HORIZONTAL DIRECTIONAL DRILLING (HDD) FEASIBILITY REVIEW

Cable Landfalls
Walney Extension Project
U.K.

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1. INTRODUCTION

1.1. Overview

DONG Energy Walney Extension (UK) Limited ("DONG Energy") has sought a second expert opinion on the feasibility of Horizontal Directional Drilling (HDD) for proposed landfalls of offshore cables from the Walney Extension Offshore Wind Farm project and potential mitigation measures associated with this. The HDD element of the cable route is designed to take the cables beneath saltmarshes in order to minimise any environmental impacts of the cable installation. The saltmarsh is an important habitat for a population of Lycia zonaria britannica (belted beauty) moths.

1.2. Scope of Work

Riggall and Associates have been invited by DONG Energy to examine documents and designs related to the project. The aim of this report is to apply Tim Riggall’s knowledge and expertise in HDD and geotechnical engineering / geology in a review of the assessment of feasibility and mitigation measures that has already been undertaken.

Tim has a rare combination of theoretical knowledge, through his BSc in Geology and MSc in Geotechnical Engineering, and practical experience, 8 years in geology followed by 14 years in HDD. His career in HDD has progressed from guidance and design of HDD pilot drilling through modelling of drilling forces and downhole fluid pressures to project evaluation and troubleshooting. Tim has guided pilot holes on over 120 HDD’s and intersections in a wide range of ground conditions throughout the world. He has consulted on over 40 projects worldwide with a particular focus on management of downhole fluid pressures to avoid ground formation damage and surface breakout. A brief CV can be found in Appendix A.

Visser & Smit Hanab ("VSH") have previously produced a HDD Feasibility Report verifying the HDD was feasible within a depth range of 6-8m beneath the saltmarsh but that there was a risk of bentonite breakouts to the surface during drilling.

This purpose of this document is to:

- review and critique existing information
- assess the risk of drilling fluid breakout from the HDD’s through modelling of ground strength and fluid pressures from drilling fluid while drilling the landfalls.
- examine the technical design and methodology for the HDD’s
- identify any additional risks, mitigations measures, or opportunities for the landfalls.

1.3. Reference Documents

The following documents were supplied by DONG Energy for review:

<table>
<thead>
<tr>
<th>Filename</th>
<th>Title / Description</th>
<th>Doc No. and Issue</th>
<th>Author</th>
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</thead>
<tbody>
<tr>
<td>Appendix 5 Report from VSH confirming Horizontal Directional Drilling feasibility at the landfall.pdf</td>
<td>Walney Extension Landfall HDD Feasibility Report</td>
<td>Doc No: E12547-DE-FS-4.4.01 Rev No: 0 Date: 16/01/2014</td>
<td>Visser &amp; Smit Hanab</td>
</tr>
</tbody>
</table>
2. DOCUMENT REVIEW

2.1. VSH Landfall HDD feasibility Report

The report from Visser & Smit Hanab (VSH) is a high level HDD feasibility study. The authors have extensive experience in the HDD industry and VSH have a very good reputation as an experienced and efficient HDD contractor, particularly in soft ground conditions.

Specific comments on parts of the VSH feasibility are as follows:

Paragraph 3.3. VSH do not make it clear that the boreholes in the area of the proposed HDD did not log the position of the bedrock. It is likely that boreholes BH10 and BH11 ended close to the position of the bedrock because they were in cobbles and they recorded incomplete Standard Penetration Test (SPT) values (N>50) indicating very hard ground. Borehole BH12 was completed in glacial till and is presumably underlain by gravel or cobbles and then the bedrock.

Paragraph 3.4. VSH state that the “bedrock and cobbled layer above are not suitable for HDD due to its instability and fractured nature”. I disagree in that HDD is possible through the cobbles and bedrock; however it is considerably more difficult with a much greater risk of failure and will require significantly longer for construction. The existing proposed design through the layer of glacial till is the preferable route. The option of drilling in the bedrock is examined in Section 6.1.

Paragraph 4.2. VSH correctly state that the likely OD of the HDPE duct is 500mm. I would add that the likely borehole size to accommodate this is in the range of 650-750mm (1.3 to 1.5 x duct OD).

Paragraph 4.4. Completion time of 15 days per HDD is reasonable.

Paragraph 5.1. Provided there is an adequate containment area around the exit, fresh water could be used for the drilling fluid. Fresh water bentonite fluid will flocculate when it comes into contact with salt water. This might be a useful property for dispersing any surface breakout.

Paragraph 6.1. In assessing breakout risk the worst case scenario is that the glacial till (reddish slightly sandy gravelly CLAY) and soft silty SAND identified in the boreholes are absent for most of the HDD alignment. The HDD would then be drilled predominantly in the very soft silty CLAY, the strata least resistant to hydraulic pressure. Additionally the crossing would be drilled with a conventionally sized drilling bit. In this worst case scenario the hydraulic fracture modelling indicates that 270m – 370 m of the saltmarshes would be at risk of breakout, dependent on where the
The drill is aligned within the order limits (the saltmarsh width within the order limits increases from north to south). If ground is prone to breakout generally those breakouts repeat every 30-50 metres. Over 270m metres the worst case is likely to be 8 breakouts, and over 370m it could be 12 breakouts. It should be stressed that this is worst case and assumes recommendations on pilot hole size and downhole fluid pressure monitoring are not followed.

Paragraph 6.1.a. Agree, a larger bit greatly reduces the breakout risk. See hydraulic fracture modelling in Section 4.

Paragraph 6.1.b. Disagree. For the pilot hole the pressure at the bit will be slightly higher (0.2 bar) if drilled from land towards the sea because the fluid must be pumped back to a higher elevation. The proposed entry point is approximately 1.5m higher than the exit. For the reaming stages the pressures will be slightly lower using the proposed arrangement; however the pilot hole drilling is the most susceptible time for breakout.

Paragraph 6.2. Agree that 4m² is common, but with real time downhole annular pressure monitoring it should be able to be reduced to 1m². Details of a downhole pressure tool are given in Appendix B.

Paragraph 6.2.a. It needs to be stressed that real time downhole annular pressure monitoring is necessary to accurately and quickly determine if a breakout has occurred. Some drilling contractors will say that they can tell from the pressure measured at the rig that they can determine breakout. This is not realistic. The pressure gauge at the rig effectively measures the pressure inside the drilling rods before it exits the nozzles in the bit at high pressure. This pipe pressure is typically 5 times the annular pressure so a drop of 50% in annular pressure is difficult to distinguish from variations caused by hard and soft ground in the pipe pressure.

