Understanding How Heat Generated in Submarine High Voltage Cables is Dissipated in the Surrounding Sediment

Tim Hughes[1], Tim Henstock[1], James Pilgrim[2], Justin Dix[1], Tom Gernon[1], Charlie Thompson[1]

Introduction

One of the defining aspects of life in the modern world is convenient access to a reliable and plentiful supply of electricity. This essential utility is delivered from power generating stations to consumers through a vast and intricate network of cables. These networks are designed with a plethora of different considerations in mind; a fine balance must be struck between them when constructing and installing cables. The supply of electricity must be comfortably accommodated by the network at times of very high demand, while minimising the amount of raw materials required to construct the constituent cables, and the amount of energy lost during the delivery of electricity to consumers.

In this context, the electric current is defined as being the movement of charged electrons along a cable (Landau & Liftshitz 1975). Inevitably, there are collisions between these electrons in motion and the constituent atoms of the cable conductor. During these collisions, electrons lose a proportion of their kinetic energy to the conductor atoms, which is manifest as an increase in the temperature of the conductor (Tayal 2009). In fact the power loss, P_{loss}, from a cable due to this effect (which is known as Ohmic, or sometimes Joule heating), is proportional to the square of the current, *I,* that passes through it (Elgerd & van der Puije 2012):

$$P_{loss} = I^2 R = \frac{V^2}{R} \tag{1}$$

Here, the resistance, *R*, is dependent on the material that the conductor is made from as well as its cross-sectional area. The transmitted power, *P*, is equal to (Elgerd & van der Puije 2012):

$$P = IV \tag{2}$$

1. Ocean and Earth Science, University of Southampton, Southampton, UK
2. Electronics and Computer Science, University of Southampton, Southampton, UK

Hence, it turns out to be much more efficient to transmit power over large distances at the lowest currents and highest voltages available. The supply voltage must be stepped down for domestic use (which is a relatively efficient process (Fardo & Patrick 2009)). In recognition of this, the electricity network is composed of large high voltage (HV) cables for bulk transmission of electricity over large distances, medium voltage cables for transmission of moderate amounts of power over smaller distances, and small low voltage cables for distributing power from local substations to consumers.

How are Submarine HV Cables Integrated into these Networks?

The incorporation of submarine HV cable links into the electricity network is becoming increasingly important. This is due in part to the large amount of recent investment into offshore power generation from renewable energy sources (*e.g.* wind, wave *etc.*), which require submarine connections to transmit generated power back to consumers on land. At the time of writing the aggregate power generation capacity of offshore wind projects in the UK alone stood at over 4GW (OWPG 2015). Draft plans indicate that up to 16GW (the UK year-averaged power consumption is currently just less than 40GW (DECC 2014)) of offshore wind generation could be available for the UK market by 2020 (DECC 2013), with a large number of wind farms currently under construction, awaiting construction, or in the planning stages.

Another application of submarine HV cable links is the continued expansion of the "European supergrid". The purpose of this initiative is to increase the number of connections between the national electricity grids of different European nations (or, over long distances within nations, *e.g.* the UK's "Moyle interconnector" (Worzyk 2009), which consists of two 250 MW cables (Atkinson *et al.* 2002)), so that energy can be more easily shared between them. Sharing electricity in this way can help to reduce the strain on the domestic power stations of the consumer region during times of peak demand, while simultaneously reducing the extent to which complicated energy storage solutions might be required in the supplying region.

Submarine cable links are becoming increasing prevalent in modern power grid networks. It is therefore of critical importance to understand as much as possible about the *in situ* operation of HV cables to ensure that they operate efficiently and reliably.

Cable Ratings

It is vital that the aforementioned Ohmic heating effect is accounted for during the design and construction of all HV cables; the material commonly used (Worzyk 2009, Thue 1999) for the cable insulation (cross-linked polyethylene, or XLPE for short) starts to degrade a lot faster when exposed to temperatures in excess of about 90°C (Anders & Radhakrishna 1988, Pigrim 2011), which reduces the lifetime of the cable. Each HV cable must be given a "thermal current rating", which denotes the maximum amount of current that it can safely and continuously transmit while maintaining the temperature of the XLPE insulation material below this 90°C threshold. In order to calculate these current ratings, an equation that describes the transfer of heat from where it is generated within the cable (largely in the conductors) to the surrounding environment must be solved. This equation must account for the thermal properties of both the cable components, and the material into which the cable has been buried.

There are two main approaches that can be taken to solve this equation and obtain current ratings for cables buried on land. The first type of approach involves solving the relevant equations *a priori* by making simplifying assumptions about the nature of the problem (one example of this kind of approach is laid out in the IEC 60287 standard (IEC 2006)). These necessary simplifications of the situation may not be reasonable under all circumstances, and may compromise the accuracy of the predictions made. For example, two common assumptions that are commonly employed are that the material into which the cable is buried is completely homogeneous with respect to its thermal properties, and that the temperature at the surface of this material is isothermal. Neither of these conditions are accurate in all circumstances; there will inevitably be some degree of inhomogeneity in the sediment, and the isothermal boundary condition essentially assumes that heat can be transferred with perfect efficiency from the top layer of the soil to the air (which is not the case, especially for shallow burial depths and low windspeeds (Swaffield, Lewin, & Sutton 2008).

