HEAVY DUTY PLOUGH PERFORMANCE IN VERY SOFT COHESIVE SEDIMENTS

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Abstract: There are still limited empirical data on which to base burial feasibility predictions for the Heavy Duty (HD) ploughs now in common use in the cable industry. Alcatel-Lucent Submarine Networks has over the last few years commissioned a series of analyses using plough data from a number of its cable installations. The intent of the research is to define the bounding geotechnical conditions governing HD plough behaviour under real installation conditions. Those bounding conditions are believed to be: the relative density that can limit HD plough burial in granular sediments (maximum relative density); the shear strength that can limit plough burial in cohesive sediments (maximum shear strength); the shear strength that leads to plough sinkage and cable overburial in very soft cohesive sediments (low shear strength); and where very soft cohesive sediment sits over very dense granular sediment. The study presented herein is for very soft cohesive sediments (clays). It meets two aims: to provide empirical tow tension and burial depth graphs in these seabed types, and to define the effect of the weight of the tow wire on tow tensions, as water depths increase.

1. INTRODUCTION

In order to improve its understanding of Heavy Duty (HD) plough behaviour, and in order to hone its Burial Assessment Survey (BAS) predictions, Alcatel-Lucent has commissioned a series of plough studies in different sediment types.

The study presented in this paper examines HD plough performance in very soft cohesive sediments (marine clays), using data from three different cable routes. Two routes were located in the Mediterranean Sea and the third was in the Baltic Sea.

All three installations were performed by the latest state of the art cable ships utilising Soil Machine Dynamics' HD ploughs, but with slightly different configurations. (See Section 2.)

2. STUDY AIMS & METHODS

The study had two main aims: to create empirical graphs for plough burial depth and tow tensions in very soft marine clays, and to assess the effect of the weight of the tow wire as water depths increase. The latter assessment is something that can be applied across the board, in all seabed types, to assist Burial Assessment Survey (BAS) report predictions.

The three routes used in the study were analysed separately, due to slight differences in the plough configurations:

- Route 1, Baltic Sea—HD Plough, but with a reduced share (1.5m) and widened skids to minimise plough sinkage in very soft sediment; resulting in a weight in air slightly <30T.
- Route 2, Mediterranean—HD Plough, 30T (in air), 2.3m share, with no plough modifications.
- Route 3, Mediterranean HD Plough, 25T (in air), 2.3m share, with no plough modifications.

The raw data sets were extensive, consisting of the following number of data points:

- Route 1—77,400 points
- Route 2—22,150 points
- Route 3—38,350 points

Initially, the analyses compared raw burial depths with tow tensions for each data set. There were specific observations for each route, and these are summarised in Sections 3.1 through 3.3.

Burial depth was then plotted against plough tow speed, to assess whether there was any significant relationship, and whether the data needed to be normalised for speed effects.

Next, raw tow tension was plotted against water depth, creating an equation that defined the effect of the tow wire on tensions as the depth increased. Then, using this equation, the tow tension data were normalised for the tow wire effect, and burial depth was replotted against this normalised tension data.

Data were then sorted on burial depth and average, minimum and maximum tow tensions were calculated for every centimetre of burial. Average, minimum and maximum normalised tow tension were plotted against burial depth. This process removed a lot of the 'noise' in the data, allowing a more meaningful interpretation of the relationships to be made from the graphs.

Trendlines were plotted for graphical relationships. R^2 values were included, to assess whether the relationships seen were statistically significant. R^2 is the Coefficient of Determination, which defines how well a linear regression (the trendline) will predict future outcomes. It is a number between 0.0 and 1.0, and the closer it is to 1.0, the stronger the trendline fits the data. In this study, it is used as an indicator of how significant the relationship is between the two parameters—i.e., an indicator of the predictability of a given burial depth in very soft clay leading to the given tow tension.

