Sediment (Soil) Controls on Lifetime HV Cable Performance

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HV Cables

• The last decade has seen a huge increase in the demand for subsea HV cable systems:
  - For connection of offshore renewable energy generation
  - For the creation of intra- and trans-national interconnectors.

A UK map of current (2017) pre-planning; planning; consented; in construction and built windfarms with actual or proposed cable routes; and actual and in construction interconnector routes: downloaded from the Crown Estates Website – © Crown copyright (2017)

In addition, 2 with Consents Application Submitted, another 17 in the concept/early planning stage and 107 MVAC/HVAC cables Commissioned.
Substrate Controls on HV Cable Performance

- The power transfer capability of HV cables is limited by thermal considerations, as excessive core temperatures can lead to premature cable failure.

- Thermal considerations play a significant role in cable rating and cable losses and therefore the choice of appropriate cable numbers and dimensions. In terrestrial settings the burial medium accounts for 70% of the temperature rise in conductors.

- With the increase use of Distributed Temperature Sensor (DTS) data, a detailed understanding of the thermal environment is required to make the most of these data e.g. for potential fault detection; cable exposure or over burial etc.

- Therefore a full understanding of the role the substrate plays in heat dissipation could reduce the Levelised Cost of Electricity (LCOE) for the ORE sector and overall capital expenditure (CAPEX) for the inter-connector market.
Substrate Controls on HV Cable Performance

• With conductor temperatures approaching 90°C and external cable temperatures approaching 75-80°C (50°-60°C for interconnectors), the host seawater-saturated sediments will endure thermal conditions at ~1-2 m depth typically only experienced following ~1 to 2 km of burial at the average geothermal gradient.

• There is also the potential for there to be effects on:
  • Benthic fauna
  • Organic content of sediments
  • Pore-water/sediment geochemical interactions.
Terrestrial vs Offshore

- A seasonally variable ambient (water) temperature.

- A much wide range of sedimentary environments along a single cable route can be temporally varying.

- Seabed sediments are almost always fully saturated. As the convective heat transfer coefficient is significantly greater for seawater than for air, heat dissipation for buried offshore cables could occur through the combined processes of conduction and convection.

- Very limited information on the thermal properties of either the ambient condition or the post-installation backfill thermal properties;

- Less precise control (decimetre rather than centimetre) on the initial burial depth or nature of the backfill;
IEC 60287 Standard

Conductor Temperature rise above ambient °C – Cable Manufacturing Controlled

\[ I = \left[ \frac{\Delta \theta - W_d [0.5T_1 + NT_2 + T_3 + T_4]}{RT_1 + NR(1 + \gamma_1)T_2 + NR(1 + \gamma_1 + \gamma_2) + (T_3 + T_4)} \right]^{0.5} \]

\[ T_4 = \frac{1}{2\pi} \rho_T \ln \left( l + \sqrt{l^2 - 1} \right) \text{ where } l = \frac{2L}{D_e} \]

Thermal Resistivity of the burial medium

Burial Depth

Cable Diameter

Crux of this equation is it assumes heat transfer only by conduction
Substrate Controls on HV Cable Performance

- We have been approaching these problems through a three stage approach: numerical modelling – physical modelling – in situ measurements.
- Numerically we (Hughes et al: 2015a and b) have used an FEM model to look at thermal processes induced by an HV cable operating in a range of typical shelf sediments and in response to trenching.

**Thermal Conductivity**

\[
Q = -\lambda_b \nabla^2 T + \rho_f C_{pf} u \nabla T
\]

- Heat Generated per unit volume of mesh
- Conductive Term
- Convective Term

**Permeability**

\[
u = -\frac{1}{n \mu} \kappa (\nabla p + g \rho_f (1 - \beta \Delta T))
\]

- Porosity
For a 132 kV cable

Hughes et al, 2015a and b
Substrate Controls on HV Cable Performance

- A 2 x 2.5 m 2D tank for undertaking fundamental experiments to test the numerical modelling results has been constructed.
- Instrumented with a 30 cm diameter heat source located in the centre of the tank and buried to a depth of 1m beneath the sediment surface. A total of 120 thermocouples have been placed in a mesh around the source (as well as measuring water column and air temperature).
- Have tested three grain sizes, coarse silt, fine sand and very coarse sand using ballotini as a proxy for sediment (silica spherules) over a range of cable temperatures from 30°C to >90°C.
- Have also tested a natural marine fine sand
Low permeability \((\kappa = 1.4 \times 10^{-13} \text{ m}^2)\) coarse silt sized ballotini \(- n = 0.2\)