Paragraph 6.4. Given the risk of breakout determined from the hydraulic fracture modelling in Section 4 it is likely to be less damaging to the flora to use layflat hoses laid out to breakout positions than to have a dedicated central HDPE line installed above the drilling line. Layflat hoses are the same type of hose as used by fire services (Figure 1 below). The hose diameter used is likely to be 75mm to 100mm, fitted with quick couplings to allow rapid connection to other hoses or pumps. HDPE pipeline is plastic pipe. The light weight of the layflat hose means that it can be installed with much less damage to the saltmarsh. A 30m length of layflat can be carried by hand in a roll; HDPE will need to be dragged into position. It is less rigid than HDPE allowing the hose route to follow any routes with minimal vegetation (natural drainage gullies for example).

Figure 1. Layflat hose with quick couplings shown on the left, HDPE pipe on the right.
Drawing No TP13194-O-X-02. Alignment is fine. It is best to keep the HDD’s straight in plan view if at all possible. Only one HDD is shown, presumably they will be relatively close at entry and fan out to their final separation distance at exit. Sectional design is reasonable. There may be scope to drill at a lower elevation, perhaps 1-2m lower, beneath much of the saltmarshes. Further ground investigations will inform the depth of the final design.

General comments:
At least one reaming stage, the process of enlarging the pilot hole to final borehole diameter, will be required for the HDD. The low strength of the ground means that it cannot be forward reamed (enlarged from entry forwards to the exit) and will need to use conventional reaming (from exit to entry). This will result in drilling fluid returning to the exit point in the intertidal zone. The drilling fluid will be contained within an exit pit before being pumped back to the rig site for recycling.

A returns line will be required to enable drilling fluid returns at exit side to be pumped back to entry; the shortest route through the saltmarsh within the order limits would be along the northern edge of the order limits between point X1 and Y1 as shown on Figure 2. The length of saltmarsh that the line would cross is 205m. Assuming 40cm width to allow for installation of the pipeline, this equates to an area of 82m² of saltmarsh affected by the pipeline.

![Figure 2. Indicative route of 150mm - 200mm HDPE returns line.](image)

An alternative option would be to use 9000 litre bowser trailers towed by tractors to transport drilling fluid between work area 4 and entry. The round trip journey time including filling is likely to be 30 minutes so two to three tractors with bowser would be required. Pumping directly from exit into bowser at work area 4 risks bentonite spillage due to communication between pump and bowser. It is advisable to have a storage tank at work area 4 so that each bowser could be filled by their tractor driver. Traffic movements from the tractors along the route would average 12 per hour.

Once the first HDD and duct installation has been completed there is the opportunity to insert a returns line through the installed duct and the surface returns line can be removed.
2.2. Update on Environmental Effects Associated with HDD

Specific comments:
Paragraph 1.2. Disagree with “a deeper drill profile is not possible”. It is technically possible to drill the HDD through the bedrock; however it is likely to result in an order of magnitude increase in time, risk and cost. The existing proposed design through the layer of glacial till is the preferable route. Refer to Section 6.1 for further comment.

Paragraph 3. Five breakouts for a worst case scenario is perhaps low. I would suggest eight to twelve maximum, however this is a worst case scenario that assumes that:
- the drilling contractor uses regular sized drilling bits rather than a large or oversize bit
- the contractor does not use real time downhole annular pressure monitoring tools
- that the HDD unexpectedly encounters very soft CLAY for most of its route

The first two points can be mitigated in full by selection and supervision of competent HDD contractors. The third point can be mitigated to a large extent by further ground investigations, as outlined in Section 6.10.

Assuming these risks are mitigated a realistic worst case scenario is 4 breakouts in the western half of the saltmarshes (at 260m, 290m, 320m and 350m) and a further 2 breakouts in the intertidal area (380m and 410m). The hydraulic fracture modelling in Section 4 expands on the risk and likelihood of breakout.

The calculations of 120m² being affected by hoses along the length of the fixed pipeline ignore the effect of foot traffic. If a fixed line is to be used it is more likely to be a corridor 0.8m wide x 300m length = 240m². However, based on the hydraulic fracture modelling in Section 4, breakouts are unlikely until the final sections of the HDD so the use of layflat hoses directly to any breakout is likely to affect a much smaller area of saltmarsh.

Actual drill element duration of 15 days is reasonable. It should be noted that if breakout occurs it is generally during pilot hole drilling and this should take between 2 and 4 days.

Paragraph 4.3. The Dunelm ground investigation did not definitively identify bedrock; however it is likely that boreholes BH10 and BH11 finish close to the bedrock because they could proceed no further in cobbles. Generally in the area the bedrock is overlain by a layer of cobbles, on top of which sits the glacial till (reddish slightly sandy gravelly CLAY).

Paragraph 4.4. See comments above for Paragraph 3 with reference to the area affected by a fixed hose along the length of the HDD.

Paragraph 4.13. Real time downhole annular pressure monitoring will give the earliest warning of a breakout having occurred. If the monitoring is used in conjunction with modelled downhole and hydraulic fracture pressures it can also show if pressures are approaching the strength limit of the ground and preventative action can be taken to avoid a breakout.

If a breakout occurs sandbags are likely to be the most effective method of containing any bentonite breakout. Booms are not normally used because they float on the surface of the bentonite (bentonite is denser than water and sea water with a typical specific gravity of 1.05).
If a breakout occurs it becomes the easiest route for drilling fluid and is unlikely to seal itself until the drill has advance some distance past the point (30-50m but this can vary). If there happens to be a natural channel nearby there might be less impact if the bentonite is allowed to flow to it and a small sandbag “dam” constructed to trap the bentonite.


Paragraph 4.18. Mitigation measures.

- Hydraulic Fracture modelling in Section 4 suggests that the drill bit should be a minimum of 12.25 inch diameter and preferably larger. A number of HDD contractors have used bits as large as 20 and 22 inches in the past.
- Assertion that drilling downhill reduces pressures is incorrect but of little consequence. See comments in Section 2.1 regarding Paragraph 6.1.b.
- Freshwater bentonite is unstable in saltwater and will flocculate when it comes into contact with seawater. This can be washed out by the tide more readily. There is an argument for using saltwater bentonite if there is saltwater ingress at the level of the HDD bore. In this case the saltwater bentonite will be more stable, reducing the risk of a failed drill.

Paragraph 4.18. Manage any breakouts.

