# Thermal Ratings of Submarine HV Cables Informed by Environmental Considerations

Timothy **HUGHES**, Timothy **HENSTOCK**, James **PILGRIM**, Justin **DIX**, Thomas **GERNON**, Charlotte **THOMPSON**; University of Southampton, Southampton, UK, t.hughes@noc.soton.ac.uk, then@noc.soton.ac.uk, jp2@ecs.soton.ac.uk, J.K.Dix@soton.ac.uk, Thomas.Gernon@noc.soton.ac.uk, celt1@noc.soton.ac.uk

## ABSTRACT

*One important consideration in determining thermal ratings for HV cables is the effectiveness of the heat transfer through the surrounding medium in which the cable is buried. We have developed 2D finite element simulations to assess the influence that certain environmental parameters have on the dissipation of heat from submarine HV cables. Attention is paid to convective heat transfer through the sediment – a factor that is often considered of little importance. The simulations show that sediment permeability has a significant influence on the nature of the heat transfer, and hence the thermal ratings of submarine HV cables.*

## KEYWORDS

Submarine HV Cables, Finite Element Method, Thermal Ratings

## INTRODUCTION

Thermal ratings of HV cables buried on land have been investigated extensively, making use of both analytical (e.g. IEC 60287[1]) and numerical techniques (e.g. [2,3,4]). The suitability of these approaches within the explicit context of cables buried under the seafloor has not been extensively investigated, despite obvious differences between the marine and terrestrial environments. Seawater, not air, lies above the burial sediment. This presence of a large body of water above the burial medium for submarine cables changes both the thermal situation and dynamics of the environment. For example migration of sedimentary bedforms can result in variations in the depth of the seabed of up to 5m per year[5] through mechanisms that are not operative on land.

It is well known that the thermal properties of the burial sediment have a large impact on the overall cable rating for HV cables buried on land[6]. Over the length of its route, it is highly likely that a submarine cable will encounter a variety of different sediment types (see Fig. 1), with differing thermal and physical properties. Understanding how the differences in environment from terrestrial cable scenarios might affect the dissipation of heat from submarine HV cables is critical for accurate ratings predictions. We have developed a numerical approach for evaluating the thermal ratings of submarine HV cables by using the finite element method to model parallel conductive and convective heat transfer in the marine sediment surrounding an HV cable[4]. Simulations are carried out for a full range of values for the relevant environmental parameters to assess their relative importance. Among the environmental characteristics of the system that have been investigated are: the sediment permeability, porosity, and thermal conductivity, as well as the cable burial depth.

