on and the swords are gradually lowered, while the trencher is moving forward. The cable is locally no longer supported and starts sinking into the fluidized seabed.

3) Maximum sword depth reached - Actual cable burial starts

Figure 3.3: Principle of lowering a cable
The 1.0-3.0 m port and starboard jet sword assemblies encapsulate both the high pressure fluidizing jet swords and the low pressure clearing jet swords. The high pressure swords each have 15-25 nozzles projecting forwards from the leading edge of the jet sword. The jet nozzles project into the soil at about 30° angle of attack (from the vertical) during operation. The high pressure swords extend all the way to the bottom of the trench. The nozzles are alternately directed slightly outward, clearing a path for the jet swords, and inward across the trench, fluidizing the soil between the arms.

The low pressure jet headers are contained in the after edge of the jet sword. The low pressure clearing water exits through three large diameter nozzles at the bottom of the trench. These nozzles are directed slightly toward the center of the trench, and create a large overall flow which tends to clear the fluidized soil from the area behind and between the arms.

### 3.6 Topside facilities

The operations platform for larger ROV systems could range from a drilling rig deck to the moon pool of a specialized dynamically positioned diver support vessel outfitted specifically for ROV operations. A suitable deck area and deck strength, external supplies, and ease of launch and recovery should be provided on deck for safe and efficient operation of ROVs.

To restrain ROV motion, while it is being lowered from the air to the water surface, a Launch and Recovery System (LARS) is used. This helps prevent, for example, damage to the umbilical by the bilge keel if side deployment is being used. The LARS consists of a winch, winch power unit, crane or A-frame with fixed block for large ROVs, and ROV guiding system, as shown in Figure 3.4.

![Figure 3.4: ROV Launch and Recovery System](image)

Generally speaking, launch and recovery activities can be achieved by a simple rope with uplift force. However, to facilitate the deployment and recovery of the rope, a reel/drum is used, and a motor to rotate the reel and provide the uplift force. The motor may be either a hydraulic or an electromotor with/without a gear box used to reduce the rotary speed and increase the torque force. The system of motor, reel/drum, base frame, and other ancillary
structures such as a brake and clutch is normally called a winch. A fixed block, sustained at the end of a crane boom/A-frame beam, is used to convert the upward direction of the required winch force to a downward direction in order to place the winch on a lower structure, for example, the deck.

3.7 Umbilical

The umbilical runs between the support vessel and the ROV and transports hydraulic/electrical power from the vessel to the ROV. In the opposite direction, gathered information is transferred from the ROV to the surface. The diameter of the umbilical should be minimized to reduce the drag forces due to waves and currents. Furthermore, the weight of the umbilical should be minimized to reduce the lifting requirements during launch and recovery of the ROV from the water to the surface. Depending upon design, the umbilical is employed as a lifting umbilical.

3.8 Jet trench operations

During trenching operations, the vehicle begins in a negatively buoyant condition, resting on the bottom and positioned over the pre-laid flexible pipe and cable with tracks parallel and on both sides of the pipe/cable. Jet swords are initially deployed from the stowed to the horizontal position, and then the jet water pumps are started. Trenching transition is then performed; it is necessary to minimize the possibility of product ‘freespan’ until full trench depth is reached. The duration of the transition is dependent on the product and the soil conditions.

As the trencher moves forward, soil fluidization occurs along the leading edge of the jet swords using the high pressure, low flow jets. Soil is evacuated from the leading edge of the trench by the clearing flow created by the high volume, low pressure clearing jets. Trenching is piloted using video cameras, sonar and a pipetracker sensor to maintain correct orientation between the trencher and the pre-laid pipe/cable.

Jet trenching performance is monitored by the system sensor equipment, and the trencher speed is manually adjusted by the operator to optimize trenching speed for the prevailing soil conditions. Optimal jetting speed for prevailing soil conditions can be established by monitoring track slippage, which is the difference between track speed and the transit speed. At the threshold of the onset of track slippage, trench excavation is usually occurring at the same rate as forward motion. Forward motion can only be achieved when soil removal had occurred. This is a factor of the light track weight displacement and bollard pull function of the vehicle. This operating principle serves to guarantee the integrity of the product being trenched.
Chapter 4  Literature review

4.1 Summary theory jet trench models

Over the years several theoretical jet trench models have been developed. Part of the knowledge on which these models are based is publicly available. An overview of the relevant theory for this thesis is presented below. Additional interesting knowledge, but not directly applied within the course of this study, is discussed in Appendix B.

4.1.1 Underwater sand bed erosion and internal jump formation by travelling plan jets

The objective is to bury cables and pipelines under a protective layer of sand, typically with a layer thickness of 1 to 2 m, in order to prevent damage by trailing anchors and/or fishing nets etc. The operation is often performed in a single pass using jet trencher ROVs. The product is first simply laid onto the sea bottom. The vehicle then uses the jetting system to inject high-speed water into the sand bed (see Figure 4.1). The jets scour a temporary trench, travelling with the vehicle, which allows the cable to descend into the sea bed before being buried under the re-depositing sand further downstream of the trench.

Motivated by practical applications and complications, an idealized variant of the jet trenching problem was examined (Perng and Capart, 2008). The action of a travelling plane jet was considered, moving steadily along an initially horizontal sediment bed composed of uniform sand. By neglecting transverse variations and assuming that the flow pattern had attained a steady state in a frame of reference attached to the jetting tool, the general unsteady three-dimensional flow (Figure 4.2) was reduced to a two-dimensional steady flow that is more readily amenable to theoretical and experimental study. Because actual jet trenching operations involve powerful jets acting on beds of relatively fine material (fine to medium sand), turbulent suspension was the only sediment pick-up and transport mechanism considered. (Appendix B.1)
Experimental procedure and observations

The bed erosion and sand suspension of a moving jet experiment are observed through the glass sidewall of the tank. After travelling some distance along the bed, a stable flow pattern and scour-hole shape are established, and translate to the left with the jetting tool without significant further deformation.

The different flow patterns produced when varying the speed of advance of the jetting tool relative to the sand bed are shown in Figure 4.3. The flow observed when the jetting tool is held stationary is presented in Figure 4.3(a). In this case, sand eroded from the bed forms two triangular heaps on both sides of a stationary scour hole. Within this leveed scour hole, a mixture of sand and water circulates counterclockwise. The bottom of the scour hole attains a dynamic equilibrium in which turbulent entrainment of sand from the bed is balanced by gravitational settling of and grains out of suspension.

When the jetting tool is moved along the bed, qualitatively different flow and scour patterns are obtained depending on the speed of advance. For very slow advance speed (Figure 4.3b), the jet-induced turbulent current separates from the bed after deflection by the scoured profile. After flowing along the curved bed in the form of a thin bottom layer, the sediment-laden jet fountains upwards, then rains down its suspended sediment.

Figure 4.3: Different flow patterns - varying speed of advance of a jetting tool (Perg and Capar, 2008)
In the case the jetting tool is moved slowly along the bed, the pattern of Figure 4.3(c) is observed. Close to jet impingement, the thin current flows along a steep trenching front where sand material is being continuously eroded from the bed. As it reaches the deepest portion of the travelling trench, the bottom current then thickens dramatically, undergoing an internal hydraulic jump. Upon expanding, the suspended sand layer adopts a thickness that exceeds the scour depth, and experiences a corresponding sudden slowdown of the longitudinal flow velocity.

Finally, as shown in Figure 4.3(d), a fast speed of advance produces a more elongated scour hole, in which the turbulent current forms a shooting flow that simultaneously entrains water from the ambient and interacts with the underlying sand bed. The current is erosional along about a quarter of the trench length, then depositional for the remaining three-quarters, until the suspended sand has settled out and the bed has recovered its original elevation. All along this course, the suspended sand current remains confined to a thin layer flowing rapidly along the bed.

4.1.2 Jet induced trenching operations

The paper of Vanden Berghe and Capart, (2008) examines the response of sandy seabeds undergoing trenching by steadily underwater jets as mounted on jet trenching machines.

They focused on the trenching process and post-trenched sand bed with the use of small-scale laboratory experiments. The processes observed include erosion and entrainment by the jet-induced longitudinal current, infill due to the breaching of the trench wall, and overspill resulting from lateral escape of the turbulent flow out of the trench. These processes are expected to act as well in the field where they may control burial depth and sediment loss from the trench.

A model, based on the gravity- and jet-driven turbidity currents theory, describes the flow of a turbulent layer of water and suspended sand along the sea bottom. It incorporates the following physical processes:

- entrainment of ambient water and sediment particles into the current
- damping of turbulence by stratification associated with the sediment suspension
- interaction of the current with sloping topography

Combined with a breaching model simulating the lateral infill of the trench, this model is able to assess the trench depth and the likely shape of the trench based on the tool travel rate, pump pressure and soil type. (Appendix B.2)

4.1.3 Development of a jet trenching model in sand

This paper of Vanden Berghe et al. (2011) presents the main principles of a jet trenching model applicable to realistic jetting configurations that has been developed based on earlier research focussing on idealised jetting configurations (Vanden Berghe, 2008). Specifically, oblique and upright swords featuring multiple jets of different orientations are considered here. The jet trenching model has been validated and calibrated on the basis of a set of laboratory small scale tests. The experiment analysed the parameters influencing the
trenching performance. It included the total jetting power, the progress rate of the trencher and the sand bed properties.

Introduction
The main issue of a trenching process is to choose the correct trencher and the appropriate trencher configuration in order to optimise the trenching process duration. The entire trench process duration is a function of the number of passes required to lower the product, the transit speed of the trencher, soil, pipeline and trencher properties.

The jet trenching model assesses the burial depth achieved after each pass of the trencher taking into account the trencher performance (available jetting power and sword configuration), the soil condition (grain size and density) and the product characteristics (weight and stiffness).

General description of the jet trenching model of Vanden Berghe
The jet trenching model is based on the combination of the two following models:
- The first model assesses the shape of the trench created by the jet trencher. This model is called the multiple jets trenching model (Appendix B.3).
- The second model computes the likely shape adopted by a pipeline or cable when the soil supporting it has been removed. This model is called the pipeline model.

The two models are combined in order to simulate the trenching process. The interaction between the two models allows the assessment of an appropriate trencher speed of advance and number of passes, for given soil, pipeline and trencher properties.

The main assumption of the model presented above is the independence of the trenching model and the pipeline model. The trenching model ignores the presence of the pipeline and the pipeline model does not consider the hydrodynamic forces induced by the jetting process in the computation of the pipeline deflection.

Pipeline deflection model of vanden Berghe
In order to assess the burial depth during trenching operations, it is required to compute the likely shape adopted by the pipeline or cable when the soil supporting it has been removed by the trencher. The assessment of the pipeline deflection into the trench is based on an elastic beam model of the pipeline.

The pipeline sinking into the trench is assumed equivalent to a hyperstatic cantilever beam uniformly loaded, in which the left-hand end is completely fixed and the right-hand end is restrained in rotation (see Figure 4.4). The left-hand end simulates the pipeline lying on the seabed whereas the right-hand end

Figure 4.4: Equivalent pipeline model
4. Literature review

represents the pipeline touchdown point in the trench. A lay tension is also applied at the right-hand position.