- The procedures outlined are the least intrusive method to manage breakouts with the exception of the umbilical line. Considering the results of the Hydraulic Fracture modelling in Section 4 any breakout is most likely to be very close to the western margin of the saltmarsh. Accessing directly to any breakout with layflat hoses is likely to affect a much smaller area than an umbilical across the entire saltmarsh.

2.3. Geoenvironmental Appraisal

Specific comments:
Paragraph 5.7. Material Properties.
Soft and Very Soft Clay/Silt. Report states “Clay of generally high plasticity and low strength”. This does not match the plasticity results for BH10 and BH11 in the soft clay. Two samples were CL, three were CI, indicating that along the HDD alignment plasticity is likely to be low to intermediate.

SPT results from the boreholes along the HDD alignment were analysed and vary slightly from the report figures. The HDD specific ranges are:

- Marine Sands: SPT ‘N’ values 6 - 9, Average =7.
- Firm to Very Stiff Glacial Clay: SPT ‘N’ values 16 - >50, Average =34.

Borehole Record BH10. Noted that the final 1.5m of borehole required 3 hrs of chiselling indicating that it may be close to the level of the bedrock.

Borehole Record BH11. Noted “Unable to advance borehole below10.50m due to dense cobbles”.
3. GEOLOGICAL MODEL

After reviewing the Dunelm report the VSH sectional drawing was amended to create a geological model along the alignment of the proposed HDD (Figure 3).

The model identifies four main lithologies:

- Loose silty SAND
- Very soft slightly sandy silty CLAY
- Firm to stiff slightly sandy gravelly CLAY (Glacial Till)
- Gravel and COBBLES

It is expected that the layer of gravel and cobbles overlies bedrock of probably sandstone or possibly mudstone.
Figure 3. Geological Interpretation along proposed alignment
4. HYDRAULIC FRACTURE MODELLING

To better understand the risk of bentonite breakout on this project hydraulic fracture modelling was undertaken as outlined in the following sections. The modelling used the alignment and profile proposed by VSH.

4.1. Methodology

Hydraulic fracture modelling examines the pressure required for drilling fluid to force its way through the ground to the surface. The programme is based on equations that account for strength characteristics of the ground. The equations were developed at the Technical University of Delft, Netherlands, and were published in the USA by the Army Corps of Engineers.

The Delft equations are based on plastic cavity expansion theory and account for the pressure required for plastic deformation and propagation of fractures from a cylindrical hole through a soil mass. The modelling incorporates the soil shear modulus as well as undrained cohesion and angle of internal friction to account for the behaviour of both cohesive (clays etc) and non-cohesive (silts, sand, gravel etc) soils.

Field use of the programme and back analysis of field data has shown a good correlation between modelled and actual pressures inducing formation damage or breakouts.

The geotechnical parameters required for hydraulic fracture modelling are soil cohesion, internal angle of friction, saturated density, and the shear modulus. Using the ground investigation borehole descriptions and testing data three separate sets of parameters were chosen for the modelling. The chosen values were checked against parameters from a range of projects in similar soil conditions to check their validity.

The parameters are given in Table 1 below. The “Likely” column contains the parameters that best match the information from the ground investigation boreholes. The “Conserv.” column contains conservative values, and the “Harsh” column uses ultra-conservative values designed to test the sensitivity of the modelling to parameters.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Lithology</th>
<th>ID</th>
<th>Internal Angle of Friction, φ</th>
<th>Undrained Cohesion, c_u</th>
<th>Shear Modulus, S</th>
<th>Saturated Density, ρ_s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Harsh (deg) Conserv. (deg)</td>
<td>Harsh (kPa) Conserv. (kPa)</td>
<td>Harsh (N/mm²) Conserv. (N/mm²)</td>
<td>Harsh (N/mm²) Conserv. (N/mm²)</td>
</tr>
<tr>
<td>0.00</td>
<td>very soft Clay</td>
<td>1</td>
<td>0.01 2.5</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>90.00</td>
<td>firm slightly sandy Clay</td>
<td>2</td>
<td>18 20</td>
<td>30 50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>418.00</td>
<td>loose sandy gravelly sand</td>
<td>3</td>
<td>25 28</td>
<td>32</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. Geotechnical Parameters used in the hydraulic fracture modelling.

To examine if the drilling fluid is likely to exceed the modelled soil strengths, the parameters from the drilling assembly, drilling fluid, and flow rate are used to model the annular pressure at the bit along numerous points of the drilling profile. The surface topography and drill profile is used to calculate the depth of the HDD at each point.

The drilling fluid downhole pressure modelling is based on American Petroleum Institute recommended practice API RP 13D 2003. The programme uses the Power Law rheological model to calculate downhole pressures losses and velocities in each section of the drilling equipment, the downhole assembly, and the annulus between downhole assembly and wall of the borehole. The
model accounts for turbulent and laminar flow regimes. An example of the parameters used in this modelling is shown in Figure 4.

A number of scenarios were modelled to test the sensitivity of break out risk to:

- the size of the drilling bit
- the different levels of conservatism in the parameters
- worst case scenarios of only predominantly loose sand or very soft clay
- changes in fluid flow rates

4.2. Results

The testing of sensitivity to flow rate showed that an increase from 600 LPM to 1800 LPM only increased the annular pressure in the borehole by 0.3 bar when the drilling bit was 400m from entry. This is a very small increase and does not add significant breakout risk.

The results of the modelling of different drilling assemblies, geotechnical parameters (Likely, Conservative, and Ultra-Conservative), and geological worst case ground conditions (loose sand from 78m and very soft clay for entire HDD) are shown in the graphs in Appendix C.
To explain the information contained in each graph, the output from modelling using conservative geotechnical parameters for 12.25” and 17.5” bits is reproduced in Figure 5 below. At the top right of the graph the drilling parameters used in modelling the downhole annular pressure are shown. The legend clearly shows the annular pressure for the different bit sizes used in the modelling and beneath them the modelled hydraulic fracture outputs.

The vertical stress indicates the weight of the overlying soil at the level of the HDD profile at each point. If the soil possessed no cohesive forces (the forces that makes clay sticky) and zero angle of internal friction (the parameter that allows sand to stay in a pile rather than collapse) this would be the limit of annular pressure before breakout occurred.

The pore pressure line indicates the modelled natural groundwater water pressure at the elevation of the HDD at each point and is of little relevance for this project. If the HDD drilled through a vertical borehole that had not been sealed and the annular pressure was greater than pore pressure, the drilling fluid would flow from the top of the borehole.