The second approach involves using numerical models to obtain an approximate solution to the equations to within a predetermined tolerance. The advantage of this method is that more complicated scenarios can be examined, without having to make as many simplifications. Advances in computing have made this approach more and more viable by reducing both the length of time required to compute simulation runs, and the associated costs of doing so (Mack 2011). Consequently, numerical approaches have been used extensively to study heat dissipation from HV cables buried on land (Anders & Radhakrishna 1988, Swaffield, Lewin, & Sutton 2008, de León & Anders 2008).

While the procedures for evaluating the current ratings for cables buried on land is well established, comparatively little work has been done explicitly on how these cables behave when buried in a marine environment. There are a number of differences between the two environments that might potentially affect the nature of the heat transfer away from the cable. Perhaps the most obvious of these is the presence of the large body of seawater that lies directly over the burial sediment (for land-buried cables, there is just air); this provides a much more effective heat sink than is present for land cable scenarios. The dissipation of heat from HV cables buried on land can cause drying out of the surrounding soil (Milne & Mochlinski 1964). Increasing the pore water temperature increases water vapour pressure and reduces the fluid viscosity, resulting in the movement of heated water away from the region around the cable. In the marine environment, the saturated nature of the sediment means that pore water transported away from the cable is replaced more readily from the surroundings with cold water. The composition of the seawater found in the porous burial sediment will also be different from the fresh rainwater that falls on land, hence there will be differences in the physical properties of the pore fluid. Additionally, the degree of saturation experienced by sediments in the marine environment is likely to be much greater than those on land. Finally, sediments in the marine environment are often altered much more quickly than those on land. For example, the migration of marine sediment features (called bedforms) along the ocean floor can result in a change in seabed depth by as much as 5m per year (van Landeghem *et al.* 2012). This kind of rapid transport of material is not experienced by sediments on land.

Method

One common numerical technique that has previously been used to model cables on land is called the finite element method (Lewis, Nithiarasu, & Seetharamu 2004) (FEM). We have developed two-dimensional computer simulations using this technique to model the dissipation of heat from HV cable cross-sections into the sediment in which they are buried (Hughes *et al.* 2015) (Submarine HV cables are commonly buried at a depth of about 1m below the seafloor into the surrounding natural sediment (Worzyk 2009)). The constructed model accounts for the dissipation of heat from both conduction and convection. The equation that describes this dissipation from a source, Q_{in}, is (Lewis, Nithiarasu, & Seetharamu 2004):

$$Q_{in} = -\lambda \nabla^2 T + \rho c_p \mathbf{u} \cdot \nabla T \tag{3}$$

where λ ($Wm^{-1}K^{-1}$) is the thermal conductivity, T (°C) is the temperature, ρ (kgm^{-3}) is the density of the seawater, c_p ($Jkg^{-1}\,{}^{o}C^{-1}$) is the specific heat capacity of the seawater, and $\mathbf{u}$ (ms^{-1}) is the velocity of the fluid within the sediment. The value for the bulk thermal conductivity that is used in the model is an arithmetic estimate based on a combination of the individual thermal conductivities of the sediment grains and the pore water (Woodside & Messmer 1961). The motion of the pore water contained within the burial sediment ($\mathbf{u}$) is assumed to be well described by Darcy's law (Darcy 1856). Buoyancy forces will also begin to act on the pore fluid as it is heated up; hotter water is less dense than cooler water and has a tendency to rise. This effect is accounted for by substituting in a temperature dependent density term into Darcy's law, $\rho = \rho_0(1 - \beta(T\text{-}T_c))$, such that the form of $\mathbf{u}$ in equation (3) that is actually used in our FEM model is:

$$\mathbf{u} = -\frac{1}{n\mu}\kappa\left(\nabla p + g\rho_0\left(1 - \beta(T - T_c)\right)\hat{y}\right) \tag{4}$$

Here, n is porosity, μ (Pa·s) is the dynamic viscosity, κ (m^2) is the permeability, p (Pa) is the pressure, g (ms^{-2}) is the acceleration due to gravity, β (${}^{o}C^{-1}$) is the coefficient of thermal expansion, and T_c (°C) is the ambient temperature.

The cable used in the model is based on a generic design of a 132kV alternating current cable. It has three cores arranged with two side by side, and the third resting on top between the other two such that the centres of the cores form an equilateral triangle. Heat is generated as realistically as possible within the cable (in a number of components, mainly the conductors at the centre of each core, but also in the other metallic parts where currents are induced which then experience resistive losses themselves (Thue 1999). The transfer of this generated heat through the cable components is by conduction only.

The main focus of this research is to evaluate the impact that the properties of the marine sediment and the environmental situation have on the dissipation of heat from HV cables (and how this may differ from the case of a cable buried on land). The relevant parameters that appear in equations (3) and (4) are: the thermal conductivity (λ), porosity (n), permeability (κ), and burial depth (b). Note that the burial depth is not present in the equations explicitly, but the temperature gradient terms (T) are dependent on it. We carried out studies to assess which quantities exhibit the greatest amount of variation between different naturally occurring marine sediments, and hence which ones are likely to influence the nature of the heat flow the most. We discovered that the permeability (κ) varies over many more orders of magnitude (~10^{-18} - ~$10^{-7}m^2$ (Hughes *et al.* 2015)) between different marine sediments than any of the other parameters previously mentioned. To put this in context, our literature review found that the range of bulk thermal conductivities was 0.80 - 3.11$Wm^{-1}K^{-1}$. We therefore selected the permeability as the primary subject of the investigation. Following this, the effects of the other parameters were also investigated.