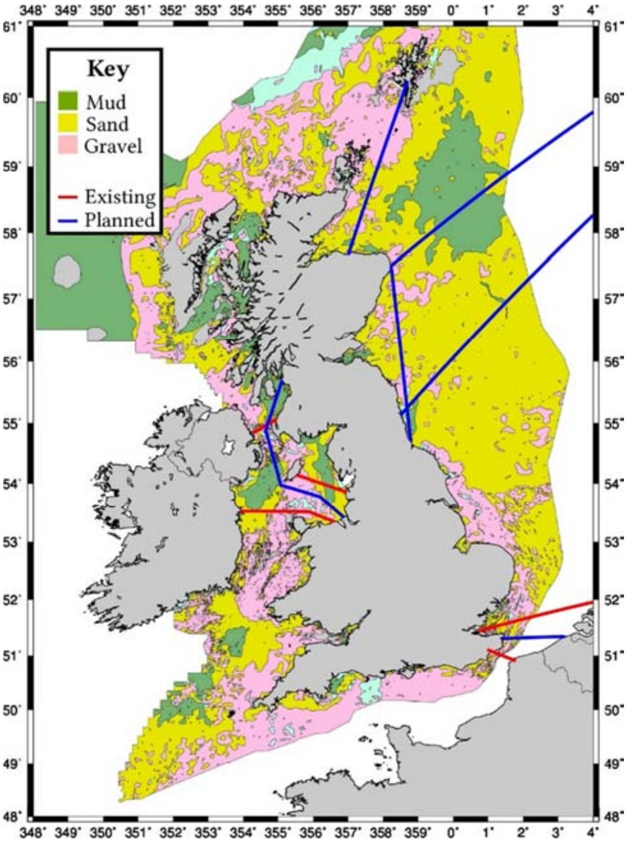

**Fig. 1: Planned and existing cable routes around the U.K. along with sediment type. Contains British Geological Survey materials, copyright NERC 2014.**

## SETUP OF THE FEM MODEL

The equation that describes the transfer of heat in a steady state with the presence of a constant heat source, $Q_i$ is[7]:

$$Q_i = -\lambda\nabla^2 T + \rho c_p \mathbf{u}\cdot\nabla T \tag*{[1]}$$

where $\lambda$ ($Wm^{-1}K^{-1}$) is thermal conductivity, $T$ $(K)$ is temperature, $\rho$ ($kgm^{-3}$) is fluid density, $c_p$ ($Jkg^{-1}K^{-1}$) is fluid specific heat capacity, and $\mathbf{u}$ is the fluid velocity field. The two terms on the right hand side of equation 1 represent the heat transferred by conduction and convection respectively. The dynamics of the fluid permeating the sediment is assumed to be well described by Darcy's law, which characterises the velocity of a fluid in a porous medium:

$$\mathbf{u} = -\frac{1}{n\mu}\boldsymbol{\kappa}(\nabla p + \rho g\hat{y}) \tag*{[2]}$$

where $n$ is porosity (the ratio of water to sediment grains), $\mu$ (Pa・s) is the dynamic viscosity, $\boldsymbol{\kappa}$ ($m^2$) is the permeability, $p$ (Pa) the pressure, $g$ the acceleration due to gravity, and $\hat{y}$ the unit vector in the vertical direction. Equations 1 and 2 form the basis of the constructed FEM model. A Boussinesq approximation is then made[9] in order to account for buoyancy forces within the permeant fluid. The density term in equation 2 is expressed as $\rho = \rho_0(1 - \beta(T - T_c))$ to functionally include temperature dependent density perturbations (here, $\beta$ (K$^{-1}$) is the coefficient of thermal expansion). It is also assumed that the permeability of the sediment is homogeneous and isotropic, such that the permeability tensor in equation 1 can be adequately described by a scalar quantity, $\kappa$. Hence, equation 2 becomes:

$$\mathbf{u} = \frac{1}{n\mu}\kappa(\nabla p + g\rho_0(1 - \beta(T - T_c))) \quad [3]$$

The thermal conductivity of the medium can be estimated from the individual thermal conductivities of the fluid, $\lambda_f$ and the sediment grains, $\lambda_s$, along with the porosity. There are several different methods for estimating the bulk thermal conductivity, $\lambda_b$ from the aforementioned quantities; our model uses the arithmetic method[8]:

$$\lambda_b = n\lambda_f + (1 - n)\lambda_s \quad [4]$$

The above equations are solved across a 2D domain that is representative of a typical submarine cable burial scenario, similar to the one displayed in Fig. 2.

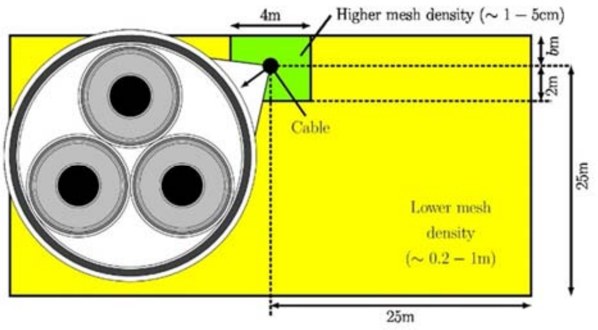

**Fig. 2: FEM simulation Geometry.**

Heat transfer within the cable is by conduction only. The internal structure for a generic 132kV SL type cable is used in the FEM model (the dimensions are given in Table [1] below). In the base case, a current of 1234A is transmitted along the cable (generating a total of about 100Wm$^{-1}$ of heat across a number of components, as illustrated in Fig. 2). Heat is applied homogeneously within each of the relevant heat generating components; the amount generated in each one is calculated using the procedures in the IEC 60287 standard.

