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State of the Art Ploughability Assessment

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ABSTRACT

Ploughing is one of the most common methods for burying subsea pipelines or cables for protection against trawls, on-bottom stability, for better thermal insulation or for meeting the legislative requirement. A ploughability assessment is undertaken during design and planning stages to evaluate suitability a plough for required burial depth and to determine the duration of offshore ploughing operation. This paper presents the insight into ploughability assessment, state-of-the-art methodology for the assessment and highlights some critical limitations that shall be undertook by the designers and engineers. An accurate ploughability assessment undertaken with full knowledge of its limitations would reduce project risks and could lead to millions of dollars in cost savings.

KEY WORDS: Plough; pipeline; offshore; seabed; cables.

INTRODUCTION

Subsea pipelines and cables are instrumental for energy and communications sectors. There are thousands of kilometers of pipelines and subsea cables buried in the seabed around the world. The subsea pipelines may have to be buried for reasons such as protection against trawlers, on-bottom stability, for better thermal insulation or for legislative requirements. Communication cables are also buried subsea for protection. The method of seabed trenching predominantly depends on the soil type, but ploughing is one of the most commonly used methods for pipeline and cable burial.

To plan for offshore operational time and to identify any areas of concern in ploughing operations, a ploughability assessment is carried out during the project design stage. The ploughability assessment for a given plough is based on geotechnical conditions at the site. The geotechnical condition of a site is characterized by geotechnical model with appropriate soil parameters. The assessment predicts the plough velocity and two force for a given trench and soil conditions. This paper presents an overview of the state-of-the-art ploughability assessment, provides in-depth view into soil mechanics of ploughing, and presents discussion on the limitations with regard to ploughability assessment results. The paper also presents parametric study results to better understand the sensitivity of soil properties in on ploughing performance.

The main aims of a ploughing assessment include:

- Assess whether the ploughing as planned can be carried out within allocated the time period using the assigned plough.
- Identify regions of concern where problems may be encountered while ploughing.
- Plan for contingency in case of any problems.

A best practice ploughing assessment methodology is presented in Fig. 1. The starting point for the ploughability assessment should be *"Geophysical Survey"* (Task A) and *"Desk Study/Geological Study"* (Task B). The next step would be "Geotechnical Survey and Testing." This will lead to *"Soil parameters & Soil Classification"* (Task A2) based on field and laboratory testing (Task A1). A geological study (Task B1) should be carried out in parallel to tasks A1 & A2 to understand the geological history of the location (i.e., any glacious ice, erosion/sedimentation history, seismicity/slope stability, etc.).

The findings from geophysical survey and desk study/geological study will lead to the soil strata identification and soil parameters (Task C), which in turn are the main input for ploughing assessment (Task D).
Depending on the variability is soil strata and parameters identified in (A2 & B1), sensitivity study and a risk assessment needs to be carried out (Task E). Results from the sensitivity assessment will highlight any risks associated due the variability in the soil data and geological factors. Thus this task E needs to be an essential part of the overall ploughing assessment. Task F which is *"Final Ploughing Assessment"* will consist of the initial assessment with the sensitivity results. The final ploughing assessment should highlight any key areas of concern for the planned ploughing and state any contingency plans (Task H) in case of ploughing difficulty.

It is good practice to update the assessment based on any initial plough data or trial tests on site (Task I). If the plough details or operational procedure is altered from what was assumed in the plough assessment, then the plough assessment should be revisited and updated to account for the changes.