Results

We ran a number of simulations for a wide range of values for permeability based on the observed natural variation. The results from two example simulations which are identical except for the value of the permeability of the surrounding sediment are displayed below in Figure 1. The permeabilities in Fig. 1(a) and 1(b) are representative of a typical clay and a medium sand respectively

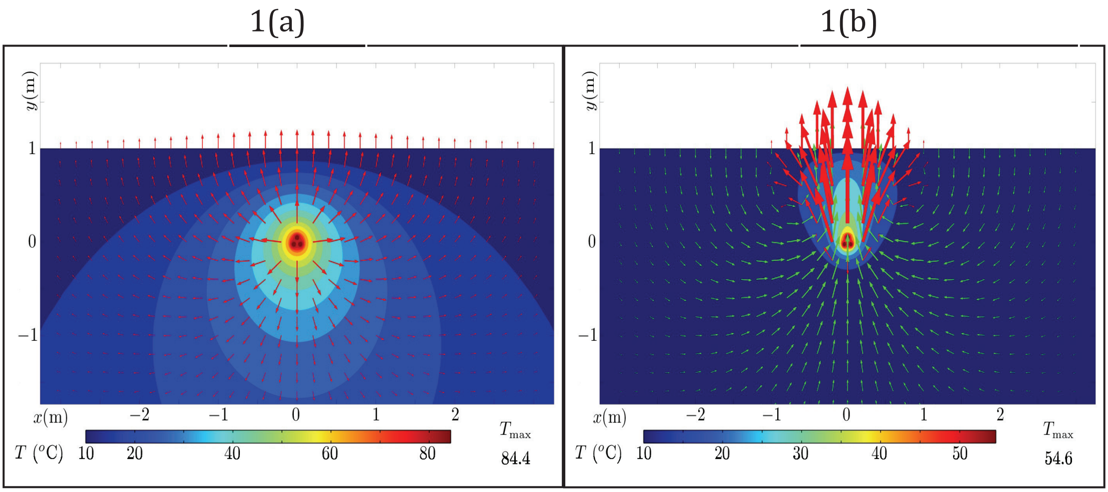

Fig. 1. Example simulation results for a low permeability (a) of $10^{-14}m^2$, and a high permeability (b) of $10^{-10}m^2$. The red arrows denote the net flow of heat from conduction and convection combined. The green arrows denote the flow of seawater within the sediment.

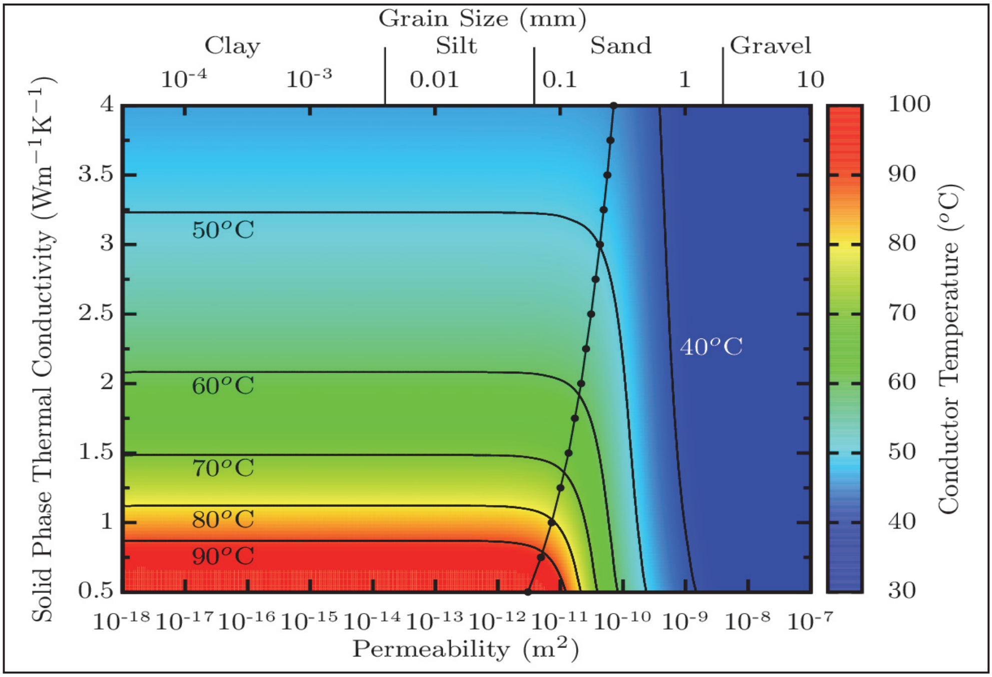

Fig. 2. The dependence of the maximum cable temperature on the permeability and thermal conductivity of the surrounding sediment. The dotted black line represents the point at which 20% of all heat is transferred by convection. *N.B.* The permeability is strongly correlated with the sediment grain size. An empirical approximation of the corresponding grain sizes for the model permeabilities is given on the top axis (Bear 1972).

For low permeability sediments, the fluid movement is restricted - hence the lack of green arrows in Fig 1(a). Consequently, the transfer of heat away from the cable is almost completely by conduction. In this case, heat is transferred away from the cable in approximately equal amounts in all directions. However, there is still a slight preference for the heat to be transferred upwards, towards the heat sink provided by the overlying seawater. For high permeability sediments (Fig. 1b), the opposite is true. Buoyancy forces act on heated seawater contained within the porous marine sediment surrounding the cable. This results in the warmed water being advected upwards, taking heat from the cable with it as it is transported out into the overlying seawater. Water is drawn in from the sediment at the sides and below the cable to replace the heated water that has been transported upwards. Convection plays a much larger role in the dissipation of heat in this case. From Figure 1 it can be seen that when there is a substantial contribution to the total heat transfer from convection, the cable does not get as hot as it otherwise would do without this additional cooling affect (Hughes *et al.* 2015).