The Delft maximum allowable pressure (solid red line) is the pressure at which the drilling fluid would breakout to the surface if the pressure was sustained. In the example below the modelled annular pressure for the 12.25” bit (green line) intercepts the red line at 418m Measured Depth. So at 418m from entry (32m from exit) surface breakout is likely if the actual ground conditions match the conservative geotechnical parameters.

The line labelled Delft 1m deformation pressure line indicates the pressure at which the ground surrounding the borehole is deformed to a distance of 1m. In practice this tends to be a useful
indicator of when irrecoverable damage is done to the surrounding ground. It can be used as a practical upper limit to trigger action (hole cleaning) to reduce the actual downhole pressures when they increase above the modelled values.

Note that the graphs have the X-axis plotted in reverse – this is to make it match the sectional view of the proposed design with entry on the right and exit on the left.

It should be stressed that the modelling assumes homogenous soil conditions in each modelled layer. If fractures, fissures, or man-made structures such as unsealed boreholes are present they may present an easier route for fluid migration to the surface and breakout might occur at lower than modelled pressures.

The intersection point between the modelled annular pressure and the Delft maximum allowable pressure was compiled for each scenario to give the distance from entry of predicted surface breakout. The results are shown in Table 2 for the exit side intersections.

To assist in understanding the likelihood of breakout a level of risk has been assigned to each of the geotechnical and geological scenarios. The percentages indicate a level of chance of each scenario occurring and are subjective; being based on experience from previous projects. The sum of the chances are not intended to equal 100% because there are two variables in each scenario along with variables that are not modelled (e.g. existence of fissured ground, geotechnical parameters stronger than expected etc). The risk percentages are tabulated in Table 2 along with modelled first breakout positions.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Geology encountered along route of HDD</th>
<th>Geotechnical Parameters</th>
<th>Allocated risk of breakout at modelled distance (%)</th>
<th>Distance from Entry of modelled breakout (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>As per geological model</td>
<td>Likely</td>
<td>90</td>
<td>416 418 419</td>
</tr>
<tr>
<td>B</td>
<td>As per geological model</td>
<td>Conservative</td>
<td>40</td>
<td>413 417 419</td>
</tr>
<tr>
<td>C</td>
<td>As per geological model</td>
<td>Harsh (Ultra-Conservative)</td>
<td>20</td>
<td>393 414 418</td>
</tr>
<tr>
<td>D</td>
<td>Loose silty SAND from 79m to the HDD exit</td>
<td>Likely</td>
<td>5</td>
<td>262 397 416</td>
</tr>
<tr>
<td>E</td>
<td>Very soft silty CLAY for entire HDD</td>
<td>Likely</td>
<td>2</td>
<td>133 257 412</td>
</tr>
</tbody>
</table>

Table 2. Summary of results from hydraulic fracture modelling with subjectively estimated risk of occurrence.

The data in Table 2 has been used to produce Figure 6, Figure 7, and Figure 8 below in an effort to illustrate the risk of breakout in the saltmarshes with differing bit sizes.

There is a risk of breakout at entry side before the flood defences, but the risk is the same, highly unlikely, for all bit sizes. It is not, therefore, shown in Table 2 but is shown on Figure 6 to Figure 8.

4.3. Conclusions

The outcome of the modelling is most easily understood by examining Figure 6, Figure 7, and Figure 8. The plans clearly show that as the bit size increases the risk of breakout in the saltmarshes greatly reduces. The simple conclusion that can be drawn is that ideally a bit size of 12.25” or larger should be used to reduce the risk of breakout in the saltmarshes. If a 12.25” bit is used there is an estimated 2-5% risk of breakout for the saltmarsh area. If a 17.5” bit is used the risk is reduced to an estimated 2% for the saltmarshes and this risk can be further reduced by additional ground investigations to ensure that the drill is not entirely within the very soft silty clay.
Figure 6. Indicative breakout risk from modelling of a 9 ⅝” drilling bit.

Figure 7. Indicative breakout risk from modelling of a 12 ¼” drilling bit.

Figure 8. Indicative breakout risk from modelling of a 17 ½” drilling bit.
5. SURFACE SETTLEMENT CALCULATIONS

There is a very small risk of settlement above the alignment of the HDD caused by collapse of the void between the final borehole (710mm diameter) and the installed duct (500mm). The risk is small because there will be bentonite slurry remaining in the void between borehole and duct after the duct is installed. This slurry typically gels to seal the annulus and prevent collapse.

The maximum possible long term settlement above the boreholes has been modelled using standard Gaussian equations as commonly used in modelling settlement above tunnels. It assumes that there is no bentonite in the annulus between borehole and duct, and the ground above collapses to completely fill this annulus. It also assumes that the collapse continues to surface and that all the sediment above the HDD is sand (clay gives a lesser settlement value). An example calculation from the program is shown in Appendix D.

The results indicate a maximum settlement trough with settlement of 36mm in the centre of the 13.2m wide settlement trough. The maximum settlement would be in the shape of a broad depression. As an indication, 1m either side of the centre of the trough the settlement is 32.6mm, 3.4mm less than the centre of the trough. The results of the modelling are shown in the graphs of Figure 9 to Figure 11. The vertical scale is 200 times the horizontal scale.

Given the topography of the saltmarsh shown on the VSH section, it is difficult to imagine that a maximum settlement of 36mm would significantly alter the drainage patterns in the saltmarsh. The major drainage along the alignment, at 334m from entry, appears to be over 0.5m, 500mm, deep and the intermediate sized gullies appear to be 250mm deep.

A second source of settlement might occur at the exit point of any surface breakout. The scale of such a feature is highly variable, being dependant on the duration and rate of flow from the breakout and the nature of the substrate. A best estimate for this project of maximum settlement around a breakout is a depression 20cm deep in the centre decreasing to nil at a 1.5m radius from the centre. Any breakout route and associated surface settlement are unlikely to become a route for drainage of surface water or ground water because of the swelling and gelling properties of the bentonite and this is why bentonite is used to backfill and seal geotechnical boreholes after completion.

It needs to be restated here that all these settlement calculations are worst case scenarios and highly unlikely to eventuate. The design of the HDD is to drill in the stiff glacial till layer; competent ground that will form a stable borehole wall and will be additionally supported by the bentonite fluid remaining in the annulus after the duct is installed. Even in the unlikely event that the bentonite fluid is replaced by groundwater it is highly probable that the clay would slowly swell, closing the annulus through expansion of the clay rather than by collapse.
Figure 9. Maximum settlement at 110m from entry (eastern edge of saltmarshes). Note that the vertical scale is millimetres, horizontal is metres.

Figure 10. Maximum settlement at 250m from entry (middle of saltmarshes). Note that the vertical scale is millimetres, horizontal is metres.