Fluid is allowed to pass in either direction across the top edge of the simulation domain. Heat transfer across this boundary (that represents the seabed-seawater interface) is proportional to the local temperature rise above ambient (the ambient seawater temperature is assumed to be 10°C), and the velocity of the overlying seawater[9] (the value of which is based on the velocities of real marine currents[10]).

An area of finer meshing was included for the region directly surrounding the cable (the green region in Fig. 2). This was done to sufficiently resolve the steeper temperature gradients and larger velocity magnitudes in this area. The maximum side lengths of the mesh elements was set to 5cm and 1m for the finer (green) and outer (yellow) meshed regions respectively.

| Component | Material | $\lambda$ (Wm$^{-1}$K$^{-1}$) | Diameter (mm) |
|---|---|---|---|
| Conductor | Copper | 400 | 34.3 |
| Conductor screen | XLPE | 1/3.5 | 37.3 |
| Insulation | XLPE | 1/3.5 | 71.3 |
| Insulation screen | XLPE | 1/3.5 | 74.3 |
| Swelling tape | Polymeric | 0.2 | 77.3 |
| Sheath | Lead | 35.3 | 81.9 |
| Oversheath | PE | 1/3.5 | 86.3 |
| Filler | PP | 0.2 | - |
| Binder tape | Polymeric | 0.2 | 189.75 |
| Armour | Steel | 18 | 200.95 |
| Serving | PP | 0.2 | 209.95 |

**Table 1: Dimensions of the simulated cable.**

A sensitivity analysis was also carried out to verify that the mesh was fine enough. Two identical simulations were compared, one with 42,546 elements, the other with 99,451. The largest difference in the temperature field was found to be 0.074°C.

## OVERVIEW OF INITIAL RESULTS

Simulations were run for a variety of different values for the permeability, porosity, and thermal conductivity of the burial sediments, as well as the cable burial depth. The ranges of each of these parameters was selected to be representative of their range as exhibited by natural marine sediments. Of particular interest was the permeability, which can vary over numerous orders of magnitude between different sediment types.

As such, the permeability is the most influential parameter in determining the nature of the heat flow in and around the cable. At very low permeabilities, the movement of the fluid is restricted; the transfer of heat is mainly by conduction, and heat is transferred approximately isotropically. At very high permeabilities, the reverse is true. Permeant fluid velocities are high, and buoyancy forces drive circulation of fluid within the sediment. Consequently, heat transfer is much more directional, with a large proportion being directed upwards, towards the overlying seawater.