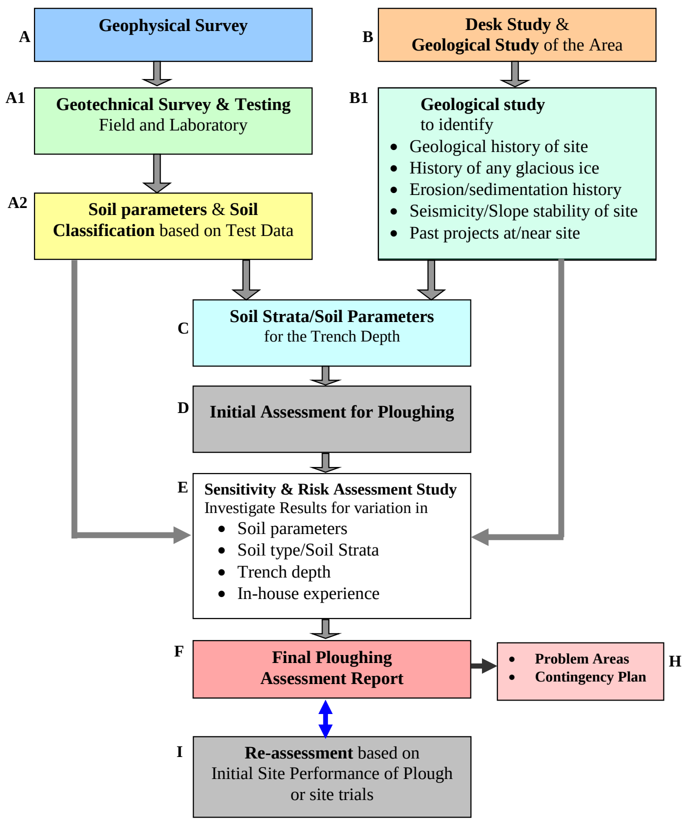

Fig. 1 Recommended Ploughing Assessment Methodology

BACKGROUND TO PLOUGHS

Ploughs are utilized offshore to trench and bury pipelines or subsea cables. The burial of the pipeline or cable can be "during-trench" or "post-trenching" depending of the project requirements and depending on the trench depth requirements, the trenching may be single or multi-pass ploughing. There are types of plough in use, including:

- Variable Multi-Pass Plough
- Advanced Multi-Pass Plough (AMP500)
- PL2 and PL3 Plough
- Advanced Pipeline Plough (APP)
- SCAR

A typical schematic of a plough is shown in Fig. 3. The basic features include: a share, which self-corrects its own depth to follow the skid settings; beam; mould boards, to move the spoil away; and two front skids. Fig. 2 presents a visualization of a PL2 plough in operation.

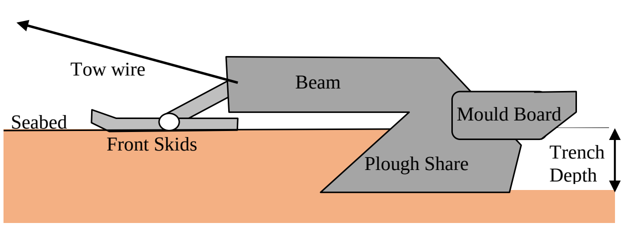

Fig. 3. Schematic of a Plough

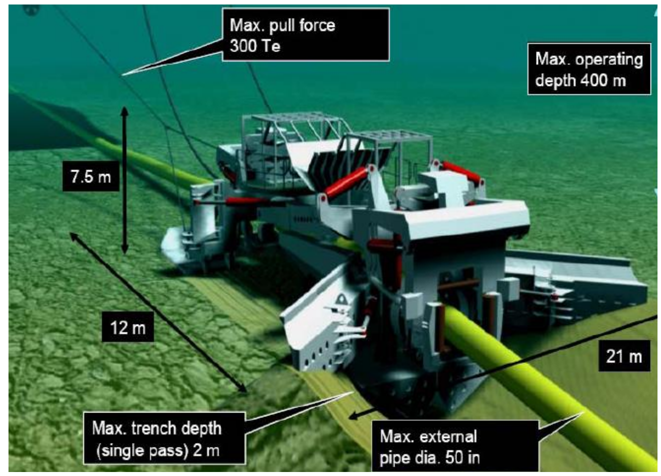

Fig. 4 Schematic of PL2 Plough (Source Rambøll Report (2008))

GEOTECHNICAL MODELS

Early work on the design and operation of underwater pipeline trenching is given by Palmer et al. (1979). Geotechnical models that can be used to predict the forces required for trenching were developed by various researchers. All relevant publications in literature on ploughing assessment were reviewed and relevant information is reported in this section (reviewed literatures are listed in the references; Allan (1998), Bransby et al. (2005), Brown et al. (2006), Brown & Palmer (1985), Cathie et al. (2007), Cathie & Wintgen (2001), Cheng et al. (2007), Hatherley et al. (2008), Lauder et al. (2008), Machin (1995), Miedema at al. (2007), Palmer (1999), Palmer et al. (1979), Reece & Grinsted (1986).

Fundamentally, there are two models; model used for CLAYs (cohesive soil) and model used for SANDs (cohesionless soil). These are presented below.

Cohesive Soil Model (CLAYs)

A plough is in contact with the soil in three points, two skids which run on the seabed and the share. The tow force (F) required to advance the plough in cohesive soil can be given as below.

$$F = F_w + C_c S_u D^2 (1 + C_d V) \tag{1}$$

Fw adhesion of the underside of the skids and share to the soil during ploughing

C_c coefficient similar to bearing capacity factor

S_u undrained shear strength

D trench depth (m)

C_d coefficient relating the strength of the soil at normal shear strain testing rates (Su) to the strength if the soil at ploughing rates of strain [0.0005 m/hr, Cathie and Wintgen (2001)]

V Plough speed (m/hour)

