Biodiversity Series

Background Document on potential problems associated with power cables other than those for oil and gas activities

OSPAR Commission

2008

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. It has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland and the United Kingdom and approved by the European Community and Spain.

La Convention pour la protection du milieu marin de l'Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d'Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. La Convention a été ratifiée par l'Allemagne, la Belgique, le Danemark, la Finlande, la France, l'Irlande, l'Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni de Grande Bretagne et d'Irlande du Nord, la Suède et la Suisse et approuvée par la Communauté européenne et l'Espagne.

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contents

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1. Executive summary

A great variety of possible impacts of submarine cables on the marine environment due to their emission of noise, electromagnetic fields and heat as well as to disturbance and various types of contamination are discussed. Marine power cables are using either Alternating Current (AC) or Direct Current (DC) transmission with their respective technical designs. Monopolar, bipolar or three-phase systems are different technical solutions in use. Modern submarine telecommunication systems are fibre optic cables using pulses of light to transport information. However, coaxial cables as the former standard are sporadically still in service.

There are no clear indications that **underwater noise** caused by the installation or operation of subsea cables poses a high risk of harming marine fauna. However, there are still significant gaps in knowledge both regarding the characteristics of sound emissions and sound perception by marine animals. Scheduling laying activities and/or performing aerial surveys for monitoring the presence of e.g. marine mammals with a subsequent suspension of activities are possible mitigation measures.

Published calculations of the **temperature effects** of operating cables are consistent in their predictions of significant temperature rise of the sediment around the cables. There is evidence that various marine organisms react sensitively to an even minor increase of the ambient temperature but respective field studies on submarine cables under operation are almost completely lacking. To reduce temperature rise in the upper layer of the sea bottom to an acceptable level an appropriate burial depth should be applied.

Electromagnetic fields are detected by a number of species and many of these species respond to them. Especially field studies on fish provided first evidence that operating cables change migration and behaviour of marine animals. Emission of magnetic fields is best limited by field compensation to be achieved by an appropriate technical design (three-phase AC, bipolar DC transmission system). Directly generated electric fields are regarded to be controllable by adequate shielding whereas induced electric fields generated by the magnetic field occur.

A risk of **contamination** arising from activities causing seabed disturbance can be anticipated for heavily contaminated localities and avoidance of such areas would be an appropriate mitigation measure. Release of contaminants from the cable itself can occur if they are not removed after decommissioning, if they are damaged at any time during their lifetime or if fluid-filled cables are used. Known effects of exposure to contaminants on benthic organisms are e.g. impairment of body functions, reduction in growth and reproduction, mortality. However, there is no indication that contamination due to the use of subsea cables is of high significance.

Disturbance effects related to submarine cables are in general expected to be temporary and localised. The application of protective structures (artificial hard bottom) may lead to an introduction of non-local fauna especially in soft sediment areas. In environmentally sensitive areas physical disturbance, damage, displacement and removal of flora and fauna might turn out to be a significant impact. Avoidance of such areas would be an appropriate mitigation measure.

1. Récapitulatif

On discute dans le présent document des impacts éventuels très variés des câbles sous-marins sur le milieu marin. Il s'agit du bruit, des champs magnétiques et de la chaleur qu'ils émettent, des perturbations et des divers types de contamination. Les câbles électriques marins transmettent soit du courant alternatif (AC) soit du courant continu (DC) et possèdent des conceptions techniques respectives. Les diverses solutions techniques utilisées sont les systèmes unipolaires, bipolaires et triphasés. Les systèmes de télécommunication sous-marins modernes sont des fibres optiques qui utilisent les pulsions de la lumière pour transporter l'information et qui ont remplacé les câbles coaxiaux. Ces derniers sont cependant encore utilisés de manière sporadique.

Aucun signe clair n'indique que les **bruits sous-marins** causés par l'installation ou l'exploitation de câbles sous-marins représentent un risque élevé d'endommager la faune marine. Les connaissances présentent encore des lacunes importantes aussi bien au titre des caractéristiques des émissions de sons que de la perception des sons par la faune marine. Des mesures éventuelles de mitigation consisteraient à prévoir l'étalement des activités et/ou à effectuer des surveillances aériennes de la présence de faune marine, en interrompant ensuite les activités.

Les calculs publiés des **effets de la température** causés par l'exploitation des câbles correspondent aux prédictions, à savoir une hausse importante de la température des sédiments à proximité des câbles. Il existe des preuves que divers organismes marins sont très sensibles à une hausse, même légère, de la température ambiante. On n'a cependant pratiquement pas effectué d'études sur le terrain respectives sur les câbles sous-marins en cours d'exploitation. Il faudrait s'assurer que les câbles sont enfouis à une profondeur convenable pour ramener la hausse de température dans la couche supérieure de fond de mer à un niveau acceptable.

Un certain nombre d'espèces détectent des **champs électromagnétiques** et beaucoup d'entre elles y réagissent. Des études de cas sur le poisson, en particulier, indiquent les premiers signes que l'exploitation des câbles modifie la migration et le comportement des animaux marins. La meilleure manière de limiter les champs magnétiques par compensation des champs est d'adopter une conception technique appropriée (système de distribution AC triphasé et DC bipolaire). On considère que les champs électriques générés directement sont contrôlables en blindant les câbles de manière adéquate mais pas les champs électriques induits générés par le champ magnétique.

On peut anticiper un risque de **contamination** découlant des activités qui perturbent le fond marin dans le cas des zones très contaminées et une mesure de mitigation appropriée consisterait à éviter de telles zones. Les câbles eux-mêmes peuvent dégager des contaminants s'ils ne sont pas retirés après la mise hors service, s'ils sont endommagés à quelque moment que ce soit ou s'il s'agit de câbles remplis de fluide. La dégradation des fonctions vitales, la réduction de la croissance et de la reproduction et la mortalité, par exemple, sont des effets connus de l'exposition des organismes benthiques à des contaminants. On ne relève aucune indication que la contamination causée par les câbles sous-marins est très importante.

On présume en générale, que les effets de la **perturbation** liée aux câbles sous-marins sont temporaires et localisés. L'utilisation de structures protectrices (fond dur artificiel) risque d'entraîner l'introduction de faune non indigène dans les zones de sédiments meubles. Dans les zones écologiquement sensibles, les perturbations physiques, les dégâts, le déplacement et le retrait de flore et de faune risquent d'avoir un impact important. Une mesure de mitigation appropriée consisterait à éviter de telles zones.

2. Background and objectives

Submarine cables have a long history in telecommunication services which started at the end of the 19th century with the deployment of the first telegraph cable across the English Channel. Today the demand for fast communication links is still growing rapidly and leads to a drive of cable laying activities around the globe. A second aspect of subsea cables gaining more importance is transmission of electric power. Power transmission via subsea cables is realized to interconnect terrestrial grids, to supply power to offshore facilities or to feed power supplied from renewable energy sources offshore such as wind and waves into terrestrial grids. Numerous submarine cables can already be found in our oceans and there will be a lot more in the years to come (e.g., Figure 2.1a, b)

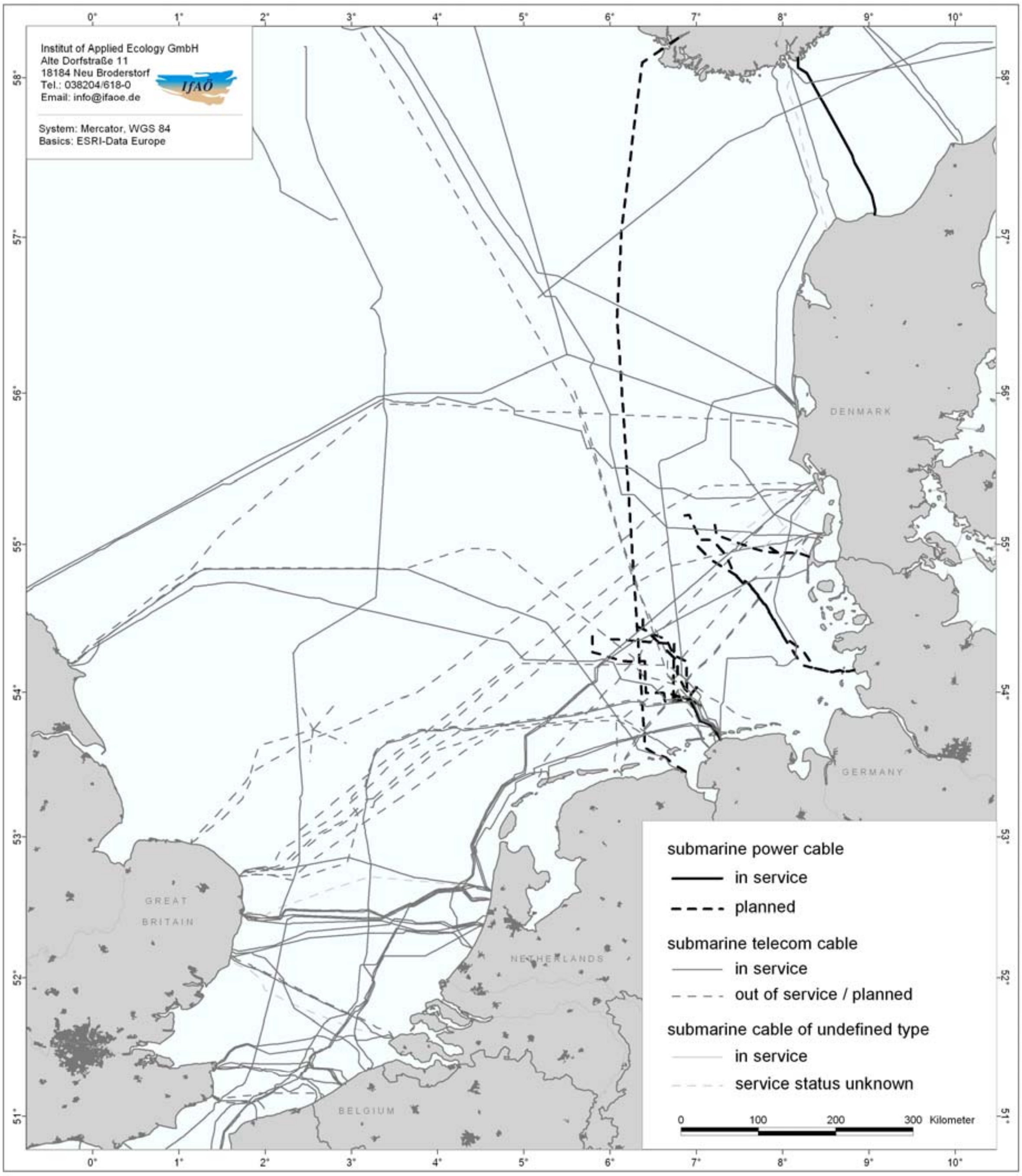


Figure 2.1a. Submarine cables in the North Sea (not complete), sources:

- Kingfisher Information Service - Cable Awareness (http://www.kisca.org.uk/charts.htm)
- ICPC (International Cable Protection Committee) - Cable Database (http://www.iscpc.org)
- CONTIS information system and maps of the German Maritime Agency (http://www.bsh.de/de/Meeresnutzung/Wirtschaft/CONTIS-Informationssystem/index.jsp; http://www.bsh.de/de/Produkte/Karten/Seekarten/index.jsp)
- Alcatel submarine fiber optic cable (www.alcatel.com)

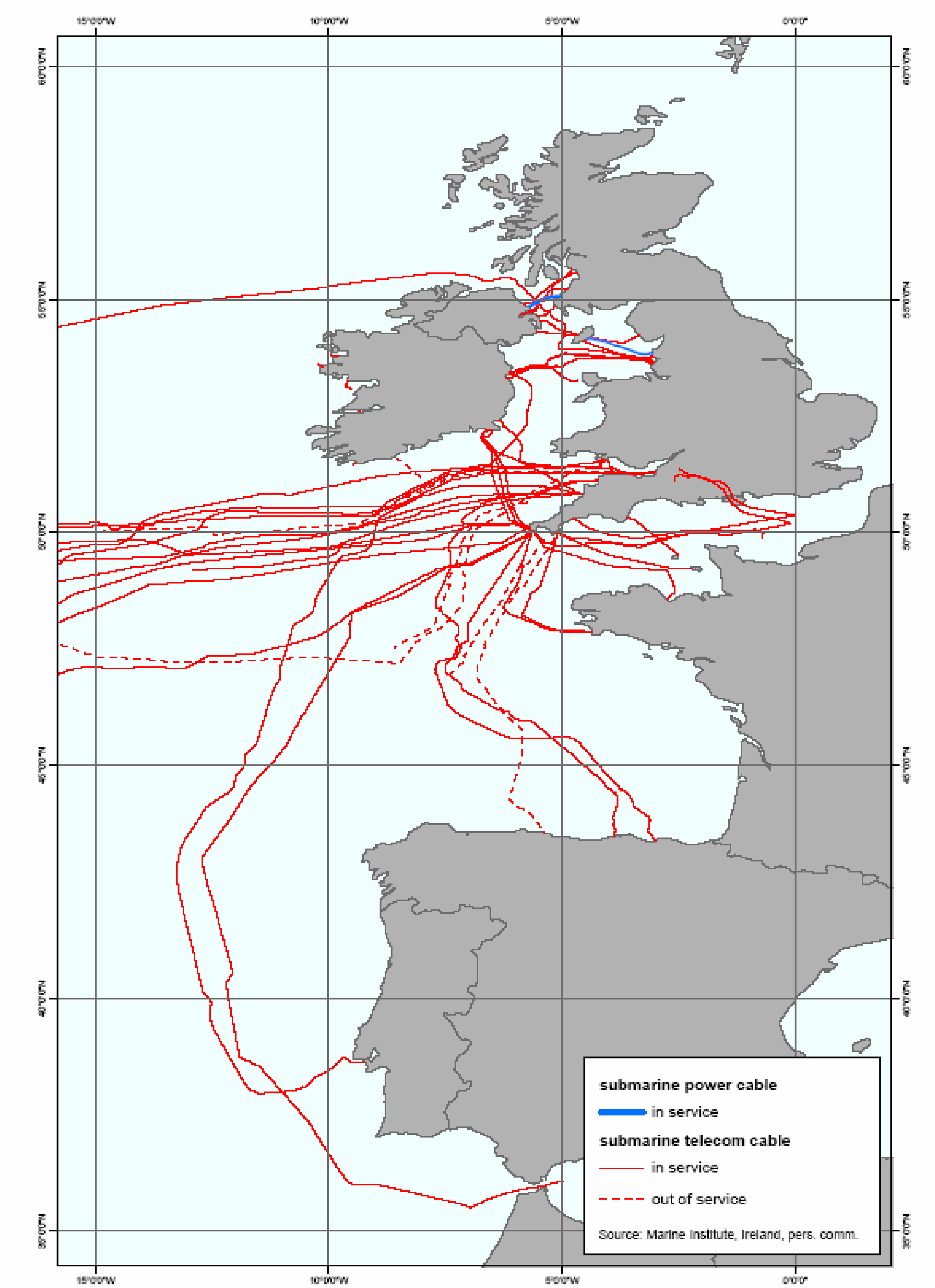


Figure 2.1b. Submarine cables in the Irish Sea and adjacent waters (not complete)

The review of currently available information presented here aims at

a. giving a short introduction to technical aspects of subsea cables
b. describing potential environmental risks related to subsea cables
c. highlighting recommended potential mitigation measures, and
d. identifying gaps in knowledge revealing the requirement of research.

3. Submarine cables – technical aspects

The most common fields of application for submarine cables are telecommunication and power transmission. Pipeline heating cables, electrical installations to allow active hydrate and wax control by controlling thermal conditions inside the pipeline, are not addressed here.

3.1 Telecommunication cables

The first type of submarine telecommunication cables were coaxial telephone cables. Coaxial cables had been the standard in a period from the 1950´s until the late eighties and are sporadically still in service today. They have copper wires carrying analogue electrical signals. The common outside diameters for coaxial telephone cables are reported to range from 40 to 100 mm and they may weigh up to 22 t per mile (Drew & Hopper, 1996). Usually they are protected by coatings of steel components and plastics (polyethylene).