Max Surface Temperature Above Ambient

\begin{align*}
\text{10 °C} & \quad \text{18 °C} & \quad \text{60 °C}
\end{align*}
High permeability \((k = 1.5 \times 10^{-9} \text{ m}^2)\) very coarse sand sized ballotini – \(n = 0.4\)

**Steady state temperature distributions**

\[ \begin{align*}
\text{Measured} & \\
(a) & \quad \text{Surface temp.} = 7^\circ\text{C} \\
(b) & \quad \text{Surface temp.} = 9^\circ\text{C} \\
(c) & \quad \text{Surface temp.} = 18^\circ\text{C}
\end{align*} \]

\[ \begin{align*}
\text{Modelled} & \\
(a') & \quad \text{Surface temp.} = 7^\circ\text{C} \\
(b') & \quad \text{Surface temp.} = 9^\circ\text{C} \\
(c') & \quad \text{Surface temp.} = 18^\circ\text{C}
\end{align*} \]

Max Surface Temperature Above Ambient

\[ \begin{align*}
7^\circ\text{C} & \\
9^\circ\text{C} & \\
18^\circ\text{C} & \\
\end{align*} \]

Emeana et al, 2016
Comparison of natural sediment experiment with Ballotini and modelled results for an Intermediate permeability

Fine sand sized ballotini: $\kappa = 1.6 \times 10^{-11} \text{ m}^2 - n = 0.32$

Natural fine sand: $\kappa = 4.3 \times 10^{-11} \text{ m}^2 - n = 0.32$

Emeana et al, 2016
Indicative Grain Size (mm)

- Clay: $10^{-4}$
- Silt: $10^{-3}$
- Sand: 0.01, 0.1, 1
- Gravel: 10

Conductor Temperature ($^\circ$C)

- $b = 0.5$ m
- $b = 1$ m
- $b = 2$ m
- $b = 5$ m

Permeability ($m^2$)

- $\lambda_S = 1 \, \text{Wm}^{-1}\text{K}^{-1}$
- $\lambda_b = 0.84 \, \text{Wm}^{-1}\text{K}^{-1}$
- $n = 0.4$

Hughes et al, 2015a and b
Natural Sediment: Fine Sand – variable skin temperatures

Low Permeability Ballotini

High Permeability Ballotini

German Federal Maritime and Hydrographic Agency (BSH)

“2K Rule”

Natural Sediment: Fine Sand – variable skin temperatures

Emeana et al, 2016
Actual Permeability and Thermal Conductivity Measurements

- However, there has been limited data collation of these key parameters from continental shelf settings.
- Further, for thermal conductivity and permeability there are significant questions about:
  - What is actually being measured?
  - What are the best approaches to measurement: in situ? on deck? in the Laboratory?
  - How robust are the measurements?
  - What about Tills!
Thermal Resistivity & Porosity Measurements – Global

879 thermal resistivity & porosity measurements

Cigre WG B1.41 Dec. 2017

Peat
The numerical and physical modelling work demonstrates that permeability, thermal conductivity and porosity are the key physical parameters determining the mode and degree of heat dissipation.

Porosity and thermal conductivity measurements of the ambient condition are standardly taken as part of pre-installation site investigation work for offshore cables but permeability is rarely acquired. More commonly permeability is predicted from empirical equations based on the functional form:

\[ \kappa = f_1(s)f_2(n)d_{eff}^2 \]

The most common of which is the Kozeny-Carman Equation:

\[ \kappa = \frac{1}{180} \frac{n^3}{(1-n)^2} d_m^2 \]
Measured vs Predicted Intrinsic Permeability

\[ \kappa = \frac{1}{180 (1 - n)^2} d_m^2 \]

where \( d_m = d_{50} \)

SANDS \( 10^{-12} \) to \( 10^{-9} \)

SILTS \( 10^{-17} \) to \( 10^{-12} \)

CLAYS \( 10^{-17} \) to \( 10^{-14} \)

Dix et al 2017

335 of 506 permeability measurements

Dix et al 2017
Measured vs Predicted Intrinsic Permeability

\[ \kappa = \frac{1}{180} \frac{n^3}{(1 - n)^2} d_m^2 \]

335 of 506 permeability measurements

Dix et al 2017
<table>
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<th>$\lambda_b$ (W$m^{-1}K^{-1}$)</th>
<th>$\rho_T$ (KmW$^{-1}$)</th>
<th>depth (m)</th>
<th>IEC $T(\degree C)$</th>
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Based on IEC 60287 Standard for a 132 kV cable

Hughes et al, 2015a
Post-installation changes to $\kappa$ and $\lambda_b$

- What we lack is quantitative assessment of the changes in geotechnical properties (permeability; thermal conductivity; void ratio/porosity; relative density;) through the installation process (both direct and indirect [e.g. scour variability]) of cables and pipelines.
- On what timescale do the sub-surface geotechnical properties change? Time-lapse sub-surface measurement, imaging and inversion to assess changes in substrate under ambient and extreme natural conditions.