After touching the re-sedimentation front, the pipeline displacements are assumed to be restrained. No pipeline settling is assumed in the re-deposited sand that still may be liquefied.

The pipeline model described above can be resolved analytically. Because the lay tension in the pipeline applied a bending moment that depends on the pipeline deflection, the formulation required the use of a differential equation. This differential equation can be resolved analytically and Vanden Berghe obtained Eq. (4.1) for pipeline deflection.

\[
y(x) = - \left[ \frac{qL}{T} \sqrt{\frac{E}{T}} \sinh\left( \frac{E}{T} x \right) \right] \cosh\left( \frac{E}{T} x \right) - \tanh\left( \frac{E}{T} L \right) \sinh\left( \frac{E}{T} x \right) - 1 - \frac{q}{E} x^2 + \frac{qL}{T} x \quad (4.1)
\]

Where \( y \) = cable deflection (positive downwards) [m], \( q \) = submerged unit weight [N/m], \( T \) = lay tension [N], \( L \) = span length [m], \( E \) = elasticity modulus [N/m²], \( I \) = moment of inertia [m⁴] and \( x \) = distance from beginning of trench [m].

Table 4.1: Several cable and pipe properties

<table>
<thead>
<tr>
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<th>Pipe 1</th>
<th>Cable 2</th>
<th>Cable 3</th>
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<td>Submerged weight [N/m]</td>
<td>693</td>
<td>589</td>
<td>598.4</td>
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<td>Bending stiffness [N m²]</td>
<td>1.83E+07</td>
<td>7.94E+04</td>
<td>1.00E+05</td>
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<tr>
<td>Lay tension [N]</td>
<td>6.93E+02</td>
<td>1.5E+04</td>
<td>8.0E+03</td>
</tr>
</tbody>
</table>

The cable profiles, schematically shown in Table 4.1, are computed with Eq. (4.1) based on the cable properties shown in Table 4.1. The minimum span length associated with a cable deflection of 2m can be determined on the basis of Figure 4.5.

![Figure 4.5: Cable profiles](image-url)
4.2 Cable burial processes

This paragraph will give an overview of flow characteristics of submerged jets and describe different phases encountered during cable burial like scour formation, fluidization, transport and sedimentation.

4.2.1 Flow characteristics of submerged jets

Erosion by circular horizontal jets is one of the most common types of erosion by jets. The flow of circular jets has been widely investigated: Rajaratnam, (1976); Rajaratnam and Beltaos, (1977); Kobus et al., (1979). The MSc thesis report of Smalt (2013) presents a review and summarizes the flow characteristics of submerged jets. The spreading of a vertical circular jet is an important aspect in the design of jets and forms the base for creating erosion of granular material.

Diffusion of a submerged jet

The paper of Niven and Khalili (2010) describes the diffusion of a jet issuing into a body of the same fluid, as illustrated in Figure 4.6. Due to turbulent shear against the surrounding fluid, the jet spreads radially, producing three flow regions: a potential core of the original velocity $U_0$, a transition region beyond the core with dissimilar flow properties and a zone of established flow, with a decreasing axial velocity $U_m$ and similar velocity profiles (Albertson et al., 1950 and Abramovich, 1963).

![Diffusion of a submerged Jet](Rajaratnam, (1976))

In the first region, the potential core region, the flow extends from the nozzle exit while the fluid velocity remains constant to the original velocity $U_0$. Moreover, the flow diverges due to shear stress present as a consequence of the different velocity between the flow and surrounding fluid. The surrounding stagnant fluid will be accelerated, thereby increasing the total amount of flow. This process is called entrainment.

At a distance of approximately $6d_j$ from the jet, the flow reaches the fully developed region. Between those two layers there is the transition region with dissimilar flow properties.
Axial velocity in a free circular jet without impinging wall

In the established zone the turbulence generated at the boundaries between the jet flow and stagnant fluid has penetrated to the axis of the jet. The central velocity of the established zone $U_m$ decreases linearly with distance $x_j$ from the nozzle tip and can be described with Eq. (4.2):

$$\frac{u_m}{u_0} = \beta \frac{d_j}{x_j} \quad \text{for } x_j > 6.3d_j$$

(4.2)

Where $U_m$ is the axial velocity at the jet center of a free circular jet, $U_0$ is the exit velocity at the center of the nozzle outlet, $d_j$ is the nozzle diameter, $\beta = 6.3$ for both water and air jets (Albertson et al., 1950 and Rajaratnam, 1976) and $x_j$ is the distance from the nozzle tip.

A circular jet issuing into a medium of opposing flow also follows a linear relationship, but with a reduced diffusion constant, $\beta = 5.8$ (Abramovich, 1963 and Rajaratnam, 1976). Thus some degree of ‘jet shortening’ occurs due to action against the opposing flow.

Flow rates

With the fluid velocity determined and the area of the nozzle known, the flow rate at the nozzle exit, $Q_0$, can be calculated with Eq. (4.3):

$$Q_0 = C_d \frac{\pi d_j^2}{4} U_0$$

(4.3)

Where $C_d$ is the nozzle discharge coefficient. The discharge coefficient is the ratio of the actual discharge to the theoretical discharge of water through the orifice, i.e., the ratio of the mass flow rate at the discharge end of the nozzle to that of an ideal nozzle which expands an identical working fluid from the same initial conditions to the same exit pressure (Wikipedia, 2012).

The entrainment for the developed flow region can be described with a formula based on Eq. (4.2) (Rajaratnam, 1976):

$$\frac{Q_s}{Q_0} = 0.32 \frac{x_j}{d_j} \quad \text{for } x_j > 6.3d_j$$

(4.4)

Where $Q_s$ is the flow rate at a distance $x_j$ from the nozzle and the constant value $0.32$ is determined by Alberton et al. (1950).

Momentum flux

The flow that is issued from the nozzle creates a force, the total momentum flux, $I_0$. It is assumed that the momentum flux remains constant along the flow trajectory.

$$I_0 = \rho_f Q_0 U_0 = \text{constant}$$

(4.5)

Where $\rho_f$ is the fluid density.
Jet diffusion on a wall

The distance between the jet nozzle and the seabed is called the impingement height, \( h \). The impingement of a submerged turbulent water jet on a deformable, erodible boundary has been investigated in many studies (Rajaratnam and Beltaos, 1977; Rajaratnam, 1982; Aderibigbe and Rajaratnam, 1996).

If a jet impinges on a smooth surface the impingement- and the wall jet region are added to the free jet region (Figure 4.7). In the impingement region the flow hits the wall and it undergoes a significant deflection that turns the flow parallel to the wall. Once the flow is parallel to the wall, the region is called the wall jet region.

Rajaratnam and Beltaos (1977) conducted experiments with short impinging distances on solid boundaries. They proposed that for the impinging distance, \( h \), \( h>8.3 \cdot d \), the impinging distance is considered as 'large' and the characteristic length scale is the impinging distance \( h \). On the other hand, if \( h<5.5 \cdot d \), the impingement distance should be considered as 'small' and the characteristic length scale switches to the jet diameter \( d \). In this region close to the sediment surface, flow from the jet lies within the potential core, and is therefore unaffected by the impingement height.

Axial velocity with a large impingement distance

In the impingement region the jet will undergo a strong deflection due to the presence of a solid boundary. For a large impingement height \( (h>8.3 \cdot d) \), the jet will start to get affected by the presence of the seabed at \( x/y>0.86 \) (Rajaratnam and Beltaos, 1974). The axial velocity in that part of the impingement region, \( U_{m,h} \), is approximated with Eq. (4.6).

\[
\frac{u_{m,l}}{u_m} = 3.10 \frac{z_j}{h} \sqrt{1 - \frac{z_j}{h}}
\]  

(4.6)

Axial velocity with a small impingement distance

Moreover, Rajaratnam and Beltaos (1977) derived an equation after experimental research, which gives the axial velocity at the jet center, \( U_{m,s} \), for impinging distances \( h<5.5 \cdot d \).
4. Literature review

\[ \frac{u_{ms}}{u_0} = \frac{z/d_j}{1.1} \left( 2 - \frac{z/d_j}{1.1} \right) \]  

(4.7)

Where \( z \) is the distance from the seabed.

4.2.2 Scour formation

A jet near an erodible boundary, discharging water vertically downward towards the bed, causes scours. Scour, a specific form of erosion, is the removal of the granular bed material by hydrodynamic forces. Three different forms of erosion are described below.

- **Scour formation by external stationary jets**
  Scour of granular material by impinging vertical jets in a static situation has been studied extensively over the past 60 years (Rouse, 1940; Westrich and Kobus, 1973; Rajaratnam and Beltaos, 1977; Kobus et al., 1979; Mih, 1979; Rajaratnam, 1982; Aderibigbe and Rajaratnam, 1996). All have involved jets held at or above the sediment surface, also called an external jet.

- **Scour formation by internal stationary jets**
  Niven and Khalili (1998) did research concerning the effect of erosion caused by a downwardly-directed, internal jet. Due to the fact that in the course of this study, no use is made of this theory, this theory is explained in more detail in (Appendix B.4).

- **Scour formation by external moving jets**
  Yeh et al. (2008) investigated the topographic deformation due to the erosion of a sand bed impinged by an external moving submerged turbulent jet. A second approach is using the theory of Vlasblom (2003), which describes the relationship between jet-production and total momentum flux of a jet system.

**Scour formation by external stationary jets**

Scour on a movable bed is mainly a function of the jet velocity, \( U_0 \), jet diameter, \( d_j \), impinging distance, \( h \), and median bed grain size, \( D_{50} \). Rajaratnam and Beltaos, (1977) showed that the scour depth, \( \varepsilon_m \), and radius, \( r \), increases with time and eventually reaches an asymptotic (i.e. equilibrium) state. For a large impinging distance \((h>8.3 \cdot d_j)\), the equilibrium scour depth, \( \varepsilon_{m,\infty} \), and scour radius, \( r_{m,\infty} \), are proportional to an erosion parameter, \( E_c \), which is the ratio of the densimetric Froude number and the relative impinging distance \((h/d_j)\).

\[ E_c = \frac{U_0}{\sqrt{g D_{50}(\rho_{sed}-\rho_f)/\rho_f}} \cdot \frac{d_j}{h} \]  

(4.8)

Where \( \rho_{sed} \) is the density of the sediment. The erosion parameter is used as a measure of the intensity of erosion caused by a vertical impinging water jet.

The scour hole profile (Figure 4.8) in the equilibrium state is self-similar and can be described by an exponential equation. Rajaratnam, (1982) later reported that the scour hole...
radius is approximately constant in a water jet impinging to a sand bed system with an $E_c$ between 0.6 and 1.5. The profile consists of two stages: a ‘static’ or settled depth and a ‘dynamic’ or fluidised scour depth. The depth difference is caused by sedimentation of particles into the fluidised zone once the jet is turned off. This differences increases as the impingement height, $h$, decreases. The equations below are based on the ‘static’ case, after the jet is turned off.

\[
\begin{align*}
\epsilon_{m,\infty} &= 0.64(1.26E_c^{0.11} - 1) \cdot h & \text{(4.9)} \\
r_{1,\infty} &= 0.78(1.46E_c^{0.15} - 1) \cdot h & \text{for } E_c \leq 0.5 & \text{(4.10)} \\
r_{1,\infty} &= 0.78(0.22 + 0.20E_c) \cdot h & \text{for } 0.5 \leq E_c \leq 5.0 & \text{(4.11)}
\end{align*}
\]

These equations may be used when $h/d_J$ is around 6. By entering too small or large values for $h$, equations (4.9)-(4.11) provide unrealistic results. For $h=0$ the equilibrium scour depth is even zero, while this is actually not the case. On the other hand, the equilibrium scour depth will most likely be overestimated for too large values of $h$.

