Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Framework for jet trenching performance prediction in cohesionless soils

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ABSTRACT: Cable (or pipeline) burial by jet trenching the seabed is one of the most widely utilized methods to protect assets against anthropogenic and natural hazards, including interaction with fishing gear and/or anchor strikes.
Over the years, offshore industry operators have all contributed to the optimization of jet trenching machines design, to improve performance. Important decisions regarding product protection requirements and trenching methods are often made at relatively early project stages, with existing public domain information generally based upon limited empirical relationships and installation contractor knowledge.
Cathie propose a framework for jet trenching performance prediction, based on a deeper understanding of the key parameters: operating jetting pressures, soil type and strength, cable properties, installation lay tension and speed. The framework is based upon Cathies in-house knowledge of jet trenching theory and practical experience, and a partnership with Asso.subsea, an industry-leader installation contractor, designer and manufacturer of subsea trenchers. This paper focuses on jetting performance in cohesionless soils and includes a detailed back-analysis of trenching data from key offshore cable projects in the North Sea and in the Mediterranean.

Keywords: trenching; cables; burial; installation; sand.

1 INTRODUCTION

Jet trenchers use water pressure jets to fluidise sands (or cut clays), create a trench in the seabed and facilitate product burial. Trenchers are usually equipped with a pair of jet legs (alternatively named jet swords) connected to a pump system. The legs extend below the seafloor with a series of nozzles of variable size and positions directing water jets into the soil. This technique is considered effective and low risk for a wide range of soil conditions (especially sands and low strength clays), for products such as pipelines, electrical interconnectors, telecom cables, offshore wind inter-array and export cables.

Jet trenching machines design optimization typically aims to increase trenching speeds and/or burial depths, and enlarge the feasibility envelope a more challenging soil conditions such as higher strength clays. The framework presented herein aims to develop a deeper understanding of the jet trenching key parameters in cohesionless soils: operating jetting pressures, grain size and density, cable properties, installation lay tension and speed.

2 JET TRENCHING MACHINES

2.1 Typical configuration

The typical configuration of a jet trenching machine includes:

- pump system, consisting of single or multiple pumps, with indicative pressure range of 2bar to 20bar, connected in parallel or in series;
- one pair of jet legs, with certain inclination to the seabed, with typical length and inclination of 2m to 3m and 45° to 65°, respectively;
- jetting nozzles, in variable number, distance and orientation, with typical size range from 6mm to 20mm diameter;
- bearing tracks or skids.

The jet trencher performance is generally a function of the jetting pressure and flow rate, as well as the target trench dimensions. The pressure and flow rate are a function of the pump system and the jet leg configuration (size and number of nozzles). The trench dimensions are generally a function of the product size (trench width) and soil type / required protection level (trench depth).

2.2 AssoJet III MK2 HP configuration

The AssoJet III MK2 is a subsea trenching machine manufactured by Asso.subsea. It is equipped with two jetting legs fed with a 1.3MW pump system. A typical High Pressure (HP) AssoJet III configuration with a 2m jet leg is showed in Figure 1, with details in Table 1.

Figure 1 – AssoJet III in skids mode.

Table 1. AssoJet III typical HP 2m jet leg configuration.

Item	Value
Jet leg length (from hinge point)	2.78 m
Leg inclination to horizontal	60°
Target leg penetration depth	1.8 m
Legs separation / outer distance	0.35 – 0.5 m
Front nozzles no.*, diameter	26, 8.5 mm
Rear nozzles no.*, size	2, 100x40 mm
Front nozzles operating pressure	18 bar
Total front flow rate (2x legs)	700 m^3/hr
Rear nozzles operating pressure	4 – 6 bar
Total front flow rate (2x legs)	1,400 – 1,600 m^3/hr

** Number of nozzle per each leg.*

The AssoJet III is a Remotely Operated Vehicle (ROV) and can be operated in either skid mode or track mode. The cable installation via Post-Lay Burial (PLB) comprises the following steps:

1. after cable laying on seabed, the machine is deployed over the cable;
2. the two jet legs are engaged into the ground at target depth / angle, one on each side of the product;
3. the cable falls by gravity into the fluidised soil between the legs, following its natural catenary; this occurs without the use of a depressor, minimizing the interaction with the product;
4. the trench (partially) backfills, with the cable installed at target burial.