Modern telecommunication cables are fibre optic cables. They were introduced in the 1980´s. A fibre optic cable sends information (including sounds converted to digital signals) by shooting pulses of light through thin transparent fibres usually made of glass or plastics (Drew & Hopper, 1996). The distance over which the optical signal can be transmitted through the fibre without any intermediate undersea signal processing is not unlimited. For that reason fibre optical cables may be equipped with repeaters. Drew & Hopper (1996) report repeaters to be placed at intervals of 17 - 34 nautical miles along a fibre optical cable. According to Williams (2000) repeaters are 100-200 cm long, 30-50 cm in diameter and weigh about 300 to 500 kg each. They have to be powered via a power cable. As an example, each repeater on a four fibre-pair cable requires about 40 W of power (Williams, 2000). The same author states that the standard approach is to send a constant current of about 1 A from one end of the cable to the other, along a copper sheath which lies outside the optical fibres and inside the armour (if present). He calculates that the total requirement for a typical 7500 km transatlantic crossing with 100 repeaters would be close to 10 kV. Drew & Hopper (1996) also give a voltage of up to 10 kV for powering repeaters.

Outside diameters of fibre optic cables range from 20 to 50 mm (Drew & Hopper, 1996).

3.2 Power transmission cables

3.2.1 Alternative solutions for power transmission: alternating current and direct current transmission

There are two general technical solutions for power transmission via subsea cables: Alternating Current (AC) transmission and Direct Current (DC) transmission. The choice of the transmission system is determined by both the capacity and length of the transmission line.

DC transmission is more commonly used, in particular at large distances and high transmission capacities. For example, most power lines crossing parts of the North Sea and the Baltic Sea to connect power grids of different countries (e. g. Fenno-Skan, Gotland, SwePol Link, Baltic Cable, Kontek, Konti-Skan, Skagerrak, NorNed) are high voltage direct current (HVDC) lines.

Monopolar and bipolar HVDC system configurations are distinguished. In a monopolar configuration the return current is carried by seawater or a separate return conductor whereas in bipolar systems a pair of conductors of opposite polarity is installed providing bi-directional transmission capacity. Monopolar systems without return conductor pass the current into seawater via electrodes, typically graphite anodes and titanium cathodes that are located on the seabed (Koops, 2000).

Usually electric power is generated as AC and delivered as AC to the consumers. Even in most transmission grids (e. g. terrestrial overhead transmission lines < 600 km) electricity is transmitted with three-phase AC (ABB 2006a). For that reason voltage conversion is required if using DC transmission. High costs of HVDC converters are regarded as one of the disadvantages of DC transmission technology. However, considerable transmission loss (due to the relatively large dielectric parallel conductance) and high costs for AC cables set the "break-even" distance at which DC is more cost effective than AC at 50-120 km (Söker *et al.*, 2000).

With both decreasing transmission capacity and distance AC transmission becomes an option. High and medium voltage AC transmission is widely used for power supply of offshore platforms and for the grid connection of offshore wind farms. For example, a typical setup for an offshore wind farm (80 turbines) at a distance of less than 100 km from the shore integrates medium voltage AC lines (33-36 kV, maximum capacity 140 MW) for grid connection within the park and high voltage AC lines (150 kV, 280 MW) linking the wind farm to the shore (Pöhler, 2006).

A disadvantage of AC transmission systems is high transmission loss which increases with cable length. However, AC systems have proved successful in numerous applications onshore.

3.2.2 Cable types

Sizes, materials, and types of modern power cables can be specifically adapted to its uses. The cable industry today offers various types of mass-impregnated (MI) cables and XLPE (cross linked polyethylene) cables, also self contained fluid filled (SCFF) or gas filled (SCGF) cables are available (Jacques Whitford Limited 2006a).

Mass impregnated (MI) cables contain a fluid impregnated paper insulation that is not pressurized. XLPE cables are equipped with insulations of a solid dielectric material. SCFF cables have conductors with hollow cores which provide a passageway for insulating fluid under static pressure provided by equipment at the cable terminals (pumping plants at the cable ends, feeding into a hollow conductor core). The insulating fluid saturates the cable insulation (being e.g. polypropylene laminated paper or conventional cellulosic kraft paper), maintaining the electrical integrity of the cable, and prevents damaging ingress of water in the event of an underwater leak. Suitable insulating fluids are refined mineral oils or linear alkylbenzene (LAB). Self contained gas filled (SCGF) cables are similar to SCFF cables except the insulation is pressurised with dry nitrogen gas.

Often cables are designed as composite cables with additional components besides the conductors for power transmission (e. g. optical fibres for data transmission). Cable conductors are usually made of copper or aluminium wires, or may be composite conductors with steel strands at their core. The overall assembly of the cable components may be round or flat. Outer diameters are usually less than 15 cm. Weights vary between 15 to 120 kg/m.

3.3 Cable installation

3.3.1 Burial depths

Subsea cables are usually buried to minimise the risk of damage by, for example, anchors and fishing gear. The cable burial depth depends on factors like types of threats present, the type of habitat, the hardness of the sediment or the depth of water. For data cables on the continental shelf Emu Ltd (2004) reports cables to be buried to a water depth of 1200 m. Drew & Hopper (1996) state that submarine cables around the British Islands in general are not buried in water depths greater than 1000 m. In German waters cables are expected to be buried (compare http://www.bsh.de). Where cables cannot be buried, e. g. in areas of exposed bedrock, or where it is not legally required to bury them, they are layed directly on the sea bed and covered fully or partially with mechanical protection (e.g. dumped rocks), or, in unconsolidated sediments, the cable is expected to self-bury (e.g. Basslink project Australia, National Grid 2000). In rivers with heavy traffic, the best solution could be to lay the cable in a tube under the river (ABB 2006b).

In German waters cable burial depths are proposed to be not less than 1 m in the EEZ and at least 3 m in areas with heavy ship traffic (e.g. shipping channels). In exclusion zones like offshore wind farms, cable burial depth is at least 0.6 m. In tidal channels of the Wadden Sea cables are buried at least 2 m below the seabed. In North America and Southeast Asia typical burial depths for all sorts of cable are between 0.9 and 3.5 m (Grzan *et al*., 1993, Hutchison Global Crossing Ltd 2000, Kerite company 2001, Northeast Utilities Service Company 2002, URS Corporation 2006, Jacques Whitford Ltd 2006A). Other sources report about preferred burial depths of 0.6 to 0.9 m in many coastal areas of the U.K. (Drew & Hopper 1996). Emu Ltd (2004) specifies typical burial depths dependent on seabed types (Table 3.1).

Table 3.1 Typical subsea cable burial depths (after Emu Ltd 2004).

Seabed type	Typical burial depths [m]
Exposed bed rock	0.0
Chalk	0.0 – 0.6
Stiff clay	0.4 – 0.8
Clay	0.6 – 1.2
Gravel	0.4 – 1.0
Coarse sand	0.4 – 1.0
Silty sand	0.6 – 1.2
Sand waves	0.0 – 3.0
Intertidal mud flats	0.6 – 3.0
Beach sand	1.0 – 2.0

3.3.2 Cable laying

Often subsea cables are laid and buried into the sea bottom in one step. Alternatively the cable may be first placed on the seabed and buried later. Cable lay methods include ploughing, trenching, jetting and directional drilling. Also mechanical excavators, such as small tracked backhoes, are employed for cable burial in the upper intertidal zone (Jacques Whitford Ltd 2006a). It seems that the different methods are more and more combined or turned into one another, in particular ploughing, jetting and trenching. Jetting or plough-jetting is usually described as a method of fluidizing the sediment by injecting water with high pressure below the sediment surface. When the water pressure is removed, the sediment would resettle over the cables.

Companies engaged in subsea cable installation have developed laying vessels and sophisticated cable laying machinery to optimise cable installation under various laying conditions. Installation equipment involves for example cable laying ships, remotely operated vehicles and ploughs.

3.3.3 Duration of the cable installation process

Duration of the cable installation process is not only a cost factor, it is also an important aspect for the magnitude of environmental impacts. EMU Ltd (2004) regard a progress rate of 1 km*h^{-1} as a typical rate in soft seabed materials, although the authors acknowledge that the rate may be very variable. Other sources give laying speeds varying between 1 - 1.5 knots (1,85-2,8 km*h^{-1}) and 3-10 km*d^{-1} (Hauge *et al.*, 1988, Basslink Pty Ltd 2002, Northeast Utilities Service Company 2002).

3.3.4 Cable protection

Where hard seabed occurs, or where cables cross or when there is a high risk of cable damage the cable may require some form of protection. Protection may be applied in form of a rock-mattress cover, cast iron shells, cable anchoring, ducting or rock dumping. Other protection measures are the use of special backfill materials for cable burial or to cover cables with reinforced concrete slabs or steel plates.

4. Environmental impacts associated with submarine cables

4.1 Introduction

Potential environmental impacts associated with subsea cables are underwater noise, heat dissipation, electromagnetic fields, contamination, and disturbance. In the following chapters these impacts are discussed taking aspects like spatial extent, timescale (duration, frequency, reversibility), and magnitude of impacts as well as their relevance for the different phases in cable life and for the various cable types into consideration. According to Stehmeier (2006) monopolar transmission systems with electrodes are no longer EU standard and therefore environmental effects related to the use of electrodes are not addressed in this report.

Table 4.1 Environmental impacts associated with different phases in cable life.

	Installation, Maintenance and Repair work, Removal	**Operational phase**
Telecommunication cable	Disturbance Contamination Noise	Electromagnetic fields (?)
Power cable	Disturbance Contamination Noise	Heat dissipation Electromagnetic fields Vibration noise

4.2 Noise

4.2.1 Introduction

Potential noise impacts associated with subsea cables occur during the construction phase and in connection with maintenance or repair. If High Voltage Alternate Current (HVAC) cables are used permanent vibration noise emission from the cable also has to be taken into account. The construction activities considered include removal of the existing support structures and cables, installation of new support structures and cables, and trenching and backfilling. Noise impact may arise from operation of vessels or machinery. Sound emission from onshore converter stations is not considered in this study.

Discussion of impacts of anthropogenic sound emissions on marine fauna is a complex issue. It requires at least a basic knowledge of technical background of underwater sound. For that reason a short introduction in regard to noise expression scales is given in this chapter followed by a review of information available on anthropogenic sound emissions related to submarine cables and their potential impact on marine life.

4.2.2 The DeciBel scale

There are various units of noise measurement, however, commonly the decibel (dB) scale is used to express noise. Explanation of this scale was, for example, by Nedwell *et al*. (2003): "The deciBel relates the measurement of noise to a reference unit; it expresses the ratio between the measurement and the reference unit logarithmically. The term "level" is applied to any unit expressed using the deciBel scale. For a sound of peak pressure P_m Pa the Sound Pressure Level (SPL) in deciBels will be given by SPL = 20 $\log_{10}(P_m/P_{ref})$, where P_{ref} is the reference pressure, which for underwater applications is usually taken as 1 microPascal (µPa). For instance, a blast wave of 1 bar (10^5 Pa) would have a sound pressure level, referred to 1 µPa, of SPL = 20 $\log_{10}(10^5/10^{-6})$ = 220 dB re 1 µPa." As shown in the example, the reference unit is appended if quoting sound levels.

Another characteristic of sound is its frequency, which is the rate of oscillation of the sound pressure wave progressing through a medium such as water or air, measured in Hertz (Hz). According to the frequency range categorisation of Hildebrand (2005), low frequency sound < 1 kHz, mid-frequency sound of 1 - 20 kHz, and high-frequency sound of ≥ 20 kHz can be distinguished.

If evaluating the impact of noise on fauna it has to be considered how noise is perceived by different species. The hearing sensitivity of a species is shown in its audiogram, in which the lowest level of sound, or threshold, that the species can hear is shown as a function of frequency. Audiograms of different species are shown in Figure 4.1

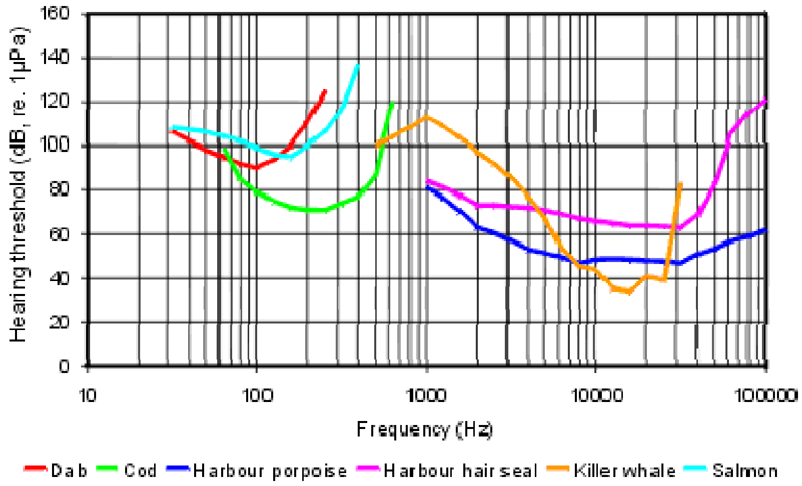


Figure 4.1 Audiograms of various species (from Nedwell *et al*., 2001).

Nedwell *et al*. (1998) addressed that problem by developing the dB_{ht} (Species) scale (the suffix 'ht' stands for hearing threshold). The idea behind this concept is to estimate dB_{ht}(Species) levels by passing the sound through a frequency dependent filter that mimics the hearing ability of the species, and measuring the level of sound after the filter. A set of coefficients is used to define the behaviour of the filter so that it corresponds to the way that the acuity of hearing of the candidate species varies with frequency. At this scale a sound of 0 dB_{ht} is at the hearing threshold of the respective species (Nedwell *et al*., 2001).

4.2.3 Anthropogenic noise emission related to submarine cables

Impact assessment studies for various cable projects have usually addressed underwater noise as a potential environmental issue. In conclusion, however, noise emission related to subsea cable installation or cable operation was not regarded a serious problem in such reports. This conclusion was in most cases based on the prediction that anticipated noise levels related to the project would not exceed already existing ambient noise in the area, although measurements of background noise as well as results from modelling of potential noise impacts related to the project were often not available (Cape Wind Associates LLC 2004, HK Offshore Wind Limited 2006, URS Corporation 2006).

A detailed presentation of a noise impact study conducted in the scope of the **Vancouver Island transmission reinforcement project** (installation of the new 230 kV HVAC system between the Lower Mainland and Vancouver Island) was presented by JASCO Research Ltd (2006). Both a measurement study to quantify existing noise levels as well as a separate modelling study to predict noise levels caused by construction activities associated with cable installations was performed to determine the relative importance of construction noise in the work areas. The primary source of underwater noise during the removal and installation operations was expected to be the cable laying ship. Shallow water workboats were also expected to generate a limited amount of noise during the shore pull operations.

Conclusion from the study was that underwater noise generated by the construction vessels used for cable laying will be similar to that of other ships and boats (e.g., pleasure boats, fishing vessels, tugs and container ships) already operating in these areas. Average 95% ranges from the cable ship to the 130 dB, 120 dB and 110 dB noise level contours were 0.38 km, 3.03 km and 13.95 km, respectively. Noise propagation from a single workboat as it could be used for shore pull operation was estimated to be less than 110 metres from the workboat for all noise level contours >110 dB (95% range). No potentially significant noise impacts could be identified according to JASCO Research Ltd (2006).

Noise measurements were also conducted **during construction of the North Hoyle offshore wind farm** off the British coast. For example, Nedwell *et al*. (2003) reported source levels of 178 dB re 1 µPa @ 1 m[1]

1 It is standard practise to refer source levels to a hypothetical distance of 1 meter from the sound source.

created by trenching of cables into the seabed and 152 to 192 dB re 1 µPa @ 1 m created by operation of vessels and machinery (based on measurements of large vessels in deep water and small vessels in shallow water) (Figure 4.2). The sound pressure level of this recording was 123 dB re 1 µPa. The noise was described as highly variable, and to apparently depend on the physical properties of the particular area of seabed that was being cut at the time. Because of the variability of the noise the authors found it difficult to establish the unweighted Source Level of the noise, but assuming a Transmission Loss of 22 log (R) a Source Level of 178 dB re 1 µPa @1 m could be concluded (Nedwell *et al*. 2003).