3. RESULTS AND DISCUSSION

The following acronyms are used in the graphs below:

- DOB—Depth of Burial
- TT—Tow Tension
- WD—Water Depth

3.1 Route 1

Route 1 was installed using an HD plough, but with a shortened share (1.5T) and widened skids, in order to reduce overburial and sinkage. This resulted in a plough that weighed slightly <30T in air. This route had the most variable seabed of the three data sets, with areas of thick, very soft clay (2-11kPa), separated by areas of stiff to very stiff glacial clay. The data set had previously been stripped of points falling in areas shown by the survey as glacial clay, but it was evident from the initial graph (Figure 1) that some of the boundary data—as the route crossed from glacial clay to very soft clay areas, or vice versa—were also included in the data set. This was evident because there were areas of high tow tensions (up to 90T), which could not have come from very soft clay areas.

There is no significant relationship seen in Figure 1 (R^2=0.01), although this data set consists of raw data is and therefore very noisy.

Tensions >25T were stripped from the data set (historical evidence shows that tow tensions are unlikely to be this high in very soft clay in these water depths), and then the burial depth/tow tension graph was replotted. (Figure 2.)

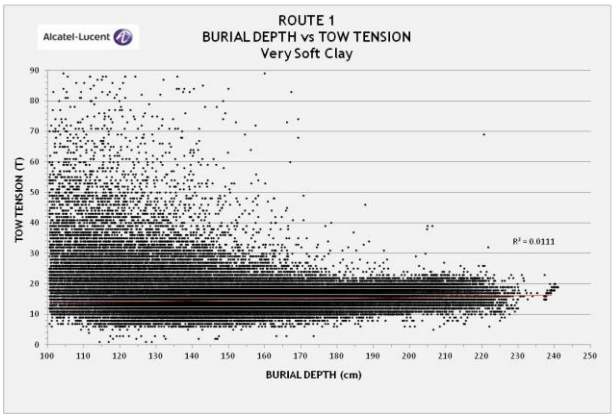

Figure 1: Route 1, Raw DOB *vs.* TT

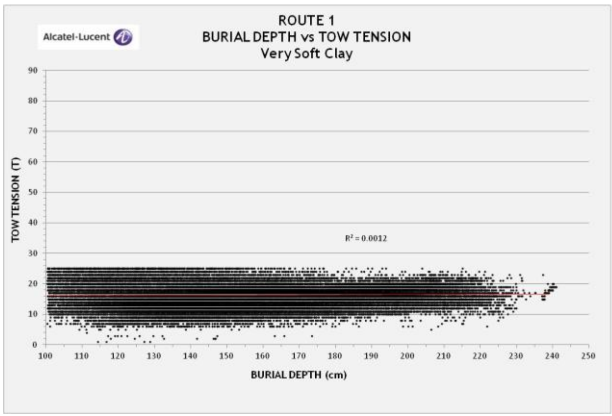

Figure 2: Route 1, DOB *vs.* TT <25T

Next, plough tow speed was plotted against burial depth, to check whether there was an obvious relationship that needed to be corrected for in the next step of the analysis. Figure 3 shows no obvious correlation between plough tow speed and burial depth (R^2=0.0058)—the full range of burial depths is seen to have been experienced at any given speed, and so no corrections were necessary. Note that the average plough tow speed on this route was 0.56m/s (2km/hr).

Water depth was then plotted against tow tension, to assess the effect of the weight of the tow wire on the tension data. (Figure 4.)

There is poor correlation in the data, because the water depths on Route 1 were generally shallow, and in a narrow range (100-200m for the most part). An equation was generated that would have allowed a

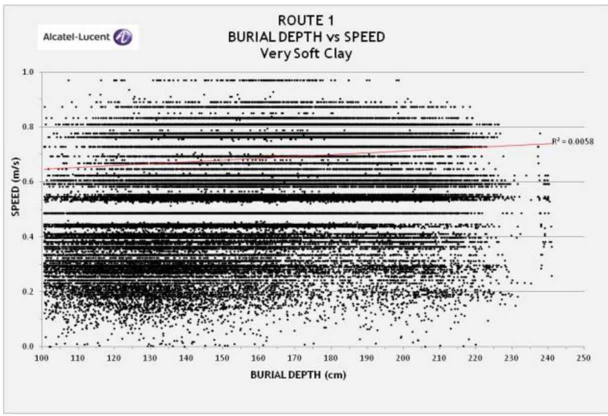

Figure 3: Route 1, Speed *vs.* DOB

minor correction to be made to tow tensions due to the tow wire:

$$TT = (0.02377 \times WD) + 12.998$$

However, even at maximum depth, the correction would have been less than 0.5T. Since this is within the normal range of tow tension variability, the data set was not corrected.