The value of the F_w term depends on whether the skids are on CLAY or SAND. A common situation is sand veneer overlying clay. In that case, the F_w is calculated as a friction term for the proportion of the plough weight applied to the skids. Assuming 50% of the plough total weight on the skids, the F_w can be calculated as below.

$$F_{wsand} = 0.5C_w W \quad (2)$$

W submerged plough weight (+ submerged weight of the pipe above seabed)

C_w friction coefficient

$$F_{wclay} = As_u \alpha \quad (3)$$

A actual area of the skid/share that is in contract with the soil (not the projected areas)

S_u undrained shear strength (kPa)

α steel-soil interface factor (initiation value~1, residual value ~0.5)

Eq.1 is often used in the form given below as coefficient provides a direct measure of trenching difficulty.

$$F = F_w + C_{cs} D^2 (1 + C_d V) \quad (4)$$

Where $C_{cs} = C_c S_u \quad (5)$

C_{cs} coefficient as a function of S_u is shown in Fig. 5. Thus C_{cs} can be obtained as $0.18S_u+7$ for S_u <150kPa and $0.3\ S_u$ -11 for $S_u \geq 150$kPa. These design lines are based on the data presented by Cathie and Wintgen (2001)

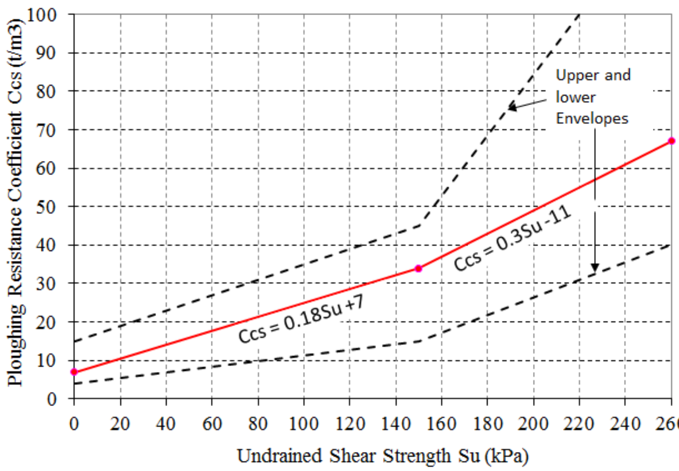

Fig. 5 C_{cs} vs *Su* (developed from Cathie and Wintgen (2001) data)

Cohesionless Soil Model (SANDs)

Ploughing resistance in cohesionless soils may be written as

$$F = F_{static} + F_{dynamic}$$

Where F_{static} is the ploughing resistance at very slow speeds – sufficiently slow for full drainage to occur, and $F_{dynamic}$ is the additional component that arises from the speed effect.

The static resistance can be written as

$$F_{static} = C_w W + C_s \gamma' D^3 \quad (6)$$

W submerged plough weight (+ submerged weight of the pipe above seabed)

C_w friction coefficient

C_s a coefficient similar to a passive pressure coefficient

The dynamic resistance principally arises from soil dilation during shearing that accompanies the advance of the plough. When dilation occurs, suction pressures are generated, and this suction increases the inter-particle effective stresses, and hence increases the soil shearing strength.

Relative Density D_r is a measure of soil packing in relation to standardized loose and dense soil states,

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \quad (7)$$

Where

e_{max} is defined as the voids ratio achieved in quickly inverting a measuring cylinder containing dry soil

e_{min} is defined as the voids achieved under optimal vibration of a compactive mass under saturated conditions and without causing crushing

A measure of dilation potential is given by S.

$$S = \frac{e_c - e}{1 + e} \quad (8)$$

Where e_c is the critical void ratio and e is the in situ void ratio.

$$S = \frac{D_r - D_c}{B + D_r} \quad (9)$$

Maximum S is 0.4 (Cathie and Wintgen (2001))

D_c is the critical relative density below which dilation does not occur, (D_c ~ 0.2 from Bolton, 1986), and B is a measure of the maximum and minimum density of the soil.

$$B = \frac{1 - e_{max}}{e_{max} + e_{min}} \quad (10)$$

Palmer (1999) has shown that, for simplified representation of a triangular plough share, the dynamic component of the force, $F_{dynamic}$, is a function of *V*, soil dilation potential *S* and the permeability *k*,

$$F_{dynamic} = f\,(D^3 SV / k) \quad (11)$$

The function *f* is linear until pore water cavitation begins to occur in some areas around the share. S can only vary up to about 0.4, while the permeability k can be at least an order of magnitude in sands of broadly similar grain size. It is clear that the dynamic resistance to ploughing will be dominated by soil permeability and variations in this parameter. This is captured in the C_d dynamic force coefficient. Thus the total ploughing resistance is provided by the following equation.

$$F = C_w W + C_s \gamma' D^3 + C_d V D^2 \qquad (12)$$

F Tow force in tonne

V Plough velocity in m/hour

W Submerged weight of the plough (tonne)

γ' Effective unit weight of the soil (tonnes/m^3)

C_w Friction coefficient

C_s A coefficient similar to a passive pressure coefficient

D Depth (m)

C_d Dynamic force coefficient, it is a function of (*S/k*), increases slightly with density and strongly as permeability reduces

Coefficients of C_w and C_s from Cathie and Wintgen (2001) are summarized below.