Nedwell *et al*. (2003) also undertook measurements of ambient noise at different localities in British coastal waters. It was found that there was little variability in the level of noise at frequencies of about 2 kHz to 100 kHz and that this band corresponded to wind and wave-generated noise. At frequencies below 1 kHz the authors observed significant variability in levels and postulated the noise to be due to shipping movements. However, cable laying is limited with regard to space and time and hence long-term noise disturbance of marine fauna can be excluded.

A factor rarely addressed during operation is **vibration of cables**. Low level tonal noise from a 138 kV transmission lines was measured in Trincomali Channel in connection with the Vancouver Island transmission reinforcement project during a very quiet period of recording: the sound pressure level at a distance of approximately 100 m from one of the cables was just under 80 dB re 1 µPa (Figure 4.3). Thus, assuming cylindrical spreading of sound (which is the appropriate spreading law for a line source) the source level of the existing submarine cables was approximately 100 dB re µPa@1m (JASCO Research Ltd 2006). Hence, anticipated sound pressure levels arising from the vibration of cables during operation are significantly lower than sound pressure levels that may occur during cable installation.

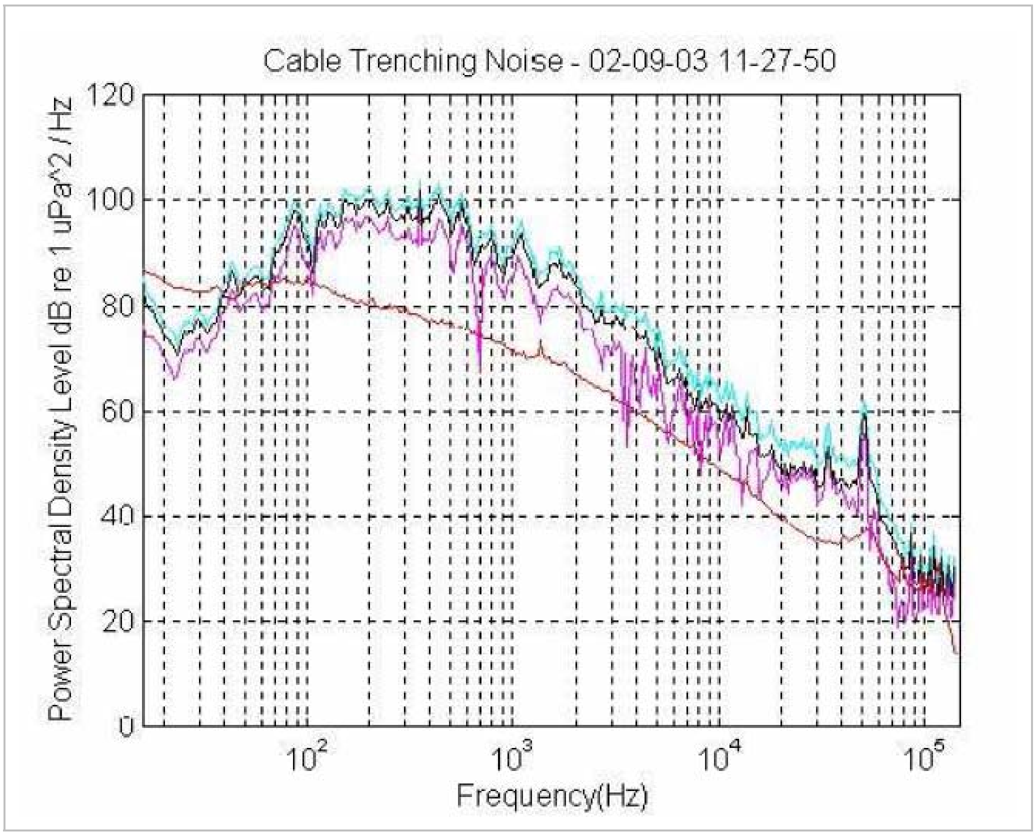


Figure 4.2 Example for the power spectral density of cable trenching noise, measurements conducted at North Hoyle offshore wind farm; the brown line indicates the mean background noise level (from Nedwell *et al*. 2003).

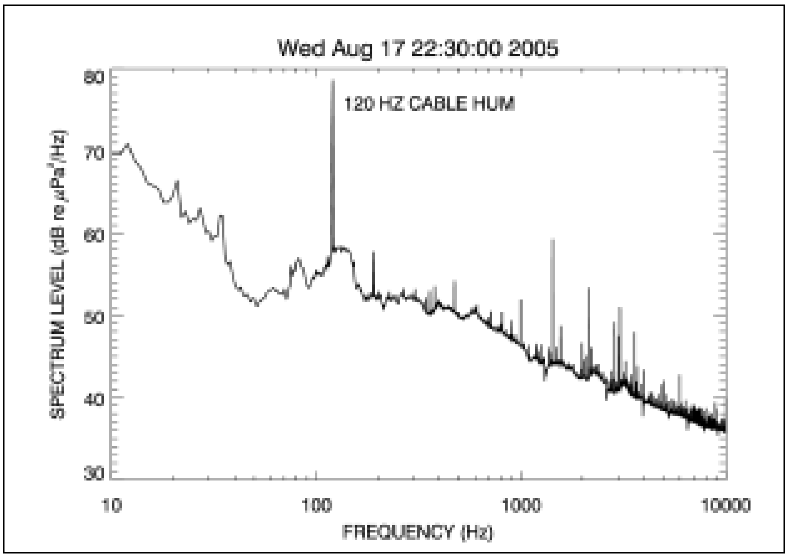


Figure 4.3 Results of field measurement at a 138 kV submarine cables in Trincomali Channel (Vancouver Island Transmission Reinforcement Project). Spectrum of 120 Hz tonal noise versus frequency recorded ~100 metres from the proposed cable (JASCO Research Ltd 2006).

Compared to seismic surveys, drilling, pile hammering or military activities maximum sound levels related to subsea cable projects may be considered to be moderate (4.2).

Table 4.2 Available information on offshore wind farm related noise (from Meißner & Sordyl 2006b based on Nedwell *et al*. 2003, DWI 2004, Nedwell & Howell 2004, JASCO Research Ltd 2006; amended)

SOURCE LEVELS* OF WINDFARM RELATED NOISE

*The Source Level is defined as the effective level of sound at a nominal distance of one metre, expressed in dB re 1 µPa @ 1 m.

Vessel and machinery	152 to 192 dB re 1 µPa @ 1 m	based on measurements of large vessels in deep water and small vessels in shallow water
Geophysical survey	215 to 260 dB re 1 µPa @ 1 m	measurements for airguns, often used in the offshore oil and gas industries
Pile driving	192 to 262 dB re 1 µPa @ 1 m	measurements from different localities worldwide, on average increase with increasing pile diameter
Drilling	145 to 192 dB re 1 µPa @ 1 m	deep water measurements of oil and gas facilities
Trenching	178 dB re 1 µPa @ 1 m	measurements at North Hoyle
Cable vibration	100 dB re 1 µPa @ 1 m	138 kV AC transmission line Vancouver Island transmission reinforcment project
Turbine noise	153 dB re 1 µPa @ 1 m	wind turbine capacity less than 1 MW

4.2.4 Impact of noise on fauna

Depending on the hearing ability of a species both the perception and the effect of anthropogenic sound emissions varies. It seems a general rule that fish are low frequency hearers whereas marine mammals hear best at high frequency. It is however supposed that most marine species have high thresholds of perception of sound, this means they are relatively insensitive to sound (Nedwell *et al*. 2003). Nevertheless, sufficiently high levels of sound on the dB_{ht} (species) scale are likely to cause avoidance reaction or damage in the hearing abilities of species. Often it is distinguished between acute and chronic effects, with acute effects including immediate auditory damage and chronic effects being, for example, behavioural effects. Other authors differentiate between primary effects (= immediate or delayed fatal injury), secondary effects (= injury or deafness, which may have long-term implications for survival) and tertiary effects (= behavioural effects, avoidance of the area).

A classification of avoidance reaction in fish related to sound was proposed by Nedwell *et al*., 2003 - based on measurements of fish avoidance of noise reported in Nedwell *et al*., 1998 (Table 2.3).

Table 2.3 Classification of avoidance reaction in fish proposed by Nedwell *et al*., 2003.

Sound level	Avoidance reaction in fish
75 dB_{ht} (species)	mild
90 dB_{ht} (species)	significant
100 dB_{ht} (species)	strong

Nedwell *et al*., 2003 investigated possible reactions of local fauna to noise created during **cable laying at North Hoyle**. Results of this analysis are illustrated in Figure 4.4 (dB_{ht} levels of the noise as a function of range). According to what is seen in the graph marine mammals would perceive higher levels of noise during cable laying than the three fish species. Among the mammals bottlenose dolphin (*Tursiops truncatus*) and harbour porpoise (*Phocoena phocoena*) perceive highest levels of noise. Among fish species salmon (*Salmo salar*) was the species least sensitive to sound. The authors admit that due to the high variability of the noise, no reliable estimates of source level or transmission loss could be made. However, they point out that, with one exception, all of the measurements were below 70 dB_{ht}, and hence below the level at which a behavioural reaction would be expected.

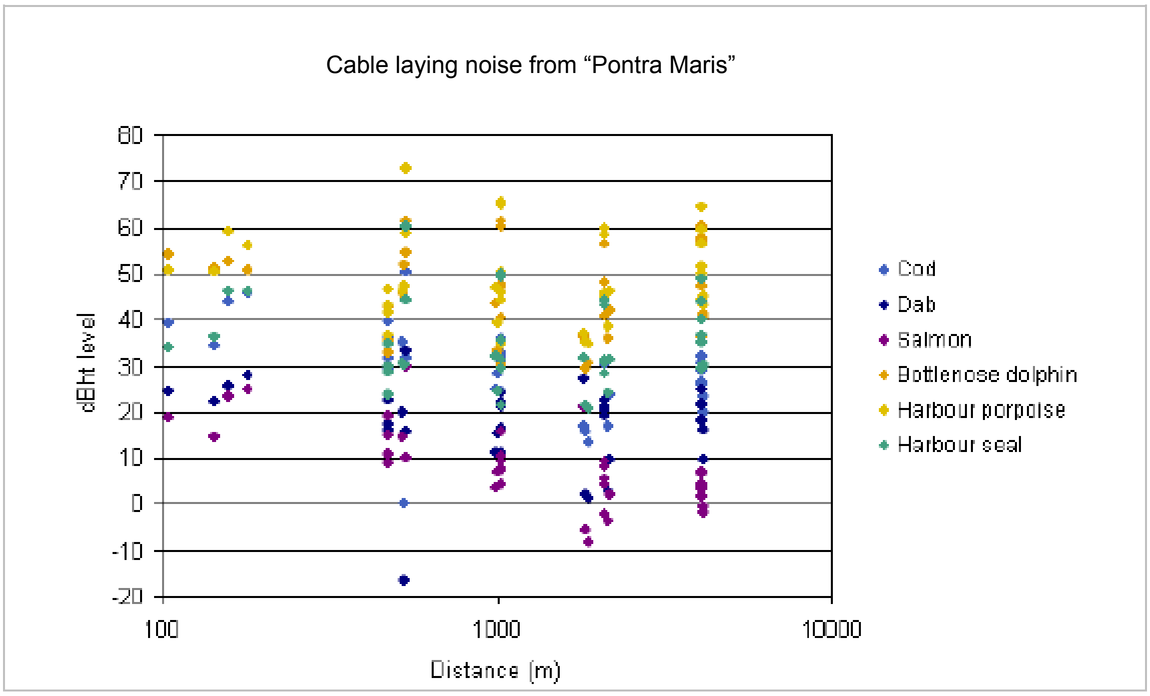


Figure 4.4 dB_{ht} values for six species as a function of range, for cable trenching at North Hoyle (from Nedwell *et al*., 2003).

The **Sakhalin II Phase 2 Project**, an integrated oil and gas project in Russia´s Far East, investigated noise impacts from the construction phase of both pipelines and cables (Sakhalin Energy Investment Company 2005). Focus of the environmental impact assessment was laid on the possible impacts of the noise from pipeline/cable installation on grey whales migrating through the project area and using it as feeding grounds. In the respective report it was mentioned that some individuals were finally observed avoiding the area in which noise levels were greater than 120 dB. Unfortunately no information more detailed about the setup of field studies and their results were given in the report.

The Office of Naval Research (2000) investigated in the frame of the environmental impact statement for the **North Pacific Acoustic Laboratory** (NPAL) the potential increases in ambient noise due to the placement of a small low-frequency sound source including the installation and removal of a power cable. Humpback whales near Kauai had a minimal chance for disturbance of a biologically important behaviour (percentage of 0.01 of the population at 120-180 dB, transmission duration of one day; no temporary threshold shift effects). No significant response was observed in rockfish at received levels up to 153 dB. Sharks were expected to be initially attracted to low frequency, pulsed sounds emitted by the NPAL source transmissions, but it was anticipated that their attractiveness would decline over a period of time, given that the transmission characteristics would be relatively constant at a duty cycle of 2-8 percent.

4.2.5 Conclusions in regard to noise impacts

There is only little information on potential noise impacts due to the installation (or removal) and operation of subsea cables. That situation is probably due to the fact that noise is obviously not regarded a key environmental issue in association with subsea cables by most environmentalists. Indeed, compared to activities such as seismic surveys, military activities or construction work involving pile hammering, maximum sound pressure levels related to the installation or operation of cables are moderate to low. In most cases modelling approaches were chosen to get an idea what sound pressure levels to expect. Only one publication of recordings of noise emissions during cable laying could be found (Nedwell *et al*., 2003, North Hoyle). It would be favourable to undertake further field measurements to allow a more profound discussion of potential risks.

As the characteristics of sound emissions associated with subsea cables are not very well known the same problem applies to the perception of sound by marine fauna. Specific knowledge such as audiograms only exists for a very limited number of species. Without such knowledge on hearing ability the assessment of noise effects is almost impossible and will remain rather hypothetical or based on conclusion by analogy.

Only few mitigation measures regarding noise impacts on marine mammals have been proposed. It included scheduling activities and/or aerial surveys for monitoring the presence of individuals in the near area with a subsequent suspension of activities.

In summary, currently there are no clear indications that noise impacts related to the installation (or removal) and operation of subsea cables pose a high risk for harming marine fauna. However, it has to be stressed that there are still significant gaps in knowledge in regard to both the characteristics of sound emissions and sound perception by fauna.

4.3 Heat emission

4.3.1 Introduction

Heat emission from cables has become an important issue over the past few years in discussions of environmental impacts related to submarine cables. The topic became a standard to be discussed in the scope of Environmental Impact Assessment studies for offshore wind farms and offshore cables leading to a number of publications on seabed temperature modelling (e. g. Brakelmann 2005a, Brakelmann 2006a, Brakelmann & Stammen 2006b, Offshore Wind Technology GmbH 2004, Worzyk & Böngeler 2003). It appears that important factors determining the degree of temperature rise are cable characteristics (type of cable), transmission rate, sediment characteristics (thermal conductivity, thermal resistance etc.) as well as ambient conditions (currents, ambient temperature etc.). As an example Figure 4.5 shows the results from modelling of seabed temperature in the vicinity of a medium voltage AC transmission cable.