Each AssoJet III jet leg is equipped with several forward-facing nozzles – vertical (forward-downward directed) and horizontal (forward-inward directed) nozzles – and two rearward facing (backwash) jets at the bottom of the legs. The nozzle arrangements are generally optimised as follows:

- forward-vertical nozzles fluidise the soil in front of the legs to allow for the initial jet leg penetration and to ensure it remains engaged during trenching operations. These are often relatively small to generate higher pressures to fluidise soils more efficiently;
- inward nozzles to fluidise soils between the legs to allow the product to 'sink' into the trench;
- rear nozzles provide 'backwash' to maintain the soils in suspension and allow the product to 'sink'/catenary into the base of the trench (without washing too much sediment out of the trench). These are generally relatively large to supply large volumes of water at relatively low pressure.

The jet legs are fed via water pumps working in parallel:

- two HP pumps, each feeding forward vertical and horizontal nozzles of one leg, with total forward jetting power in the range from 250kW to 380kW, which can be adjusted by the operator;
- two Low Pressure (LP) pumps, each feeding the backwash nozzles of one leg.

The AssoJet III can handle products with up to 530mm outer diameter, and its jet legs can be extended to a maximum target trench depth of 3.2m.

The ROV has two motion configurations:

- skid mode, with the trencher relying on the rear jetting as thrusters, and the skids sliding on the seabed;
- track mode, with the trencher moving thanks to the rotation of the tracks, which would penetrate the seabed and exploit its surface adherence.

3 JET TRENCHING DATA

3.1 Viking Link Interconnector (North Sea)

Cathie carried out a detailed review of data from cable burial campaigns undertaken for the Viking Link HVDC interconnector project, located in the North Sea and connecting Bicker Fen (UK) to Revsing (Denmark). The AssoJet III was used for the cable burial campaigns C1 to C7 from 2021 to 2024. Data from C4 and C5 campaigns in Spring / Summer 2022 were analyzed, including:

- Site data from geotechnical campaign;
- Kilometre Post (KP) profiles of depth of cable lowering / burial, jet leg depth and tool speed.

Trenching data were selected over a total of 28km, where the trencher performance – in terms of jet leg penetration, cable lowering and speed – were noted to be reasonably stable over a 1-km route stretch. These data are summarised in Figure 2, where the excavation rate predictions as per Section 4.3 are also presented. In the selected areas, the shallow geology was anticipated to be dominated by (very) loose to medium dense, silty sand; locally the sand would become denser and/or coarser. The granulometry was characterised by a d50 in the range of 0.01mm to 0.8mm, with an average of 0.13mm. Gravel particles were anticipated only locally, as well as localised higher strength clays.

Note that the characterisation was mainly derived based on the geotechnical data – interpreted CPTs and VCs (including PSDs). No KP profiles data were available on operational jetting pressure and flow rate, however Asso.subsea's operators indicated the typical range of Table 1 as appropriate. The tool was used in skid mode. Mechanical properties were provided for the HDVC bundle, comprising two power cables and one fibre optic cable, as reported in Table 2.

Table 2. Viking Link Bundle mechanical properties.

Item	Value
Outer diameter (min - max)	180 - 260 mm
Weight in seawater	73 kg/m
Bending stiffness (horizontal)	9 kN·m^2
Bottom residual lay tension	5.0 – 7.5 kN