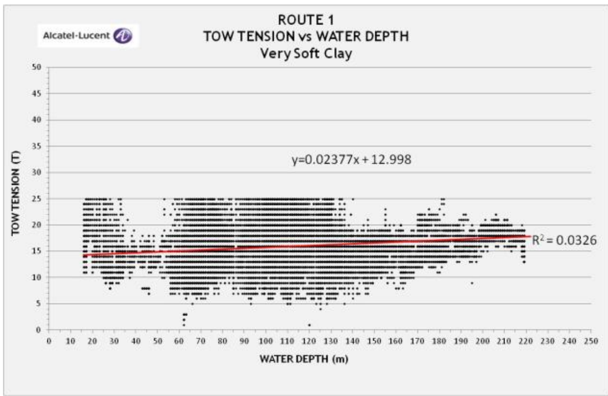

Figure 4: Route 1, WD *vs.* TT

The final analysis sorted the entire data set on burial depth, and then average, minimum and maximum tow tensions were calculated for each centimetre of burial. (Figure 5.)

The shear strength of the very soft clay on Route 1 was 2-11kPa, although most of the route had shear strengths at the lower end of this range. Average tow tensions on Route 1 are seen to be 15-16T. This is ~3T higher than seen on Routes 2 and 3, even though the plough share was shortened

(1.5m) and the plough had widened skids to minimise plough sinkage.

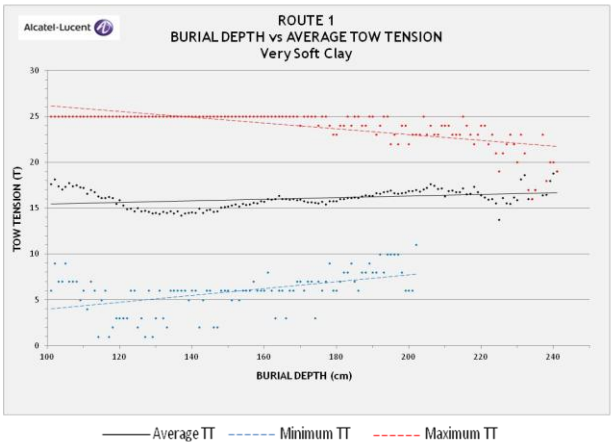

Figure 5: Route 1, DOB *vs.* Average TT

The additional tow tension increment seen on this route is probably due to the fact that the plough was heavier than usual and considerable sinkage occurred. The plough had to be recovered for cleaning on a few occasions because the glacial clay was highly cohesive and it tended to build up around the plough. When the plough crossed into the very soft clay areas, it sank considerably, due to the extra weight. The sinkage is believed to have led to extra drag, and therefore higher tensions.

Burial depth is seen to have very little effect on tow tensions in this sediment type—Figure 5 shows that the range of average tensions across the 100-250cm burial depth range is only 1T. It should be noted that the maximum tow tension trendline does not indicate decreasing tensions with depth, just that deeper and deeper burial only occurs in softer and softer sediment.

3.2 Route 2

With regard to predictions for typical Alcatel-Lucent installations, Route 2 is the most appropriate of the three routes in the study. The route primarily consisted of very soft clay, and the plough was typical of most Alcatel-Lucent installations—an unmodified 2.3m-share, 30T HD plough. The clay shear strength seen along the route was generally in the 2-10kPa range. (Note that the maximum water depth was 1255m.)

Initially, raw burial and tow tension data were plotted, to assess the overall relationship. (Figure 6.) There are two bands of tension seen in Figure 6. This is due to two distinct areas with different seabed profiles—there is a short section of shallow water, followed by a long stretch of deep water, where the longer tow wire led to higher overall tow tensions.