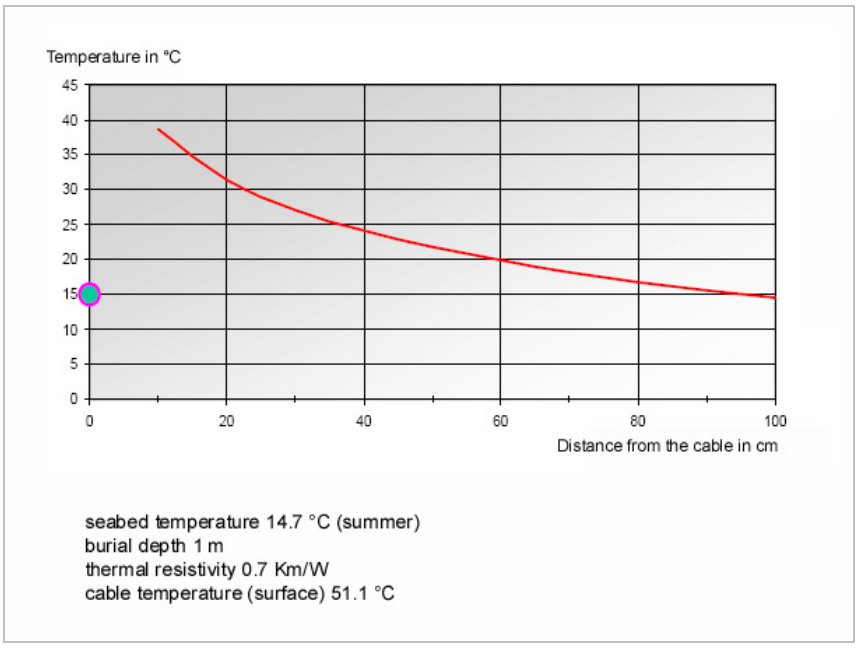


Figure 4.5 Example for modelling of seabed temperature in the vicinity of a medium voltage AC transmission cable in an offshore windpark with high production capacity (Poehler 2006).

Discussing heat dissipation from offshore cables, focus can certainly be laid on high and medium voltage power transmission cables. As transmission losses are high for HVAC-cables compared to HVDC-cables (Deutsche WindGuard GmbH 2005), heat dissipation during cable operation can be expected to be more significant for AC-cables than for DC-cables at equal transmission rates. Transmission capacity of power cables powering repeaters of telecommunication cables (see chapter 0) is comparably low and heat emission by them is supposedly negligible.

At an international expert workshop on experiences on the assessment of the ecological impacts of offshore wind farms held in Berlin in 2005 the change caused by an increase of the sediment temperature in the vicinity of power cables has been mentioned as one of the main impact correlations with respect to benthic flora and fauna (Zucco *et al*., 2006). Although respective field studies are almost completely lacking, studies on the impact of e.g. global warming provided evidence that various organisms react sensitive to an even minor increase of the ambient temperature. For example with increasing water temperature the recruitment of eastern populations of the Atlantic Cod decreases (Drinkwater 2004), whereas mortality rates of some intertidal gastropods (snails) increases due to rising temperatures (Newell 1979). An increase of the mean winter water temperature of less than 1 K led to a measurable shift in the seasonal occurrence of some pelagic species in the North Sea (Greve *et al*., 2004). The resilience of certain cold stenothermic benthic molluscs (bivalves) against environmental stress (e.g. O_2 depletion) decreases with increasing temperature (von Oertzen & Schlungbaum 1972). The above mentioned concerns regarding temperature induced changes in the benthic flora and fauna are based on such findings. Alteration of the physico-chemical conditions in the sediment or an increase in bacterial activity are additional potential ecological impacts of heat emission from power cables (Meißner & Sordyl 2006b).

4.3.2 Project-specific assessments on heat generation

The Offshore Wind Technology GmbH (2004) investigated thermal dispersion around cables of a proposed **wind farm in the German Bight, North Sea**, buried at 3 m depth (110 kV AC cable). Preconditions considered for calculations of heat generation were a thermal resistance of the seabed of 0.5 mK*W^{-1} (sand, Wadden Sea) and a thermal production of the cable of 23.8 W*m^{-1}. The authors predict a temperature increase of about 0.37 K at 0.30 cm sediment depth if full cable capacity is considered.

A study by Worzyk & Böngeler (2003) investigates sediment temperature rise in the vicinity of a single cable connecting 5 turbines with the transformer station (30 kV AC) at a proposed **wind farm site in the German EEZ**. Preconditions for their calculation model included a cable burial depth of 1 m, a sediment temperature of 6 °C, a turbine capacity of 4.5 MW each, and turbines running at full capacity. Based on the results from that study, a sediment temperature of 11.6 °C is expected in 0.5 m sediment depth above the cable. If the same cable connects 10 turbines with the transformer station the temperature could increase up to 30 °C according to their calculations.

Heat generation during cable operation was briefly discussed for the **monopole HVDC Basslink subsea cable** crossing the Bass Strait in Australia (National Grid 2000). The external surface temperature of the cable was calculated to reach about 30 - 35 °C. The seabed surface temperature directly overlying the cable was expected to rise by a few degrees Celsius at a burial depth of 1.2 m. Information was not specified any further.

4.3.3 Field measurements of seabed temperature in the vicinity of power cables

Field measurements of seabed temperature near power cables were so far only published from Nysted offshore wind farm (Denmark, Baltic Sea). Measurements were conducted by the Institute of Applied Ecology Ltd (IfAÖ Ltd) (Meißner *et al*., 2007). Seabed temperature was measured in the vicinity of the 33 kV and 132 kV AC power cables at defined distances from the cable. The wind farm consists of 72 turbines, each with a capacity of 2.3 MW. The turbines are placed in eight north-south oriented rows, nine turbines are interconnected in each row. The most northerly turbine in each row is connected to the transformer platform located on the northern boundary of the wind farm area. From here the wind farm is linked to the shore by a 132 kV AC cable. The park-internal cable grid consists of 33 kV AC cable lines. All cables are buried into the seabed. The targeted cable burial depth of 1 m could not be realized consistently.

The two sites of measurement were both in close vicinity to the transformer platform (at a distance less than 30 m). Recording equipment included two sets of instruments, each comprising two titanium poles equipped with 16 PT100 thermosensors (T1 to T32) spaced at intervals of 10 cm (Figure 4.6 left). The poles were deployed parallel to each other so that one pole was exactly perpendicular to the centre of the cable and the second pole 30 cm to the side (Figure 4.6 right). T32 was the sensor closest to the cable.

It was found that seabed temperature was generally higher at the 132 kV cable than at the 33 kV cable (Figure 4.7). The highest temperature recorded closest to the cable (sensor T32) between March and September 2005 was 17.7 °C (132 kV cable, 16 July 2005).

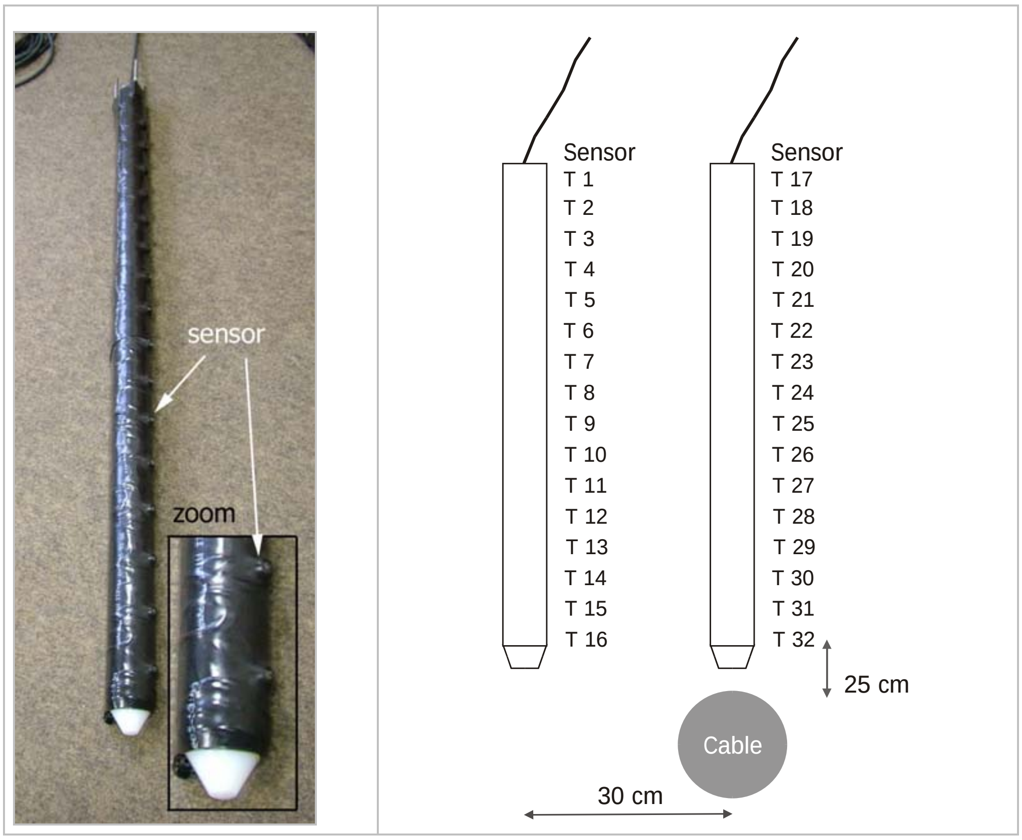


Figure 4.6 Equipment for measurements at Nysted: titanium pole with 16 thermosensors spaced at intervals of 10 cm (left), schematic drawing of experimental setup in the field (right).

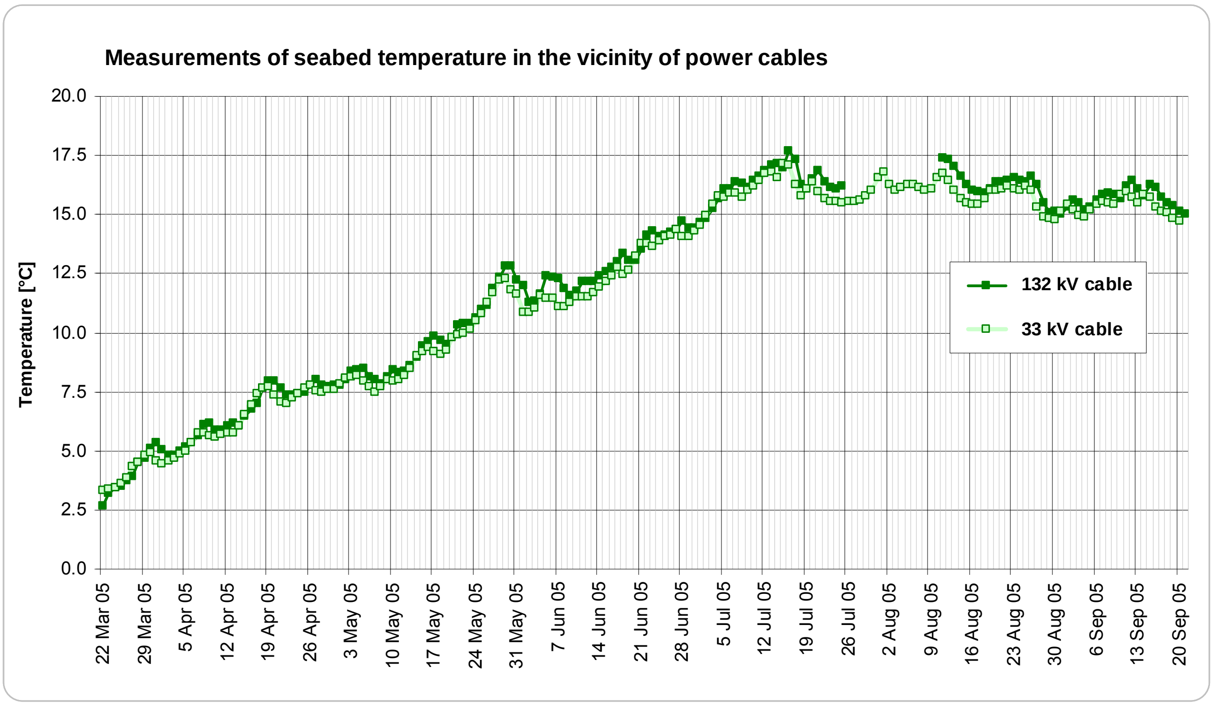


Figure 4.7 Seabed temperature recorded at Nysted offshore wind farm in 2005 in vicinity to the 132 kV and the 33 kV cable, shown are data collected by sensors closest to the power cable (T32); data loss in August 2005.

From September 2005 till March 2006 seabed temperatures at the 132 kV cable could be compared with seabed temperatures at a control site (unaffected by heat emission): seabed temperatures at the cable were higher at any time during this period (Figure 4.8). The maximum difference between sensor T32 and the control site was 2.5 K (26.10.2006, measured in adequate depth below seabed), the mean difference was less than 1 K (0.8 K). All temperatures recorded by IfAÖ Ltd in Nysted offshore wind farm at the 26th October 2006 are listed in 4.4.

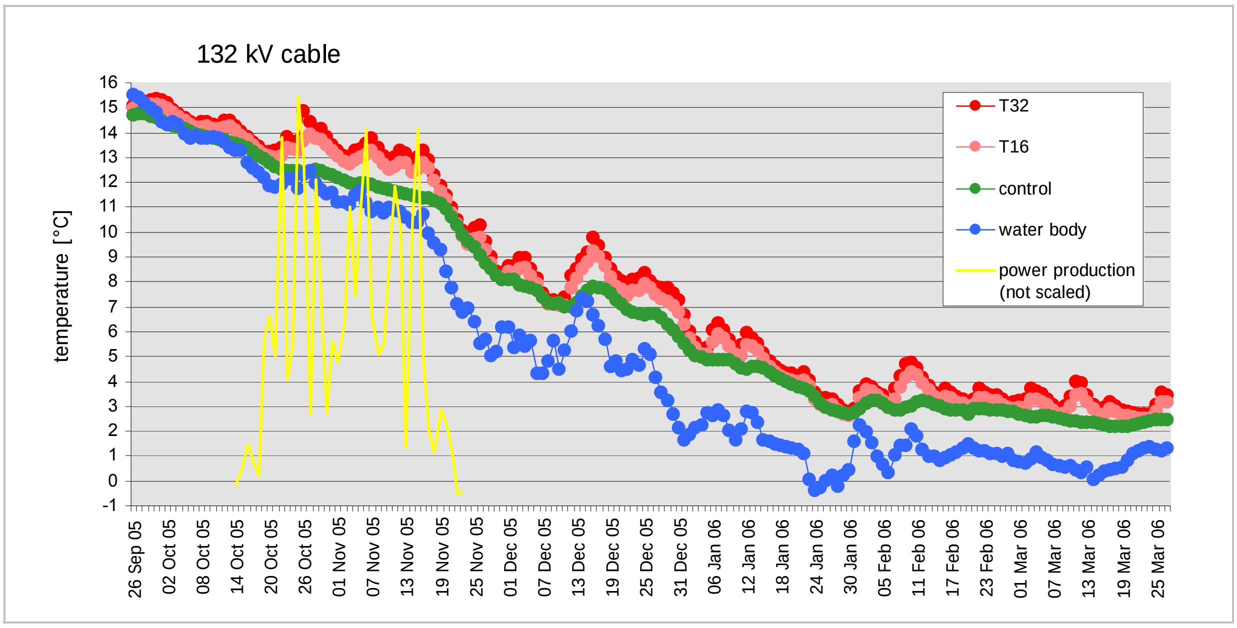


Figure 4.8 Measurements of seabed temperature from Sep 2005 until Mar 2006 at the 132 kV cable at Nysted offshore wind farm: shown are data recorded by sensors T32 and T16 (see Figure 4.6), seabed temperature at a location unaffected by heat emission, and temperatures measured in the water body. In addition, power production of the wind farm is illustrated for a short period of time (not scaled).

Table 4.4 Temperatures (°C) recorded at the 26th Oct 2006 (date of maximum difference of seabed temperature between the affected site in vicinity of the 132 kV cable and the control site) at Nysted offshore wind farm by IfAÖ Ltd.

depth below seabed		132 kV cable		reference	Δ T max
		directly above the cable	30 cm to the side		
seabed	50 cm	14.8	13.6	12.3	2.5
	40 cm	14.6	13.2	12.3	2.3
	30 cm	14.4	12.9	12.2	2.2
	20 cm	13.5	12.6	12.1	1.4
	10 cm	12.5	12.4	12.2	0.3
	0 cm	12.1	12.2	12.3	- 0.2
water body		12.1	12.2	12.4	

A second result of the seabed temperature recording was that temperatures varied significantly close to the cable whereas seabed temperatures at the control site changed more smoothly. Seabed temperature was positively correlated with power production and water temperature (Figure 4.8).