Moreover, extrapolating the formulae beyond $E_c=5$ without modification does not allow reliable predictions of the scour radius. Proposed modifications, based on trials with the MFE, by Cathie Associates (2013) provide a better match, but should not be considered as a validated design equation.

Based on the results of the trial tests (i.e. lower dependency of nozzle height than predicted using the relationship presented by Yeh et al.) and theoretical considerations, the following modifications were implemented into the scour depth equation proposed by Yeh et al (2008):

- Scour depth multiplied by $(0.76/h)^{0.5}$
Exponent 0.2 (instead of 0.11) on the erosion parameter $E_c$. An exponent 0.2 is commonly used in scour prediction models.

The resulting equation is:

$$
\varepsilon_{m,\infty} = 0.64 \sqrt[3]{\frac{0.76}{h} (1.26E_c^{0.2} - 1) \cdot h}
$$

(4.12)

Scour formation by external moving jets

According to Aderibigde and Rajaratnam (1996), jet scour may take hours or even days to reach its equilibrium scour depth. In contrary, moving jets are only for a short duration at the same location. Therefore, the maximum scour depth may not be the equilibrium scour depth of a stationary jet.

Yeh et al. (2008)

Yeh et al. (2008) proposed simple mathematical relationships for moving jets based on tests. In the case of the moving jets, the dimensions of the scour hole also depend on the erosion parameter, $E_c$. The Scour depth, $\varepsilon_m$, and ridge height, $\Delta$, are influenced by the ratio of water jet velocity to transit velocity, $s=U_o/V_c$.

The equations for trench depth and radius created by a moving jet are shown in Eq. (4.13) and Eq. (4.14). The stationary scour depth and radius are incorporated as asymptotic values for $s$ tending towards infinity. The equations are again based on the ‘static’ case, once the jet is turned off.

$$
\varepsilon_m = \frac{s-4.0}{305.44 - \frac{h}{\varepsilon_{m,\infty}} (s-4.0)} \cdot h \\
\text{for } S > 4
$$

(4.13)

$$
\frac{\varepsilon_m}{h} = 0 \\
\text{for } S \leq 4
$$

(4.14)

The depth of the scour profile (Figure 4.9), with $s$ ranging from 4 to 24, seems to follow a hyperbolic behaviour (Yeh et al., 2008). The profile is the mean scour profile, averaged over the longitudinal direction of the trench in the ‘static’ case.

Figure 4.9: Mean bed profiles for moving jet test (Yeh et al., 2008)
The maximum scour depth in Eq. (4.13) and the maximum scour radius in Eq. (4.14) occur when \( s \to \infty \), by reducing the transit velocity \( V_s \). While the scour depth increases as a hyperbolic function, the scour radius stays relatively constant when the ratio of water jet velocity to transit velocity, \( s \), increases (Figure 4.10).

![Figure 4.10: (a) Maximum scour depth versus velocity ratio (s) with Ec=5.28), (b) Normalized scour radius versus velocity ratio (s) (Yeh et al., 2008)](image)

**Vlasblom (2003)**

Smalt (2013) suggested using the theory of hydraulic excavation of modern drag heads from trailer suction hopper dredgers (TSHD), to obtain an impression of the behaviour of lowering a jet head into a sand bed. He discovered that for the investigated range of parameters, the sinking velocity is linear proportional to the jet momentum and that the behaviour of lowering an object below the sand bed appears to be comparable with the relationship between jet-production and total momentum flux of the jet system as described by Vlasblom (2003).

Vlasblom (2003) assumes that the jet-production, \( M_{sand} \), is linear with the total momentum flux of the jet system, \( I_0 \). The jet-production is a parameter to define the eroded sand mass in kg/s per jet and can be calculated with Eq. (4.15).

\[
M_{sand} = \alpha \cdot I_0 \cdot c_v = \alpha \left( \rho_w c_d n_j \left( \frac{\pi d^2}{4} \right) U_0^2 \right) \tag{4.15}
\]

Where \( c_d \) is a discharge coefficient, \( n_j \) total number of nozzles and \( \alpha \) is a coefficient depending on the particle size, jet pressure, jet capacity and trailspeed. A reasonable assumption for alpha is \( \alpha = 0.1 \) and it has the remarkable dimension of \( \text{s/m} \).

The eroded sand mass can also be calculated with Eq. (4.16) when the nozzles are divided well over the length of the sword.

\[
M_{sand} = \rho_s Q_{soil} c_v \tag{4.16}
\]

Where \( c_v \) is the volumetric concentration and \( Q_{soil} \) is the volume of excavated soil per unit of time.

The volume of excavated soil per unit of time, \( Q_{soil} \), is an important parameter since it shows a relationship between the sinking velocity, \( V_{sk} \) (vertical velocity of the jet system), and the
necessary jet momentum. \( Q_{	ext{scour}} \) is determined by multiplying the area underneath the object by the required sinking velocity, \( V_{	ext{ss}} \).

The jet pressure, \( p_j \), at the nozzle exit can be calculated according Eq. (4.17).

\[
p_j = 0.5 \cdot \rho_w \cdot U_0^2
\]  

(4.17)

According to Vlasblom (2003) the effectiveness of the jet decreases somewhat with increasing the pressure at a constant momentum. As a consequence low pressure-high discharge jets are more effective than high pressure-low discharge jets.

Comparison theory Yeh et al. and Vlasblom.
The theory of Yeh et al. (2008) and Vlasblom (2003) are based on different principles. The main consequences as a result of different approaches are discussed below.

The mathematical relationships for the ‘static’ scour depth of moving jets proposed by Yeh et al. are influenced by the transit velocity and impingement height, while the jet production according to Vlasblom is independent of both parameters.

According to Yeh, the scour depth of a moving jet decreases as a hyperbolic function for increasing transit velocities. The scour profile of a moving jet is tested for transit velocities in the range of 0.05-0.51 m/s.

The jet production determined based on the theory of Vlasblom is independent of the transit velocity. However, by dividing the volume of excavated seabed per unit of time with the transit velocity, a relation between the scour profile (cross sectional area of the trench) and the transit velocity is created. Figure 4.11 shows the relation between the transit velocity and scour depth for both theories under the same conditions. In order to compare both theories, the scour depth of Yeh is presented as the sum of the scour depth of 30 individual nozzles (which symbolizes the performances of a jet sword).

![Figure 4.11: Influence transit velocity on scour depth](image)

The profile of the scour depth based on the theory of Vlasblom is independent of impingement height, while the profile generated by the mathematical relationships of Yeh is influenced by the impingement height. Figure 4.12 shows the influence of the impingement height on the scour depth. As mentioned above, the theory is applicable around \( h/d_j = 6 \) and
too small values of $h/d_j$ will underestimate the scour depth, while too large values will overestimate the scour depth.

![Figure 4.12: Influence impingement height on scour depth](image)

4.2.3 Fluidization

Fluidisation occurs when a granular solid is subject to an upward fluid flow which created a drag force sufficient to support the weight of the particles (Leva, 1959). The particles become separated and in motion, and the bed expands. In other words, the weight of the grains is no longer supported by resting on other grains, but by fluid forces, and the bed behaves like a fluid, so that a heavy object placed on the bed sinks through it. By taking the fluid energy loss equal to both the viscous and kinetic energy losses, Ergun (1952) derived an equation to determine the pressure drop per length of a columnar fluidised bed.

\[
\frac{\Delta p}{\varepsilon} = \frac{15\mu}{\varphi_s D_{50}^2} \frac{(1-n_0)^2}{n_0^3} U_s + \frac{1.75\rho_f}{\varphi_s D_{50}} \frac{(1-n_0)}{n_0^3} U_s^2
\]  

(4.18)

Where $\varepsilon_d$ is scour depth in the ‘dynamic’ stage, $\mu$ is dynamic viscosity, $\varphi_s$ is particle shape factor, $n_0$ is porosity and $U_s$ is superficial fluid velocity. At the point of minimum fluidization the upwards pressure exactly balances the buoyant weight of the material.

\[
\frac{\Delta p}{\varepsilon} = (1 - n_0)\left(\rho_s - \rho_f\right)g
\]  

(4.19)

Minimum fluidization velocity

By neglecting the second term in the right, the kinetic energy term, in Eq. (4.18) and solving Eq. (4.18) and Eq. (4.19), Leva (1959) determined the minimum viscous superficial fluidisation velocity, $U_{mf}$

\[
U_{mf} = \frac{D_{50}^2 \left(\rho_s - \rho_f\right)}{15\mu} \frac{\varphi_s^2 n_{mf}^3}{1-n_{mf}}
\]  

(4.20)

Where $n_{mf}$ is the porosity at minimum fluidisation $\approx$ fixed bed porosity. Equation (4.20) is only valid for particle Reynolds number $Re_p = D_{50} U_{mf} \rho_f / \mu < 20$. 


4.2.4 Sedimentation

Sedimentation is the process of letting suspended particles settle under the influence of gravitational forces. Sedimentation is accomplished by decreasing the velocity of water flow to a point below which the particles will no longer remain in suspension. A model for the settling process of particles is described by Van Rhee and Talmon (2010).

**Sedimentation velocity**

In order to lower a cable below the seabed, the soil has to remain fluidized over a certain period. If this time window is too short, the cable will not be able to reach the acquired burial depth. The sedimentation velocity, which is the velocity interface between the settled sediment bed and the mixture flow above, is one of the parameters which ultimately determine whether the acquired burial depth will be reached or not.

The sedimentation velocity, $v_{sed}$, is often expressed as the difference between sedimentation flux, $S$, and erosion (pick-up) flux, $E$ (Van Rhee and Talmon, 2010).

$$v_{sed} = \frac{S - E_f}{\rho_s(1 - n_0 - c_b)}$$  \hspace{1cm} (4.21)

Where $c_b$ is the near-bed volumetric concentration and $n_0$ the porosity.

**Sedimentation flux**

The settling flux, $S$, can be calculated with Eq. (4.22).

$$S = \rho_s v_{th} c_b = \rho_s v_t c_b (1 - c_b)^m$$  \hspace{1cm} (4.22)

Where $v_{th}$ is the settling velocity (including hindered settling) and $v_t$ is the settling velocity of one particle (at a very low concentration).

**Settling velocity**

The terminal settling velocity of a spherical particle in a quiescent liquid is the product of a balance between the submerged weight of a solid particle and the drag force of the liquid acting on the settling particle in the direction opposite to the settling velocity vector. The Budryck equation, only valid for sand particles between $0.1 \text{ mm} < D_{50} < 1 \text{ mm}$, can be used to determine the settling velocity, $v_t$.

$$v_t = \frac{8925}{D_{50}} \left( \sqrt{1 + 95 \frac{\rho_s - \rho_f}{\rho_f} D_{50}^3} - 1 \right)$$  \hspace{1cm} (4.23)

Note: The settling velocity obtained with Eq. (4.31) is in $\text{mm/s}$, while the particle diameter, $D_{50}$, is in $\text{mm}$.