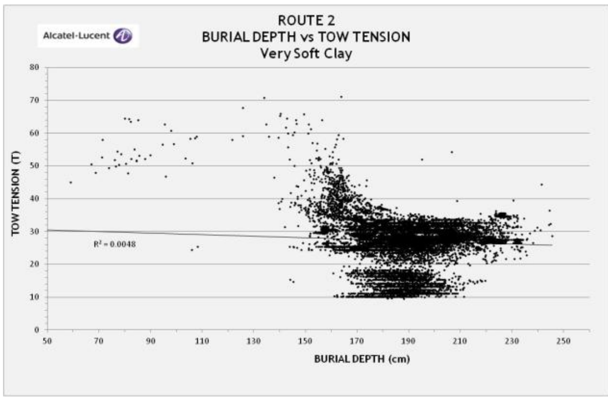

Figure 6: Route 2, Raw DOB *vs.* TT

Next, plough tow speed was plotted against burial depth, to check whether there was an obvious relationship that needed to be corrected for in the next step of the analysis. Figure 7 shows no obvious correlation between plough tow speed and burial depth (R^2=0.0008)—the full range of burial depths is seen to have been experienced at any given speed, and so no corrections were necessary. Note that the average plough tow speed on this route was 0.39m/s (1.4km/hr).

Water depth was then plotted against tow tension, to assess the effect of the weight of the tow wire on the tension data. (Figure 8.) There is fairly good correlation in the data (R^2 approaching 0.65), although there are some outliers, which are believed to be a result of localised firmer seabed. The outliers were >35T, and when these were filtered out, there is seen to be very good correlation, with an R^2=0.85. (Figure 9.)

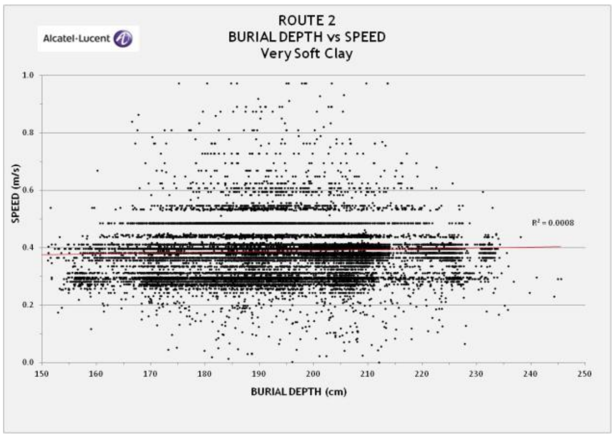

Figure 7: Route 2, Speed *vs.* DOB

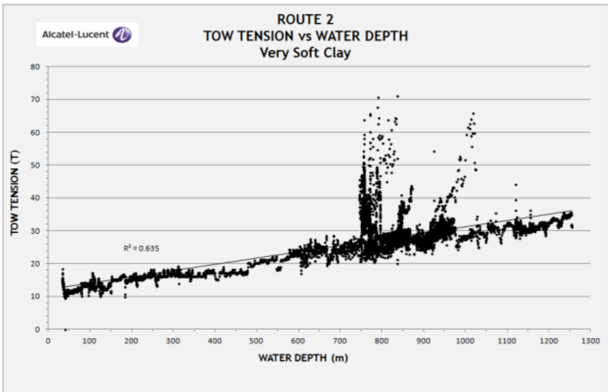

Figure 8: Route 2, WD *vs.* TT

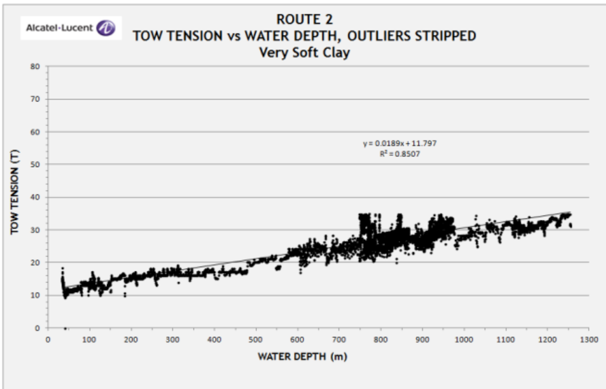

Figure 9: Route 2, WD *vs.* TT, Outliers Removed

Figure 9 provides an equation to correct the plough tow tensions for the weight and drag of the tow wire as water depth increases:

$$TT = (0.0189 \times WD) + 11.797$$

This equation is the most appropriate correction produced by the study for the tow wire effect—see Section 3.4 for further explanation.