For cables buried on land, the thermal conductivity of the surrounding soil is often a significant factor in determining how effectively heat generated within the cable will be dissipated into the surrounding environment (de León & Anders 2008). We have run numerous simulations with different values of sediment permeability and thermal conductivity to investigate how these two parameters affect the heat flow together for submarine cables. The model predicts that the thermal behaviour of the cable is partitioned into two distinct sections; to the left of the dotted line in Figure 2, the thermal conductivity has much more influence on the cable conductor core temperatures than the permeability. To the right, the reverse is true. The change in behaviour seen here is a consequence of the transition from mainly conductive to mainly convective heat transfer. It is important to note that there are naturally occurring marine sediments with permeability on either side of this transition.

Implications for Cable Design

The established methods for calculating the thermal rating for a cable assume that all heat transfer through the sediment is by conduction only. However, our model suggests that under certain environmental conditions, convection can make a significant contribution to the transfer of heat away from HV cables buried under the seafloor. This conclusion is supported by the results of a number of laboratory experiments that have been conducted in parallel with the modelling work discussed herein (Emeana *et al.* 2014), which show that convection can occur in situations representative of HV cables buried in the submarine environment. For cables buried in sediments that do support convection, heat can be dissipated from them a lot more effectively than the current methods of estimating cable ratings suggest. If the extent of this additional cooling can be determined by accurate measurements of all the relevant parameters of the sediment, it might allow for an increase in the overall rating of the cable (Hughes *et al.* 2015). An increase in the current rating would either allow an increase in the amount of power that the cable is able to transmit, or a reduction in the amount of material required to construct the cable conductor. For example, a 132kV cable identical in design to the one used in our FEM model that is buried in a sediment with a permeability of $10^{-14}m^2$ as illustrated in Fig. 1(a) has a predicted current rating of 168MW. If instead, it could be ensured that the cable only passed through sediments with a permeability in excess of the $10^{-10}m^2$ value displayed in Fig. 1(b), the same cable could be used to transmit 235MW of power.

Conclusions

Two dimensional computer models have been developed to investigate the dissipation of heat from HV cables buried under the seafloor, and how certain physical characteristics of the soil influence this heat flow. It was discovered that the permeability of the sediment can have a significant impact on the nature of the heat transfer away from these cables, while the exact behaviour of the system is a function of many variables.

Traditional techniques for calculating the thermal ratings for submarine cables can significantly underestimate the effectiveness of environmental cooling. This may mean that more resources are used during the manufacture of some cables than is strictly necessary. Understanding more about how heat is dissipated from HV cables buried in a submarine environment will help to make their construction and operation more economical.

References

Anders, G.J. and Radhakrishna, H.S. 1988. Power Cable Thermal Analysis with Consideration of Heat and Moisture Transfer in the Soil. *IEEE Trans. Power Del.* 3 (4), 1280-1288.

Atkinson, I. et al. 2002. The Moyle Interconnector. *Power Eng. J.* 16 (3), 117-128.

Bear, J. 1972. *Dynamics of Fluids in Porous Media.* New York, USA: American Elsevier.

Darcy, H. 1856. *Les Fontaines Publiques de la Ville de Dijon*. Paris, France: Dalmont.

DECC. 2014. *Digest of United Kingdom Energy Statistics 2014*, London, UK: DECC.

DECC. 2013. *UK Renewable Energy Roadmap Update 2013*, London, UK: DECC.

De León, F. and Anders, G.J. 2008. Effects of Backfilling on Cable Ampacity Analyzed with the Finite Element Method. *IEEE Trans. Power Del.* 23 (2), 537-543.

Elgerd, O.I. and van der Puije, P.D. 2012. *Electric Power Engineering*. 2nd ed. Dordrecht, Netherlands: Springer.

Emeana, C.J. *et al.* 2014. Sediment Thermal Properties and Heat Flow Implication on the Performance of Sub-seabed HV Cables, Paper presented at British Geophysical Association Postgraduate Research in Progress Meeting 2014, University of Liverpool, UK, 4 - 5 September.

Fardo, S.W. and Patrick, D.R. 2009. *Electrical Power Systems Technology*. 3rd ed. Lilburn, GA, USA: Fairmont Press.

Hughes, T.J., *et al* .2015. Effect of Sediment Properties on the Thermal Performance of Submarine HV Cables, *IEEE Trans. Power Del.*, accepted, doi:10.1109/TPWRD.2015.2398351.

Landau, L.D. and Liftshitz, E.M. 1975. *The Classical Theory of Fields*. 4th d. Oxford, UK: Pergamon Press.

Lewis, R.W et al. 2004. *Fundamentals of the Finite Element Method for Heat and Fluid Flow.* Chichester, UK: John Wiley & Sons.

Mack, C.A. 2011. Fifty Years of Moore's Law. *IEEE Trans. Semiconduct. M.* 24 (2), 202-207.

Milne, A.G. and Mochlinski, K. 1964. Characteristics of Soil Affecting Cable Ratings. *Proc. IEE,* 111 (5), 1017-1039.

OWPG. 2015. Offshore Wind Programme Board Annual Report March 2015, London, UK: Crown Estate.

Pilgrim, J.A. 2011. *Circuit Rating Methods for High Temperature Cables*. PhD Thesis. University of Southampton.