Since temperature rise in the seabed also depends on ambient conditions (e.g. sediment characteristics) it also has to be mentioned that sediment at the measurement sites was relatively coarse. Grain size analysis revealed d50 values (grain size median) of 310 – 390 µm (medium sand). Compared to fine sand or mud, coarser sediment types rather favour heat abduction into the water body than keeping it back in the seabed (Table 4.5).

Table 4.5 Thermal resistance of different types of marine sediment (after different authors).

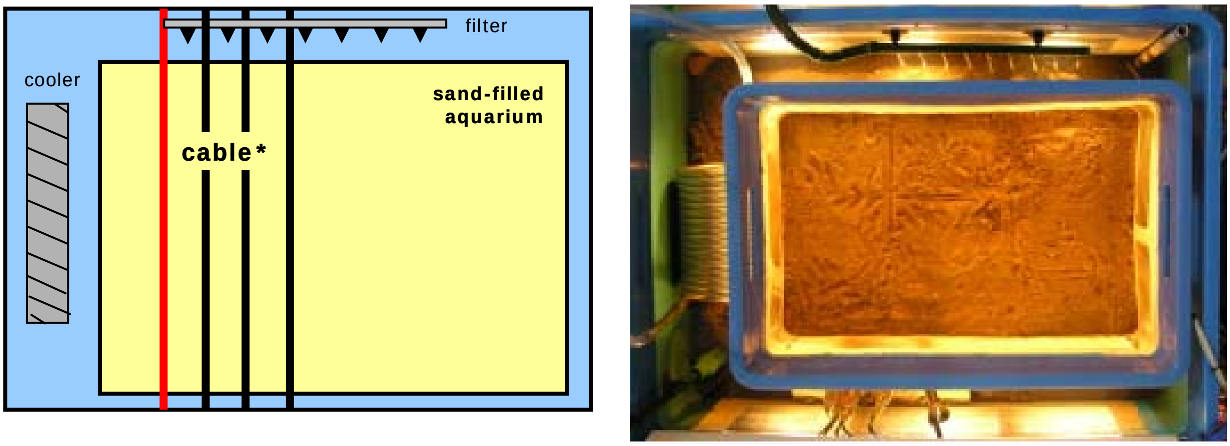
Sediment type	**Thermal resistivity [K*m/W]**
Gravel	0.3 – 0.5
Sand	0.4 – 0.7
Sand (Wadden Sea)	0.5
Fine sand	0.7
Clay	0. 6 – 1.1
Till and lag sediments	0.3 – 0.4
Mud	0.5 – 0.7

For evaluation of the results it should also be referred again to the comparatively low production capacity of Nysted offshore wind farm (166 MW). A direct comparison between power production and seabed temperature rise was not possible because only few and unscaled data were available. However, grid layout and cable parameters also play an important role for increase of seabed temperature in vicinity to the power cables. For example, with increasing transmission capacity the potential heat emission increases too. Also, conductor diameter is decisive: the thicker the conductor the lower the conductor temperature at a constant transmission rate and hence, heat emission of the cable. Since the conductor diameter also strongly influences the costs of the cable, conductor diameters are aimed to be kept as small as possible within the limits of technical requirements. As a result, cable parameters may differ within the wind farm grid.

4.3.4 Laboratory studies

In a laboratory study the **effects of heat emission** into the sediment **on the distribution of two benthic species**, the mud shrimp *Corophium volutator* and the polychaete worm *Marenzelleria viridis,* were investigated (Figure 4.9) (Borrmann 2006). Both species build tubes into the sediment. The tubes of *C. volutator* may penetrate into the sediment down to about 3 cm whereas those of *M. viridis* may reach a depth of more than 30 cm. The mud shrimp also spends more time outside the tube on the sediment surface whereas *M. viridis* spends most of the time inside the tube. Individuals were kept in aquaria with sediment from their natural habitats and seawater which was constantly cooled. After an adaptation period of several days a horizontal temperature gradient was generated in the sediment (Figure 4.10). A comparison between the distribution of individuals / tubes at the start of the experiment (no temperature gradient) and after 7 d of exposure to heated sediment was made.

Figure 4.9 Benthic species investigated by Borrmann (2006): mud shrimp *Corophium volutator* and spionid *Marenzelleria viridis*



*cable employed for sediment heating; red cable to the left with highest temperature, next three cable to the right with stepwise lowered temperatures

Figure 4.10 Experimental setup for laboratory studies conducted by Borrmann (2006) to investigate effects of heat emission into the sediment on the distribution of the mud shrimp *Corophium volutator* and the polychaete worm *Marenzelleria viridis*: schematic drawing (left) and view from above (right).

Results are shown in Figure 4.11 Borrmann (2006) revealed that distribution of the mud shrimp *C. volutator* was not correlated with the temperature gradient in the sediment. For the polychaete *M. viridis* the tendency to avoid areas with highest temperatures in the sediment was postulated. After 7 d of exposure most individuals and tubes were found in the right part of the aquarium where temperatures were lowest. Twenty hours after the start of the experiment first significant “movements” of the worms away from the heated area were observed. Whether these results can be directly applied to field conditions has to be examined.

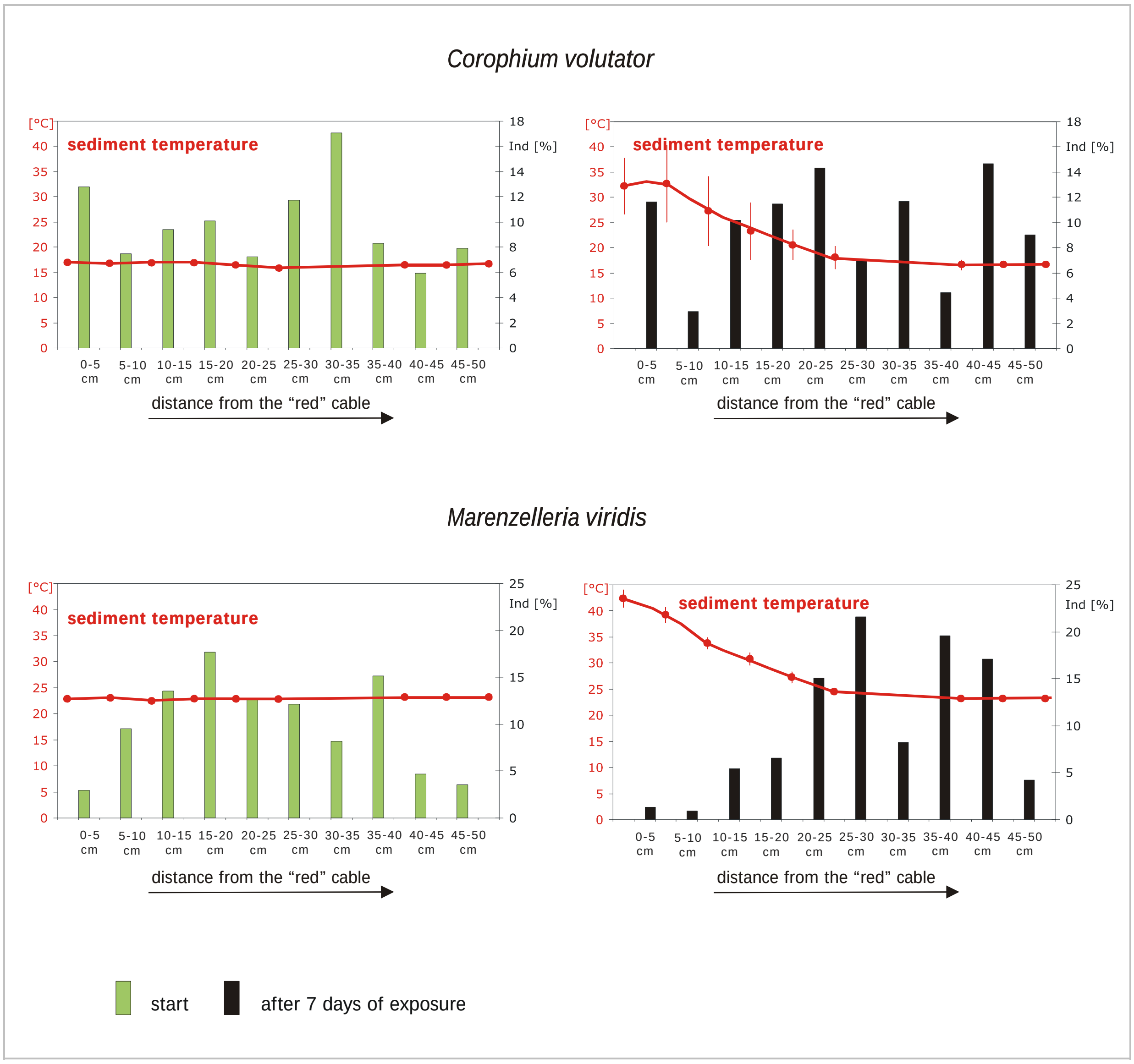


Figure 4.11 Results of laboratory studies investigating effects of heat emission into the sediment on the distribution of the mud shrimp *Corophium volutator* and the polychaete worm *Marenzelleria viridis*.

Another laboratory study investigated **effects of inverse temperature gradients on the biogeochemical circular flow in natural sediments** (Prokop 2006). The assumption was that the artificial temperature gradient would influence natural processes in marine sediments. The experimental setup is illustrated in Figure 4.12. Incubation time for sediment cores of different sediment types (sand with 2 – 7 % organic dry weight) was between 9 and 14 days. Parameters investigated were O_2, redox parameters, NH_4^+, phosphate, sulphide, DOC and microbial activity (FDA, α/β glycosidase).

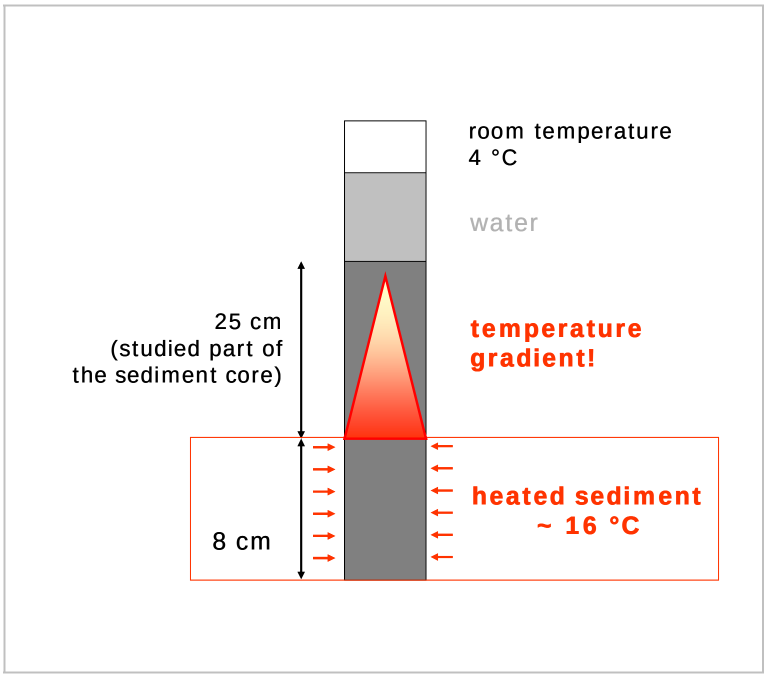


Figure 4.12 Experimental setup for laboratory studies conducted by Prokop (2006) to investigate the effects of an inverse temperature gradient on the biogeochemical circular flow in natural sediments; schematic drawing (left) and setup in the lab (right) (after Prokop 2006).

Analysis of the results had not been finished at the time of writing, but first preliminary results of the study can be cited already (after Prokop 2006):

1. increase in microbial activity at minor temperature increase of 0.5 K
2. increase in ammonium concentration in deeper sediment layers (Figure 4.14), sulphide concentration decreases
3. O_2 and redox profiles were unchanged during incubation times examined

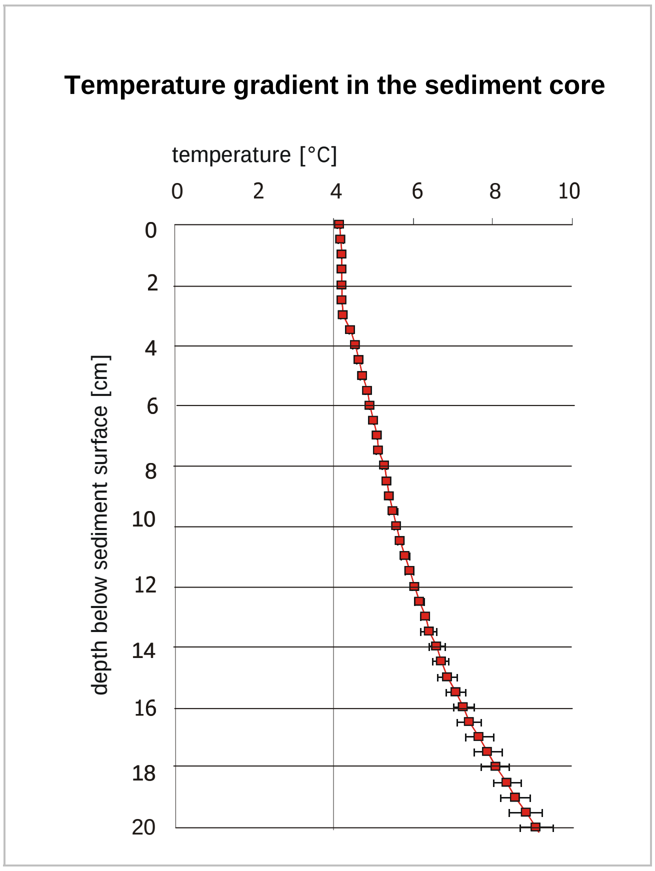


Figure 4.13 Temperature gradient in sediment cores studied by Prokop (2006).

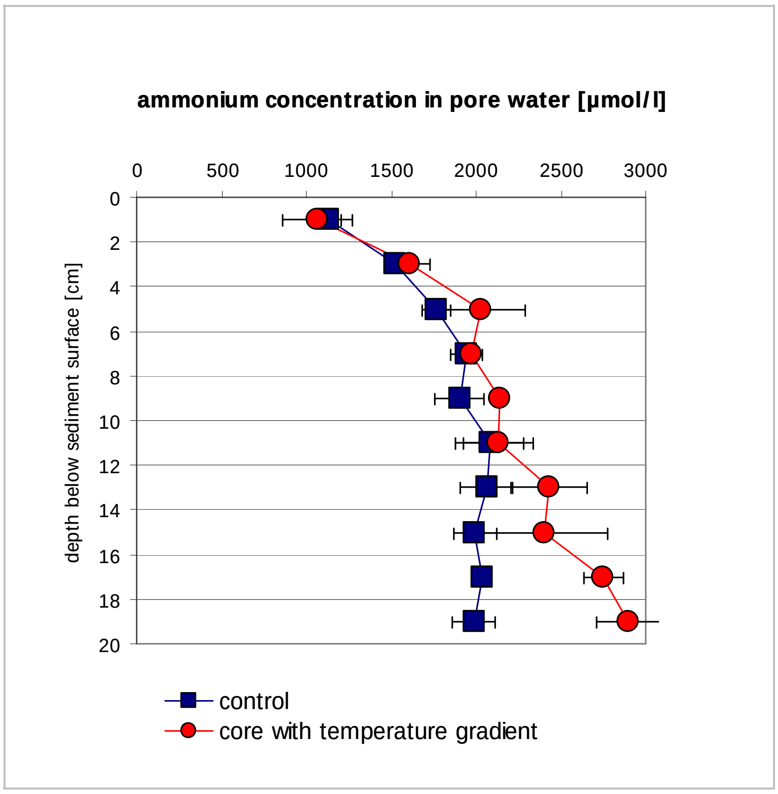


Figure 4.14 Ammonium concentration in pore water of sediment cores with applied temperature gradient (Prokop 2006).

Increase in microbial activity due to heat generation by power cables was also considered in a statement by the German Federal Office for Radiation Protection (BfS). Reviewing scientific articles on bacterial activity and natural aerobic / anaerobic processes in marine sediments the authors came to the conclusion that a temperature increase caused by heat dissipation into the seabed facilitates degradation of organic matter (BfS 2005).