Jetting/Fluidisation  Ploughing  Mechanical Cutting  Open Trench Dredging
3D Chirp System Overview

Physical dimensions: 1.816m L x 2.906m W x 0.455m H,

Weighs 232kg in air, neutrally buoyant in water.

Comprises 60 hydrophone groups, 0.25 x 0.25 m grid

4 central Chirp transducers, 1.5 kHz to 13.0 kHz bandwidth

RTK GNSS + GNSS Compass & MRU for pitch and roll.

http://www.soes.soton.ac.uk/3dchirp/
3D Cable Detection

Point Hyperbolae classic seismic representation of a cable in 2D


Vertical Exaggeration x3
3D Cable Detection

Vertical Exaggeration x3

Linear Hyperboloid in horizontal time slice section only seen in true 3D data enables cable tracking

No disturbance of sediment above cable!

*Dix et al (2016, 2017)*
3D Cable Detection

Can digitize apex of feature to get accurate location and depth of burial

Vertical Exaggeration x3

Geo-acoustic Inversion of 2D and 3D seismic

- A genetic algorithm approach to geo-acoustic inversion applied to derive 1D post-stack acoustic impedance

- Impedance can be empirically related to soil properties:
  - P-wave velocity, m/s
  - Bulk density, g/cm³
  - Porosity, %
  - Mean Grain Size, Φ

- These values used to predict permeability using the K-C equation and thermal conductivity using the geometric mean

Vardy (2015, 2016)
Conclusions I

• Both the numerical and the tank based experimental work suggest that in the marine environment heat dissipation from HV cables is controlled by both convection and conduction.

• The degree of conduction and convection is controlled primarily by the permeability and to a lesser extent the thermal conductivity of the sediment.

• Current IEC standards are based on pure conduction and so can over-estimate cable temperatures. These therefore need to be re-considered for the marine environment as cables could be incorrectly rated.

• The work has also explored the implications of changing burial depths and changes in the physical environment in response to actual installation, on heat dissipation.
Conclusions II

• A review of currently publically available data shows:
  • Ambient continental shelf sediments and substrates have permeabilities with a range of 10 orders of magnitude.
  • The Kozeny-Carman equation predicts permeabilities for sands but is not as appropriate for finer grained sediments and over consolidated materials (e.g. Tills)
  • Thermal resistivities range from 0.3 to 1.5 KmW\(^{-1}\) and the bounding limits of this range can be predicted by the harmonic and geometric means.
• However, there are uncertainties in the measurement method of both parameters and most importantly no information on if and how these values may change during installation.
Potential Gains

• Knowledge of the permeability and thermal resistivity variation along the proposed cable route could be used to preferentially locate cables in higher permeability sediments and higher conductivity sediments.

• Thus being able to maintain lower cable temperatures through increased convective dissipation could slow the rate of degradation and extend their life.

• Further, consideration of the contribution of convection in the design phase could enable the use of entire cables or partial sections of cables with smaller diameters.

• Well constrained numerical models could be used to maximise the environmental information that can be determined from DTS monitoring. This could include the early identification of locations that have been scoured or over-buried.

• Implications of heat on geochemical reactions adjacent to the cables and local benthic communities could be properly constrained.
Current Work

- We are undertaking prototype scale studies through the analysis of long time series DTS data (with concomitant Current Load Data and Oceanographic data) and correlating against a combined geological, geotechnical and geophysical ground model of the cable route. We are undertaking this exercise with both windfarm export and inter-connector cables. *Always looking for more sites to test.*

- Undertaking 3D tank models on actual cable sections to look at the spatial and temporal variability of heat dissipation of cables buried at different depths and under different burial conditions.

- In tandem we are developing 3D Comsol models to work in conjunction with DTS data to understand the potential of such data to identify exposure and/or over burial of cables.

- We are utilising the 3D Chirp system, developed by our group at the University of Southampton, to do not intrusive quantitative 4D imaging (pre- and post-installation) of cable routes to assess changes in permeability and thermal resistivity during installation.

- We are at the early stages of developing an in situ testing laboratory to take direct measurements of seabed disturbance in conjunction with our non-intrusive methods.