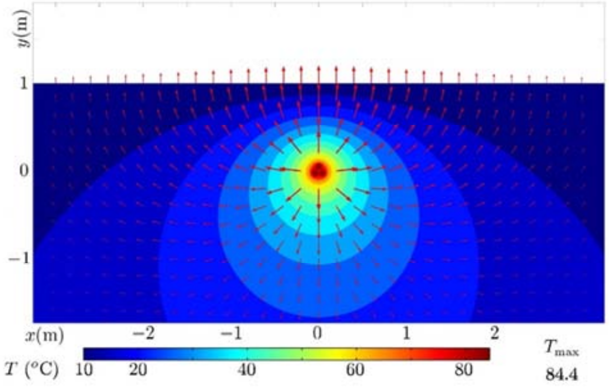

**Fig. 3a: $\kappa = 10^{-14}$ m$^2$**

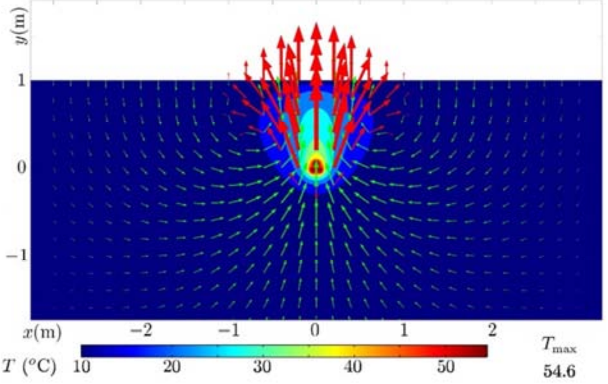

Fig. 3b: $\kappa = 10^{-10}\mathrm{m}^2$

**Fig. 3: Example solutions for (a), a low and (b), a high permeability sediment. Red and green arrows represent the total heat flux and fluid velocity fields respectively. Here, $\lambda_s$ = 1Wm$^{-1}$K$^{-1}$**

## EFFECTS OF ENVIRONMENTAL PARAMETERS

The dependence of the thermal behaviour of the system on permeability and solid phase thermal conductivity was investigated by repeating the simulation, incrementing the value of the aforementioned parameters between runs. The results are summarised in Fig. 4, which plots the maximum conductor temperature against both permeability and thermal conductivity. It is clear that there is a transition in behaviour between the regions either side of the dotted black line.

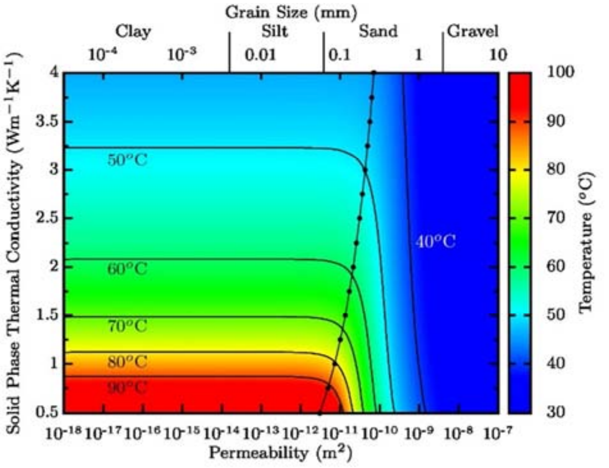

**Fig. 4: Dependence of maximum conductor temperature on permeability and solid phase thermal conductivity.**

It is also possible to directly extract data regarding the local convective fluxes within the simulation domain. The convective flux across a line of length 4$r$ (where $r$ is the cable radius) at a distance $r$ above the top of the cable serving was recorded for a subrange of permeabilities that span the transition in behaviour shown in Fig. 4. The convective flux as a function of permeability and thermal conductivity is shown in Fig. 5. The dotted black line is identical to the one in Fig. 4, and represents the point at which 20% of the total heat transfer away from the cable is by convection.

For low (*i.e.* less than ~$10^{-12}$m$^2$) permeability sediments, heat transfer is overwhelmingly by convection. Conversely, for sediments with a high permeability, essentially all heat is transferred by convection. The initial onset of convection is itself a weak function of the thermal conductivity. It should also be noted that the range of permeabilities exhibited by naturally occurring marine sediments spans the transition from conductive to convective behaviour[11].