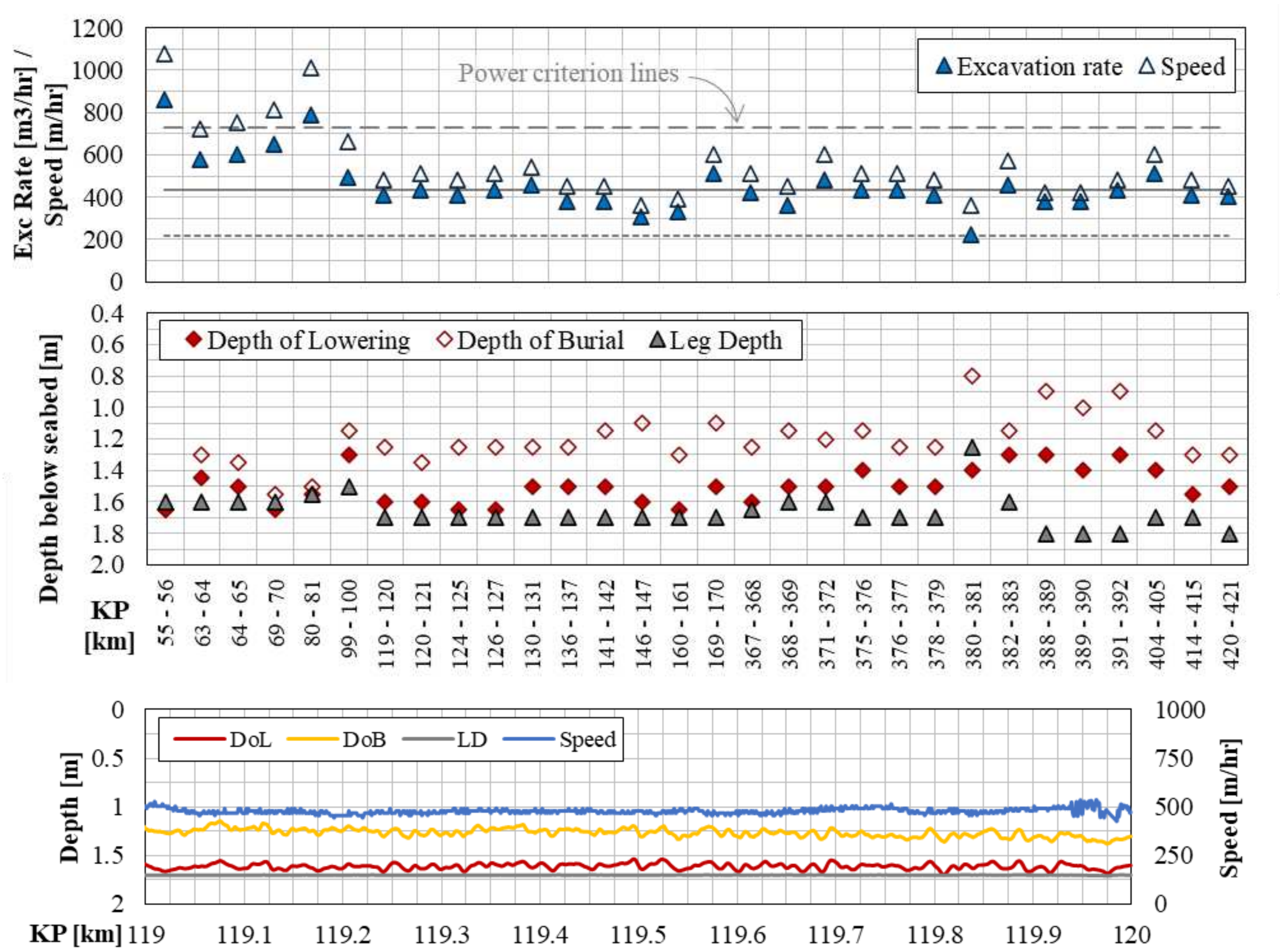

Figure 2 – Viking Link Interconnector, AssoJet III trenching data analysis (top); example data KP 80-81 (bottom). Power criterion lines are as per model of Section 4.3.

Performance was noted to be good along the 26km of route dominated by sands and low strength clays: speeds generally in the range from 400m/hr to 600m/hr, locally up to 1,000m/hr; lowering in excess of the target DoL of 1.0m and good bundle cover. Sub-average performance – slightly reduced leg penetration and lowering – were noted in presence of gravel and very high strength clays.

3.2 Lavrio-Serifos-Milos Interconnections (Mediterranean Sea)

Asso.subsea also made available the trenching data from the cable burial campaign for the Lavrio-Serifos-Milos (LSM) interconnections carried out in 2024, between mainland Grece and the islands.

Data for burial performed via the AssoJet III over a total length of over 9km were reviewed and back-analyzed with the same approach as the Viking Link data. The trencher was mainly used in areas of medium dense to dense sand. Logs with operational jetting pressure and flow rate were provided, noted to be aligned with the typical ranges of Table 1.

3.3 Cathie's inhouse trenching database

Cathie's inhouse trenching database includes data from offshore installation projects and laboratory testing data. Data from trenching in sand areas cover operational (forward) jetting power ranging from 100kW to 800kW. The challenge with creating such databases was that it could not always be established for each datapoint that a trencher was operating at its peak performance, i.e. maximum excavation rate.

The associated back-analysis is presented as anonymised in paragraph 4.3, along with the aforementioned Asso.subsea's datasets (Viking Link and LSM).

4 JET TRENCHING PERFORMANCE PREDICTION MODELLING

4.1 Jet trenching suitability

The initial jet trenching feasibility is generally assessed in early stages of the project, as part of the Burial Assessment Study (BAS). Jet trenching is generally deemed suitable for sands and low to medium strength clays, while it may not be feasible – or feasible with reduced performance – in higher strength clay, cemented sand or gravel; however, the feasibility envelope may be widened by optimising the jetting configuration.