Table 1. Coefficients of C_w and C_s.

Coefficient	Relative Density	Value
C_w	All	0.4
C_s	Loose ($0 \leq D_r < 35\%$)	5
	Medium Dense($35\% \leq D_r < 65\%$)	10
	Dense ($65\% \leq D_r < 85\%$)	15
	Very Dense ($D_r \geq 85\%$)	20

Table 1. Coefficients of C_d .

Coefficient	Relative Density	Value
C_d	loose ($0 \leq D_r < 35\%$)	$0.00027(D_{10})^{-2.6}$
	Medium Dense ($35\% \leq D_r < 65\%$)	$0.00045(D_{10})^{-2.6}$
	Dense ($65\% \leq D_r < 85\%$)	$0.0007(D_{10})^{-2.6}$
	Very Dense ($D_r \geq 85\%$)	$0.00011(D_{10})^{-2.6}$

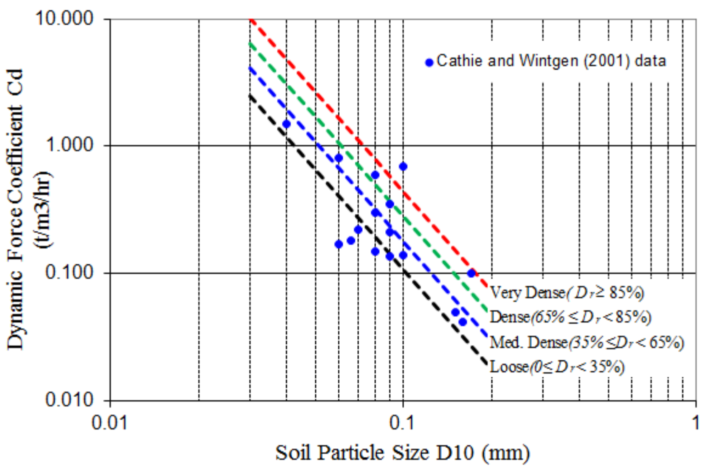

Fig. 6. Dynamic Force Coefficient C_d vs D_{10}

OBTAINING C_w, C_s AND C_d FROM BACK ANALYSIS.

If trenching trail data is available for a plough at site, then the three coefficients C_w, C_s and C_d can be obtained as given below.

- ***C_w* (Friction coefficient)** - This is determined by considering stops and starts, when both the share depth and the speed is very low, also guided by steel-sand interface friction angle published.
- ***Cs* (a coefficient similar to a passive pressure coefficient)** - This is determined from transitions and stops and starts, carefully picking tow force that is just sufficient to initiate movement, or just present before the plough stops. A chart of $(F - C_w W)/\gamma'$ *vs* D^3 yields C_s .
- ***C_d* (dynamic force coefficient)-** is obtained from Eq, 13 with known *Cw* and *Cs*. Below equation can be utilized to obtain C_d .

$$C_d = (F - C_w W - C_s \gamma' D^3) \,/\, (V D^2) \qquad (13)$$

It shall be note that the ploughing performance, reported by Allan (1998) highlights the fact that two different soil conditions can result, is similar to ploughing performance due to permeability effects of silty soils. A region of very dense sands and a region of loose silty sand both can result in similar slow ploughing rates, thus it is not possible to conclude accurately and reliably on soil properties, based on back-analysis of plough data, as two different soil conditions can result in very similar plough data.

PLOUGHABILITY ASSESSMENT

Based on the geotechnical models described in previous section, a simplified flow chart for undertaking the ploughability assessment is developed. This flow chart is presented in Fig. 7. This flow chart methodology was implemented in Excel with automation to produce a simple tool for the ploughability assessment. It shall be noted that this analytical ploughability assessment does have its limitations, as the geotechnical model utilized is limited to pure SANDs or pure CLAYs, and furthermore, no details of plough are utilized in this assessment. Therefore, results from this assessment may not be accurate in all soil conditions. The ploughability assessment can be made to be more accurate, if the assessment is calibrated with site ploughing data and with known soil conditions.