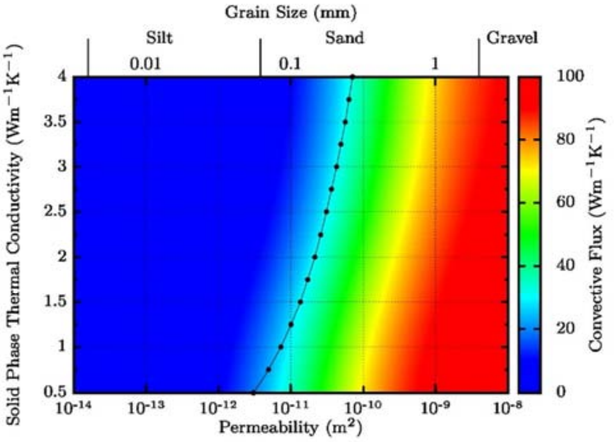

**Fig. 5: Vertical convective flux measured at one cable radius above the outer serving for different permeabilities and solid phase thermal conductivities.**

The effect of varying the cable burial depth was similarly investigated. Fig. 6 shows that its influence on the maximum conductor temperature is similar in nature to that of the thermal conductivity. For low permeabilities, the burial depth has a strong influence on cable temperature. This is because altering the distance from the heat source (cable) to the sink (the seawater interface) is akin to altering the $\nabla T$ term in equation 1. By contrast, at high permeabilties, the cable temperature is approximately insensitive to burial depth.

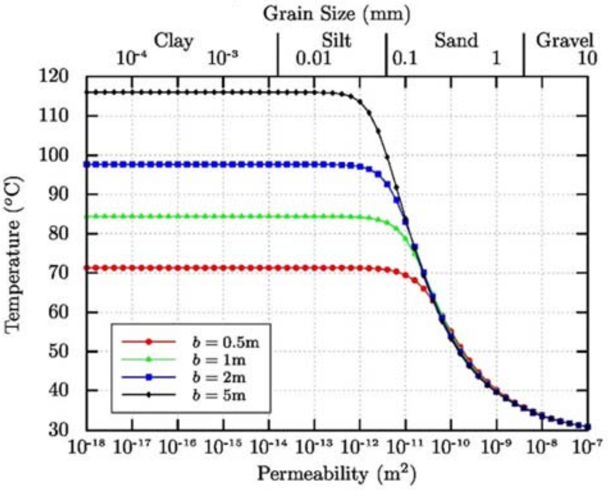

**Fig. 6: Dependence of maximum cable conductor temperature on permeability and burial depth.**

The strong dependence of cable temperature on burial depth at lower permeabilities may be important, especially in the context of the statement made earlier that the seabed can be dynamic, with significant variations in height occurring on timescales as short as several months. It is also worth mentioning that very fine grained sediments are less susceptible to bed migration (sediments composed of clays tend to be more cohesive than larger grained sediments), but may still experience a variation in burial depth through erosion and scouring.

A comparison of simulation solutions with differing sediment porosities was also carried out. The porosity has a slightly more obfuscated effect on the flow of heat, as according to equations 2 and 4, the bulk thermal conductivity and the permeant fluid velocity are both dependent on the porosity. Hence the conductive and convective flux terms in equation 1 will both be altered by a change in the sediment porosity. To complicate things even further, the permeability of a sediment is well known to be a function of porosity as well. The simulations for exploring porosity variation were done accordingly in grain size space (rather than permeability space, as the grain size is the parameter with which the permeability is most strongly correlated), with the permeability of the sediment assumed to be well described by the Kozeny-Carman equation[10,4]:

$$\kappa = \frac{1}{180}\frac{n^3}{(1-n)^2}d^2 \qquad [5]$$

where *d* (m) is a representative grain size. The bulk thermal conductivity will usually be decreased by increasing porosity (because the grain thermal conductivity is usually greater than the fluid thermal conductivity), while the permeant fluid velocity will increase with increasing porosity.