4.2 Pump and nozzle discharge point

Pumps are designed to supply water at a given pressure and flow rate (discharge point). There is generally an inverse relationship between pressure and flow rate, i.e. increasing pressure tends to reduce flow rate, as shown in Figure 3.

The total nozzle demand is a function of the flow rate and nozzle pressure (Rajaratnam, 1982). The following relation based on Bernoulli law is used to describe the nozzle demand curve:

$$p = \xi \cdot \frac{\rho_w}{2} \cdot \left(\frac{Q}{A_n}\right)^2 \qquad (1)$$

where p (kPa) is the average nozzle pressure, ξ (-) the nozzle efficiency factor in the range of 0.5 to 1.0, ρ_w (kg/m3) the seawater density, Q (m3/hr) the volumetric flow rate, A_n (m^2) the total nozzle area fed by the specified flow.

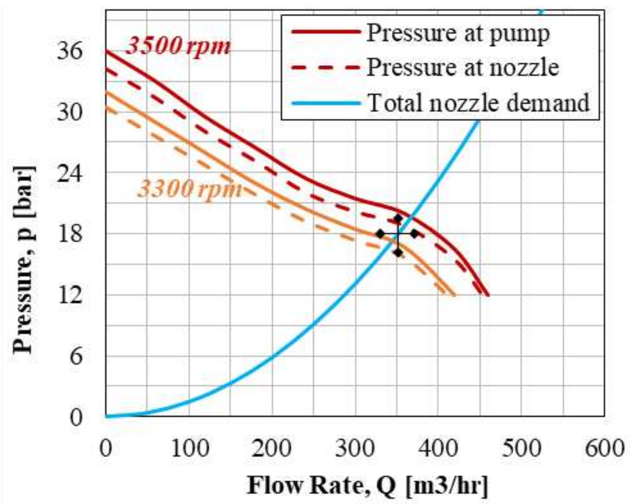

Figure 3 – AssoJet III, HP pump and front nozzles discharge point, with envelope for different power levels and assumed losses marked in black.

The nozzle demand curve is then matched to intersect the corresponding pump curve as shown in Figure 3. The pump curve is generally provided by the manufacturer; the corresponding nozzle pressure curve shall include pressure losses through the pipes and the jet leg. Pressure losses can be assessed via Computational Fluid Dynamics (CFD) or estimated based on experience: a typical range is 5-20%, generally higher at higher flow rates and lower at the pump system highest efficiency point.

A combination of multiple pumps is often adopted to increase the jetting power: e.g., in the AssoJet III the front nozzles (horizontal and vertical) from each leg are fed separately by two HP pumps, each run at max 3,500rpm, with highest efficiency at 20bar and

350m³/hr. The two pumps work in parallel, doubling up the total discharge flow rate at fixed pressure. The AssoJet III front nozzles discharge point assessment is showed as example in Figure 3 for the configuration of Table 1. Via an optimisation of pipes and jet leg design – informed by CFD – Asso.subsea managed to minimize pressure losses to < 10% at working point. Resulting nozzle pressure and flow rate is estimated at 18bar and 350m³/hr, corresponding to a total forward power for two legs of 350kW. A similar system is employed for the rear nozzles, separately fed by two LP pumps.

Multiple pumps can also be set in series, to increase discharge pressure at fixed flow rate. This may be required if the front nozzles pressure is not deemed sufficient (e.g. only LP pumps available), therefore the theoretical pressure – excluding losses – can be doubled up.

4.3 Trench creation and sand fluidisation

The jet trencher sand fluidisation capabilities are assessed as function of the discharged nozzle flow rate and pressure, of the trencher progress rate (speed) and sand density. The forward power and flow rate should be designed to erode and fluidise the sands anticipated along the route, at a given progress rate, to ensure a good jet leg penetration into the seabed.

Industry practice typically relates the limiting trencher progress rate U_{max} (m/hr) to the required water volume pumped into the soil (White and Cathie, 2011), as per the below *volume criterion*:

$$ER_{max} = U_{max} \cdot A_{tr} = {}^{Q_{fw}}/_{\alpha} \qquad (2)$$

where ER_{max} (m³/hr) is the limit Excavation Rate, Q_{fw} (m³/hr) is the forward flow rate, α (-) the fluidization ratio (in the range of 3–5), A_{tr} (m²) the trench cross area; note that by convention the trench width is considered as the leg outer edge separation, and the trench depth as the leg penetration depth.