4.3.5 Conclusions in regard to heat dissipation impacts

With regard to effects of heat dissipation apparent gaps in knowledge exist. A large number of publications about technical aspects of transmission losses is opposed to an almost negligible number of publications on ecological consequences of the heat release into the seabed. Transmission losses and subsequent heat dissipation can be expected to be more significant for AC than for DC cables. Published calculations of the temperature effects of operating cables are consistent in their predictions of significant temperature rise in the vicinity of the cables. Whether these predictions hold true under operational conditions still has to be examined.

The only field measurements published so far from Nysted offshore wind farm in Denmark (Meißner *et al*., 2007) draw a more differentiated picture. The transferability of these preliminary results to other locations is, however, questionable. Even if the seabed temperature rise might not be as pronounced as predicted according to the different calculation models seabed temperature will be permanently higher compared to natural conditions (as long as the power cable is in operation) and highly variable.

The effects of such artificially altered temperature on bottom organisms are difficult to assess. There is evidence that various marine organisms react sensitive to an even minor increase of the ambient temperature. Nevertheless, respective field research is needed on how organisms react to increasing ambient seabed temperature (changes in physiology, reproduction or mortality, emigration, immigration etc.) and whether living conditions for the benthic communities are altered either in the short-term or long-term.

For German offshore waters the respective nature conservation authorities agreed on a threshold of a maximum tolerable temperature increase of 2 K in 20 cm depth in the sediment. This value was originally asked for by the German Federal Agency for Nature Conservation as to be appropriate applying the precautionary approach to prevent bottom organisms from harms and benthic communities from changes caused by anthropogenic temperature rise. The so called 2 K criteria can be met by an appropriate burial depth of power cables.

What is not reflected by this criteria is the alteration of biogeochemical circular flows in sediments. Processes set off in deeper sediment layers due to heat dissipation are likely to finally affect the entire seabed above the cable due to pore water contact. It is not guaranteed that increasing the burial depth would remediate this problem. Alteration of sediment chemistry will possibly exert secondary impacts on benthic fauna and flora. Impacts are most likely to be detected in shallow water areas, the Wadden Sea (especially during warm periods in summer) and areas with high organic content. Further investigation into effects of heat dissipation is required. Field measurements of seabed temperature in the vicinity of operating power cables as well as further laboratory and field studies are necessary to allow a well-founded assessment.

4.4 Electromagnetic fields

4.4.1 Introduction

Another concern arising from subsea power cables is the occurrence of electromagnetic fields. First a short introduction to the technical background on electromagnetic fields is given followed by a review of information available on field strength related to submarine cables and their potential impact on marine life.

4.4.2 Technical background

Electric fields are produced by voltage and increase in strength as voltage increases. Hence, high voltage transmission in general produces stronger electric fields than medium or low voltage transmission. **Magnetic fields** are generated by flow of current and increase in strength as current increases. Since the voltage on a power line remains more or less constant with time, changes to the power or load will result in changes to the current, and hence the magnetic field. Another aspect to be considered is the **induced electric field** generated by the magnetic field around a submarine cable.

Parameters of electromagnetic fields generated during power transmission strongly depend on the setup of the power transmission system. As already mentioned before (chapter 0), for DC transmission it is distinguished between monopolar and bipolar systems. Since monopolar system no longer meet environmental standards of most Western countries (in particular because of the electrolysis products and the occurrence of strong magnetic fields) they are the solution least favourable. For bipolar transmission different options are available. The first is to install two separate cables and operate them with opposite polarity. A second option is to use a bipolar two-conductor cable where a single cable includes both conductors for forward and return current. A bipolar two-cable system is more powerful than a bipolar two-conductor cable. Deutsche WindGuard GmbH (2005) quotes a maximum voltage of ± 400 kV for a two-conductor cable compared to ± 600 kV for a system with two separate cables. Maximum transmission capacity is 800 MW and up to 1 GW (in future development up to 2.5 GW), respectively. The system with higher capacities can potentially generate stronger electromagnetic fields.

The occurrence of directly generated electric fields can be controlled by application of metal shields (steel plates, sheaths within the cable insulating the conductor etc.), those of magnetic fields (and consequently of indirectly generated electric fields) by neutralisation using appropriate conductor / cable placement patterns and/or configuration geometry. For example, when using two separate single-conductor cables, they should be buried in the seabed parallel to and at the shortest distance possible from each other, so that the (electro)magnetic fields would neutralise each other as far as possible. In a two-conductor cable this neutralisation reaches ideally 100 % when using a coaxial-design. In addition, here the two conductors lie within a common shield. With perfect shielding a cable does not directly generate an electric field outside the cable, however, as already mentioned an electric field is also induced[2] by the presence of the magnetic field in the vicinity of the cable (Kramer 2000, CMACS 2003).

For three-phase AC transmission the same options as for DC transmission exist: either a three-conductor cable solution or three single conductor cables can be considered (Deutsche WindGuard GmbH 2005). In a three-conductor cable each conductor is insulated separately, with the metal shield and outer insulation covering all three conductors in one. The electromagnetic field of the three conductors is almost neutralised at the surface of the cable, since the sum of the voltages and currents of the three phases is zero at any one time. Using three single conductor cables again they have to be installed as close as possible and parallel to each other to achieve sufficient field compensation.

While electric fields are readily attenuated by materials that conduct electricity (e.g., buildings, trees), magnetic fields pass through most materials (Acres 2006). CMACS (2003) investigated the influence of the conductivity of cable sheathes and armour on the generation of electromagnetic fields and found that as the conductivity of the sheath and armour increased the resultant electromagnetic field strength outside the cable decreased. This indicates that using thicker sheaths or materials with higher conductivity values for the sheathing and armouring of submarine power cables can help to reduce the electromagnetic fields generated. Armouring material used for cables is, for example, steel wire or, alternatively, steel tape. The relative permeability μ_r of steel wire is about 300 whereas that of a steel tape is about 3000 (CMACS 2003). Hence steel tape would be the better option in regard to reduction of electromagnetic fields outside the cable.

For subset cables it was also investigated how cable burial affects field strength (CMACS 2003). Magnetic fields are unaffected (no 'dampening') by burial as long as the sediment had non-magnetic properties. As the magnetic fields are unaffected by burial the electric fields induced by them will be unaffected too. Due to the higher conductivity the induced electric fields will be higher in the seawater than in the sediment (Fig. 16). The authors mention that although the burial of a cable will not effectively mitigate magnetic fields and induced electric fields (if it is buried to the suggested 1 m depth) it is likely to reduce exposure of electromagnetically sensitive species to the strongest electromagnetic fields that exist at the 'skin' of the cable owing to the physical barrier of the substratum.

[2] The time-varying magnetic field outside the cable (AC) induces (Faraday's induction law) an electric field in surrounding conductive materials (e.g. seawater, seabed) whereas the movement of seawater through a magnetic field (AC or DC) also generates (Lorentz law) an induced electric field.

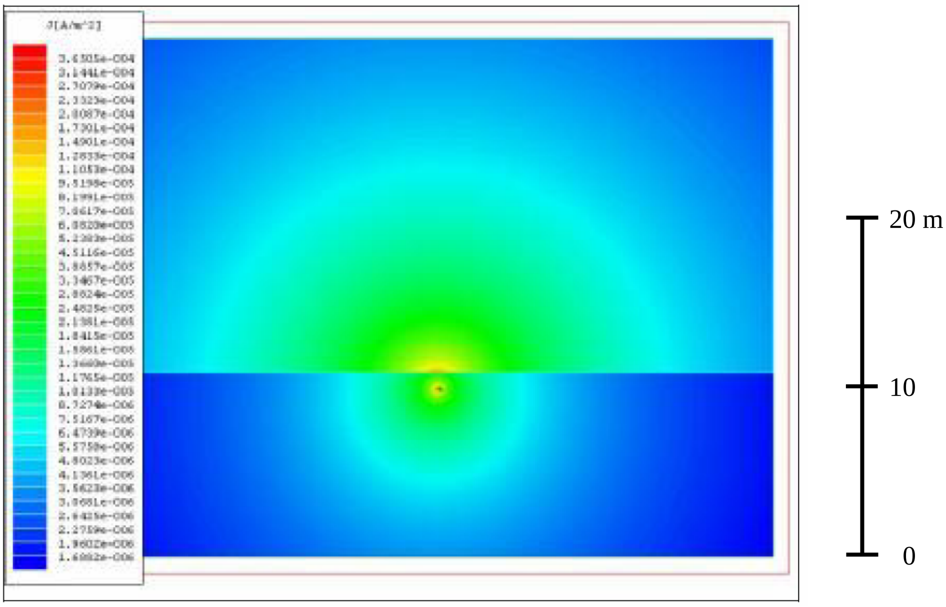


Figure 4.15 Magnitude of current density outside a buried cable (from CMACS 2003).

The strength of both magnetic and induced electric fields rapidly declines as a function of distance from the cable. Magnetic fields are measured in microtesla (µT), another unit often used is milligauss (1 milligauss = 0.1 microtesla). Electric fields are measured in kV per meter (kV*m^{-1}). The geomagnetic field of the earth is approximately 50 µT. An electric field of about 25 µV*m^{-1} is regarded a natural ambient level in the North Sea (Koops 2000).

4.4.3 Strength of electric and magnetic fields in the environment of power cables

Information on strength of electric and magnetic fields in the vicinity of cables are available from either calculations or measurements. A few examples shall be given here.

According to Koops (2000) a **monopolar DC** transmission line carrying 1500 A produces a magnetic flux density of approximately 300 µT on the seabed above the cable, falling off to 50 µT at a distance of 5 m above the seabed, and 13 µT at 20 m above the seabed. Electric fields range from approximately 1 V*m^{-1} at a distance 10 cm from the cathode, to 0.07 V*m^{-1} at a distance 1 m from the cathode, falling to levels in the range 1 – 50 µV*m^{-1} far from the sea electrodes.

A 10 cm diameter monopolar HVDC cable carrying 500 A will induce a magnetic field of 2000 µT at the surface of the cable, 20 µT at a distance of 5 m, and 5 µT at a distance of 20 m (Acres 2006). For two monopolar HVDC cables in British Columbia the same author calculated magnetic fields of up to 5000 µT produced at the surface of these cables, decreasing to about 50 µT (approximately equal to the Earth's geomagnetic field) at a distance of about 5 m. The maximum transmission values of these cables, operating at approximately 1200 A, are 312 MW at 260 kV and 370 MW at 280 kV, respectively (Acres 2006).

According to calculations for Baltic Cable (monopolar DC transmission, 450 kV, 600 MW) weak electric fields (1 µV cm-1) may occur at distances of up to 10 km from the electrodes. A direct current magnetic field occurs around the cable reaching up to 250 µT directly above the cable and decreasing to about 50 µT at a distance of 6 m (Matthäus 1995). As reported by Söker *et al*., 2000 magnetic compasses show considerable deviations at the surface of the water directly above the Baltic Cable. As a consequence a warning had to be issued to navigators informing about compass deviation in the vicinity of the Baltic Cable.

Grzan *et al*., 1993 report about the installation of a 12.7 mm steel plate to limit above ground magnetic field to less than 2 milligauss (< 0.2 µT) for the underwater Long Island Sound cable (four 2,000 mm^2 SCFF cables, 345 kV).

The current state of knowledge regarding the electromagnetic fields emitted by **AC cables** was summarised by CMACS (2003). The authors investigated electromagnetic fields generated by a 132 kV XLPE three-phase submarine cable with both perfect and non-perfect shielding (AC, 350 A) through simulation by models. It was reported that no directly generated electric fields occur outside the cable in case the cable is perfectly shielded (conductor sheathes are grounded). However, magnetic fields generated by the cable will create induced electric fields outside the cable. The induced electric field is related to the current in the cable. Modelling predicted that magnetic fields of a cable buried at 1 m depth would induce electric fields of around 91.25 µV m^{-1} in the overlying seawater. At a distance of 8 m the strength of electric field in seawater would still amount to approximately 10 µV*m^{-1}. The magnitude of the magnetic field in close proximity of the cable (i.e. within millimetres) is about 1.6 µT according to the simulations. A smaller current would proportionally produce a lower induced electric field, i.e. a cable current of 175 A will give rise to half the induced current density at 350 A and therefore half the induced electric field.

From simulations for the same cable with non-perfect shielding (poor grounding of sheathes) the occurrence of a directly generated electric field was predicted. The leakage electric field was stated to be smaller than the induced electric field. According to the authors again if the cable were operated at a lower voltage the electrical field results would need to be scaled. E.g. for a 33kV cable the scaling factor is 0.25 (CMACS 2003).

Calculation results were compared with data from field measurements of magnetic fields near both a 33 kV and an 11 kV cable. Near the 33 kV cable the magnetic field was measured as 50 nT. The field decreased with distance from the cable axis (Figure 4.16). At 400 m from the cable the sensor picked up only noise (0.5 nT). The magnetic field from the 11 kV cable appeared to be more widely distributed than the 33 kV cable. The authors suggested that this may have been a consequence of the individually sheathed conductors.

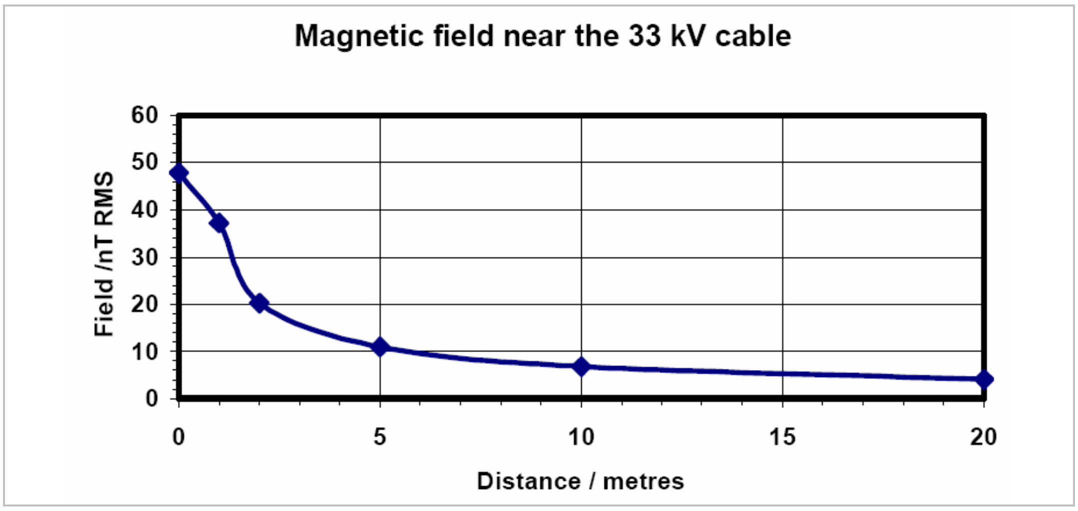


Figure 4.16 Results of measurements with magnetic field sensors in the environment of a 33 kV cable (from CMACS 2003).

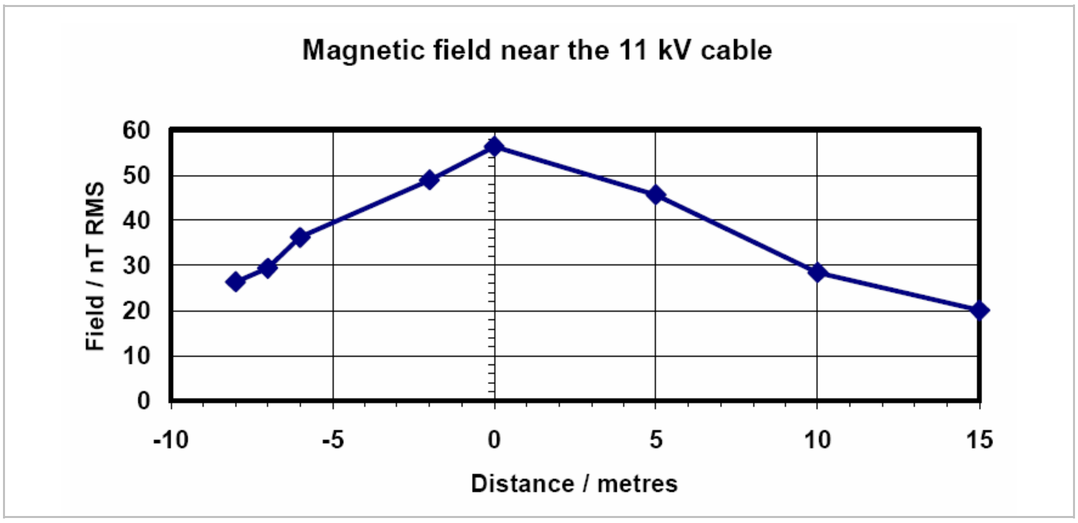


Figure 4.17 Results of measurements with magnetic field sensors in the environment of an 11 kV cable (from CMACS 2003).