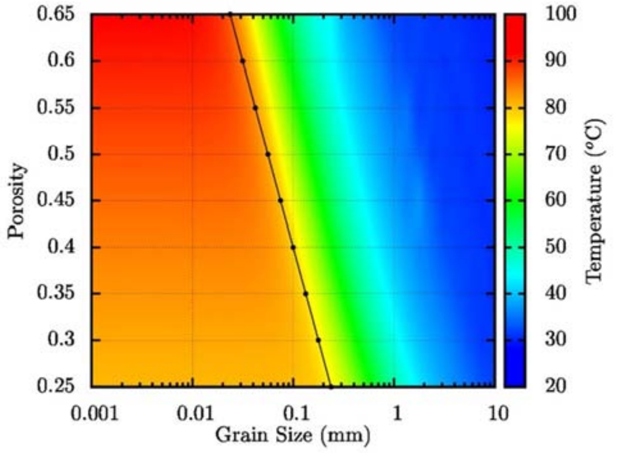

**Fig. 7: Dependence of maximum cable conductor temperature on porosity.**

Again, the dotted black line distinguishes between greater than and less than 20% convective heat transfer. However, the porosity still has a weak effect on the cable temperature even when the grains size (which is strongly correlated with permeability) is large. This is probably an artifact of the dependence of the permeability on the porosity, as it is clear from Figs. 3-6 that the permeability has a strong effect on thermal behaviour, especially when it is large.

## INCLUDING A TRENCH WITH A DIFFERENT PERMEABILITY

The results presented above have been obtained from running simulations that assume that the sediment is perfectly homogeneous with respect to its thermal and physical properties. However, the process of cable installation may involve a significant departure from this assumed homogeneity. The sediment that backfills the trench that accommodates the cable may experience different depositional conditions than those experienced by the background sediment (perhaps leading to a change in grain packing and porosity). The composition of the backfilling sediment may also differ, if it has been transported a considerable distance in suspension. Digging trenches into more cohesive sediments (*e.g.* fine grained clays) that can hold their structure comparatively well allows more time for larger volumes of external sediment to be backfilled into the trench. This could result in quite a sharp permeability contrast between the trench and background material, depending on the physical properties of the extrageneous transported backfill. It may also be worthwhile to consider the thermal implications of artificially backfilling the cable trench with a high permeability material. Any potential benefit would only be worthwhile implementing if it could be demonstrated that material transport would not occur in a particular sediment bed, or if the material directly around the cable could be prevented from being perturbed.

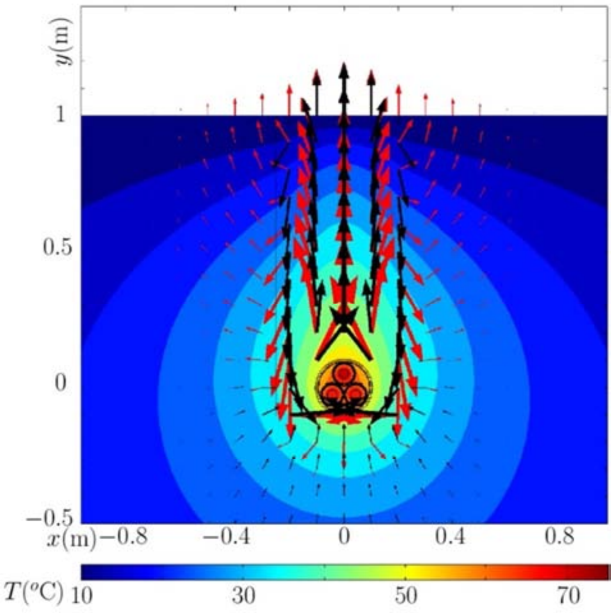

**Fig. 8: Example simulation including a trench with a different permeability ($\kappa_{\text{trench}} = 100\kappa_{\text{ext}}$). Red and black arrows are total heat flux and fluid velocity vectors.**