Nevertheless, this ploughability assessment tool enables us to undertake parametric studies, and hence understand the effect of differing soil conditions on the performance of a plough. Such a parametric study was undertaken to provide an insight, into how the soil properties affect plough tow force and plough speed. The assessment was done for a trench depth of 1.35m, and tow was limited to 250te and plough velocity limited to 500m/hour. Assessment was done in SAND and in CLAY separately and the results shown in Fig. 8 and Fig. 9 respectively.

The parametric study results in SAND (Fig. 8) show the effect of soil state (loose to very dense) and particle size (D_{10}) on the plough tow force and speed. The speed of the plough decreases with the soil particle size even when the same plough tow force (maximum) is applied. It is clear that the D_{10} plays a critical role in the plough performance. Therefore, D_{10} shall be carefully assessed in sands prior to using it for the assessment. The plough assessment results in CLAY are shown Fig. 9. The results show the effect of increasing in the undrained shear strength of clay from 25kPa to 400 kPa. As it may be expected, for maximum plough speed to be maintained, the required tow force increases with the shear strength of the clay. At 300 kPa, the maximum tow force is insufficient to maintain the tow speed and the hence the tow speed reduced to 405m/hour. Further increase in shear strength reduced the plough speed quickly to almost zero. It should be noted that these results are presented to show trends in plough performance, with typical changes in the soil properties, and the results should not be directly used or related to specific projects.