Swaffield, D.J. et al. 2008. Methods for Rating Directly Buried High Voltage Cable Circuits. *IET Gener. Transm. Distrib.* 2 (3), 393-401.

Tayal, D.C. 2009. *Electricity and Magnetism*. Mumbai, India: Himalaya Publishing House.

Thue, W. A. ed. 1999. *Electrical Power Cable Engineering*. New York, USA: CRC Press.
Van Landwege, K.J.J. *et al.* 2012. Reversed Sediment Wave Migration in the Irish Sea, NW Europe: A Reappraisal of the Validity of Geometry-based Predictive Modelling and Assumptions. *Mar. Geol.*, 295-298, 95-112.
Woodside, W. and Messmer, J.H. 1961. Thermal Conductivity of Porous Media. I: Unconsolidated Sands. *J. Appl. Phys.,* 32 (9), 1688–1699.
Worzyk, T. 2009. *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects*. Berlin, Germany: Springer-Verlag.

UK maritime disasters since 1950 and their implications for ports, coastline and the Exclusive Economic Zone (EEZ)

Esmé Frances Flegg

Introduction

For an island state such as the UK, economic activity and trade associated with its maritime regions of ports, coastline, and the Exclusive Economic Zone (EEZ) is vital. Recent studies have found 95% of trade by volume and 75% by value enters the UK by shipping (Department for Transport, 2012; HR Wallingford, 2012). In 2011, additionally to its key role in transporting traded goods, the port sector was responsible for 0.4% of total UK employment and 0.5% of its GDP (Oxford Economics, 2013). In contrast air transport, a sector focused on the transportation of people rather than commodities, provided 1% of total UK employment and 3.6% of UK GDP in 2009 (Oxford Economics, 2011). The continued success and safety of operations in these maritime regions are predicted to be tested in future decades through sea-level rise, rising average temperatures, possible changes in extreme weather events, competition for business from other ports and shifts in demand of commodity types. An understanding of past and present vulnerability to extreme conditions provides an important context which will inform assessments of these future challenges (McEvoy and Mullett, 2013; Scott *et al.*, 2013; Met Office, 2014). This study aimed to investigate two key aspects of maritime disasters affecting the UK since 1950:

- To assess how the severities of disasters differ.
- To investigate how the vulnerability of ports, coastline and EEZ differs both spatially (such as between different ports) and temporally (for example if comparable events occurred in 1950 and 2010).

In the context of this study the following definitions were used:

- EEZ – An area of water extending up to 200 nautical miles from the baseline. In this zone the sovereign, or coastal, state has rights of using, exploiting and managing the waters and seabed (*United Nations Convention on the Law of the Sea, Article 55*, 1982).
- Natural variability – Climate varies naturally through time, and variability occurs in stable unchanging environments (Madden, 1976).

For example one June may be hotter than mean conditions; or rainfall in one year may be less than the recorded average.

- Climate Change – It is identified as long-term changes in climate (either in mean or extreme conditions) which can be confirmed by scientific analysis, such as statistical tests (IPCC, 2012). Climate change can arise from both natural conditions (such as the solar cycle), and anthropogenic forcing. In the context of this study climate change refers to changes caused by anthropogenic activity (such as from burning of fossil fuels).
- Risk – the probability of a circumstance occurring with a particular severity of impact(s) (Schneider *et al.*, 2007).
- Vulnerability – the extent to which a system or society is likely to be negatively affected by a situation – such as a storm surge (IPCC, 2012).
- Maritime disasters – situations caused by a hazardous event, or sequence of events, that negatively affects 'business as usual' conditions. The outcomes of such situations can affect many variables such as the environment, finance and construction.

In many historical cases maritime disasters have left a legacy of damage and disruption, often requiring physical and financial support from internal and external organisations beyond local or national government. Examples of this include €166.91 million contribution from the European Union Solidarity Fund (EUSF) to Germany following damage caused by storm Kyrill (European Commission, 2015) and payments from the Federal Emergency Management Agency (FEMA) for those affected by events such as hurricanes Katrina, Rita and Wilma (Federal Emergency Management Agency, 2006). Such disasters have been found to have a wide range of severe impacts on the built environment and construction zones of the marine region (Wilby, 2007). Impacts have included the loss of, or damage to, offshore oil platforms; port closures or damage; or result in coastal damage (such as breaching of sea defences and/or flooding of coastal communities).

The legacy of severe maritime disasters, and their impact on society, cling on in public memory, as more recent disasters are often touted as "the worst of its kind since…". The aptly named 'Great Storm' of 1703 captured the imagination of Daniel Defoe and was immortalised in his book *The Storm,* which was one of the first publications to combine journalistic analysis and scientific observation (Defoe, 1704). Approximately 8,000 men lost their lives (Lamb, 2012), with most deaths occurring on vessels sunk by the storm, making it as one of the most severe, and deadly, disasters in UK history. The significance of loss of life from this event is made even more apparent considering the UK's population was only an estimated 5.2 million (Lee and Schofield, 1981). Other damages included extensive flooding, damage to traded goods (e.g. sugar and tobacco), structural damage to a number of ports and harbours (including Bristol, Gloucester, Portsmouth and King's Lynn) and a loss of over 300 vessels, including 12 from the Royal Navy (Anon, 1826; Brayne, 2003).

Methodology

There is no catalogue of maritime events and disasters, their impacts, severity and legacy. However, records of maritime disasters are available, primarily through media reports rather than academic articles, allowing the development of such a database. This study aimed to build a database of maritime disasters affecting the UK since 1950. Events prior to this were excluded as a consequence of inconsistent recording of events. This is particularly apparent during the two world wars, as events including maritime disasters, which highlight vulnerability, tended not to be published in order to prevent contradiction of positive propaganda produced by Allied Forces for British citizens (Marquis, 1978). Data were analysed from the UK's 111 active commercial ports (Department for Transport, 2014), with a focus on its 45 major ports.