Figure 11. Maximum settlement at 380m from entry (western edge of saltmarshes). Note that the vertical scale is millimetres, horizontal is metres.
6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Drilling through bedrock

While it is technically possible to drill the HDD through the bedrock it is likely to result in an order of magnitude increase in time, risk and cost. The existing proposed design through the layer of glacial till is the preferable route.

To drill through the bedrock the potential cobble and gravel layers overlying the bedrock would need to either be pre-treated with grout or sealed with casing pipe installed from the surface. It is probable that grouting or casing would be required both near entry and exit.

Pre-treating with grout would require a grid pattern of vertical holes 10–20m deep to be drilled over the planned HDD path through the cobble layer. Grout would be injected into the layer to stabilise the ground and prevent collapse as the HDD passes through the zone. The HDD would probably need to be extended a further 50m in length to the west to ensure that the pre-treating of the exit area is located beyond the saltmarsh.

If casing were used the steel casing length would need to be at least 40m with diameter of 32 inches or more; this is at the upper end of capability for casing installation in the HDD industry. Both entry and exit of each HDD would require casing. Intersection techniques might also be needed to ensure the HDD pilot successfully entered the casing at the exit side.

The HDD final borehole size will probably be 28” (710mm) diameter. Within the rock the borehole may be susceptible to roof collapse if the fracture spacing of the rock is less than the bore diameter. Collapse of part of the roof would in the least require cleaning of the affected area by rotating the drilling head through the zone to break up the rock. Collapse of large blocks, or an extended length of roof, could potentially result in the equipment being stuck in hole and a new hole would have to be drilled in another position.

Quantifying the risk of roof collapse is difficult because the spacing of vertical fractures in the bedrock is difficult to assess. Vertical ground investigation boreholes typically sample a core of rock 100mm or 150mm in diameter and cannot give an indication of the larger scale fracture spacing that might impact the HDD. This risk of borehole collapse or failure cannot therefore be accurately assessed.

Drilling time in the bedrock will be significantly longer and equipment wear will be high due to the abrasiveness of the rock. Drilling times are likely to be four to five times longer in the rock than in the overlying sediments drilled in the current proposal.

If a deeper HDD profile is to be used the cable design will need to be checked to ensure it is suitable for heat dissipation during operation.

6.2. Feasibility of the proposed HDD design

Based on an assessment of the geotechnical boreholes currently available for the site, it is considered that the proposed HDD is feasible for the expected ground conditions. The risk of HDD failing for the project as a whole is considered to be extremely low. If an individual HDD fails there is sufficient room to allow for another HDD to be drilled parallel to it and in a different stratum if
necessary. HDDs of this length in ground of this nature have been successfully drilled on hundreds of projects in the UK and worldwide.

The risk of failure of an individual HDD is very low, provided that:

- Further ground investigations are carried out prior to construction to improve the accuracy of the geological model and refine the HDD design profile
- An experienced, competent HDD drilling contractor is chosen
- Real time downhole pressure monitoring is proactively used to keep annular pressure within acceptable limits
- A competent drilling fluid engineer is employed by the drilling contractor

The two greatest risks to successful completion of an individual HDD are adverse ground conditions and contractor incompetence or inexperience.

The risk of adverse ground conditions can be minimised by ensuring that ground investigations provide a good three dimensional model of what can be expected along the route of the HDD. Recommendations on further ground investigations are given in Section 6.10.

If adverse ground is encountered, a competent contractor will have options available to treat the ground or they can withdraw the drilling bit to a safe distance before the adverse ground and drill above, below or around it. An experienced contractor will quickly recognise a problem and modify their drilling techniques and drilling fluid to alleviate it while a poor drilling contractor will attempt to push their way through and risk losing their equipment or the borehole.

For this project the most likely scenarios that might cause an individual HDD to be abandoned or cause equipment to be lost are:

- Drilling through cobbled ground and continuing on without regularly monitoring drilling forces and taking remedial action when required
- Encountering swelling clays and not modifying the drilling fluid to allow the clays to be sealed
- Drilling without adequately cleaning the drill cuttings from the borehole

The risk of the first two scenarios can be minimised by thorough ground investigations prior to construction and further reduced by ensuring the HDD contractor is competent and proactive in their approach to drilling. The third risk is entirely down to the ability and attitude of the drilling contractor and their drilling fluid engineer.

### 6.3. Risk of breakout

The outcome from the hydraulic fracture modelling in Section 4 suggests that if the HDD contractor uses a typical sized drilling bit (9.625 inch) for the pilot hole the risk is low for most of the marsh but rising towards the western edge (Figure 6). A larger 12.25” pilot hole reduces the risk further (Figure 7) and an oversized pilot hole (Figure 8) reduces the risk to extremely unlikely.

Based on previous projects in similar ground if a breakout occurs I consider that it is likely to be in a zone 3m either side of the HDD alignment. The drilling fluid will take the path of least resistance to the surface. If the ground is homogenous this is the shortest distance through the soil, directly upwards. If there are fissures or fractures in the ground the fluid might follow those but they are usually near vertical planes such as expansion cracks and generally limited to several metres depth. Cases where breakout occurs at greater distance from the line tend to be areas where the level of the
bedrock varies with surface outcrops in places and in areas where surface sediments are discontinuous horizontally.

For the worst case scenario for the modelled HDD, I would suggest eight to twelve as the maximum number of breakouts however this is a worst case scenario that assumes that:

- the drilling contractor uses regular sized drilling bits rather than a large or oversize bit
- the contractor does not use real time downhole annular pressure monitoring tools
- that the HDD unexpectedly encounters very soft silty CLAY for most of its route

The first two points can be mitigated in full by selection and supervision of competent HDD contractors. The third point can be mitigated to a large extent by further ground investigations, as outlined in Section 6.10.

Assuming these risks are mitigated a realistic worst case scenario for the first HDD is 4 breakouts in the western half of the saltmarshes (at 260m, 290m, 320m and 350m) and a further 2 breakouts in the intertidal area (380m and 410m). It should be noted that a contractor would know immediately if they were drilling in very soft clay rather than stiff glacial till. They could then modify the design profile (e.g. deeper) and drilling techniques (e.g. reduced drilling fluid flow rate or change to a larger diameter drilling bit) to further reduce the chance and scale of any breakouts. The hydraulic fracture modelling in Section 4 expands on the risk and likelihood of breakout.