The electric field sensor used for the field measurements produced a maximum output (indicating an electric field in excess of 70 µV*m^{-1}) when placed in the cable environment (CMACS 2003). Measurements taken at a distance of approximately 1 km still recorded an electric field of greater than 70 µV*m^{-1}. The authors had not expected electric fields of such strength. They discussed the lack of steel armour in the 33kV cable to be a contributory factor. However, it would not sufficiently explain such large electric field detected at a distance of approximately 1 km from the cable. Time limitations did not allow further investigation of the detected field including the development of other sensors in the scope of the study (CMACS 2003).

Also, information on 33 kV XLEP cables carrying AC current was obtained by CMACS (2003). AEI Cables Limited, a company designing and manufacturing electrical cables, provided calculations of magnitudes of magnetic fields. According to that, for current flows of 641 A a magnetic field strength at 0 m and 2.5 m of 1.7 µT and 0.61 µT, respectively, was calculated.

For the Nysted offshore wind farm the magnetic field of three-core PEX-composite cable (AC) buried at a depth of 1 m was calculated to be about 5 µT at a distance of 1 m when the wind farm produces at full effect (600 A) (Hvidt 2004).

The Horns Rev wind farm was planned with an internal connection of 33 kV, 400 A cables and a shore connection using 3-core 150 kV, 600 A cable for which Gill & Taylor (2001) calculated electric field strengths at different distances from the cable (Figure 4.18, Figure 4.19). As seen in the diagrams electric fields directly above the cables were calculated to reach 1000 µV*m^{-1}. Ambient conditions of about 25 µV*m^{-1} would be reached at a distance of more than 30 m from the cables. These calculated data are in contrast to results for AC transmission cables published by other authors who give electric field strengths a fraction of what was calculated by Gill & Taylor (2001) (Table). The differences might be explained by the high currents considered for the Horns Rev cable. A discussion of the results was not presented in the report by Gill & Taylor (2001).

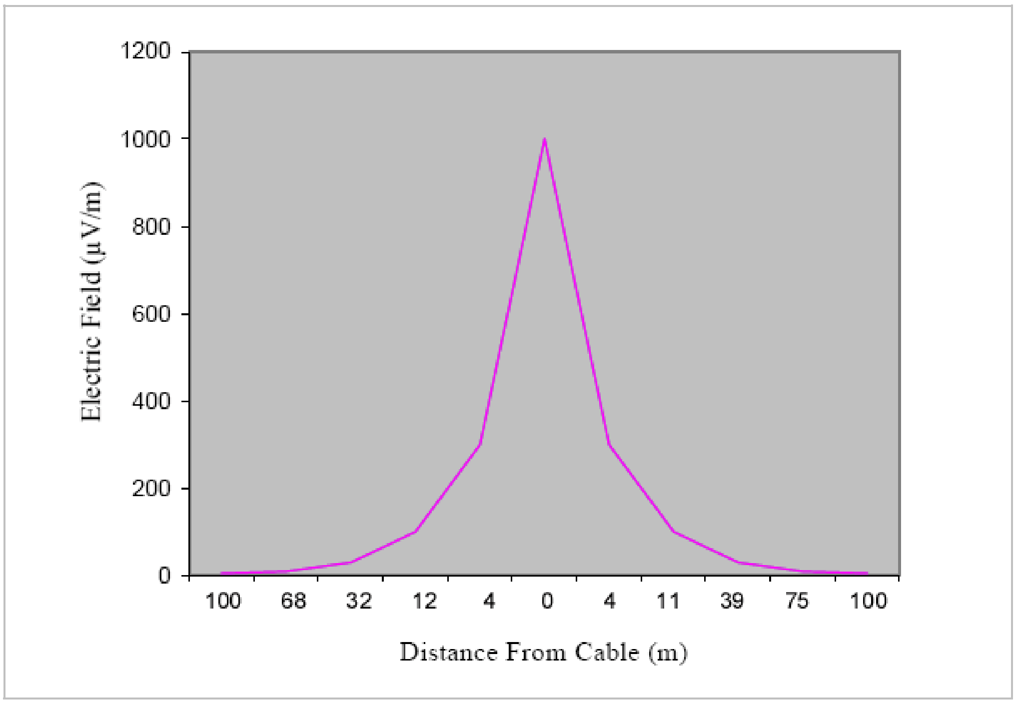


Figure 4.18 Electric field intensity for a 33 kV cable (400 A current) deployed at Horns Rev offshore wind farm with a seabed resistance of 0.7 ohms (from Gill & Taylor 2001, slightly amended).

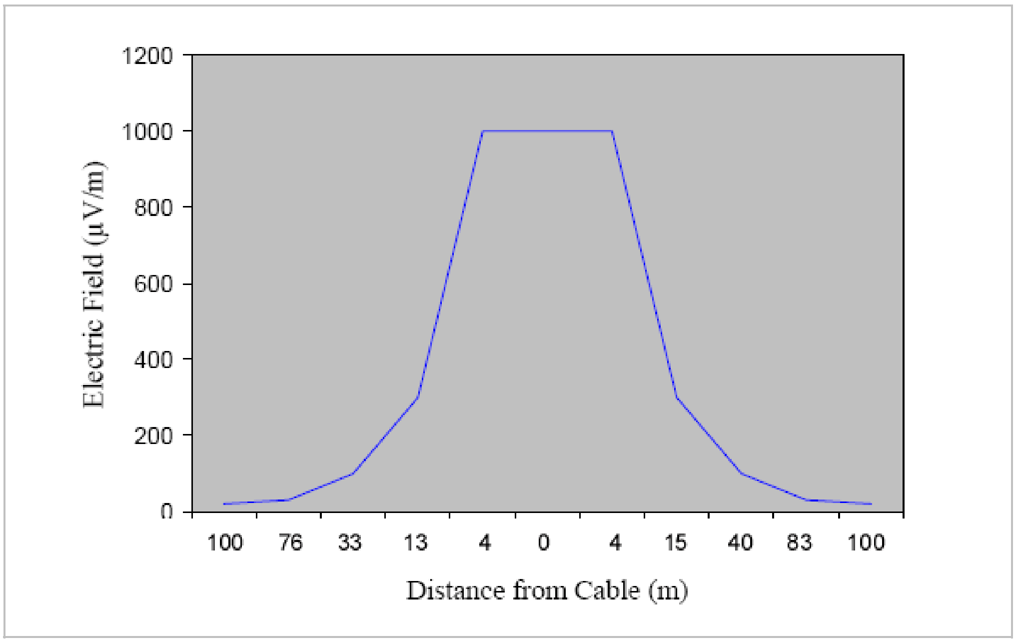


Figure 4.19 Electric field intensity for the 150 kV cable (600 A current) deployed at Horns Rev offshore wind farm with a seabed resistance of 0.7 ohms (from Gill & Taylor 2001, slightly amended).

Other subsea power cables to potentially emit electromagnetic fields are **communication cables** with repeaters. Marra (1989) published information on a major communication cable. The induced electric field was quoted with 6.3 $\mu V*m^{-1}$. Since this is the only information found on communication cable no general assessment can be made.

Table 4.6 Data on electromagnetic field strength for various cables obtained by both calculations and *measurements.

Cable type	**Capacity**	**Electric field strength**	**Magnetic flux density**	**Reference**
Monopolar DC	500 A		2000 µT at the surface of the cable 20 µT at 5 m distance 5 µT at 20 m distance	Acres (2006)
	1200 A (312 MW at 260 kV; 370 MW at 280 kV)		5000 µT at the surface of the cable 50 µT at 5 m distance	Acres (2006)
	max. 1335 A, 450 kV, 600 MW (Baltic cable)	100 µV*m^{-1} at 10 km distance from the cable	250 µT above the cable 50 µT at 6 m distance	Matthäus (1995)
	1500 A	10^6 µV*m^{-1} at 10 cm from the cathode 7*10^4 µV*m^{-1} at 1 m from the cathode 1-50 µV*m^{-1} far from the cathode	300 µT above the cable 50 µT at 5 m distance 13 µT at 200 m distance	Koops (2000)
Biploar DC	1333 A, 150 kV, 400 MW		30 µT at 1 m distance 10 µT at 2 m distance	Brakelmann (2004),
	1200 A, 150 kV, 360 MW		29 µT at 1 m distance 7 µT at 2 m distance	Pahlke & Hinrichs (2005)
AC (3-phase)	11 kV, 60 A, 50 Hz	17.5 µV m^{-1} at a distance of 0 m 12.5 µV m^{-1} at 5 m 6.2 µV m^{-1} at 20 m	*~57 µT above the cable *50 µT at 2 m distance *45 µT at 5 m distance *20 µT at 15 m distance	CMACS (2003)
	33 kV, 50 A, 50 Hz	15 µV m^{-1} at a distance of 0 m 4 µV m^{-1} at 5 m 1 µV m^{-1} at 20 m *>70 µV m^{-1} at >1 km distance	*50 µT above the cable *20 µT at 2 m distance *10 µT at 5 m distance	CMACS (2003)
	33 kV, 641 A		1.7 µT at 0 m 0.61 µT at 2.5 m	CMACS (2003)
	33 kV, 400 A	1000 µV m^{-1} at a distance of 0 m about 300 µV m^{-1} at a distance of 4 m 25 µV m-1 at >30 m		Gill & Taylor (2001)
	132 kV (with perfect shielding)	No directly generated electric field, but induced electric fields: 91.25 µV m^{-1} at 0 m distance, 10 µV m^{-1} at 8 m (seawater), 1-2 µV m^{-1} at 8 m (sediment)	*56 nT in the surrounding water 1.6 µT within mm around the cable	CMACS (2003)
	132 kV, 600 A (Nysted offshore wind farm)		5 µT at 1 m	Hvidt (2004)
	150 kV, 600 A	1000 µV m^{-1} at a distance of 0 m 1000 µV m^{-1} at a distance of 4 m 25 µV m^{-1} at >30 m		Gill & Taylor (2001)
Natural ambient conditions (marine)		**25 µV m^{-1}**	**50 µT**	**after different authors**

4.4.4 Impacts on fauna

Not much information is available on impacts of electric or magnetic fields associated with subsea cables on benthic marine invertebrates. In terms of potential impacts and effects of electromagnetic fields on marine invertebrates available information does not allow conclusive assessments. The WHO fact sheet "Electromagnetic fields and public health" (WHO 2005) concludes that "…none of the studies performed to date to assess the impact of undersea cables on migratory fish (e.g. salmon and eels) and all the relatively immobile fauna inhabiting the sea floor (e.g. molluscs), have found any substantial behavioural or biological impact". Key findings of a literature review by Acres (2006) on potential electromagnetic field effects on aquatic fauna associated with submerged electrical cables were as follows:

- "No studies describing adverse effects on aquatic species or systems associated with anthropogenic EMF emissions in either field or experimental settings at the field strengths associated with submarine power cables were identified.
- No studies were found that described the potential effects of anthropogenic EMF associated with submerged power cables on fish populations or fish distribution. Similarly, no studies were identified that specifically described the potential effects of submerged AC cables on salmonid migration or behaviour.
- Although it is known that some elasmobranch species are capable of detecting and responding to electric fields within the range of levels induced by submerged power cables, no studies were found describing the effects of such exposure on elasmobranch behaviour under field conditions.
- Some aquatic species, such as the spiny lobster and loggerhead turtle, use the earth's geomagnetic field as a means of navigation and positioning. The presence of magnetite within many other migratory species, including salmonids, suggests that they also may use the earth's geomagnetic field for navigation. Experimental evidence to determine whether migrating salmon can detect and/or could be affected by anthropogenic magnetic fields of a magnitude comparable to the earth's geomagnetic field is inconclusive.
- Experiments involving cultured cells and animal models indicate that there is little to no evidence that extremely low frequency EMF causes damage to chromosomes or affects cell division or other cellular functions. No laboratory studies describing similar experiments on aquatic species or cultured cell lines from aquatic species were identified during this literature review." (Acres 2006)

The author concludes that based on the limited number of studies undertaken to date it is not possible to form any conclusions regarding the possible impacts of EMF exposure on aquatic species and systems.

Laboratory studies on survival rate and fitness of **benthic macroinvertebrates** common in the southern Baltic Sea (*Crangon crangon, Rhithropanopeus harrisii*, *Saduria entomon,* Mytilus *edulis)* in response to exposure to static magnetic fields were undertaken by Bochert & Zettler (2004). The studies could not prove any significant effect on tested organisms.

Other species have been shown to use the earth's magnetic field as an orientation cue. Among them are for example the spiny lobster *Panulirus argus* (Lohmann *et al*., 1995*, Talitrus saltator* (Arendse 1978, Scarpini & Quochi 1992), *Orchestia cavimana* (Arendse & Barendregt 1981), *Talorchestia martensii* (Pardi *et al*., 1985), *Idotea baltica* (Ugolini & Pezzani 1992) and the nudibranch gastropod *Tritonia diomedea* (Lohmann & Willows 1987, Willows 1999). Whether orientation of such species is affected by artificially generated electromagnetic fields in the vicinity of power cables is unknown.

Wang *et al*., 2003 report evidence of increased electrical activity of particular neurons in response to alterations of a magnetic field around specimens. Foster & Repacholi (2005) recognise a variety of mechanisms by which electric and magnetic fields can interact with biological structures. These include electrically or magnetically induced forces and torques on biological structures, and excitation and electrical breakdown of cell membranes.

Among **fish**, electroreception has been recorded for a number of species (Walker 2001). The majority of electroreceptive fish studied so far are either freshwater species, Elasmobranchii (sharks, skates and rays), or other chondrichthyans (e.g. sturgeons). Marine chondrichthyans are the most sensitive fish with receptor thresholds ranging from 0.005 $\mu V\ cm^{-1}$ to 0.2 $\mu V\ cm^{-1}$ in different species, hence electric fields generated by cables have successfully been used as a barrier for sharks to prevent attacks on humans (Gill & Taylor 2001, Walker 2001). Also lampreys (Petromyzontiformes) show behavioural responses to fields of 1-10 $\mu V\ cm^{-1}$ (Poléo et al. 2001, Walker 2001). Among teleost fish freshwater species have been studied whereas information on marine species is scarce.

Also species that lack electroreceptors may react to electric fields as is demonstrated by the effect of electrotaxis with a direct current in freshwater electrofishing. In general small fish require a higher field strength and repetition rate for effective electrotaxis than large fish (Walker 2001), but exact measurements are rare and do not reveal a clear general pattern. Also eggs and larvae of many fish species react very sensitive to electric fields. According to Fricke (2000) magnetic fields can potentially affect the orientation of marine fish during their migrations or even redirect the migration. Electric fields can have scaring effects on marine fish and probably also redirect the migration pattern. In the German North Sea and the Baltic Sea possible impacts might be considered for herring-like fish (Clupeidae), sharks and rays (Elasmobranchs), flatfishes (Pleuronectidae), and other demersal migratory fishes (Teleostei).