The tow tension data were corrected using the equation produced in Figure 9, and the normalised tow tensions are plotted against burial depth, as shown in Figure 10.

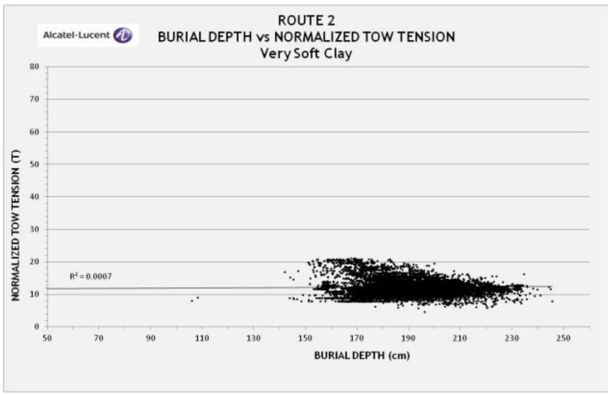

Figure 10: Route 2, DOB *vs.* Normalised TT

The final analysis sorted the entire data set on burial depth, and then average, minimum and maximum tow tensions were calculated for each centimetre of burial. (Figure 11.)

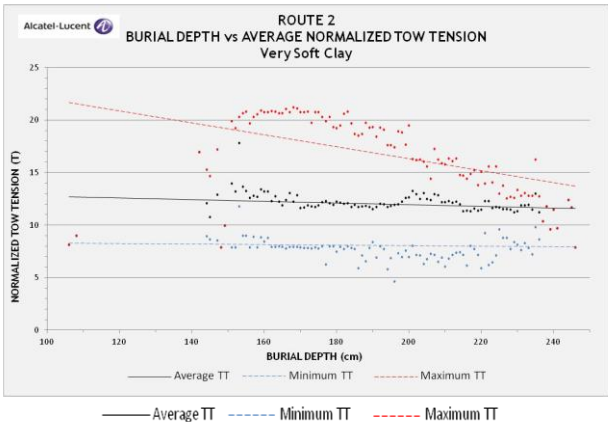

Figure 11: Route 2, DOB *vs.* Av TT

The shear strength of the very soft clay on Route 2 was 2-10kPa. Average tow tensions are seen to be 12T. Similar to Route 1, burial depth is seen to have very little effect on tow tensions—Figure 11 shows that the range of average tensions across the 100-250cm burial depth range is only 1.5T. It should be noted that the maximum tow tension trendline does not indicate decreasing tensions with depth, just that deeper and deeper burial only occurs in softer and softer sediment.

3.3 Route 3

A slightly lighter SMD HD plough was used on Route 3 (25T in air), with a 2.3m share. The route primarily consisted of very soft clay, with shear strength generally in the 2-11kPa range.

Initially, raw burial and tow tension data were plotted, to assess the overall relationship. (Figure 12.) The data show that the tow tensions are already corrected for the weight of tow wire out, since tensions are 12-16T throughout the entire water depth spectrum. (Note that the maximum water depth was 1245m.)