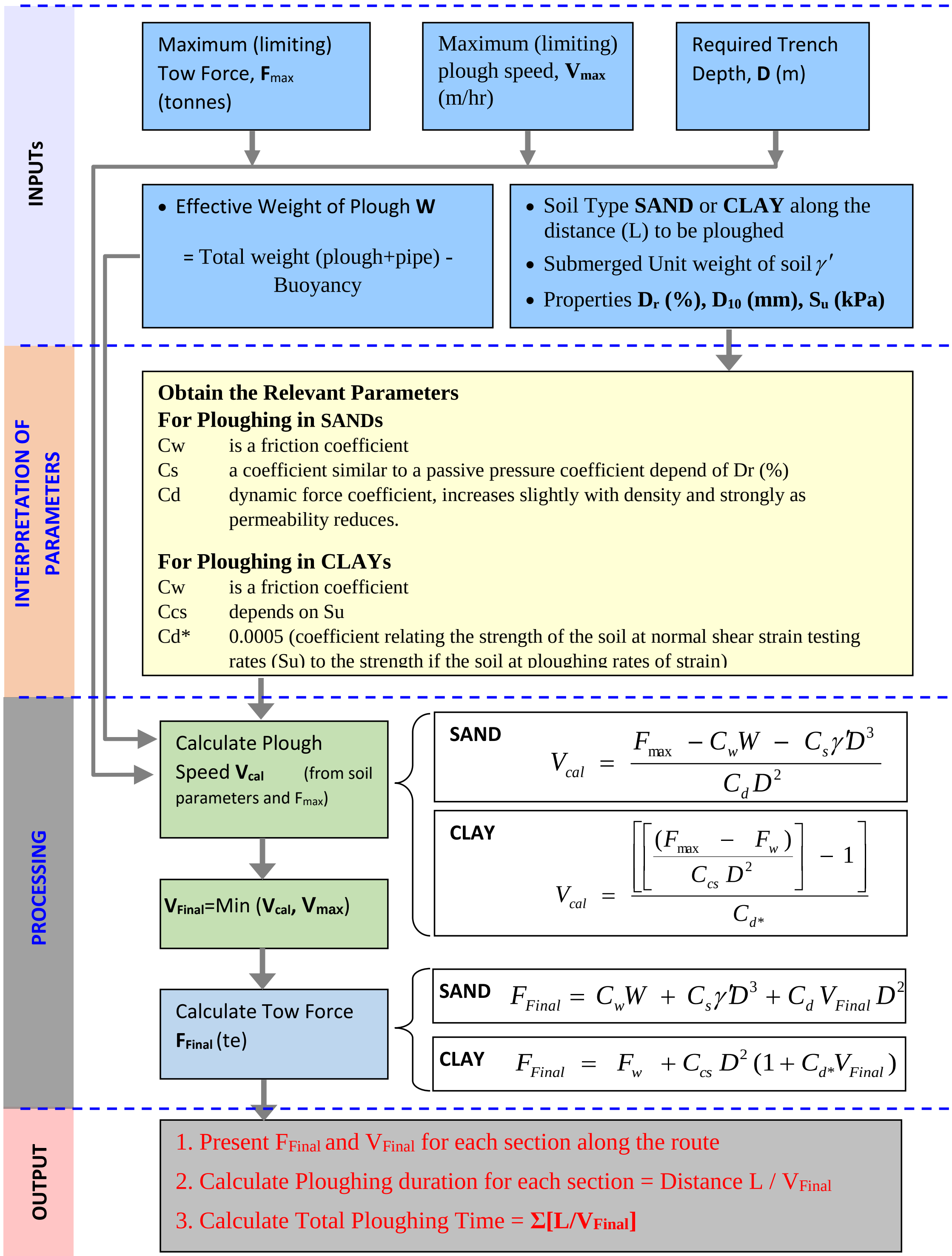

Fig. 7 Ploughability Assessment Calculation Flow Chart

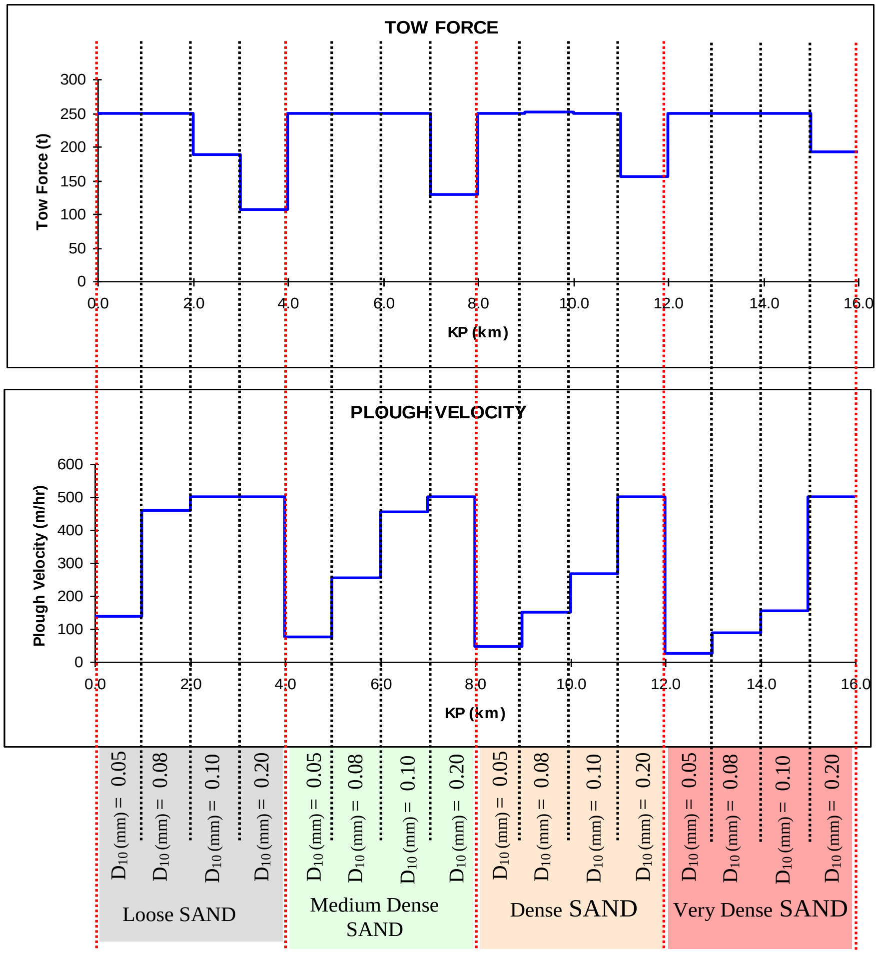

Fig. 8   Parametric Study Results in SANDS

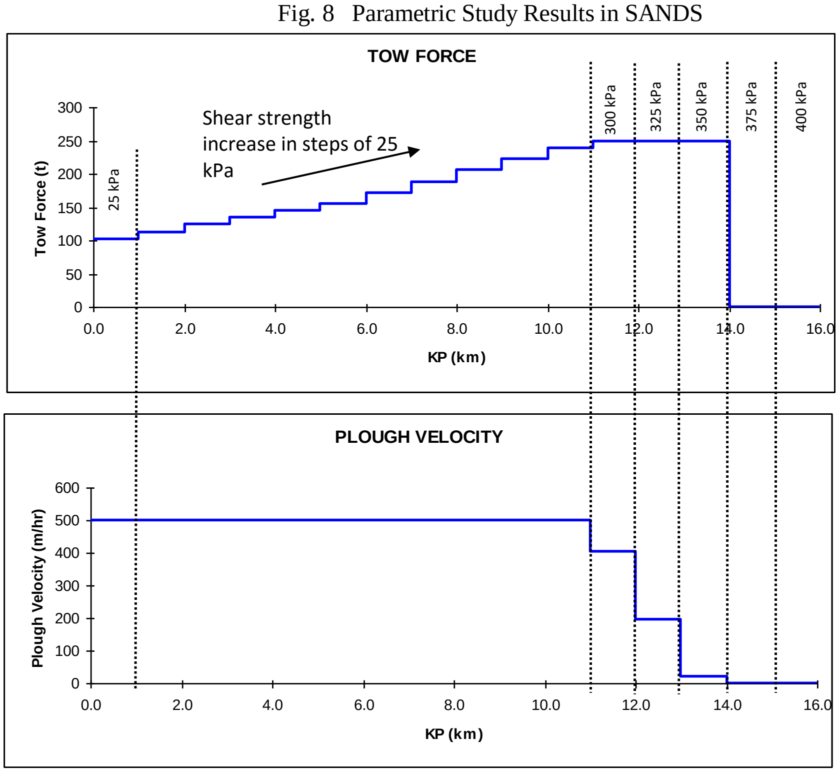

Fig. 9   Parametric Study Results in CLAYS

GEOTECHNICAL RISKS

The ploughability assessment does have its limitations in that the assessment cannot capture certain geotechnical risks involved in ploughing operations. Based on published literature and engineering experience, the below are factors that cannot be predicted by the ploughability assessment, and hence needs to be considered as geotechnical risks in any ploughing operation, and needs to be accounted for as risks. Sensitivity study or site trial tests can be used to assess these risks.

Slow Ploughing due to Soil Variability

The geotechnical model used in a ploughability assessment is based on either SAND or CLAY seabed soils, and does not have any parameters to account for any soil variations, or variation with depth or presence of different soil contents such as peat. Therefore, plough performance can be affected in areas where soil is highly variable.

Slow Trenching due to Operational Risks

The ploughability assessment is based on a fixed trench depth with assumed stable plough operation. Therefore, any variation in trench depth or undercutting of the seabed by the mould boards will affect the plough operations. Therefore, any results from the presented ploughability assessment shall be viewed with caution, as offshore operations may not be performed with the same assumed conditions.

Plough Sinkage due to Soft Soils

In very soft clays (<10kPa), a general purpose plough is likely to be sink by bearing failure (Allan 1998, Cathie and Wintgen (2001)). Both the skids and share should be checked for bearing stability by comparing the load path (horizontal and vertical loads on the skids/share) with the full bearing capacity failure envelope. The load path must intersect the failure envelop in the sliding region, not the bearing failure region. The recommended factor of safety for static vertical loading is 2 on the skids and 1.5 on the share at the target depth, to ensure sliding and no bearing failure. Full failure envelope analysis is recommended.