**Hindered settling velocity**

The settling velocity of a cloud of solid particles settling in a quiescent liquid encounters two additional hindering effects. The first hindrance is caused by the increased drag force due to the proximity of particles within the cloud, and in addition there is the influence of the up flow of fluid displaced by the descending particles. The hindering effects are strongly
dependent on the volumetric concentration of solids in the cloud, $c_b$ (Richardson and Zaki, 1954).

$$v_{th} = v_t (1 - c_b)^m$$ (4.24)

Where $m$ is an empirical exponent related to the particle Reynolds number and can be determined by the approximation of Wallis (1969).

$$m = \frac{4.7(1+0.15R_e^0.687)}{1+0.253R_e^0.687}$$ (4.25)

Erosion flux

The pick-up flux or erosion flux is computed for non-stagnant flow conditions. Commonly the pick-up flux is presented dimensionless as $\phi_p$ (Van Rhee and Talmon (2010)).

$$\phi_p = \frac{E_f}{\rho_s \sqrt{\frac{\rho_s - \rho_f}{\rho_f} D_{50}}}$$ (4.26)

In a limit situation where the near bed concentration is almost equal to the bed concentration there will be no net sediment transport from the bed to the flow due to turbulent eddies. Following this reasoning, the effect of the near-bed concentration on the pick-up flux can be written as a reduction factor (Van Rhee and Talmon, 2010).

$$\phi_{pn} = \frac{1-n-c_b}{1-n} \phi_p$$ (4.27)
Chapter 5 Calculation models

Tideway considers conducting the cable burial proceedings themselves, rather than hire a subcontractor. Instead of acquiring a new vessel, specifically designed to execute cable burial operations, Tideway wants to know if it is possible to utilise one of their own vessels.

Main question
1. Based on the available power, is it feasible to utilize the fall pipe ROV as a trencher?

Sub questions
1.1 Given the available power, which burial depths can be reached?
1.2 Given the available power, which transit velocities can be reached?
1.3 Based on the trench performances, can the trencher compete with existing trenchers?

In order to give an answer to those questions, the trench performances are predicted by three different calculation methods. The combined results provide a range of achievable burial depths versus ROV transit velocity.

The three different calculations methods are based on various theories. All assumptions and simplifications will be explained in detail. After the models are discussed, several general calculations, that are applicable to all three of the models, are explained.

The three calculation methods are combined into one computational model, which allows the user to obtain an initial estimate of the trench performances. Images of the interface of the spread sheet are added to the corresponding parts of the calculation for illustration purposes.

The Input sheet (Figure 5.1) forms the base of the model, in which all the information required to execute all the calculations is gathered. From this sheet, the user is redirected to the various calculation methods, where the calculation steps are also explained.
### Calculation models

#### 5. Calculation models

<table>
<thead>
<tr>
<th>Trench properties</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Required burial depth</td>
<td>$\varepsilon_b$</td>
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<tr>
<td>Trench width at the bottom of the trench</td>
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<td>Required cable deflection</td>
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<td>Submerged weight</td>
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<td>Bending stiffness</td>
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<td>Pressure jet</td>
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<td>Density water</td>
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<tr>
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<td>Density sediment</td>
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<td>Kinematic viscosity seawater(T=20°C)</td>
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<th>Flow processes</th>
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<td>Vlasblom coefficient</td>
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<td>Pick-up flux</td>
<td>$Q_f$</td>
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<td>Ratio impingement height over nozzle diameter</td>
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<th>Horsepower factors</th>
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<td>Inward nozzles</td>
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<td>Number inward nozzles</td>
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<td>Number of backward nozzles</td>
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<tr>
<td>Sword length</td>
<td>$L_s$</td>
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</tbody>
</table>

---

**Figure 5.1: Spreadsheet - Input**

After changing the input values, press 'Calculate' to obtain the new trench performances.

- **Vlasblom**
- **Multiple nozzles**
- **Single nozzle**

---

**Explanation**

- **Vlasblom**
- **Multiple nozzles - Yeh**
- **One large nozzle - Yeh**
- **Required burial depth**

Export data

---

**Tideway**

---

27
5.1 ‘Vlasblom’ model

The first calculation method is based on the theory of hydraulic excavation of modern drag heads from TSHD. Vlasblom (2003) discovered a relationship between jet-production and total momentum flux of a jet system.

The calculations are based on the equations explained in Chapter 4. The main calculation steps are shown in Figure 5.2 and the meaning of several symbols is graphically depicted in Figure 5.3. Despite the fact, that the sword configuration is not taken into account in this model, part of the equations are based on the assumption that the nozzles are well divided over the length of the sword.

\[
M_{\text{sand}} = \alpha \cdot I_{0,t} = \alpha \left( \rho_f c_d U_0^2 A_t \right)
\]

Where

\[
\begin{align*}
M_{\text{sand}} & \quad \text{Eroded sand mass} \quad \text{[kg/s]} \\
\alpha & \quad \text{Vlasblom coefficient} \quad \text{[s/m]} \\
I_{0,t} & \quad \text{Total momentum flux} \quad \text{[N]} \\
\rho_f & \quad \text{Density fluid} \quad \text{[kg/m}^3]\end{align*}
\]
5. Calculation models

<table>
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<td>( c_d )</td>
<td>Discharge coefficient</td>
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</tr>
<tr>
<td>( U_0 )</td>
<td>Exit velocity nozzle outlet</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( A_t )</td>
<td>Total required area nozzles</td>
<td>[m²]</td>
</tr>
</tbody>
</table>

The excavated volume of seabed per unit of time can be determined with Eq. (4.16), as shown in Figure 5.4. Equation (4.16) is only applicable when the nozzles are well divided over the length of the sword and the equation is based on the erosive power of jets, the volumetric concentration and density of sand.

\[
Q_{soil} = \frac{M_{sand}}{\rho_s c_v}
\]

Where

- \( Q_{soil} \): Volume excavated seabed per unit of time [m³/s]
- \( c_v \): Volumetric concentration of sand [-]
- \( \rho_s \): Density sand [kg/m³]

5.1.2 Trenched area

The cross sectional area of the trench, shown in Figure 5.5, is dependent on the width of trench at the bottom of the trench, the desired burial depth of a cable and the associated overdepth, required to achieve this burial depth.

The required burial depth and trench width are specified, while the overdepth is a parameter depending upon the sedimentation velocity, excavated volume of seabed per unit of time, required burial depth and the span length.

**Overdepth**

The overdepth is necessary to compensate for the bed rise due to settling sand particles in the period the cable is not yet in contact with the seabed. The overdepth should at least be equal to the bed rise and on the basis of this condition, Eq. (5.1) may be drawn.

\[
B \cdot \varepsilon_b \geq V_{sed} \cdot t^*
\]

Where

- \( B \): Overdepth [-]
- \( \varepsilon_b \): Required burial depth [m]
- \( V_{sed} \): Sedimentation velocity [m/s]
- \( t^* \): Time required to trench span length [s]
The time required to trench the distance of the span length can be calculated with Eq. (5.2).

\[ t^* = \frac{L}{V_s} \]  

(5.2)

The transit velocity is not yet known, but can be expressed as the volume of excavated seabed per unit of time, divided by the cross sectional area of the trench, see Eq. (5.3). It is assumed that the slope of the trench is constant.

\[ V_s = \frac{Q_{soil}}{A_{trench}} \]  

(5.3)

Where

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Span length</td>
<td>m</td>
</tr>
<tr>
<td>( V_s )</td>
<td>Transit velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>( A_{trench} )</td>
<td>Cross sectional area trench</td>
<td>m²</td>
</tr>
</tbody>
</table>

By substitution of Eq. (5.2) and Eq. (5.3) into Eq. (5.1) the minimum required overdepth can be expressed by Eq. (5.4).

\[ \left[ \frac{1}{5} \varepsilon_b \frac{V_{soil}}{Q_{soil}} \right] B^2 + \left[ \frac{V_{soil}}{Q_{soil}} (W_b + 1/5 \varepsilon_b) - 1 \right] B + \left[ \frac{V_{soil}}{Q_{soil}} (W_b + 1/5 \varepsilon_b) \right] = 0 \]  

(5.4)

Where

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_b )</td>
<td>Width trench bottom</td>
<td>m</td>
</tr>
</tbody>
</table>

5.1.3 Transit velocity

Finally, also the transit velocity can be determined with Eq. (5.3) by dividing the volume of excavated seabed per unit of time with the cross sectional area of the trench.

5.1.4 Modify obtained trench performances

In the above calculations no constraints are yet taken into account imposed by the configuration of the trencher. The jet sword is designed for a specific trench depth. Deviations from the optimum position (jet sword at an angle of 60 degrees with respect to the seabed, while the nozzles form an angle of 90 degrees with respect to the seabed) are possible, but up to a certain limit. Various limitations and modifications are discussed below.

Limit trench depth to maximum depth feasible

Check whether the desired trench depth is feasible with the currently selected sword. In case the desired trench depth exceeds the maximum trench depth feasible, the desired trench depth is limited to the maximum achievable depth.

The trench depth is based on the required burial depth and the corresponding overdepth and can be calculated with Eq. (5.5). The maximum trench depth feasible is dependent on the sword length and can be determined with Eq. (5.6). The maximum angle between the sword and the seabed is 60°.

\[ \varepsilon_t = \varepsilon_b (1 + B) \]  

(5.5)
5. Calculation models

\[ \varepsilon_f = L_s \sin(60) \]  \hspace{2cm} (5.6)

Case  \hspace{2cm} \varepsilon_t \geq \varepsilon_f \hspace{2cm} \varepsilon_t = \varepsilon_f

Elsewhere  \hspace{2cm} \varepsilon_t = \varepsilon_f

Where

\begin{align*}
\varepsilon_t & \quad \text{Trench depth} \\
\varepsilon_f & \quad \text{Maximum trench depth feasible} \\
L_s & \quad \text{Sword length}
\end{align*}

[m]

Burial depth for slower transit velocities than the optimum velocity

In the case the transit velocity is slower than the optimum transit velocity, the burial depth reduces due to the fact that the time a specific part of the cable is not in contact with the seabed increases, and consequently the bed rise increases during that time interval.

\[ \varepsilon_b = \varepsilon_f - V_{\text{sed}} \frac{L_{\text{max}}}{V_s} \]  \hspace{2cm} (5.7)

Where

\begin{align*}
L_{\text{max}} & \quad \text{Span length maximum burial depth feasible} \quad \text{[m]}
\end{align*}

Limit operating range of the swords

It is assumed that the trench performances are only reliable if the angle of the nozzles with respect to the seabed is equal to or greater than 45 degrees. The results obtained for angles smaller than 45 degrees are therefore removed from the data set.

5.2 Yeh - Multiple nozzles

The second and third model are based on the mathematical relationships for moving jets developed by Yeh et al. (2008). The difference between the two models is the way in which the theory, explained in paragraph 4.2.2, is implemented.