Illustrated in Fig. 8 is an example of a submarine cable buried in a trench that has a permeability 100 times that of the surrounding material. According to equation 5, this corresponds to an increase in grain size of a factor of 10 between the external material and the trench sediment. In this particular example, heat transfer through the sediment surrounding the trench region is conductive (i.e. falls on the left hand side of the dotted lines in Figs. 4, 5, and 7), while heat transfer through the material in the trench is convective (i.e. simulation parameters fall to the right of the dotted lines in Figs. 4, 5, and 7). In this case, the greatest fluid velocities (and to a lesser extent, the total heat transfer) are restricted to the trenched region. A convection cell is established within the trench, with limited fluid exchange across the boundary with the background sediment. This convection aids the cooling of the cable, such that the temperature of the cable conductors is reduced (in this example case, by about 9°C). For a 0.5m wide trench, and a permeability contrast between the trench and surrounding material of 100, convection starts to become appreciable when the permeability of the background material is around $10^{-12}$m$^2$. For background permeabilities of $10^{-13}$m$^2$, $10^{-12}$m$^2$, $2\text{x}10^{-12}$m$^2$ and $10^{-11}$m$^2$, the corresponding current ratings are: 1282A, 1297A, 1364A, and 1916A respectively.

The extent to which the cable is cooled with the inclusion of a trench with a different permeability to the background sediment depends on a number of factors. The greatest difference in the results between these two classes of simulations will occur when there is a large permeability contrast between the trench and background materials, these permeabilities fall on either side of the transition between conduction dominated and convection dominated heat transfer, and the trench width is maximised. For a trench that has a higher permeability than the background sediment, the temperature of the cable conductors is reduced by: increasing the trench permeability, increasing the permeability contrast between the trench and background (assuming they fall on opposite sides of the transition to convective behaviour), and decreasing the burial depth.

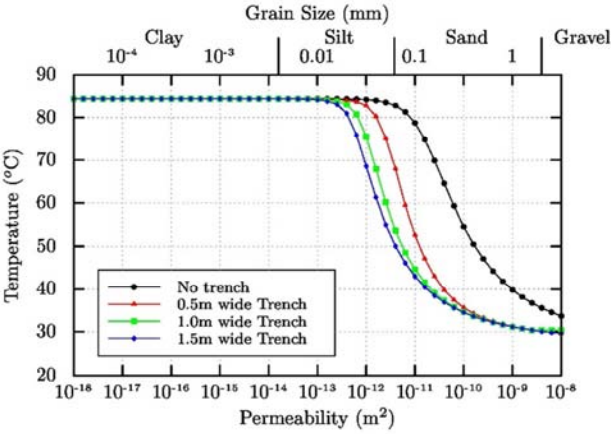

**Fig: 9: Comparison of conductor temperature in simulations with trenches of different widths and no trench, $\kappa_{\text{trench}} = 100\kappa_{\text{ext}}$.**

The most radical alteration of the sediment permeability will occur in scenarios where the physical characteristics of the sediment grains (particularly grain size and porosity, with which the permeability is most strongly correlated) of the backfilled sediment differ from the background, either through natural transportation of sediment to the trenched region, or through artificial interference. Variations in permeability due to a reorganisation of bed structure (resulting in altered grain packing or sorting) are not likely to be as severe as changes involving non-native grains. Hence, the greatest change in the thermal conditions will be experienced by cables with trenches backfilled with foreign sediment material.

## IMPLICATIONS FOR SUBMARINE CABLE DESIGN

Most contemporary approaches for assessing the thermal ratings of HV cables assume that the transfer of heat within the porous medium surrounding the cable is overwhelmingly dominated by conduction. However, the model suggests that in the marine environment, it is possible for convective processes to make a significant contribution to the dissipation of heat from HV cables. The assertion that convection can play an important role in dissipating heat from cables buried in the marine environment is supported by the results of an analogue physical experiment conducted in tandem with the initial modelling results discussed herein[12], which clearly demonstrate that for representative sediments and thermal conditions, convection can occur[4,12].