Slow Trenching due to Dense Fine Sands

Trenching/ploughing may be slow to very slow in fine silty dense sands. It is recommended that detailed study of grain size distribution and additional sample, should be collected if there are only a few samples to make reliability estimates, Cathie and Wintgen (2001) stated that any fine sand with D_{10} less than 0.08mm should be scrutinized carefully. There is no direct evidence in published data, but the general guidance can be that for medium dense to dense fine sands, where dilation is bound to occur under shear failure, the permeability will play a vital role in determining the ploughing resistance. D_{10} is a good measure of the soil permeability, as permeability is proportional to $(D_{10})^2$. Hence if soil consists of 10% or more of silts, then careful scrutiny may be required in the ploughing assessment. Figure 6 shows the variation of the dynamic force coefficient C_d with D_{10}.

Trench Instability due to Very Loose Fine Sands

In very loose sands, ploughing can be easy but the side slopes may be unstable as the plough passes. At the interface between plough and soil, the shear stress ratio is at a failure condition, and very high pore pressures will be developed, unless the excess pore pressures are dissipated very quickly. As the plough passes, the soil experiences unloading, and some areas of the side wall may be stable, due to the negative pore pressures providing increased effective stresses. As the pore pressure dissipates, the side wall becomes unstable. The length of time to which the walls may be stable, due to negative pore pressure is very hard to predict. Hence additional assessment of the slope stability may be required in trenching very loose sands.

Slow Trenching due to Fine Sands/Silts

The prediction of trenching speeds in fine sands and silt presents a major challenge in interpretation of geotechnical data, and its application to plough performance. Dilation potential and permeability of sands play a major role in soil resistance to ploughing. Permeability of soil can change from 10^{-4} m/s for clean fine sand to 10^{-6} m/s for a silt (Allan, 1998). If only CPT results are available, then it is difficult to estimate the speed component of the tow force (i.e., the dynamic force coefficient).