In the second calculation method, 'Multiple nozzles – Yeh', the scour depth of the trench is the sum of the scour depth created by each individual nozzle on a jet sword (Figure 5.6).

In the third calculation method, 'One large nozzle – Yeh', each jet sword is simplified and regarded as one large nozzle, of which the surface area of the nozzle orifice is equal to the sum of the surface area of all the individual nozzles (Figure 5.6). The similarity of the profile of the flow generated by a single nozzle and the actual flow profile along the bottom of the trench (Figure 4.3) is the main reason to describe the trench performances in this way.
5.2.1 Main calculations steps ‘Multiple nozzles – Yeh’

The calculations of the multiple nozzles calculation method are divided into two parts, as illustrated in Figure 5.7 and Figure 5.8. The first part of the calculation can be calculated without additional steps, while the second part requires an iterative process.

In contrast to the first calculation method, this model takes the sword configuration partially into account. The trench performances are dependent on the sword length, the number of vertically installed nozzles and their corresponding diameter. The influence of the inward orientated nozzles is calculated, but not reflected in the final trench performances.

5.2.2 First part calculation method ‘Multiple nozzles’

Instead of taking the required burial depth as a starting point, the transit velocity is taken as a starting point for this method.

According to Rajaratnam and Beltaos, (1977) the maximum scour depth is proportional to the erosion parameter, which can be determined with Eq. (4.8).

\[
E_c = \frac{u_0}{\sqrt{gD_{50}(\rho_{sed}-\rho_f)/\rho_f}} \cdot \frac{d_{n,v}}{h}
\]

Where

- \(E_c\) Erosion parameter [-]
- \(g\) Gravitational acceleration [m/s²]
- \(D_{50}\) Median grain size [m]
- \(\rho_{sed}\) Sediment density [kg/m³]
- \(d_{n,v}\) Diameter vertical nozzle [m]
- \(h\) Impingement height [m]
The ‘static’ scour depth for an individual nozzle under stationary conditions can be determined, based on the previously determined erosion parameter, with Eq. (4.12).

\[ \varepsilon_{m,\infty} = 0.64 \sqrt{\frac{0.76}{h} \left(1.26E_c^{0.2} - 1\right)} \cdot h \]

Where
\[ \varepsilon_{m,\infty} \quad \text{‘Static’ equilibrium scour depth} \quad \text{[m]} \]

In the case of moving jets, the scour depth is also influenced by the ratio of the velocity of the fluid leaving the nozzles to transit velocity of the trencher. The ‘static’ scour depth created by moving jets can be calculated with Eq. (4.13).

\[ \varepsilon_m = \frac{s - 4.0}{30.4 + \frac{h}{\varepsilon_{m,stat}}(s - 4.0)} \cdot h \]

Where
\[ \varepsilon_m \quad \text{‘Static’ scour depth moving jet} \quad \text{[m]} \]
\[ s \quad \text{Ratio jet velocity to transit velocity} \quad \text{[-]} \]

**Scour depth jet sword**

The scour depth of a moving jet sword is dependent on the scour depth of an individual nozzle, the number of nozzles and the length of the jet sword. It is assumed that the nozzles are uniformly distributed over the entire length of a jet sword.

First, it is examined whether the sum of the scour depths, created by individual nozzles, exceeds the maximum distance of the sword below the initial seabed. In the case the combined scour depth is larger than the depth of the sword below the initial seabed, the total scour depth is determined by Eq. (5.8). Equation (5.9) calculates the vertical position of the lowest nozzle and adds the scour depth of one individual moving nozzle. In this situation, the sword is located under an angle of 60 degrees with respect to the seabed (Figure 5.9).

\[ \varepsilon_m \cdot n_v \geq \sin(60) \cdot L_s \quad \varepsilon_{m,total} = (n_v - 1) \frac{\sin(60)L_s}{n_v} + \varepsilon_m \quad (5.8) \]

Where
\[ \varepsilon_{m,total} \quad \text{Scour depth moving jet sword} \quad \text{[m]} \]
\[ n_v \quad \text{Number of vertical nozzles} \quad \text{[-]} \]

![Figure 5.9: Sword position](image)
When the combined scour depth is smaller than the distance of the end of the sword below the initial seabed, the angle of the sword is adjusted (Figure 5.9). By adjusting the angle of the sword, the angle of the nozzles with respect to the seabed also changes. By equating both equations and rewriting it, the required reduction of the angle between the seabed and the jet sword can be determined, see Eq. (5.9) – Eq. (5.11).

\[ n_v \varepsilon_m \sin(90 - \gamma) = L_s \sin(60 - \gamma) \]  \hspace{1cm} (5.9)

\[ \frac{L_s}{n_v \varepsilon_m} = \frac{\sin(90 - \gamma)}{\sin(60 - \gamma)} = \frac{\frac{1}{\sqrt{3} / 2 \cos(\gamma) - 0.5 \sin(\gamma)} \tan(\gamma)}{\sqrt{3}/2 - \tan(\gamma)} \]  \hspace{1cm} (5.10)

\[ \gamma = \tan^{-1}\left(\sqrt{3} - \frac{2 \frac{n_v \varepsilon_m}{L_s}}{\sqrt{3}/2 - \tan(\gamma)}\right) \]  \hspace{1cm} (5.11)

Where
\[ \gamma \]  Reduction of the angle between the seabed and the jet sword

The scour depth of a moving jet sword can now be determined with Eq. (5.12).

\[ \varepsilon_m \cdot n_v < \sin(60) \cdot L_s \quad \varepsilon_{m,total} = n_v \varepsilon_m \sin\left(90 - \tan^{-1}\left(\sqrt{3} - \frac{2 \frac{n_v \varepsilon_m}{L_s}}{\sqrt{3}/2 - \tan(\gamma)}\right)\right) \]  \hspace{1cm} (5.12)

**Near bed concentration**

In order to calculate the sedimentation velocity the near bed concentration still has to be determined. It is assumed that the fraction of mixture volume that is occupied by solids can be determined by taking the volume of sand particles brought into suspension and dividing it by the sum of the volume of excavated seabed and the flow rate at the point of impingement (Figure 5.10).

By calculating the volume of seabed excavated per unit of time with Eq. (5.3) and multiplying it with the fraction of volume that is occupied by sand particles, \( C_v \), the volume of sand particles that is brought into suspension per unit of time can be determined. The cross sectional area of the trench, required to calculate the volume of seabed excavated per unit of time, is determined with Eq. (5.13).

\[ A_{trench} = W_b \varepsilon_{m,total} + 1/5 \varepsilon_{m,total}^2 \]  \hspace{1cm} (5.13)

Where
\[ A_{trench} \]  Cross sectional area trench
\[ W_b \]  Width trench bottom

[m²]

[m]
Eventually, the near bed concentration can be calculated with Eq. (5.14). In the case of multiple nozzles, the entrainment of the flow leaving the nozzles is neglected, due to the fact that the nozzles are placed inside the seabed and surrounded by fluidized sand. On the other hand, in the case of one large nozzle, the entrainment is taken into consideration and determined with Eq. (4.4).

\[
c_b = \frac{c_v Q_{soil}}{Q_{soil} + Q_{pump}} \quad \text{case multiple nozzles} \quad (5.14)
\]

\[
c_b = \frac{c_v Q_{soil}}{Q_{soil} + 0.32 \frac{h}{d_n} Q_{pump}} \quad \text{case on large nozzle}
\]

Where

- \(c_b\) Near bed concentration [-]
- \(c_v\) Volumetric concentration sand in seabed [-]
- \(h/d_n\) Ratio impingement height over nozzle diameter [-]

### 5.2.3 Second part calculation method ‘Multiple nozzles’

This part of the calculation requires an iteration, due to the fact that the span length depends on the burial depth, but in order to calculate the span length, the burial depth is required.

1. Start with the required burial depth as the initial value.
2. Determine the span length corresponding to the required burial depth with Eq. (4.1).
3. Determine the time required to trench the distance of the span length with Eq. (5.2).
   \[t^* = \frac{l}{v_s}\]
4. Determine during which time interval the bed is able to rise, by subtracting the time required to create the trench from the time required to trench the distance of the span length.
   \[t = t^* - \Delta t \quad (5.15)\]

   Case \( \varepsilon_{m,\text{total}} < \sin(60)L_s \)
   \[\Delta t = \frac{\sqrt{l^2 - \varepsilon_{m,\text{total}}^2}}{v_s} \quad (5.16)\]

   Case \( \varepsilon_{m,\text{total}} \geq \sin(60)L_s \)
   \[\Delta t = \frac{L_s \cos(60)}{v_s} \quad (5.17)\]

Where

- \(t\) Duration bed rise [s]
- \(t^*\) Time required to trench span length [s]
- \(\Delta t\) Time delay bed rise [s]

5. Determine the burial depth with Eq. (5.18) by subtracting the bed rise during time interval, \(t\), from the scour depth of a moving jet sword.
5. Calculation models

\[ d_b = \varepsilon_{m,\text{total}} - V_{sed} \cdot t \]  

(5.18)

Where

- \( d_b \) Burial depth [m]

6. Replace the initial required burial depth with the obtained burial depth. Repeat steps 1-6 until the burial depth remains the same.

5.2.4 Limit operating range of the swords

It is assumed that the trench performances are only reliable if the angle of the nozzles with respect to the seabed is equal to or greater than 45 degrees. The results obtained for angles smaller than 45 degrees are therefore again removed from the data set.

5.3 Yeh – One large nozzle

The calculation method has many similarities to the calculation method of the ‘multiple nozzles’. The main difference lies in the fact that in this model the sword is modelled as one large nozzle. The surface area of the nozzle orifice is equal to the sum of the surface area of all the individual nozzles of one sword.

5.3.1 First part calculation method ‘One large nozzle’

Figure 5.11 shows the part of the equation that requires no iteration. It is very similar with Figure 5.7. The same equations apply, only the input values of the nozzle diameter and the impingement height differ.

For this model, the ‘static’ scour depth of a moving jet obtained with Eq. (4.13) is equal to the scour depth of a moving sword.

5.3.2 Second part calculation method ‘One large nozzle’

The second part of the calculation is identical to the second part of the calculation method ‘Multiple nozzles’, and is therefore not discussed again.