The data gathered were used to develop an understanding of how ports, coastline and EEZ are vulnerable to maritime disasters. 91 disaster events were identified since 1950. Disaster severity were scaled from those that caused only disruption, to events which caused extensive damage and loss of life. Disasters can arise from a single factor, such as human error, or can be composite events. Composite disasters refer to events where damage is caused by multiple causes, such as a combined wind storm and storm surge (Wisner *et al.*, 2004). For the purpose of this study each event was classified according to the primary cause of damage or disruption, even if the event types were related. This method was used to improve the understanding of whether particular aspects of composite events tend to be most disastrous.

Severities of maritime disasters

Ports were found to have been affected by the most maritime disasters – 56 out of 91; whilst the EEZ was impacted by 35 and the coastline 27 events respectively. If a disaster affected more than one region, for example both ports and coastline, it was recorded twice. Twenty of the recorded events affected multiple regions, with eight of these affecting ports, coastline and the EEZ. The majority of the events were recorded since the 1990s. This does not reflect a change in the number of disasters but instead points to increased reporting of minor events recorded following the development of internet based news reporting. Serious maritime disasters tend to be recorded in multiple reports (e.g. newspapers, online articles, audio and visual media) whereas less severe events tend to have smaller readerships and are usually recorded in online reports alone (Althaus and Tewksbury, 2002).

Eight primary causes, or mechanisms, were identified for maritime disasters:

- Coastal flooding
- Human error
- Mechanical fault (occurring on board a vessel, aircraft or offshore platform)
- Poor visibility
- Rough seas
- Snow and ice
- Storm surge
- Wind storm

The most common disasters were wind storms and human error which caused over 60% of events. Maritime disasters caused by natural processes, such as storm surges, showed a strong seasonal distribution, with the most events occurring between November and January. This result was expected, as during the winter months UK maritime conditions tend to be worse. Planning mechanisms can be put in place by stakeholders in anticipation of periods of increased risk or vulnerability.

The UK government (both local and national), industry and port operators were shown to suffer a range of negative financial implications following maritime disasters. These impacts included loss of trade, and the necessary measures of setting up compensation schemes, and implementing environmental clean-up operations (such as recovery after oil spills).

Ports were impacted by four of the five most expensive maritime disasters (Table 1). The majority of the costliest maritime disasters were found to be primarily caused by wind storms. Impacts from wind storms included damage to infrastructure and vessels, and delays to services (such as transport of goods and passengers).

Date	*Event classification*	*Insured losses (2014 values)*
January 25th 1990	Wind storm	£4 billion
October 15th – 16th 1987	Wind storm	£3.46 billion
January 31st – February 1st 1953	Storm surge	£1.2 billion (absolute)
January 2nd – 4th 1976	Wind storm	£816 million
January 17th – 19th 2007	Wind storm	£484 million

Table 1. Insured losses resulting from the five most expensive maritime disasters since 1950 (nb. losses from 1953 are absolute – total losses – as many businesses and houses were uninsured at that time).

Spatial and temporal differences in vulnerability

It was found that few maritime disasters affected the entire UK, but instead particular regions were impacted. The extent of the region displaying negative impacts varied greatly, mainly in accordance with the disaster type and severity. The majority of recorded events affected part of the south of England (from Selsey Bill to Lyme Regis), the shipping regions of Fair Isle (around Shetland in Scotland) and Dover, and the ports of Felixstowe and Dover.

The most common maritime disaster recorded varied by the zone of interest; namely wind storms affected ports and the coastline most frequently, whilst the EEZ demonstrated a particular vulnerability to disasters caused by mechanical faults from vessels, oil platforms and related aircraft (such as those transporting platform staff) (see Figure 1).