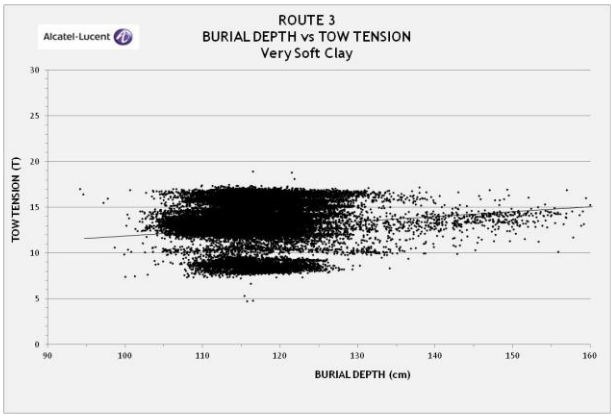

Figure 12: Route 3, Raw DOB *vs.* TT

Next, plough tow speed was plotted against burial depth, to check whether there was an obvious relationship that needed to be corrected for in the next step of the analysis. Figure 13 shows no obvious correlation between plough tow speed and burial depth (R^2=0.0323)—the full range of burial depths is seen to have been experienced at any given speed, and so no corrections were necessary. Note that the average plough tow speed on this route was 0.2m/s (0.72km/hr).

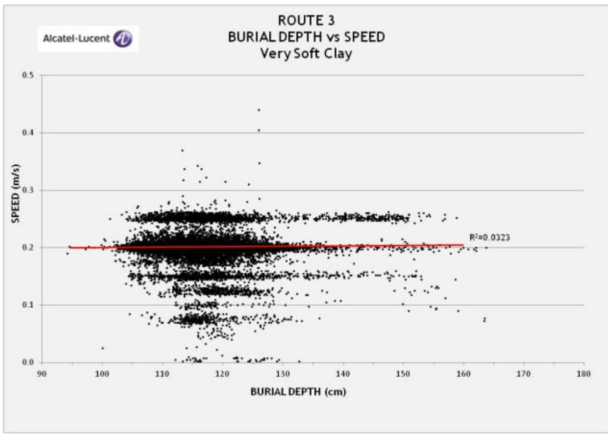

Figure 13: Route 3, Speed *vs.* DOB

Water depth was then plotted against tow tension, to assess the effect of the weight of the tow wire on the tension data. (Figure 14.)

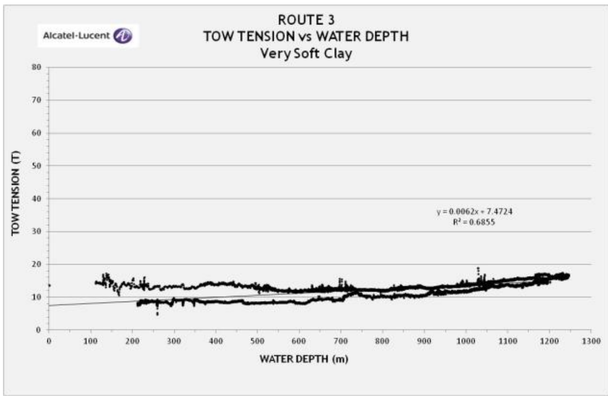

Figure 14: Route 3, WD *vs.* TT

There is fairly good correlation seen in Figure 14 (R^2 approaching 0.7), although it seems that two distinct correction factors were used for the weight of tow wire out (two distinct lines on the graph). It is understood that the correction for tow wire was based on the unit weight of the wire, and the wire out, as measured at the winch. This would not account for additional tension created by drag, due to currents in the water column. Even though there are two distinct lines on the graph in Figure 14, there is single trendline, and so an additional correction can be made to the data, as follows:

$$TT = (0.0062 \times WD) + 7.4724$$

The correction removed up to 3T from the data in the deepest water depths. The normalised tow tension data are plotted against burial depth in Figure 15.

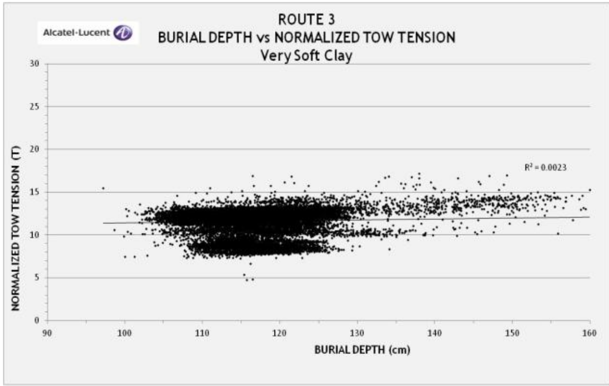

Figure 15: Route 3, DOB *vs.* Normalised TT

The final analysis sorted the entire data set on burial depth, and then average, minimum and maximum tow tensions were calculated for each centimetre of burial. (Figure 16.)