Geotechnical data from Cone Penetration Tests (CPT)

CPT data shall be interpreted with caution, as a standard 10cm^2 cone operating at 20mm/s will result in true undrained response of the soil, if the soil permeability is less than 10^{-9}-10^{-8}m/s (Allan, 1998). Soils with a permeability range 10^{-8} to 10^{-5} m/s, including most silts is anticipated to behave in a partly drained manner. It is to be noted that a plough being pulled at 500m/hour (140mm/s) is 7 times faster, and hence may result in more undrained behaviour, compared to that during cone penetrating tests. With the mini-cones (being increasingly used in subsea investigation) the drainage path is shortened and finer grained soils are likely to behave in a drained manner, resulting is smaller cone resistance. When ploughing is carried out at much higher speeds, the soil resistance can be much greater than anticipated, due the effect of negative pore pressures that are created, due to dilation potential of the soil. Thus, the above facts shall be taken into account when reviewing the results of ploughability assessment.

CONCLUSIONS

This paper provides the industry best-practice methodology for ploughability assessment, and an insight into analytical frame work for undertaking such assessment. The presented analytical ploughability assessment cannot capture some geotechnical risks involved in ploughing operations. These risks include unknown soil variability, slow trenching/stoppage operational risks (undercutting of seabed, increase in trench depth), plough sinkage due to soft soils, slow trenching due to dense fine sands, trench collapse due to loose sands, and slow trenching due to fine sands/silts.

The ploughability assessment is significantly dependent on soil parameter selection from geotechnical investigation data. The accuracy of the ploughability assessment results depend greatly on the selected model parameters, which have been established for a specific plough, based on known soil conditions. If the actual soil conditions are different to those used in the calibration of the model's parameters, then the model's predictions are also likely to be inaccurate. The ploughability models are calibrated by reference to specific ploughs and their individual ploughing history. Therefore, the coefficients involved in the ploughability assessment needs to be fine-tuned for each plough, based on its ploughing performance.

Particle size distribution of the soil is a critical parameter for ploughablity assessment and hence proper geotechnical investigation is required to characterize the soil along the ploughing route. While this paper provides insight into ploughability assessment and its limitations, further research is required to better understand and quantify all the geotechnical risks associated with ploughing operations.

REFERENCES

Allan, P.G.(1998), "Geotechnical Investigation for performance prediction of submarine trenching ploughs," *Offshore Site Investigation and Foundation Behaviour* 1998 SUT

Bransby, M.F., Yun, G.J., Morrow, D.R., & Brunning, P. (2005),"The performance of pipeline ploughs in layered soils," *Frontiers in Offshore Geotechnics: ISFOG 2005*, Gourvenec & Cassidy (Eds). 597-606

Brown, M.J., Bransby M.F. & Simon, F. (2006), "The characteristic of a model pipeline plough," *Proc. International Conference on Physical Modelling 2006*

Brown, R.J., Palmer, A.C.(1985), Submarine Pipeline Trenching by Multipass Ploughs," *OTC Conference.* OTC4925

Cathie, D.N. , Morgan, N., Pyrah, J. and Steward, J. (2007), "Pipeline and Cable Plough Stability in Soft Clays," *Proc. 6th International Offshore Sote Investigation and Geotechnics Conference, UK*

Cathie, D.N. and Wintgen, J. F. (2001), "Pipeline Trenching Using Plows:Performance and Geotechnical Hazards," 2001, *OTC 13145.*

Cheng, X.H., Ngan-Tillard, D.J.M. and Den Haan, E.J. (2007), "The causes of the high friction angle of Dutch organic soils," *Engineering Geology*, 93, 31-44

Hatherley, A., Bransby, M.F., Lauder, K. & Brown, M. (2008),"Model testing to reveal the mechanics of pipeline ploughing in mega-ripples," *ISOPE 2008 TPC-187*

Lauder, K., Bransby, F., Brown, M., Cathie, D., Morgan, N., Pyrah, J. & Steward, J. (2008), "Experimental testing of the performance of pipeline ploughs," *ISOPE 2008* TPC-174

Machin, J.B. (1995),"Operational Experience of Multipass and backfill ploughs," *Subtect 95, Society for Underwater Technology*, 237-248.

Miedema, S.A., Lagers, G.H.G. and Kerkvliet, J. (2007), "An overview of the drag embedded anchor holding capacity for dredging and offshore applications," *WODCON*, Orlando, USA

Palmer, A.C (1999), "Speed effects in cutting and ploughing," *Geotechnique* 49, (3), 285-294

Palmer, A.C, Kenny, J.P., Perera, M.R. and Reece, A.R. (1979), "Design and operation of an underwater pipeline trenching plough," *Geotechnique* 29, (3), 305-322

Rambøll Danmark Report (2008), "offshore pipeline through the Baltic Sea, Spreading of sediment and contaminants during works in the seabed," Memo 4.3A-5.

Reece, A.R. and Grinsted, T.W. (1986), "Soil Mechanics of Submarine Ploughs," *OTC Conference.* OTC5341