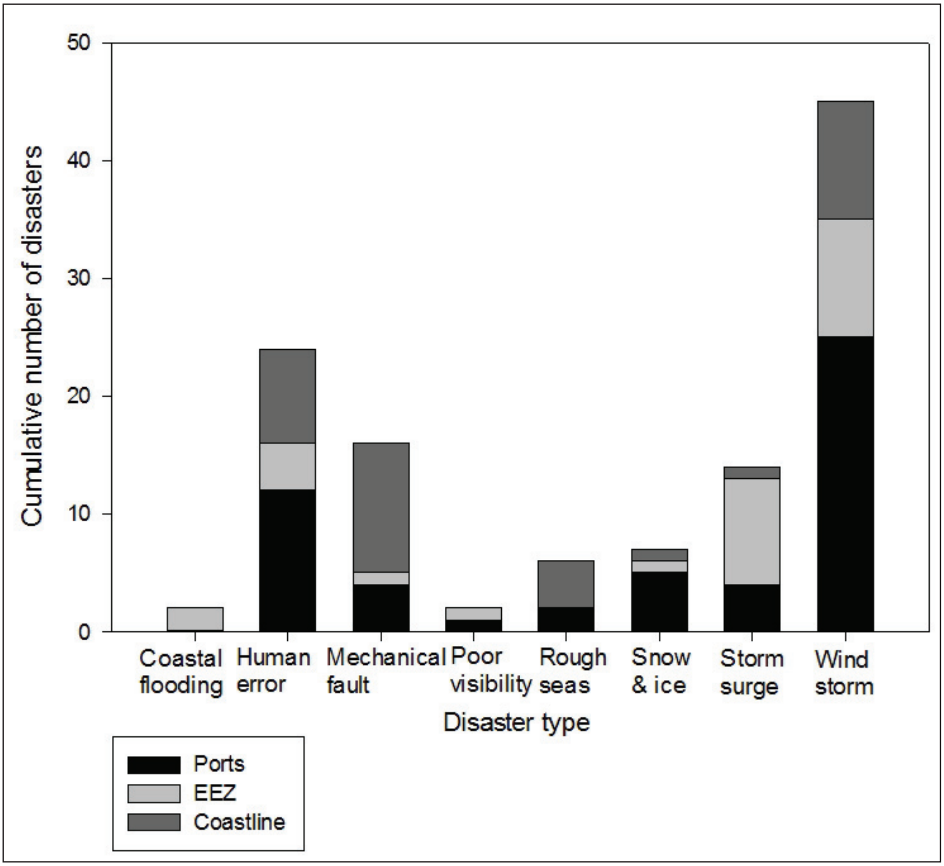

Figure 1. Stacked bar graph of the 8 recorded disaster types and the number of recorded occurrences in ports, EEZ and coastline since 1950.

The number of wind storms has increased significantly since the 1990s (see Figure 2). A concern that has developed alongside this trend is that ports have become more susceptible to wind storms in recent decades. This is a direct consequence of the increased mechanisation in ports, such as the use of high level cranes, and containerisation of trade (Bakermans, 2014). This infrastructure is vulnerable in high winds, reducing much of its functionality and putting the safety of workers at risk. Other causes of this increased frequency of recorded wind storm events arises from pre-emptive closures following implementation of more rigorous health and safety regulations, and improved communications through announcements and blogs covering closures and disruptions.

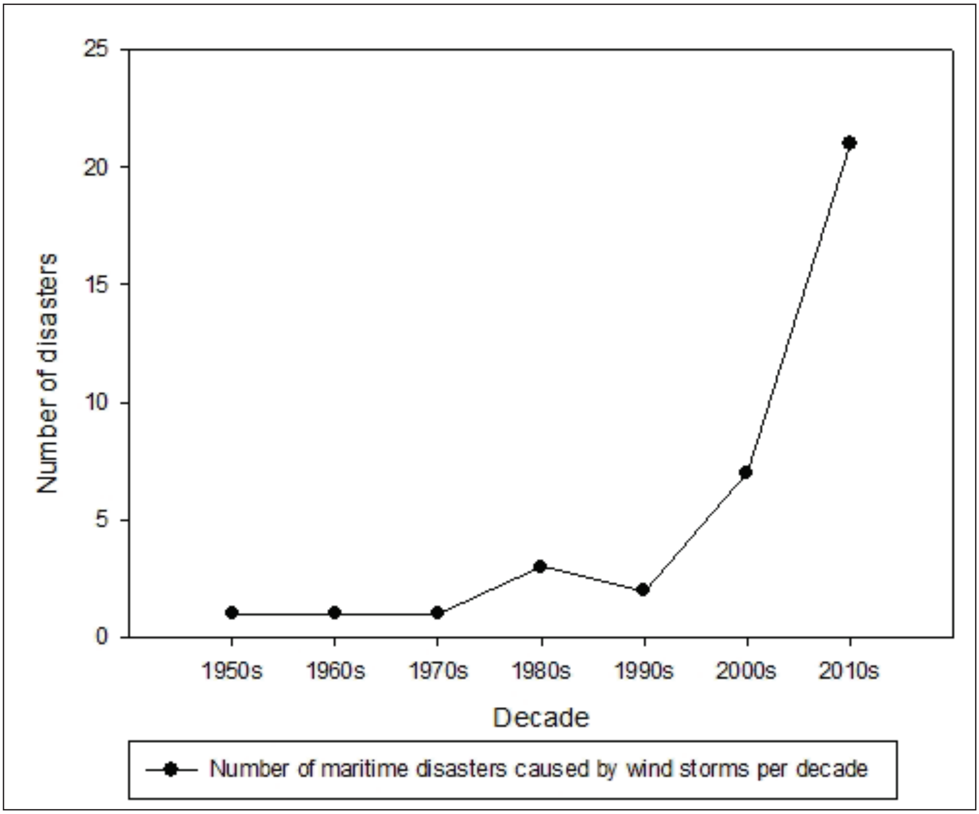

Figure 2. Graph of the number of recorded events caused by wind storms per decade since 1950.

Events located at the start of the study period tended to be associated with lives lost, extensive inland flooding and consequential damage to homes, businesses, infrastructure and agricultural land. The severity of these disasters were met by strong, active, responses by the government and other bodies of authority. Examples of their acceptance of the risk and dangers posed by these events are detailed in Table 2.

Measures such as these have acted to assist in a reduction in the UK's vulnerability to storm surges and flooding. This is represented by a decline in the recorded severity of such events. For example, during the winter storms of 2013/2014, waters higher than the devastating 1953 storm surge were recorded (BBC, 2013b; BBC, 2013a; BBC, 2013c), but the extent of the disaster was mainly restricted to major disruptions and financial losses. This is in strong contrast to the extensive damage and loss of life experienced as a consequence of the 1953 storm surge.

Date of disaster(s)	Response to maritime disaster
31st January to 1st February 1953 13th December 1981	Improved sea defences (Burnham on Sea, 2011; Lumbroso and Vinet, 2011)
31st January to 1st February 1953	Development of early warning systems (Lumbroso and Vinet, 2011)
3rd April 2012	The Met Office clarified terminology used to describe severe weather conditions (MAIB, 2013)

Table 2. Responses by the Government and other bodies of authorities to disaster events.