Nonetheless, the above *volume criterion* has often proved to be overly conservative for HP configurations, as it does not account for the nozzle pressure. Cathie propose a refined *power criterion* method to determine the limiting progress rate U_{max} (m/hr), based on in-house database compiled from trenching campaigns and inhouse experience:

$$ER_{max} = U_{max} \cdot A_{tr} = a \cdot \left(\frac{P_{fw}}{b}\right)^{\frac{2}{3}} \qquad (3)$$

$$P_{fw} = p_{fw} \cdot Q_{fw} \qquad (4)$$

where ER_{max} (m³/hr) and A_{tr} (m²) as above, P_{fw} (kW) the forward jetting power function of pressure p_{fw} (kPa) and flow rate Q_{fw} (m³/hr), a and b (-) calibration parameters, as defined in Table 3. Parameter a is a scaling factor, while b is a multiplier of the power and therefore can be seen as an efficiency factor. They were selected such that the low and high estimate envelope the database points.

Table 3. Power criterion calibration parameters.

Parameter	ER_{max} LE	ER_{max} HE
a, scaling (-)	150	500
b, $efficiency$ (-)	200	200

The resulting Lower and Higher Estimate (LE and HE) ER_{max} curves and data from Viking Link, LSM and Cathie's database are presented in Figure 4. The curves provide a reasonable envelope of the available data points and are generally aligned respectively with very loose and very dense sands.

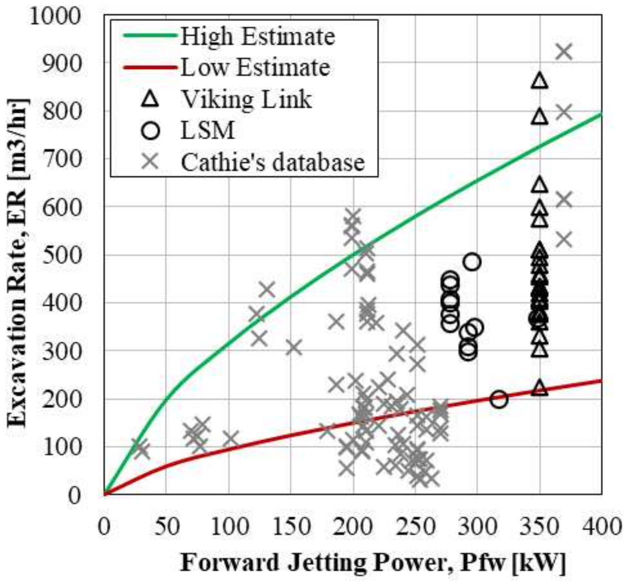

Figure 4 – Back-analysis of trenching data from Viking Link, LSM and Cathie's database; excavation rate function of jetting power; derived Power Criterion bounds.

The general trends indicate that higher forward jetting power leads to high excavation rates. Previous experience indicated that higher sand densities lead to lower excavation rates, however, this may have been associated with relatively low powered trenchers with limited pressure. The observations at Viking Link indicated some of the fastest progress rates in the densest soils, where trenches are likely to be more stable benefiting the cable lowering – as discussed in Section 4.4.

An example feasibility envelope for the AssoJet III is presented in Figure 2, which indicates the best estimate power criterion – derived with average of high and low estimate parameters – provides a reasonable match along the route sections considered, whilst the traditional volume criterion would tend to significantly under estimate trenching rates.

4.4 Fluidisation model limitations

Although valid for a wide range of sands, neither criterion explicitly accounts for jetting pressure or soil properties such as grain size or specific gravity. Both jetting pressure and soil properties would be expected to have a significant influence. It is anticipated that jetting would perform well in medium to fine and silty sands as found at Viking Link, while reduced performance may occur in presence of significant amount of gravel or other larger particles, cemented layers, and higher strength clays, as loss of fluidisation in these soils may result in reduced leg penetration and reduced cable lowering (more details on the latter in §4.5). In-house experience indicates that in these conditions high pressure jetting would work better than lower pressure jetting, however this topic is outside the scope of this paper.

ROV motion configuration and environmental factors such as currents would also influence the performance. Currents would affect the vehicle balance, with additional effort being required to maintain the position. Generally, for the AssoJet III, currents exceeding 1m/s may limit the trenching speed. The impact would be higher in skid mode, as the vehicle would be lighter than in track mode, however thrusters could be adjusted to counteract the effect of the currents. In track mode, as mitigation measure, the tracks rotation could be increased.