There is no major impedance to drilling a large or oversized pilot hole. The minor downsides are:

- Drilling time is slightly longer for the pilot hole but the overall schedule is not significantly affected because the time for the reaming passes will be reduced.
- A larger drilling bit makes the drill a little more difficult to steer but it is not expected to cause problems with this project.
- Greater drilling fluid volumes are required to ensure the larger volume of drill cuttings are removed from the borehole. Sensitivity analysis of breakout risk shows low sensitivity to flow rates so the risk of breakout is not significantly altered by having to pump a higher volume. If a breakout occurred it would mean perhaps double the amount of fluid at surface before pumping was stopped, resulting in say a 2m² breakout rather than 1m². This equates to a circular breakout 1.6m diameter rather than 1.1m diameter.

6.4. Mitigating breakout risk

Hydraulic Fracture modelling in Section 4 suggests that the drill bit should be a minimum of 12.25 inch diameter and preferably larger. A number of HDD contractors have used bits as large as 20 and 22 inches in the past.

It would be prudent to drill the northernmost HDD first because it is traverses the shortest length of saltmarsh and access to any breakouts will be shortest in length. If any breakouts occur the drilling contractor can adapt and improve drilling designs and procedures for subsequent crossings to further minimise the risk of breakout.

Further ground investigations would improve confidence in the geological model and better identify the most suitable profile of the HDD to reduce breakout risk.

Real time downhole pressure monitoring will give early warning of increasing annular pressure and immediate indication when drilling fluid breaks out.
6.5. Downhole pressure monitoring

The drilling equipment should be equipped with sensors that monitor the pressure in the annulus between the drill and the wall of the borehole. The sensors are commonly available as an add-on module to the downhole guidance system and can be shown on a live display on a console in the driller’s cabin.

Real time downhole annular pressure monitoring will give the earliest warning of a breakout having occurred. If the monitoring is used in conjunction with modelled downhole and hydraulic fracture pressures it can also show if pressures are approaching the strength limit of the ground and preventative action can be taken to avoid a breakout.

If a breakout occurs the sensors will show a >50% drop in values (the readings are real-time) and the pumps can be stopped immediately. Remedial action can then be instigated.

6.6. Mitigating the effects of breakouts that occur

Considering the results of the Hydraulic Fracture modelling in Section 4, any breakout is most likely to be very close to the western margin of the saltmarsh. Given the proposed depth of the drill it is expected that any breakout would occur within 3 m of the HDD centre line. Accessing directly to any breakout with layflat hoses is likely to affect a much smaller area than the VSH proposal for an umbilical pipeline across the entire saltmarsh.

Real time downhole annular pressure monitoring will give the earliest warning of a breakout having occurred. If the monitoring is used in conjunction with modelled downhole and hydraulic fracture pressures it can also show if pressures are approaching the strength limit of the ground and preventative action can be taken to avoid a breakout.

If a breakout occurs sandbags are likely to be the most effective method of containing any bentonite breakout. Once a breakout occurs it becomes the easiest route for drilling fluid and is unlikely to seal itself until the drill has advance some distance past the point (30-50m but this can vary). An electric submersible pump can be placed at the lowest point in the sandbag bunded area to pump away the fluid. Typically the pumps require 15 - 20cm of fluid to pump out effectively so the sandbag wall is likely to be 30cm high. If there happens to be a natural channel close there might be less impact if the bentonite is allowed to flow to it and a small sandbag “dam” constructed to trap the bentonite.

The fluid can be pumped to the nearest convenient storage or transfer point. If the breakout is in the middle of the marshes it may be best to pump to a bowser trailer that can then be towed by tractor to the drill site for emptying. If the breakout is close to the HDD exit it could be pumped to the exit area and then back to the drill site via the returns line.

The person at the breakout location should be in direct radio communication with the driller to ensure that the pumping out of the containment area keeps pace with fluid emerging from the breakout when drilling continues. The driller can stop his pumps immediately if the clean-up operator requests, so the possibility of the breakout overtopping the sandbags should not occur. Containment of a breakout should therefore be entirely successful.

Sandbags are typically 25cm wide, so the area affected by a placement of sandbags is likely to be 8 lineal metres x 0.25m width = 2 m².
Once the breakout has sealed itself any remaining bentonite covering the ground in the containment area can be diluted and washed with seawater to be pumped out of the containment area. A second dedicated layflat hose will be required to pump the seawater into the bunded area while the other line is used to pump the diluted fluid away. A thin layer of perhaps 1-5mm of bentonite might remain on the ground after washing. Using a single line for both diluting and removing fluid is unlikely to be practical. There is no risk of the bentonite soaking into the saltmarsh ground.

If a breakout occurs and is left uncontained it will gradually spread outwards at ground level until either the drilling fluid returns bypass the fracture and return to surface as normal or another breakout occurs closer to the drilling bit. Assuming 30m of additional drilling before the breakout sealed there could be 9m$^3$ of bentonite from the breakout. At an average depth of 0.2m this equates to 45m$^2$ covered by bentonite. The drilling fluid acts as a gel and generally has a specific gravity of 1.05 to 1.10. To give an idea of the consistency and behaviour of the bentonite it is similar in thickness and viscosity to mayonnaise. An incoming tide is unlikely to disperse the bentonite without accompanying wave action. An outgoing tide will probably only remove bentonite in gully areas. Given that the saltmarsh is only covered by tides twelve times per year, leaving the breakout uncontained is unlikely to result in successful removal of the drilling fluid.

![Figure 12. A bentonite breakout of moderate to high viscosity, typically used to drill gravels. The bentonite for the Walney Extension landfalls is likely to be of lower viscosity and the same volume would conceivably spread out an extra third of the distance shown in the photograph.](image)

If surface breakout occurs it is highly unlikely to cause failure of the HDD provided the drill is allowed to continue with any continuing flow of fluid to the surface breakout being transferred back to the drilling. Failure of an individual HDD on this project would primarily be due to either:

1. Inadequate removal of cuttings from the borehole leading to sections of borehole where cuttings accumulate and pack around the drill rods. This can increase friction to a point where the drilling rods become stuck. The mitigation is to ensure drilling fluids are able to remove the cuttings from the hole and that the borehole is not advanced at a faster rate than the cuttings can be removed.
2. Collapsing gravels or cobbles packing off the drilling rods to make them stuck. On this project the mitigation is to stay above the cobble layer.
3. Collapse of blocks of rock in a borehole drilled through fractured rock, as discussed in Section 6.1.

The conditions in Scenario 1 has a small potential for causing failure of a HDD in the case where large cuttings fall out of suspension from the bentonite as it migrates upwards to the breakout. Mitigation involves the monitoring of push and pull forces as each drilling rod is swabbed or cleaned. If there is a sharp increasing trend in friction the rods can be tripped backward past the zone of cutting accumulations to clean the borehole before continuing.