5.4 General calculations

5.4.1 Calculations based on pump specifications

The starting point of all computations is the hydraulic power delivered to the water pumps. By multiplying the hydraulic power with the efficiency of the water pumps, the available power in the water outflow is determined (Figure 5.12).
5. Calculation models

Figure 5.12: Pump specifications

\[ P = P_t \cdot \eta \quad (5.19) \]

Where

- \( P \): Available Power [W]
- \( P_t \): Total power [W]
- \( \eta \): Efficiency water pumps [-]

The water pumps are designed to operate at a specific pressure, \( p_j \). The corresponding flow rate, \( Q_{pump} \), can be calculated with Eq. (5.20)

\[ Q_{pump} = \frac{p}{p_j} \quad (5.20) \]

Where

- \( Q_{pump} \): Water flow rate [m³/s]
- \( p_j \): Jet pressure [Pa]

Besides the flow rate, the velocity of the fluid leaving the nozzle can be calculated by rewriting Eq. (4.17). The exit velocity at the nozzle outlet is based on the jet pressure, the density of the fluid and the discharge coefficient.

\[ U_0 = \sqrt{\frac{2 \cdot p_j}{\rho_f}} \quad (5.21) \]

Where

- \( U_0 \): Exit velocity nozzle outlet [m/s]
- \( \rho_f \): Fluid density [kg/m³]

5.4.2 Calculations based on sword specifications

The jet sword consists of nozzles orientated in three different directions, i.e. vertical-, inward- and backward orientated nozzles. The flow factor determines how the total flow rate is divided over these nozzles. Subsequently, the diameter of the nozzles can be determined, based on the number of nozzles (Figure 5.13).
The total area of the combined nozzles can be calculated by rewriting Eq. (4.3). The discharge coefficient is assumed constant for all nozzles.

\[ A_t = \frac{Q_{pump}}{u_0 c_d} \]  

(5.22)

Where
- \( A_t \): Total required nozzle area [m\(^2\)]
- \( c_d \): Discharge coefficient [-]

The flow rate is divided over the nozzles of the three different directions by the flow factor. By multiplying the total required nozzle area with the flow factor, the combined nozzle area of the nozzles orientated in one direction is determined (Eq. 5.23). Dividing the combined nozzles area by total number of nozzles in that direction, leads eventually to the nozzle diameter (Eq. (5.24)).

\[ A_{t,x} = f_{factor,x} \cdot A_t \]  

(5.23)

\[ d_{n,x} = \sqrt{\frac{4(A_{t,x}/n_x)}{\pi}} \]  

(5.24)

Where
- \( f_{factor,x} \): Flow rate factor [-]
- \( n_x \): Number of nozzles orientated in x direction [-]
- \( d_{n,x} \): Diameter nozzle of nozzles orientated in x direction [m]

### 5.4.3 Trench specifications

Once the trencher has passed, suspended particles start settling under the influence of gravitational forces. The velocity, with which the bed rises, is called the sedimentation velocity. In all three calculation models the sedimentation velocity is required to calculate the final burial depth of a cable.

The sedimentation velocity is determined with Eq. (4.21) in which the sedimentation velocity is expressed as the difference between sedimentation flux and erosion flux.

**Sedimentation flux**

The sedimentation flux is calculated according the theory explained in section 4.2.4. Figure 5.14 graphically shows the computational steps of Eq. (4.22) - Eq. (4.25).

Figure 5.14: Calculation sedimentation flux
The settling velocity of one particle is calculated according Eq. (4.21).

\[ v_t = \frac{8.925}{D_{50}} \left( \sqrt{1 + 95 \frac{\rho_s - \rho_f}{\rho_f} D_{50}^3} - 1 \right) \]

Where

- \( v_t \) Settling velocity [mm/s]
- \( D_{50} \) Median grain size [mm]
- \( \rho_s \) Solid density [kg/m³]

Subsequently, the hindered settling velocity of a solid particle is calculated based on the terminal settling velocity and the empirical exponent \( m \).

\[ m = \frac{4.7(1+0.15R_{ep}^{0.687})}{1+0.253R_{ep}^{0.687}} \]

\[ v_{th} = v_t (1 - c_b)^m \]

Where

- \( m \) Empirical exponent [-]
- \( R_{ep} \) Particle Reynolds number [-]
- \( v_{th} \) Hindered settling velocity [mm/s]
- \( c_b \) Near-bed concentration [-]

The sedimentation flux is obtained by solving Eq. (4.22).

\[ S = \rho_s v_{th} c_b = \rho_s v_t c_b (1 - c_b)^m \]

Where

- \( S \) Sedimentation flux [kg/m²s]

**Erosion flux**

The Erosion flux is computed for non-stagnant flow conditions (Figure 5.15). For simplicity, the dimensionless pick-up flux in Eq. (4.26) is assumed as a constant.

\[ E_f = \phi_f \cdot \rho_s \cdot g \left( \frac{\rho_s - \rho_f}{\rho_f} \right) \frac{D_{50}^3}{\rho_f} \]

Where

- \( E_f \) Erosion flux [kg/(m²s)]
- \( \phi_f \) Dimensionless pick-up flux [-]
- \( g \) Gravitational acceleration [m/s²]
**Sedimentation velocity**

The sedimentation velocity is expressed as the difference between the sedimentation flux and the erosion flux (Figure 5.16). Despite the fact that in reality the flow and scour patterns depend on the speed of advance of the jetting tool, one standard flow pattern is assumed for all cases.

\[
V_{sed} = \frac{S - E_f}{\rho_s(1 - n_0 - c_p)}
\]

Where
- \(V_{sed}\) Sedimentation velocity [m/s]
- \(n_0\) Porosity [-]

5.4.4 Span length

The cable deflects once the soil supporting it has been removed by the trencher. In order to reach the required burial depth, the cable has to obtain the same cable deflection. The cable deflection depends on the cable properties, the lay tension and the distance the cable is not supported, also called the span length.

The pipeline deflection into the trench is based on an elastic beam model of the pipeline and can be calculated with Eq. (4.1).

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

Where
- \(y\) Cable deflection (positive downwards) [m]
- \(q\) Submerged unit weight [N/m]
- \(T\) Lay tension [N]
- \(L\) Span length [m]
5. Calculation models

- **E** Elasticity modulus [N/m²]
- **I** Moment of inertia [m⁴]
- **x** Distance from beginning of trench [m]

By giving a desired cable deflection and using Eq. (4.1), the minimum required span length, for which the right-hand side of Eq. (4.1) is greater than the left-hand side, can be determined.

Figure 5.17 shows the spreadsheet interface of the span length calculator. On the left the input values are displayed, which still can be changed manually to see the influence of a specific parameter on the overall process, and on the right the output values are given. For illustration, a representation of the cable profile is shown.
5.5 Compare results

The trench performances predicted by the model for the three different calculation methods, under the same conditions, are presented in Figure 5.18. The combined results provide a range within which the actual performances are expected.

![Figure 5.18: Trench performances](image)

The attempt to predict the trench performances by simplifying both jet swords and regarding them as two large nozzles, of which the surface area of the nozzle orifices is equal to the sum of the surface area of all the individual nozzles of a jet sword, was unsuccessful. The combined scour depth created by multiple nozzles cannot be described on the basis of the same equations by a nozzle based on the same total orifice surface area.

Both the ‘Vlasblom’ calculation method and the ‘Multiple nozzles – Yeh’ calculation method provide a better estimate of the trench performances. Up to transit velocity of approximately 360 m/hr, both methods follow a similar trend. Changing the input values may shift this point to the left or right, but the trend remains the same. However, the point at which the optimum transit velocity is reached differs between the two methods. The ‘Multiple nozzles’ calculation method reaches earlier the optimum transit velocity.

Entering data obtained on the basis of actual cable burial operations and comparing the predicted performances with the actual performances, will clarify which method is most consistent with the actual trench performances.

5.5.1 Comparison of model predictions with actual trench data

This paragraph discusses the comparison of the trench performances of the Q13 project with the predictions obtained by the computational model. The Q13 Power Cable Trenching project consisted of laying and burying a high voltage cable, that runs from the shore of Scheveningen to a newly constructed platform. The route of this cable is located in blocks Q13 and Q16 in the Dutch sector of the North Sea. Canyon Offshore Ltd has been subcontracted to perform trenching and survey operations on the high voltage cable. Canyon’s scope of work was performed from the Grand Canyon vessel utilising the T1200 trencher.
Data computational model
The specifications regarding the Q13 project are shown in Table 5.1. Figure 5.19 shows the predictions of the model based on the input of Table 5.1.

<table>
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<td>Trench width at the bottom of the trench</td>
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<tr>
<th><strong>Cable properties</strong></th>
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<td>Required cable deflection</td>
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<tr>
<td>Submerged weight</td>
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<td>Bending stiffness</td>
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<td>Lay tension</td>
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<td>Efficiency water pump</td>
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<td>Pressure jet</td>
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<th><strong>Soil specifications</strong></th>
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<td>Density sand</td>
</tr>
<tr>
<td>Density water</td>
</tr>
<tr>
<td>Porosity</td>
</tr>
<tr>
<td>Volumetric concentration</td>
</tr>
<tr>
<td>Density sediment</td>
</tr>
<tr>
<td>Kinematic viscosity seawater($T=20^\circ$)</td>
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<table>
<thead>
<tr>
<th><strong>Trench processes</strong></th>
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</thead>
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<tr>
<td>Vlasblom coefficient</td>
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<tr>
<td>Pick-up flux</td>
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<tr>
<td>Ratio impingement height over nozzle diameter</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th><strong>Sword specifications</strong></th>
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</thead>
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<th>Flow rate factor</th>
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<tr>
<td>Inward nozzles</td>
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<tr>
<td>Backward nozzles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single sword configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number vertical nozzles</td>
</tr>
<tr>
<td>Number inward nozzles</td>
</tr>
<tr>
<td>Number of backward nozzles</td>
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<tr>
<td>Sword length</td>
</tr>
</tbody>
</table>
Data trenching performances Q13 project
The data of the Q13 project is gathered from the log- and survey files of the deployed trencher. The transit velocity of the trencher is derived on the basis of the time stamp and the respective location expressed in terms of longitudinal and lateral values. The corresponding burial depth is obtained on the basis of the survey data.

Modifying data:
Due the cable properties, the burial depth of a particular point of the cable is depending on the depth of adjacent points. In order to reduce the influence of the neighbouring points, the average of ten consecutive points is taken, which corresponds to an average value per 10 meter. This is in the same order of magnitude as the required span length. The results are shown in Figure 5.20 and combined with the predictions generated by the model.

The data is then simplified by dividing the data into groups of transit velocity with an interval of 0.04 m/s. Subsequently, the average transit velocity and corresponding burial depth is calculated for each group. The results are shown in Figure 5.21 and Figure 5.22.

Discussion results
The results of both the ‘Vlasblom’ calculation method and ‘Multiple nozzles’ method show many similarities with the actual trench performances in the transit velocity range of 430m/hr - 720m/hr. The ‘Multiple nozzles’ method gives the most accurate approximation of the trench performances in this range, but beyond a transit velocity of 720 m/hr, the predictions are no longer consistent with the actual results. The ‘Vlasblom’ method, however, predicts the trench performances even better in the range of 720 m/hr up to 1050 m/hr.
5. Calculation models

Figure 5.20: Comparison model predictions with data Q13

Figure 5.21: Simplified Q13 data vs model predictions
Figure 5.22: Enlarged results Figure 5.21
At this point, the model is only compared with a single dataset. It is therefore not possible to make a pronouncement about the accuracy of the predictions, outside the compared range of transit velocities. Data of future trenching projects will provide more insight about the reliability of the model.

It is important to note, that for this specific case, the relative impingement height is assumed equal to 15. Whether this is generally applicable is not yet clear. Again, additional data is required to verify this.

5.6 Conclusion

Based on the predicted trench performances by the calculation methods, the following sub questions are answered in order to obtain an answer to the main question.