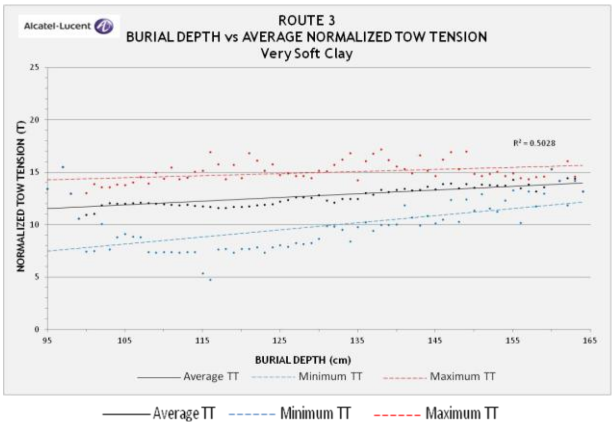

Figure 16: Route 3, DOB *vs.* Av TT

The shear strength of the very soft clay on Route 3 was 2-11kPa. Average tow tensions are seen to be 12-14T. Similar to Routes 1 and 2, burial depth is seen to have very little effect on tow tensions—Figure 16 shows that the range of average tensions across the 90-165cm burial depth range is only 2T.

3.4 The Effect of the Tow Wire

Plough tow tensions are particularly low in very soft clays, and the weight of the tow wire in the water column becomes a significant portion of the overall tension as water depth increases.

The incremental increase in tow tension due to the tow wire must be factored when compiling BAS reports, so the study provides useful data in this respect. The study provides a better analysis than a simple calculation based on wire out at the winch/unit weight of the wire, because there is likely to be an additional effect due to drag from currents in the water column.

The tow wire obviously affects tow tensions in all sediment types, but its effect is overshadowed in other seabed types, due to the variability of plough behaviour. Since very soft marine clays produce very steady state ploughing conditions, the effect of the tow wire can be very clearly seen—this can then be applied across the board to all seabed types during BAS reporting.

Route 2 provides the best data set with regard to a typical Alcatel-Lucent installation, because it utilised an unmodified 2.3m-share 30T HD plough. In addition, the installation covered a wide water depth range, from 33m to 1255m. Therefore, for normal BAS reporting, Alcatel-Lucent will be using the results from the Route 2 tow wire analysis. The correction factor for tow wire out can be given as:

TT Correction (T) = 1.85% x Water Depth

Table 1 will be used for plough tow tension predictions in BAS reports, in all seabed types.

Tow Tension Correction for Water Depth (Weight of Tow Wire) in Depths >100m					
Assuming 12T at 100m					
Extrapolated to 1500m					
WD	Add Tonnes to BAS Predictions	% Correction	WD	Add Tonnes to BAS Predictions	% Correction
150	3	1.75	850	16	1.87
200	4	1.79	900	17	1.87
250	5	1.81	950	18	1.87
300	5	1.82	1000	19	1.87
350	6	1.83	1050	20	1.87
400	7	1.84	1100	21	1.87
450	8	1.84	1150	22	1.87
500	9	1.85	1200	22	1.87
550	10	1.85	1250	23	1.87
600	11	1.86	1300	24	1.87
650	12	1.86	1350	25	1.87
700	13	1.86	1400	26	1.88
750	14	1.86	1450	27	1.88
800	15	1.86	1500	28	1.88
Correction can be assumed to 1.85% x WD					

Table 1: TT Correction for Tow Wire

4. CONCLUSIONS

The plough study described herein used data from three different cable routes, which were analysed separately, due to slight differences in the plough configurations. All routes used SMD HD ploughs, but Route 1 used a shortened share (1.5m instead of 2.3m) and widened skids, in order to minimise overburial and sinkage. Route 2 used a slightly lighter SMD HD plough, but with a 2.3m share. Route 3 used a 30T HD plough with a 2.3m share.