In the case where there is no surface breakout, before Scenario 1 occurs there will be a significant trend of increasing pull and push forces and an increasing trend in annular pressure. Given that
annular pressure is key to this project it would be expected that remedial action would be taken to clean the borehole long before scenario 1 could become a danger to the completion of the HDD. Cleaning the borehole could involve either circulating fresh drilling fluid without advancing the borehole any further or retreating the drill but back through the hole and then back in again.

There is an argument for using freshwater bentonite as the drilling fluid because it is less stable in saltwater and will flocculate when it comes into contact with seawater. This can be washed out by the tide more readily. However this will need to be balanced with the risk of saltwater ingress at the level of the HDD bore affecting the filter cake around the borehole wall and causing instability. A specialist drilling fluid engineer will need to be consulted by the drilling contractor to determine the best solution for their needs.

6.7. Guidance

The HDD could be guided using a walkover system; however the walkover operator would need to follow the drilling head along the path of the HDD. This footfall could be expected to impact on the saltmarshes.

A wireline guidance system is recommended because it will allow monitoring and surveying of the HDD from the driller's cabin and with no need to access the saltmarsh. The guidance tool is located a few metres behind the drilling bit and sends real time information back to the drillers cabin through a cable inside the drilling rods. A wireline system also enables an add-on downhole annular pressure sensor to be connected (refer to Section 6.5).

The two main options for a wireline system are a gyro system or a Magnetic Guidance System (MGS). The MGS will have additional surface tracking capability to calibrate the magnetic bearing of the HDD. The surface tracking system would not need to be positioned in the saltmarshes so they would be unaffected. Either system is suitable for the project.

6.8. Drilling Fluid

Drilling fluid tailored to the ground conditions is an important part of the HDD process for both completing the HDD efficiently and minimising the risk of breakout. The HDD contractor should use a reputable mud engineer and quality products to ensure a stable borehole and that all cuttings are carried from the borehole.

The pH of bentonite drilling fluid is typically 7-9. Glacial till typically has a pH of around 8. Analysis of samples from the ground investigation boreholes indicated a pH of 7.4 – 8.1 in the very soft silty clay in BH10 and a pH of 6.8 from the sample in the peat. Sample tests in loose sands from boreholes further out on Middleton sands were pH 8.7 and 8.8. Seawater is typically pH 7.5-8.4. The bentonite pH is therefore not significantly different from ground or seawater.

6.9. Noise and Vibration

The proposed drilling at a depth of 6 – 8 m is not expected to cause any noticeable vibration at the surface. At shallow depths the drilling bit can be heard as a low frequency rumble so there is some vibration. Generally it is only audible to humans when the bit is <5m depth below surface. I have never noticed any vegetation swaying or vibrating because of it.
6.10. Further Investigations

Additional ground investigations are recommended before construction in order to validate the geological model and optimise the design profile of the HDD for drilling and reduction of breakout risk. Ground Investigation boreholes should be located with the aim of producing a three dimensional ground model covering the alignment of all the HDDs.

Consideration should also be given to surface geophysical techniques. For example the strong contrast in strength between the glacial till and overlying soft clay and loose sand should be very well defined by a seismic reflection survey. Such a survey would define the boundary in much greater detail than projecting a line between two boreholes spaced 100m apart.

A combination of boreholes and surface geophysics is ideal because it allows more accurate interpretation (“ground truthing”) of the geophysics.

The elevation of the glacial till in BH12 indicates that there may be scope to drill at a lower elevation, perhaps 1-2m lower, beneath much of the saltmarshes, subject to the results of further geotechnical investigations. This additional depth would further reduce breakout risk.
# Tim Riggall

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## Experience

**Director, Riggall & Associates Ltd, Gloucestershire, UK** (October 2005 – Present)

**Geotechnical consultancy specialising in Horizontal Directional Drilling (HDD)**

HDD Feasibility Studies, HDD Planning and Design, Tender Evaluation, Project Supervision and Training.

I have a rare combination of theoretical knowledge, through his BSc in Geology and MSc in Geotechnical Engineering, and practical experience, 8 years in geology followed by 14 years in HDD. My HDD experience has progressed from guidance and design of HDD pilot drilling through modelling of drilling forces and downhole fluid pressures to project evaluation and troubleshooting. I have guided pilot holes on over 120 HDD’s and HDD intersections in a wide range of ground conditions throughout the world. In a consulting capacity I have worked on over 40 projects. Key projects have included:

### Environmentally sensitive HDD’s

- **Whitburn, UK, January 2014.** Technical proposal for a 440m HDD outfall for The Coal Authority. Design passes beneath SSSI and SAC coastal zone and through the magnesian limestone aquifer. Hydrofracture analysis was a key to assess the risk of breakout and aquifer contamination.
- **SSE Iver-Yiewsley, 2013.** Feasibility study including hydrofracture modelling of 650m and 330m length crossings beneath contaminate ground. Contract awarded and in construction.
- **QCLNG project, Gladstone, Australia, 2011-2012.** Drilled beneath protected tidal mudflats in swelling clays. Hydrofracture analysis and real time downhole annular pressure management was key to successful completion of 4 x 1300m HDD’s for large diameter gas pipelines. R&A undertook hydrofracture analysis, pressure modelling and pullback modelling for the project.
- **Anglesey, October 2012.** Landfall feasibility report for Celtic Array project, working as a sub-consultant for Halcrow. Assessment of a number of potential landfall sites along the northern Anglesey coast for offshore windfarm cable landings with SSSI zones included in some of the sites.
- **Grohdepolder, Nordeney, Germany, August 2011.** Guidance on installation of 580m length landfall HDD’s beneath salt marshes in the Wattenmeer National Park. Installation was 450mm HDPE duct for Dolwin 1 windfarm.
- **Isle of Wight, 2008-2010.** Two 3900m gas pipelines installed by HDD beneath the Solent. Drilled through swelling clays with SSSI areas above. R&A provided technical support to the client, SGN, at feasibility and trial stages and hydrofracture modelling to the contractor, LMR, during construction.
- **Barra Nova, Brazil, March 2005.** Guidance on HDD landfalls for an oil pipeline beneath beaches protected for turtle nesting.
- **Sublime Point, Australia, 2002.** HDD adjacent to World Heritage listed National Park with stringent environmental constraints. Guidance role as well as assistant Project Manager.