5.6.1 Sub questions

1.1 Given the available power, which burial depths can be reached?

1.2 Given the available power, which transit velocities can be reached?

1.3 Based on the trench performances, can the trencher compete with existing trenchers?

5.6.2 Main question

1. Based on the available power, is it feasible to utilize the fall pipe ROV as a trencher?
Chapter 6  Design methodology jet trencher

The content of this chapter is confidential
Chapter 7  3D Model final concept

*The content of this chapter is confidential*
Chapter 8  Conclusions and recommendations

The main goal of this study is to develop a concept to combine burial and rock placement operations such that they can be carried out, as separate activities, using a single vessel by integrating the burial equipment into the fall pipe ROV. The main research questions are:

1. Based on the available hydraulic power of the fall pipe ROV, is it feasible to utilize the ROV as a trencher?

2. How can the fall pipe ROV be converted, such that it can operate as a trencher as well?

The first research question is examined by means of a computational model, based on three different calculation methods. This model provides an initial estimate of the trenching performances, expressed in transit velocity of the trencher and corresponding burial depth of a cable.

In order to answer the second research question the main function of the trencher is subdivided in several partial functions. For each partial function several solutions are presented in a morphological overview. Subsequently, a multi-criteria analysis is applied to evaluate five different concepts.

8.1 Conclusions

The literature review has shown that there are two publicly available jet models that describe the scour formation by external moving jets and are relevant for this study. Yeh et al. (2008) proposed mathematical relationships for moving jets and Vlasblom (2003) gave a relationship between jet-production and total momentum flux of a jet-system.

The computational model contains three different calculation methods. The attempt to predict the trenching performances by simplifying the jet sword and regarding it as one large nozzle was unsuccessful. This method underestimates the trenching performances.

On the other hand, the results of both the ‘Vlasblom’ and ‘Multiple nozzles’ calculation method show, within the tested range of transit velocities, many similarities with the trenching performances of an actual trenching project (Q13). However, beyond a certain transit velocity, the predictions of the ‘Multiple nozzles’ calculation method are no longer consistent with the actual results, while the ‘Vlasblom’ method continues to approach the trenching performances quite well. This turning point varies by case and depends on the specific conditions and configurations. For the Q13 trenching project, the turning point lies at 720 m/hr.
8.2 Recommendations

The following recommendations for improving the computational model can be made:

- Implement the influence of the backward nozzles into the model.
- Compare the model with data from several completed trench projects instead of a single project.
  - Compare the model with data obtained from executed projects of trenchers with a different amount of power.
  - Compare the model for a wider range of transit velocities.
  - Investigate whether there is a certain relationship for the value of the relative impingement height, or find an appropriate value that is valid for general situations.
- Perform a laboratory experiment with a scale model of the jet swords.
Bibliography


Appendix A  Visit fall pipe vessel Flintstone

*The content of this chapter is confidential.*
Appendix B  Additional literature review

B.1  Underwater Sand Bed Erosion and Internal Jump Formation

Over recent decades, extensive experimental work on erosion by fixed jets has been performed by Rajaratnam and co-workers (Rajaratnam, 1981; Aderibigde and Rajaratnam, 1996; Mazurek et al., 2003), who examined plane and circular jets impinging at various angles of attack onto beds composed of different sediment materials. In all these works, the eroding jets were kept at a fixed position relative to the sand bed. In the work of Perng and Capart (2007), by contrast, the special phenomena arising when the jets travel along the bed were documented. First, it became possible for the scour hole to attain a steady shape (in a frame of reference moving with the jetting tool) despite ongoing net erosion and deposition of sand across the loose bed interface. Secondly, different speeds of advance yielded distinct patterns of flow and scour, including shooting flows with and without separation, as well as flows featuring an internal hydraulic jump. Finally, provided that the speed of advance is not too slow, the jet-induced water and sediment motions became sufficiently well-behaved to permit development of a hydraulic theory.

To describe theoretically the jet-induced current and the resulting sand erosion, suspension and deposition, they relied both on shallow-water theory (see e.g. Abbott, 1979) and work on turbulent entrainment (see e.g. Ellison and Turner, 1959). To merge these avenues together, they followed the roadmap laid out in a seminal paper by Parker et al. (1986). Based on the energy approach inaugurated by Bagnold (1966), Parker et al. showed that the influence of turbulence and erosion on the dynamics of gravity-driven turbidity currents could be described by shallow-flow equations, provided that one keeps track of the energy budget in addition to mass and momentum balance. A similar approach has been adopted by Kobayashi and coworkers (Kobayashi and Johnson, 2001; Kobayashi and Tega, 2002) to model suspended sediment transport in the coastal surf zone.

To describe the geomorphic turbidity currents induced by travelling jets, they made various refinements to this basic theoretical approach. First, they introduced a sublayered description in which the turbulent bottom current was assumed stratified into sediment-laden and sediment-free sublayers. A generalization of the sharp interface view adopted by Fraccarollo and Capart (2002) was used to treat erosion and entrainment across the interfaces bounding these sublayers. Secondly, the steep trenching fronts obtained near the point of impingement motivated the adoption of curvilinear coordinates. In similar contexts, such curvilinear coordinates have been used in two recent works to describe turbulent entrainment by curved jets (Jirka, 2006) and basal erosion by shallow subaerial landslides (Chen et al., 2006). Finally, they transformed the governing equations to moving coordinates in order to describe the steady flows observed after long travel times in a frame of reference attached to the moving jets.
B.2 Jet Induced Trenching Operations

The in paragraph 4.1.2 proposed model can help engineers in assessing the performance of the jet trenching machines. Appendix B.2 describes this model more extensively.

Experimental Observations
The steadily advancing circular jet erodes a trench of permanent form (in a frame of reference travelling with the jetting device). The jet suspends sand from the bed and wall, and simultaneously entrains water from the upper ambient. After flowing along the bed in the shooting flow regime, the jet-induced current undergoes an internal hydraulic jump across which the flow thickens and decelerates, before depositing the sand grains further away to backfill the incised trench.

The Circular jet can erode the loose sidewall of the trench as well as the bottom. Nevertheless, vertical erosion is much more rapid than lateral erosion, and the jet-induced turbulent current at first confines itself within a narrow trench. Beyond the internal hydraulic jump, overspill occurs once the upper boundary of the turbid current exceeds the trench wall. At this point turbid water flows laterally outwards and entrains suspended sand out of the confines of the trench. The corresponding sand loss leads to an incomplete backfill of the trench.

The different mechanisms observed are illustrated in Figure B. 1. The longitudinal mechanisms related mainly to the direct jet action are erosion of the trench front, transportation of the particles and deposition. Two lateral mechanisms also play an important role in the trenching process: the lateral infill of the trench due to the collapse of the wall and the loss of particles due to the lateral spreading when the particles in suspension are above the initial bed level.

The important operational parameters that influence the trenching performance are mainly the jetting power and the progress rates. This influence is illustrated in Figure B. 2.
B. Literature review

**Numerical Model**

**Introduction**

Based on the experimental observations, a jet trenching model was developed that takes into account the five most important processes that were identified: entrainment, erosion, deposition, breaching and overspill Figure B. 3).

In the longitudinal direction, the dynamics of the jet-induced turbulent current are assumed to be controlled by entrainment of ambient water into the current, erosion of seabed material (water + sediment) into the current, and deposition of material due to the gravitational settling of grains back to the bed. From their initial erosion to their eventual deposition, suspended sand grains cause the current density to exceed the density of seawater, and the corresponding density stratification tends to damp turbulent mixing.

In the lateral direction, the trench cross-sectional shape is affected by the lateral erosion of the jet and the breaching of the sidewalls. Breaching is a type of underwater slumping driven by reduced gravity and paced by the rate of infiltration of seawater required for sand bed dilatancy to take place. When sediment-laden current rises above the trench walls, moreover, overspill of suspended sediment out of the trench occurs. This is important in practice because it causes a loss of sand cover over the cable or pipeline, decreasing the level of protection achieved even if a deep trench has been incised.

Figure B. 2: Experimental results for a fine sand:

Figure B. 3: Key physical process during jet trenching
Main assumptions
The theory envisions a slender current of water and suspended sand flowing along a sand bottom of variable topography submerged in a deep water ambient. The vertical structure in Figure B. 4 is assumed. Motion is confined to a fully turbulent layer of thickness \( h_t \). The overlying ambient water is assumed quiescent, and the underlying solid-like sediment bed is assumed static. Embedded within the turbulent layer is a fluidized layer of sand and water of thickness \( h_s \) inside which the weight of the dilute sand phase is entirely supported by turbulent eddies.

It is assumed that the interfaces between the layers are sharply defined and that the distribution of flow properties (longitudinal flow velocity \( u_t \), turbulent kinetic energy \( k \) and sediment concentration \( c_v \)) is uniform within a given layer. Transfer of mass and momentum between the layers and across the interfaces are however allowed to take place.

Figure B. 4: Shallow layer jet-induced suspension flow model

It is further assumed that vertical accelerations are negligible, and that the vertical velocities are cinematically constrained by the thickness variations of the different layers.

The theory thus involves the following five variables, or degrees of freedom:
- Thickness of the turbulent bottom current (\( h_b \))
- Thickness of the fluidized layer in which sand is entrained by the turbulent water (\( h_t \))
- Elevation of the loose, static sediment bed (\( z_s \))
- Sediment concentration inside the fluidized layer (\( c_t \))
- Longitudinal velocity of the water and sand inside the turbulent layer (\( u_t \))

Governing equations
All five variables are functions of both longitudinal coordinate and time, and their coupled evolution must be described by a set of five governing equations. These equations are obtained by applying mass conservation and momentum balance to the various layers.

The different layers defined above interact and this interaction is characterized by the three following exchange fluxes:
- The flux $e_w$ of the entrainment of quiescent water into the turbulent current is computed based on common model in hydrodynamic, i.e. proportionally to the current velocity:

$$e_w = -bE_e u$$  \hspace{1cm} (B.1)

Where $E_e$ is entrainment coefficient, $b$ is the effective width of the turbulent layer flowing along the trench bottom and $u$ is the velocity of the turbulent layer.

- The flux $e_t$ between the two turbulent layers is only depending on the settling velocity of the grains:

$$e_t = -\omega_s$$  \hspace{1cm} (B.2)

Where $\omega_s$ is the effective fall speed of the sediment grains.

- The Flux $e_s$ between seabed and the turbulent current is governed by the following equation:

$$e_s = b\varepsilon_s E_e u - b\frac{\varepsilon_s}{1+2\varepsilon_s}\omega \cos \theta$$  \hspace{1cm} (B.3)

The first term is a turbulent erosion rate, formulated with analogy with turbulent entrainment, and the second term is a deposition rate due to settling of sediment grains back to the seabed. Dimensionless coefficient $\varepsilon_s$ ($0 \leq \varepsilon_s \leq 1$) depends on the size of the sediment grains and expresses the relative ease with which they can be eroded by the current. Upon erosion, the trenched seabed transfers sand to the current ($e_s > 0$), whereas the opposite occurs upon deposition ($e_s < 0$). The parameter $\theta$ denotes the angle below horizontal formed by the tangent to the bottom profile of the trench

Turbulence, which controls both entrainment and erosion, is strongly damped by density stratification. In other words, the erosion flux and the entrainment flux decreases and could eventually be equal to zero when the density and the thickness of the turbulent layer increase. This is taken into account by expressing the entrainment coefficient $E_e$ as a function of the Richardson number, which accounts for the increase of the potential energy relative to the kinetic energy.