The nature and extent of maritime disasters have been shown to alter through time regardless of availability of data. This has arisen from increased preparedness for disaster and shifts in the activity and use of these regions. For example, an increase in events affecting the EEZ was identified from the 1960s following the discovery of oil in the North Sea. The first British offshore oil platform Sea Gem was installed in 1965, and also resulted in the first UK disaster involving an oil rig (Burke, 2013). The majority of disasters recorded in the EEZ until 1990 were related to oil platforms; 50% of events in the 1960s, 100% in the 1970s and 83% in the 1980s.

Conclusions

This research has filled a vital gap in records of maritime disasters by building a catalogue of events which have affected the UK. The events recorded have had severe damaging and disruptive consequences for many sectors in the UK – such as industry, environment, trade and society.

The UK is vulnerable to maritime disasters from a number of sources that are both natural and anthropogenic. Wind storms and human error were identified as the most common causes of maritime disasters. Ports were shown to have experienced more disasters than the coastline and EEZ. Decision makers have, and are continuing, to take key steps to tackle the sensitivity of ports, coastline and the EEZ. However, many of these decisions have occurred in the wake of events. This means that decisions are often response-led, rather than in line with predictions of likely risk or vulnerability.

The next stage of this research will be to look at in further detail what the consequences of maritime disasters are for UK ports. This will allow answers to be given for many questions, such as what aspects of ports are most vulnerable to disasters, and what techniques are currently used to recover from damage and disruption. The overall goal of this work will be to aid port decision-makers in their preparations for the challenges they face from extreme events.

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References

Althaus, S.L. and Tewksbury, D. (2002) Agenda Setting and the "New" News: Patterns of Issue Importance Among Readers of the Paper and Online Versions of the New York Times. *Communication Research,* 29 (2), 180-207.

Anon (1826) Eddystone Lighthouse *Mechanics' Magazine*. Knight and Lacey.

Bakermans, B.A. (2014) *Open ports for container vessels: An exploratory study into the possibilities for offshore and exposed container ports*, Master of Science, Deldt University of Technology.

Brayne, M. (2003) *The Greatest Storm: Britain's night of destruction November 1703*. The History Press.

Burke, L. (2013) The Sea Gem: A story of material failure. *Journal of Undergraduate Engineering Research and Scholarship*.

Burnham on Sea (2011) *30 years ago today: Major 1981 storm hits Burnham-On-Sea*. Available from: http://www.burnham-on-sea.com/news/2011/1981-storm-anniversary-13-12-11.php [Accessed 18 November 2014].

Defoe, D. (1704) *The Storm*. Penguin Classics.

Department for Transport (2012) *National Policy Statement for Ports*. London: The Stationary Office.

Department for Transport (2014) *UK Port Freight Statistics: 2013*. London: The Stationary Office.

European Commission (2015) *Report from the comission to the European Parliament and Council: European Union Solidarity Fund annual report 2013*.

Federal Emergency Management Agency (2006) *Information for taxpayers affected by hurricanes Katrina, Rita, and Wilma*. Internal Revenue Service. Available from: http://www.irs.gov/publications/p4492/index.html.

Hr Wallingford (2012) *Climate change risk assessment for the transport sector*.

IPCC (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation*. Press, C.U.

Lamb, H.H. (2012) *Weather, Climate and Human Affairs: A Book of Essays and Other Papers*. Routledge Revivals.

Lee, R.D. and Schofield, R.S. (1981) *Volume 1: 1700-1860*. Cambridge University Press.

Lumbroso, D.M. and Vinet, F. (2011) A comparison of the causes, effects and aftermaths of the coastal flooding of England in 1953 and France in 2010. *Natural Hazards and Earth System Science,* 11 (8), 2321-2333.

Madden, R.A. (1976) Estimates of the Natural Variability of Time-Averaged Sea-Level Pressure. *Monthly Weather Review,* 104 (7), 942-952.

MAIB (2013) *Report on the investigation of the grounding of the cargo ship Carrier at Raynes Jetty in Llanddulas, North Wales on 3 April 2012*. Southampton: Office, H.M.S.S.

Marquis, A.G. (1978) Words as Weapons: Propaganda in Britain and Germany during the First World War. *Journal of Contemporary History,* 13 (3), 467-498.

Mcevoy, D. and Mullett, J. (2013) *Enhancing the resilience of seaports to a changing climate: Research synthesis and implications for policy and practice*.

Met Office (2014) *The recent storms and floods in the UK*. Exeter.

Oxford Economics (2011) *Economic benefits from air transport in the UK*.

Oxford Economics (2013) *The economic impact of the UK Maritime Services Sector: Ports*. Oxford.

Schneider, S.H., Semenov, S., Patwardhan, A., Burton, I., Magadza, C.H.D., Oppenheimer, M., Pittock, A.B., Rahman, A., Smith, J.B., Suarez, A. and Yamin, F. (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,*.

Scott, H., Mcevoy, D., Chhetri, P., Basic, F. and Mullett, J. (2013) *Climate change adaptation guidelines for ports*.

United Nations Convention on the Law of the Sea, Article 55 (1982).

Wilby, R.L. (2007) A review of climate change impacts on the built environment. *Built Environment,* 33 (1), 31-45.

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. (2004) *At Risk: Natural hazards, people's vulnerability and disasters*. Routledge.