Note that the two model criteria only focus on trench creation and jet leg engagement, and are deemed suitable to further refine the initial trenching feasibility studies. The detailed product lowering shall be assessed separately, as detailed below.

4.5 Product lowering into open trench

The key physical phenomena associated with cable lowering into the open trench during jetting are sediment transport and deposition, sidewall collapse and overspill. These phenomena are not explicitly accounted for in the model of section 4.3; they are discussed in detail in the available literature (Vanden Berghe et al., 2008 and 2011) and they are briefly recalled in the following.

While the jet legs are engaged, the water flow deployed by the rear nozzles (backflow), along with a portion of the front flow redirected backward, will encourage the sands to remain in suspension for some distance behind the trencher to allow the cable catenary to lower into the trench. Observations indicate that the stable trench length would generally be linearly proportional to the backward directed flow rate. The sidewall collapse (breaching) increases the amount of material that need to be kept in suspension behind the trencher. Looser sands result in larger collapsed volume due to lower friction angle. Finer sand yields longer stable trenches than coarse sand, due to the lower settling velocity of finer sand which are easier to keep in suspension.

The product (e.g. cable, bundle or pipeline) lowered into the fluidised trench can be modelled as a hyperstatic cantilever beam (Vandenberghe, 2011). The product deflection into the trench depends on its weight, lay tension and bending stiffness, and the extension of the soil resedimentation front. The contact point between the product and resedimentation front corresponds to the touchdown point, i.e. product depth of lowering.

Cathie is currently working on further developing their in-house trenching performance tool for cohesionless soils (sands): along with fluidisation model of section 4.3, the product lowering model is based on volume balance and soil-to-water concentration, which aims to define resedimentation front, touchdown point and cable cover. It is benchmarked against trenching data, and is being updated as different trenchers are analysed.

4.6 Sediment cover over product

Based on the Asso.subsea data presented in Figure 5, at a given jetting power and pressure, overspill of suspended sediment out of the trench was noted to be higher at lower excavation rates, likely due to the higher concentration of backwash. Operating towards the upper bound of the feasibility speed range would therefore reduce sediment loss and increase product cover.

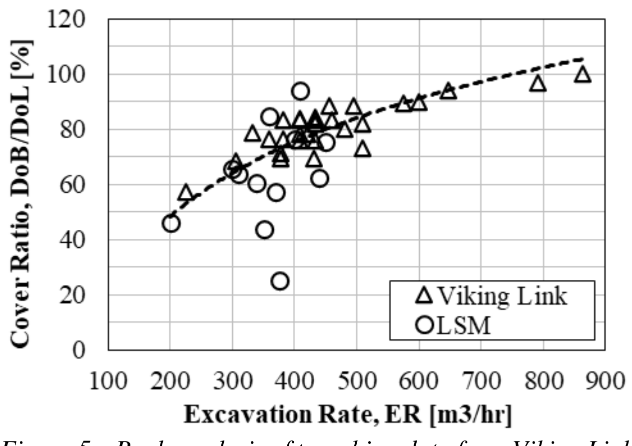

Figure 5 – Back-analysis of trenching data from Viking Link and LSM; cover ratio function of excavation rate.

5 CONCLUSIONS AND RECOMMENDATIONS

The presented data and associated analyses indicate that a jetting power-based approach would lead to a more accurate and less conservative definition of feasible jet trenching speeds in sandy soils. The presented framework can be used to:

- better inform the jetting tool selection;
- provide a more accurate jetting performance prediction;
- inform on jet trencher configuration conceptualization (during manufacturing) and optimization (during operations).

Additional jet trenching data could be used to further refine the proposed prediction method and derive a narrower, tool-specific feasibility envelope, and explicitly factor in the product lowering assessment.

AUTHOR CONTRIBUTION STATEMENT

C. Ortolani: Data curation, Methodology, Formal Analysis, Writing - Original draft. **J. Irvine**: Methodology, Formal Analysis, Supervision, Reviewing and Editing. **L. Burley**: Writing- Reviewing and Editing. **H. Falepin**: Writing- Reviewing and Editing. **A. Prousanidou**: Supervision, Review and Editing. **A. Tsopela**: Data Curation and Acquisition.

ACKNOWLEDGEMENTS

The authors are grateful to Asso.subsea and Prysmian Group for the trenching data acquisition and curation.

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