### HDD’s in very similar conditions to proposed Walney Extension landfalls


### HDD Hydraulic Fracture Modelling

- QCLNG project, Australia,
- Scotland Gas Networks, Glasgow
- SGN Isle of Wight HDD’s 2008-2010

Guidance on over 40 HDD’s including intersections on World Record HDD’s at Isle of Wight (3.9km, 2010-2011), China (3.2km, 2013), Milford Haven (3.0km, 2009).

Senior Guidance Engineer, Prime Horizontal, Beverwijk, Netherlands, (2003 - 2005)
Guidance on over 60 HDD’s including intersections and World Record HDD at Elbe, Germany (2.6km).

Guidance on over 20 HDD’s and Surface to Seam Coal Bed Methane drilling.

Geologist, Australia, Ghana, Tanzania (1992 - 1999)
Mine Geologist / Senior Mine Geologist at three Western Australian gold mines.
Chief Development Geologist at Obotan gold mine in Ghana.
Mine Geologist at Golden Pride gold mine in Tanzania.

Education

2006 - 2008 M.Sc. Geotechnical Engineering and Management (Distinction), University of Birmingham,

1987 - 1990 University of Sydney, BSc. Geology (Honours)

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APPENDIX B  Pressure While Drilling Tool

In conjunction with a Pressure Module and a Pressure While Drilling (PWD) Orienting Sub, the ParaTrack 2 system tool is used to measure downhole pressure. It allows real-time measurements of mud pressure both inside the drill pipe and in the annulus just behind the drill bit. Pressure measurements are taken behind the bit when jetting. When using a mud motor, the pressure is measured directly behind the mud motor.

**Pressure Module**
The ParaTrack 2 tool must be the PWD enhanced version to allow the connection of the Pressure Module as shown in Figure 1.

**Pressure Module Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>6000 mm</td>
</tr>
<tr>
<td>Drillpipe annulus gauge</td>
<td>350 bar full scale</td>
</tr>
<tr>
<td>Pilot hole annulus gauge</td>
<td>35 bar full scale</td>
</tr>
</tbody>
</table>

**Pressure While Drilling (PWD) / orienting sub**
The pressure module has a grease-filled access port in its side for measurement of the pipe pressure and another grease-filled access port at the bottom which allows transport of pressure from the specialized Pressure While Drilling (PWD) orienting sub as shown in Figure 2. The PWD sub uses a grease-filled access port to transport pressure measured from the outside of the PWD sub to the Pressure Module. The Pressure Module then sends the pressure data up the wire line to the interface box and computer located at the top of the hole.

The pressure data is monitored and stored by the standard RvCross software used with the ParaTrack 2 system. The pressure can be viewed in real time. It is also stored for later use. The software allows easy graphical representations of pressure variations with time, an example of which is shown in Figure 3. Alarms can also be set in the software and will trigger if pressure limits are exceeded during drilling.

Because it is capable of giving a rapid indication of any increase in downhole pressure, the measurement of pressure while drilling is an effective technique to reduce the risk of bentonite (drilling mud) pressure during the drilling process. It can also help ensure that a cohesive is kept clean and free of debris, thus reducing operational risks.
Likely ground conditions graphs

### APPENDIX C  Output graphs from hydraulic fracture modelling

#### Modelled Annular Pressure & Hydrofracture Limits

**Dong Energy - Walney Extension Landfalls, 4-2-2014**

- **Parameters**
  - Drill pipe: 6.625" OD, 5.901" ID
  - Collars: 6.75" OD, 2.8125" ID
  - Jetting: 6.75" OD, Bit: 9.875"
  - Viscosity: Fann 600=80, 300=60, 100=40, 3=25
  - Flow=600 (l/min), MW=1.05

#### Graphs

- **6 5/8 DHA, 9.875 and 12.25 bit**

- **8.5 DHA, 12.25 and 17.5 bit**
Conservative ground conditions graphs

6 5/8 DHA, 9.875 and 12.25 bit

8.5 DHA, 12.25 and 17.5 bit
Ultra - Conservative ground conditions graphs

Modelled Annular Pressure & Hydrofracture Limits
Dong Energy - Walney Extension Landfalls, 4-2-2014

Parameters
Drill pipe: 6.625” OD, 8.5” ID
Cables: 6.3” OD, 2.8125” ID
Jetting: 6.75” OD, 9.875” ID
Flow= 600 (l/min)   MW= 1.05
Viscosity: Fann 600=80,300=60,100=40,3=25

Modelled Annular Pressure & Hydrofracture Limits
Dong Energy - Walney Extension Landfalls, 4-2-2014

Parameters
Drill pipe: 6.625” OD, 9.875” ID
Cables: 8.5” OD, 2.8125” ID
Jetting: 6.75” OD, 12.25” ID
Flow= 600 (l/min)   MW= 1.05
Viscosity: Fann 600=80,300=60,100=40,3=25

6 5/8 DHA, 9.875 and 12.25 bit

8.5 DHA, 12.25 and 17.5 bit
Loose silty SAND from 79m away graphs

6 5/8 DHA, 9.875 and 12.25 bit

8.5 DHA, 12.25 and 17.5 bit
All soft silty CLAY worst possible scenario graphs

6 5/8 DHA, 9.875 and 12.25 bit

8.5 DHA, 12.25 and 17.5 bit
## HDD SURFACE SETTLEMENT ESTIMATOR

Estimates surface settlement trough based on gaussian equations (U of B notes)

Assumes volume loss at surface = volume loss in tunnel, \( V_s = V_t \)

Indicates absolute maximum long term settlement. Bentonite stabilisation and bridging assumed to be non existent.

### Client:
DONG Energy

### Project:
Walney Extension

### Date:
12th February 2014

<table>
<thead>
<tr>
<th>Soil type</th>
<th>sand</th>
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<tbody>
<tr>
<td>Pipe depth below surface, ( z_0 )</td>
<td>6.3 metres</td>
</tr>
<tr>
<td>Final ream diameter</td>
<td>710 mm</td>
</tr>
<tr>
<td>Product pipe OD</td>
<td>500 mm</td>
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<tr>
<td>Inflection point, ( i )</td>
<td>2.21 metres</td>
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<tr>
<td>Trough width</td>
<td>13.2 metres</td>
</tr>
<tr>
<td>( W_{\text{max}} )</td>
<td>36 mm</td>
</tr>
</tbody>
</table>

### Settlement at any point

| Distance from centrel ine, \( x \) | 1 metres |
| Settlement, \( W \), at \( x \) | 32.6 mm |

\[
W_{\text{max}} = 0.607 W_{\text{max}}
\]