**Lateral variation of the trench**

The last component of the model is the procedure used to evolve the cross-sectional shape of the trench. Because multiple processes are considered, it was found that the trench shape cannot be limited to a predefined geometry with limited degrees of freedom. Instead, the trench shape should be able to evolve freely. For this reasons, it was decided to characterize the trench transversal profile by a polygonal line allowing, for example, the trench to be wider at its bottom than at its surface, as observed in some experiments.
The evolution rules used to update the trench shape under the influence of the various processes are illustrated in Figure B. 5. The three processes can be identified:

- The first process that influences the shape of the transversal section of the trench is the lateral erosion of the bottom current. As the turbulent current erodes the bottom of the trench, it also erodes the sidewalls. The lateral erosion is slower than the vertical erosion and can reasonably be assumed to vary proportionally with the trench depth as illustrated in Figure B. 5a.

- The second process is the redeposition of the sediments that is assumed to be horizontal and uniform on the trench width (see Figure B. 5b).

- The last process is the breaching i.e. the collapse of the sidewall toward the natural equilibrium slope of the sand. This mechanism acts to widen the trench independently of jetting action and depends on the speed of retreat of a vertical trench wall $\lambda_{0}$, the natural angle of repose of the sand and the slope of the trench wall. Parameter $\lambda_{0}$ is dependent on the properties of the seabed material (void ratio and permeability). The approach is similar to the breaching speed formulated in Mastbergen and Van den Berg (2003).
B.3 Development of a Jet Trenching Model in Sand

Multiple Jets Trenching Model

Model basis
Several laboratory observation (Su, 2007; Vanden Berghe, 2008) indicate that the interactions between the jet-induced current, ambient seawater and sand seabed can be characterised into five different processes: entrainment, erosion, deposition, breaching and overspill (see Figure B.3).

The model development proceeded in the following steps. Based on prior experience with 2D horizontal plane jets (Perng, 2006; Perng and Capart, 2008), a model for a single 3D round jet travelling along the seabed was developed. This model incorporated all five processes and took stratification into account. This model was validated by comparison with a series of small-scale lab experiments involving point jets originating from a travelling needle (Su et al., 2007). This model was then extended to multiple jets, injected at various locations and orientations, and coalescing into different currents inside the evolving trench.

Laboratory experiments
The laboratory results are scaled to the prototype scale assuming a geometrical scale factor. The non-geometrical variables (velocities, discharge and power) are scaled according to Froude similarity, which preserves the relative influence of inertial, density and gravity effects (Vanden Berghe, 2008).

Experimental results
The main findings of the experimental campaign can be summarised as follows:

- The trench lengths achieved by a given set of jetting tools depend greatly on sand size and to a lesser degree on the density of the seabed. Finer sands lead to longer trenches by slowing the pace of resedimentation. Denser beds lead to longer trenches by reducing the pace of sidewall breaching and slumping.

- Regardless of conditions, giving a downward orientation to the forward jets lead to increased maximum trench depths. However, this increase in depth is limited to the immediate vicinity of the front jetting sword. An increase in localised trench depth does not translate into an overall increase in trench length.

- For loose beds, the orientation of the forwards jets appears to exert little to no influence on the ultimate length of open trench maintained behind the sword.

- The length of open trench varies approximately linearly with the total flow rates supplied to the jetting tools. For a given jetting configuration, an increase in flow of about 25% associated with doubling the jetting power leads to an increase in trench length of about 20 to 25%.

Numerical model
Comparison of the model with experimental data
Both quantitatively and qualitatively, a good level of agreement is recorded between computation and experiment. Trench shapes and dimensions are well reproduced, and their responses to parametric variations are well captured by the model.

For different sand, only three parameters must be set differently: the single grain fall velocity $\omega_s$, the erodibility $\varepsilon_s$, and the breaching speed $\lambda_\phi$. 
B.4 Scour formation

**Scour Formation by Internal Static Jets**

Niven and Khalili (1998) did research concerning the effect of erosion caused by an internal jet. Internal jets (Figure B. 6) are positioned below the original soil surface, where they inject water. The geometry of the scoured zone with internal jets always has a dynamic shape, which indicated that the eroded zone is filled with a suspension.

The scour depth for internal jets depends on the Froude number. The Froude number is closely related to the Shields number, which is one of the three equations necessary to determine the scour depth for an external jet. The part below briefly explains the relationship between the jet velocity to create scour and the scour depth.

**Critical Scour Velocity**

It is possible to attribute the calculated velocity at the jet penetration point to a minimum scour velocity of the bed material (Rouse, 1940; Rajaratnam and Beltaos, 1977). Taking $U_m = U_m^*$, which is the minimum shear velocity to create erosion, and $x_j = a$ at the jet penetration point, (Eq. 4.2) gives:

$$
\frac{u_m^*}{u_0} = \frac{\beta}{a/d_j}
$$

(B.5)

The maximum scour depth, $\varepsilon_m$, is equal to the jet penetration, $a$, added to the jet depth, $H$.

With correlation plots and multiple regression analyses Niven & Khalili (1998) empirically determined an equation for the dimensionless jet penetration depth:

$$
\frac{a}{d_j} \approx 2.25 Fr_p \left( \frac{D_{50}}{d_j} \right)^{0.39} \quad \text{for} \quad \frac{D_{50}}{d_j} < 0.2
$$

(B.6)

Where $Fr_p$ is the densimetric particle Froude number and $a$ the jet penetration depth.

Combining Eq. (B.5) and Eq. (B.6) produces a critical scour Froude number, $Fr_p^*$, dependent only on the ratio of particle- and jet diameter:

$$
Fr_p^* = \frac{u_m^*}{\sqrt{\gamma (\rho_s - \rho_f) D_{50}/\rho_f}} = 0.44 \beta \left( \frac{D_{50}}{d_j} \right)^{-0.39}
$$

(B.7)
Equation (B.7) can be considered as a shields-type relationship for penetration of a jet vertically through a bed. The shields relationship for a horizontal sediment transport is given in Eq. (B.8).

\[ Fr_{\text{shields}}^* = \frac{u^*}{\sqrt{\rho_s - \rho_f} d_{50} / \rho_f} = f\left(Re_p^*\right) \left(\frac{\text{Large } Re_p^*}{\text{constant}}\right) \]

Where the velocity and hence Froude and Reynolds numbers are defined in terms of a shear velocity, \( U^* \), or shear stress, and in which \( Fr_{\text{shields}}^* \) tends to a constant value with large \( Re_p^* \). \( Re_p^* \) is the particle Reynolds number (\( Re_p = d_j U_0 \rho_f / \mu \)). Whilst several external jet workers have used the value for diffusion into a motionless, identical fluid (\( \beta = 6.3 \)), results of Niven and Khalili (1998) indicate that if the potential core is not totally developed and a counter flow is interacting against the jet diffusion, a value of \( \beta = 5.8 \) can be chosen.
B.5 Fluidization

In Situ Fluidization

Fluidization by horizontal submerged pipe

In situ fluidization was proposed by Hagyard et al. (1969) for the creation of offshore channels with perforated horizontal submerged pipes, and has been studied extensively by Weisman, Lennon and co-workers. By injecting water from a submerged pipe, the pore water pressure increases and consequently the effective stress in the soil reduces. With a sufficient injection rate of water, the soil on top of the buried pipe will eventually fluidize. Once the soil is fluidized, it can either be transported by natural currents or hydraulic pumping.

The width of a fluidized zone depends on both the flow rate and the depth of sand covering the submerged pipe. Once completely fluidized, the fluidized region behaves as a dense fluid flowing upwards, while the non-fluidized region has characteristics similar to the initial fixed bed. Hagyard et al. (1969) and Weisman et al. (1988) discovered that there is some flow leakage to the surrounding non-fluidized soil, but that the leakage decreases with increasing flow rates and that the angle of the fluidized region increases with corresponding increases in the flow rate. Moreover, the fluidized region widens with increased flow rate ($Q_2 > Q_1$) (Figure B. 7). Eroded soil particles have either the option to remain in suspension or leave the fluidized region to form a berm.

![Fluidized region above submerged pipe for two flow rates (Weisman et al., 1988)](image)

The leakage across the fluidized/unfluidized region interface, as shown in Figure B. 7, is less than 5% of the total flow rate injected into the system. But just prior to fluidization, the flow outside the zone about to be fluidised is approximately 40% of the total flow rate, indicating that initiation of fluidization from a buried pipe requires an energy input (flow rate) that is larger than required to maintain fluidization. This phenomenon can be explained by to the energy necessary to overcome grain interlocking (Weisman et al., 1988).

Kelly (1977) investigated the top width of the fluidized region and concluded that the size and shape of the fluidized region and the flow rate required for incipient fluidization is strongly influenced by the nozzle configuration and by the erosive power of the jets. He also concluded that in the optimal jet configuration the nozzles are oriented in horizontal directions along opposing sides of the source, in order to create the widest fluidized region.
Incipient fluidization
Lennon et al. (1990) used the theoretical critical hydraulic gradient to predict the incipient fluidization flow rate, $Q_i$, required to initiate fluidization of a bed of fine sand. Moreover, they developed a fluidization system chart for the determination of the flow rate factor required for incipient fluidization (Figure B.8).

$$Q_i = \left( \frac{Q_i}{Kd_b} \right)^* \cdot K \cdot d_b \quad (B.9)$$

Where $(Q_i/(Kd_b))^*$ is the incipient flow rate factor, $K$ the hydraulic conductivity, $d_b$ the burial depth of the pipe [distance initial sand bed – center buried pipe] and $D_p$ the pipe diameter.

In order obtain the flow rate factor, the relative burial depth, $d_b/D_p$ and the domain size, $X_d/D_p$ and $Y_d/D_p$, have to be determined. $X_d$ is the horizontal distance to the non-fluidized zone and $Y_d$ is the vertical distance to the non-fluidized zone below the jet.

Fluidization by internal static jets
Niven and Khalili (1998) also described the profile of the fluidized zone during the different stages of lowering a jet into the bed (Figure B.9).

Figure B. 8: Chart for isotropic conditions providing required incipient flow-rate factor versus relative depth of burial $d_b/D_p$, for various domain sizes (Lennon et al., 1990)

Figure B. 9: Transition from stable in situ fluidisation to cavity formation (Niven and Khalili, 1998)
At first, the profile of the in situ fluidized zone remains about the same, for any given soil, jet diameter and flow rate, until the jet depth approaches the critical depth (Figure B. 9). The effluent water takes the form of an open, approximately ellipsoidal profile at a shallow jet depth (Figure B. 9), which evolves in a fixed asymmetric spouted zone with increasing the jet depth (Figure B. 9). Eventually, at greater depths, a submerged fluidized cavity is formed (Figure B. 9). Cavities rapidly decrease in size with further increasing the jet depth, till a point at which the dimensions of the cavity are negligible and no fluidization occurs.
Appendix C  Morphological overview

The content of this chapter is confidential.