The slight configuration differences provide a good opportunity to cross correlate plough behaviour in very soft clay seabeds (2-12kPa). Since the results of the separate analyses produced very similar results, despite these differences, data from all three routes were analysed together as a final step in the study. Average, minimum and maximum tow tensions were calculated for every centimetre of burial. (Figure 17.) The relatively large difference between maximum and minimum tow tensions is likely associated with data points from localised firmer and softer areas of sediment respectively.

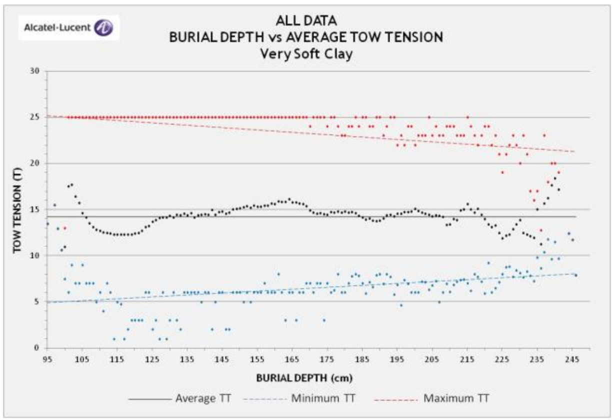

Figure 17: All Routes, DOB *vs.* Av TT

The study shows that tow tensions in very soft clay, irrespective of the share length or plough modifications, are around 12-14T on average. It has been shown that burial depth has very little effect on tow tensions in very soft clay. As water depth increases, the weight of the tow wire has more of an impact on tow tensions than the sediment does. In fact, the weight of the tow wire has a notable impact on tensions—as much as 28T at 1500m water depth.

The impact of the tow wire is harder to see in other seabed types, because tow tensions tend to be much more variable and the tow wire effect is hidden. Ploughing conditions in very soft clay tend to be steady state, and this has allowed a quantification of the effect the tow wire. The following equation can now be used during BAS reporting in all seabed types, to more accurately predict tow tensions as water depth increases:

TT Correction (T) = 1.85% x Water Depth

The installation vessel for Route 2 confirmed that plough sinkage occurred in the very soft clay and grade in was seen to be instantaneous, as soon as the plough touched down. Typically, the sinkage was limited to just above the front skids. Plough control was still possible on steep up slopes, but some loss of control (sliding) was seen on steeper down slopes, due to the very low traction seabed. The stablisers were generally used in fixed mode, and the plough pilots were able to observe the effect of stabliser motion on the burial depth measurement. Plough pitch was seen to naturally be to the stern. It is also worth noting that the recorded burial depth is less than the actual burial depth, due to the design of the depth skid. Actual burial depth would add the plough sinkage.

The study has shown that tow speed does not significantly affect burial depth when ploughing in very soft clays (<12kPa). Historical experience has shown that plough speed is generally increased in these seabed conditions, in order to minimise overburial and plough sinkage. Average speeds of up to 2km/hr are usual in such soft seabed.

As mentioned in the Introduction, Alcatel-Lucent has commissioned a series of plough studies over the last few years, in order to define the boundary conditions at which the HD ploughs can operate. Primarily, the focus is on defining the conditions that could limit or impair plough burial. A study of plough behaviour in dense granular sediments (sands) was presented at SubOptic 2010 [1].

A small scale study has also been conducted for the situation where very soft/loose sediment sits over very dense sediment. The results from this study support the dense granular sediment study, and overall it appears that the boundary between the soft/loose and underlying dense sediment has little effect on HD plough behaviour. This differs from the smaller standard ploughs—a previous Alcatel study showed a tendency for the standard ploughs to ride along the buried surface of a sediment unit >65% Relative Density.

The study reported in this paper completes the very soft cohesive end of the spectrum, and defines HD plough behaviour when the seabed is too soft to effectively support the plough.

A study into plough behaviour in stiff to very stiff clays is underway, as appropriate data become available, although currently the data set size is inadequate to perform a robust analysis.

5. REFERENCES

[1] G. Holland & S. Dzinbal. "Heavy Duty Plough Performance in Dense Granular Sediments." SubOptic 2010, Yokohama, Japan, Paper 295_Poster_MN_09.