For cables buried in sediments that can support convection, heat can be dissipated into the surrounding sediment a lot more effectively than would otherwise be expected if only conduction were considered. By artificially cooling the traditionally limiting sections of the cable route (*e.g.* J-tubes and beach landing points) and avoiding sediments that are less thermally beneficial may result in an increase in transmission potential. Alternatively, a current rating augmented by considering convection may allow a reduction in the required conductor size for part of the route for a given current load.

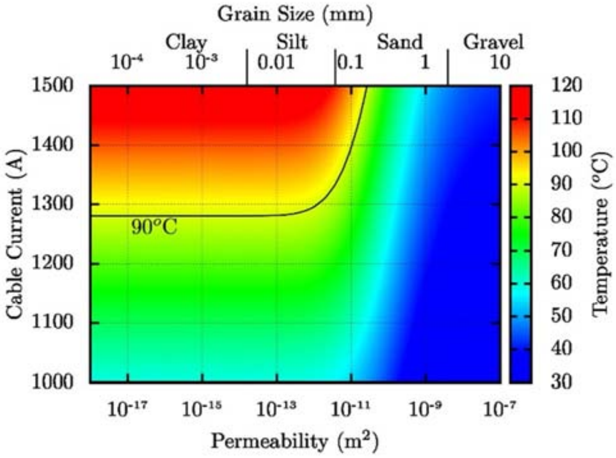

**Fig. 10: Dependence of cable conductor temperature on current load and permeability according to the FEM model.**

For permeabilities less than about $10^{-12}$m$^2$, the current rating is similar to analytical predictions (in this example case, 1279A). However, for more permeable sediments, the current rating can increase quite considerably (see Fig. 10). For example, for permeabilities of $10^{-12}$m$^2$, $10^{-11}$m$^2$, and $10^{-10}$m$^2$, the current ratings are 1281A, 1345A, and 1782A respectively. It would appear that this represents a large increase in the cable current rating, but any increase will be limited by the cable section with the least thermally favourable sediment. If a cable route can be planned to avoid these types of sediment, then an appreciable increase in the rating of the cable may be achievable.

It is also important to take into account the potential effects of a dynamic seabed on the thermal conditions experienced by the cable. From Fig. 6, it is clear that the cable burial depth can have a strong influence on the cable conductor temperature. However, migration of sedimentary bedforms and other marine processes may mean that cables may not remain at the same depth below the seabed-seawater interface for long, and might experience significant variation in burial depth over a period of several years. Any post-installation change in the depth of the cable below the seabed could have unexpected consequences, either by exposing the cable to a less than ideal thermal environment (if the cable becomes buried more deeply in the sediment), or making it more exposed to potential mechanical hazards, such as ships' anchors, trawling.

Consideration of the additional contribution to the dissipation of heat provided by convection may provide an alternative explanation of suspected anomalous DTS measurements of operating cables. If pre-installation surveys give little indication of a significant variation in sediment thermal conductivity along the cable route, a dip in temperature along a cable section is likely to be interpreted as a reduction in the cable burial depth (or even direct exposure of the cable to the seawater). One possible alternative explanation is that the sediment along this section is more permeable than the rest of the cable lay, and hence there is a greater capacity for heat dissipation via convection.

## CONCLUSIONS

FEM models of the dissipation of heat away from operational submarine HV cables has been carried out. The common perception that heat transfer is dominated by conduction has been challenged by illustrating that for certain types of sediment (those composed of grains with diameters larger than about 0.25mm) convection may not only be significant, but might be the primary mechanism by which heat is transferred away from cables buried in the marine environment.

Submarine HV cables will encounter a variety of different sediment types along their route. As such, the nature of the heat transfer away from these cables will vary between different locations along the cable length. Understanding these variations in the way heat is transferred away from HV cables in the marine environment is crucial to making accurate and reliable predictions of current ratings, and for efficient deployment of these assets.

## Acknowledgements

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## GLOSSARY

**FEM:** Finite Element Model
**HV:** High Voltage
**DTS:** Distributed Temperature Sensing