Magnetic fields generated by cables might impair the orientation of fish and marine mammals and therefore negatively affect especially migratory behaviour. Although the biological process of magnetoreception is less well understood than that of electroreception there is sufficient evidence for the importance of magnetic information for orientation in a variety of animals. Marine fish use the earth's magnetic field and field anomalies for orientation especially when migrating (Fricke 2000). Especially elasmobranch fish can detect magnetic fields which are weak comparable to the earth's magnetic field (Poléo *et al*., 2001) and react to fields of 25 - 100 µT (Gill *et al*., 2005). The influence of magnetic fields on orientation in teleost fish is still under discussion as some studies reported effects in salmonids and eels while other failed to do so (Poléo *et al*., 2001). According to references in Warneke (2001), eels and several salmonid species react to experimental magnetic fields. Fricke (2000) assumes magnetic orientation and thus a potential impact of artificial anomalies of the earth's magnetic field for allis shad (*Alosa alosa*), twait shad (*Alosa fallax*), Atlantic pomfret (*Brama brama*), herring (*Clupea harengus*), sardine (*Sardina pilchardus*) and Baltic sprat (*Sprattus sprattus*). While eels *Anguilla anguilla* under laboratory conditions show orientating reactions to relatively weak fields (4 % of the earth's magnetic field; Tesch 2000), much stronger disturbance reactions have been shown only for field strengths by far exceeding those of the earth's magnetic field (Westerberg 2000, Poléo *et al*., 2001). Benthic fish are more exposed to magnetic fields around bottom cables and are thus expected to be stronger affected than pelagic species.

Investigations into potential effects on fish from electromagnetic fields from submersed cables have been carried out in relation to the demonstration project "Nysted Offshore Wind Farm at Rødsand" using pound nets on both sides of the cable (132 kV AC) trace (Klaustrup 2006). The main result of this study was that some species (baltic herring, common eel, atlantic cod, flounder) showed changes in their behaviour after the commissioning of the cable. In addition the results indicate that the migration of some species across the cable route was impaired. However, a weakness of the study is that the electromagnetic fields were not measured directly.

For the Baltic Cable, a HVDC cable with a constant magnetic field of 5 µT at a distance of 60 m, Westerberg & Begout-Anras (2000; in Walker 2001) found that 57 % of 21 transmitter-tagged eels crossed the cable in spite of the magnetic anomaly within 3.6 hours after release. Only marginal changes of the swimming direction in the moment of crossing indicated an effect of the cable. Similarly, migration of elvers (young eel) was not notably affected by HVDC cables (references in Poléo *et al*., 2001).

Concerning **electric fields** eels and salmonids show a bradycardial response (i.e. a reduction in heartbeat rate) at minimum field strengths of 7 $mV*m^{-1}$ whereas lower threshold values reported in certain studies could not be reproduced later (Poléo *et al*., 2001). Behavioural responses of marine teleost species could be observed at 0.5-7.5 $V*m^{-1}$ (Poléo *et al*., 2001) but it should be noted that observable changes in behaviour can be expected to occur at values well above the threshold of perception.

The behaviour of **elasmobranch fish** can be influenced by weak electric fields in different ways. Gill & Taylor (2001) tested the reaction of a benthic shark, the dogfish *Scyliorhinus canicula*, to simulated electric fields in a pilot laboratory study. The sharks avoided electric fields at 10 µV cm^{-1} which were the maximum expected to be emitted from 3-core undersea 150kV, 600A AC cables like those used in the Horns Rev wind farm but they also showed a high between-individual variance. Some very low threshold values for physiological responses of only 0.006 mV/m were questioned by Poléo *et al*., 2001. According to other studies eels and salmon responded to electric field strengths between 7 and 70 mV/m (Poléo *et al*., 2001).

In **cetaceans** which probably use magnetic cues for navigation a disturbance of the local geomagnetic field has been suggested to cause strandings of whales in the USA and the UK (Warneke 2001 and references therein). Although such an effect could not be detected in stranding records from Australia and New Zealand there is sufficient circumstantial evidence to conclude that changes in magnetic fields may affect cetacean orientation (Warneke 2001). Circumstantial evidence further indicates that they would be capable of detecting variations in the geomagnetic field at the very least within a range of 30-60 nT and probably at much finer levels of discrimination (Warneke 2001).

4.4.5 Conclusions in regard to electromagnetic fields

Our current knowledge about effects of electromagnetic fields on the marine environment, in particular fauna, is not sufficient. Only a few preliminary conclusions can be reached.

Occurrence of magnetic fields associated with power transmission is best limited by field compensation to be achieved by an appropriate transmission system layout (preference of AC transmission systems or bipolar DC transmission system against monopolar systems). In case of monopolar transmission systems magnetic fields in close vicinity to the cable exceed natural ambient conditions significantly.

Directly generated electric fields are regarded to be controllable by adequate shielding. However, an induced electric field generated by the magnetic field occurs. In case of high current flows during power transmission the electric fields in proximity to the cable significantly exceed values typical under natural conditions.

Simulation studies revealed the potential for induced electric field mitigation by using highly specialised materials with high permeability or conductivity values for armouring of cables. Development of modern materials with such properties has to be encouraged. Though cable burial will not effectively mitigate against magnetic fields and induced electric fields it is likely to reduce exposure of electromagnetically sensitive species to the strongest electromagnetic fields that exist at the ‘skin’ of the cable owing to the physical barrier of the substratum i.e. the greater distance to the cable, and cable burial should therefore be realized.

There is an apparent lack of information on electromagnetic fields emitted from communication cables (with electric components).

In regard to effects on fauna it can be concluded that there is no doubt that electromagnetic fields are detected by a number of species and that many of these species respond to them. However, threshold values are only available for a few species and it would be premature to treat these values as general thresholds. The significance of the response reactions on both individual and population level is uncertain if not unknown. More field data would be needed to draw firm conclusions but data acquisition under field conditions is complicated.

4.5 Contamination

4.5.1 Introduction

Anthropogenic contamination of the marine environment including its fauna and flora is an intensively studied field. A review of the huge amount of available information would be beyond the ambit of this literature review. For that reason the following chapters concentrate on information directly related to cable projects. Regarding the impact of contaminants on fauna it is referred to existing data sources (web portals) which can be searched for detailed information.

A risk of contamination associated with subsea cables arises from activities causing seabed disturbance and from release of contaminants of the cable itself due to cable damage or degradation. Hence contamination can become an environmental issue during installation and removal as well as during service life.

4.5.2 Contamination related to seabed disturbance

The risk of contamination related to seabed disturbance is restricted to the potential release of contaminated sediments into the water column from cable burial, recovery of buried cables and repair work. Usually, sediment quality is assessed before a cable is laid and a cable route is designated which avoids so-called “toxic hot spots” (e.g. URS Corporation 2006). Typical potential contaminants the areas are screened for are arsenic, cadmium, copper, lead, mercury, nickel, selenium, silver, zinc and total polycyclic aromatic hydrocarbons (PAH). However, there might be circumstances in which areas with contaminated sediments can not be avoided. Of special concern are areas in the vicinity of major ports, oil and gas industrial areas (drilling/exploration sites, platforms), areas which have historically been used for industrial, sewage or ammunition disposal, or localities which have acted as a natural sink for oil or chemical contamination. In such cases proposed mitigation measures to minimize potential risks of contaminant release included the use of hydro-jetting, a method regarded to cause least sediment disturbance, in soft sediments or a plow method to bury the cables where the bottom substrate is harder and water-jetting is not feasible. Also it was recommended to schedule the work to coincide with slack tides to minimize potential for tidal currents and wave action from carrying the suspended sediments away from the work area (BCTC 2006).

The problem of release of contaminants to the water column was addressed in a **review of information from the UK on cable decommissioning** (Emu Ltd. 2004). The authors concluded that the concentration of contaminants released to the water column resulting from grappling / cable removal, will be very low even in heavily polluted areas and rapidly diluted beyond the immediate area of release. Effects were therefore assessed as temporary and insignificant.

4.5.3 Contamination related to cable deterioration

Discussing contamination in relation to subsea cables the potential long-term risk of releasing heavy metals into the sediments caused by cable deterioration has to be included. Service life is limited since the cable coating weathers over time due to changing cable temperature during operation or wave action and current (BCTC 2006, Schreiber *et al*., 2004). Cable components posing a potential risk, as there are conductors and sheaths made of copper, lead and other metals, might become exposed and eventually leach into sediments in which they are buried. Schreiber *et al*., 2004 calculate an amount of about 12 kg lead*m^{-1} for cables with a 3.5 mm lead sheath. However, studies investigating this effect of elevated contamination levels in the vicinity of cables could not be found. Nevertheless, the removal of cables from the marine environment after termination of service life is usually proposed (BCTC 2006, Schreiber *et al*., 2004).

4.5.4 Contamination effects on fauna

Contamination effects on fauna have been intensively studied under laboratory conditions. There are several web portals providing very detailed information on toxicity of chemicals for aquatic and terrestrial life. From such sources information could be sought what effects on species are to be expected due to contaminant exposure of defined dosages. A background in chemistry will be helpful for drawing some general conclusion. The basis for a project-related risk assessment however is to be in the position to predict contaminant concentrations specimens will be exposed to in the course of a planned project.

Some examples for such web portals shall be given here: The DATEST Portal (http://projects.cba.muni.cz/datest/) functions as information source for ecotoxicological tests and bioindication methods. It features a public on-line database of methods used in Ecological Risk Assessment process. The ECOTOXicology database (ECOTOX, http://cfpub.epa.gov/ecotox) is a source for locating single chemical toxicity data for aquatic life. With the search tools integrated in this database it is possible to search for data on certain species, species groups or genera as well as for data on specific chemicals. Another example provided here is TOXNET (http://toxnet.nlm.nih.gov/), a database on toxicology, hazardous chemicals, environmental health, and toxic releases. The PAN Pesticides Database (http://www.pesticideinfo.org/Index.html) provides current toxicity and regulatory information for pesticides. The Aquatic Ecotoxicity section at current includes 223,853 aquatic toxicity results from U.S. EPA's AQUIRE database. These data can be searched by species, chemical or effect.

Results from field studies are in comparison less numerous. A publication discussing the topic with focus on a cable project could not be found. The few examples cited in the following paragraph are intended to serve as reference for some common effects of exposure to contaminants on benthic organisms as there are impairment of body functions, reduction in growth and reproduction, lethality.

Klari *et al*., 2004 investigated seasonal variation of total arsenic concentration in the edible part of mussels *Mytilus galloprovincialis* as well as in the tail muscle of the lobster *Nephrops norvegicus* in the coastal area of Rijeka Bay (North Adriatic Sea, Croatia). Facilities like an oil refinery and an oil thermoelectric power plant are located in the area. A linear relationship between arsenic concentration in specimens and shell length or body length, respectively, was found. Ussenkow (1997) studying contamination of harbour sediments in the eastern Gulf of Finland (Neva Bay), Baltic Sea found an inverse correlation of biomass of Chironomidae with contaminant concentration (oil products, Hg, Pb, and Cu) in the sediment of Kronstadt port. Contamination of sediments with oil-based drilling muds have been found to cause changes in faunal composition and to lead to both, low diversity and dominance of opportunistic species (Gray *et al*., 1990, Kingston 1992, Daan *et al*., 1994, Olsgard & Gray 1995, Daan & Mulder 1996, Grant & Briggs 2002). The sea urchin *Echinocardium cordatum,* the bivalve *Montacuta ferruginosa* and the amphipods *Harpinia antennaria* and *Ampelisca* spp. were identified sensitive species in respect to sediments contaminated by oil-based drilling muds (Daan *et al*., 1994, Daan & Mulder 1996, Gómez Gesteira & Dauvin 2000). Chronic exposure of adult sea scallops from Georges Bank, *Placopecten magellanicus*, to different types and concentrations of used operational drilling fluids and their major constituents under laboratory conditions caused high mortalities at concentrations as low as 1.0 mg*l^{-1} (Cranford *et al*., 1999). Also effects on growth and reproductive success could be documented in this study.

4.5.5 Additional risks of contamination related to fluid-filled cables

A last point to be taken into consideration only applies to a certain cable type, the fluid filled cable. There is a potential risk that insulating fluid may enter the aquatic environment from cable leaks (due to mechanical damage) or complete severing of the cable (by ship anchors or other mechanical damage). The amount of fluid spilled will be related to the response and repair time, extent of damage and its location (Schreiber *et al*., 2004, Jacques Whitford Ltd 2006b).

Schreiber *et al*., 2004, consider flat-type cables to generally release the greatest amount of oil among different types of **oil-filled cables**. For the planned NorNedcable the authors calculate an initial spill rate of approximately 50 $l*h^{-1}$ after spontaneous cable rupture. A spill of 2000 l of oil is considered the worst case scenario. The overall risk of such event was assessed low. Effects on the marine environment were not discussed in this article. Typical consequences known from major oil spills are that birds and marine mammals get injured or killed by oil that pollutes their habitat. Also small organism (planktonic and benthic) would be affected. However, considering the maximum amount of oil potentially spilled from the cable (for the above mentioned example), severe effects on the marine environment are unlikely[3].

Other dielectric insulator in submarine electrical transmission cables is **linear alkylbenzene (LAB) fluids.** For the Vancouver Island Transmission Reinforcement Project (VITR) the maximum volume of LAB fluid potentially released has been estimated as up to 3,400 litres for a leak and up to 40,000 litres for a completely severed cable (Jacques Whitford Limited 2006b). The pathway of cable fluid in the marine environment is migration to the surface to form a very thin slick, evaporation or transportation via adsorption to suspended particles and biodegradation in the water column. According to Jacques Whitford Limited (2006b) accumulation in benthic sediments is possible if leaks occur in areas where the cable is buried near shore. LAB is reported to biodegrade rapidly in marine waters (80 to 99% in 21 days), with complete mineralisation by microorganisms under aerobic conditions (producing carbon dioxide and water). The rate of biodegradation is affected by temperature, sunlight, water flow patterns and types of microorganisms in the area. In anaerobic conditions (marine sediment) LAB biodegrades slowly, as it has a high affinity to soil, sediments and organic matter and is known to persist in aquatic sediments for 10 to 20 years (Jacques Whitford Limited 2006b). In regard to impacts on the marine environment it was concluded that alkylbenzene has a low order of fish, mammalian and human toxicity.

4.5.6 Conclusions in regard to contamination

The toxicity of different chemicals to aquatic organisms was examined mainly under laboratory conditions. It can be concluded that if fauna is exposed to contaminants in their natural environment an uptake of the substances in any form usually takes place. Common effects of exposure to contaminants on benthic organisms are e.g. impairment of body functions, reduction in growth and reproduction, lethality.

A risk of contamination associated with subsea cables arising from activities causing seabed disturbance can only be anticipated for heavily contaminated localities. Avoidance of (sediment disturbance in) such areas would be an appropriate mitigation measure. Information available on contaminant release due to disturbance of polluted sediments during cable installation (as well as removal and operation) reported about temporary and insignificant effects. Only little information however was available.

Introduction of contaminants into the environment from the cable itself can only occur if cables are not removed after decommissioning, if they are damaged or if fluid-filled cables are used.

Due to gradual cable deterioration, contaminants, in particular heavy metals, will in the long term be released into the sediment. In regard to fluid-filled cables it has to be considered that they pose a permanent risk of release of contaminants into the environment. Thus their use seems debatable under aspects of environmental protection.

A potential risk of contamination due to the operation of subsea cables (including installation, repair-work, cable removal) certainly exists. A project-specific risk assessment is required.

4.6 Disturbance

4.6.1 Introduction

Among disturbance effects which might occur in association with subsea cables are direct effects on organisms such as physical disturbance, damage, displacement and removal as well as effects on the marine environment, in particular water quality effects, physical alteration to the seabed and habitat destruction. Most of these effects are restricted to the installation phase and cable recovery. Physical alteration to the seabed however may be long-term.

4.6.2 Physical disturbance, damage, displacement and removal of flora and fauna

Physical disturbance, damage, displacement and removal of flora and fauna occur during trenching, cable burial and cable removal. Emu Ltd (2004) summarized results of a comprehensive review of available information and concluded that mobile species are able to avoid disturbance and survive. Although a

[3] It should be mentioned that eventually the cable type used for the NorNed cable changed from an oil filled type to an bipolar mass impregnated direct current cable.

principal risk to sessile species could be postulated the long-term significance was only likely to occur in sensitive habitats which included slower growing vulnerable species. This conclusion is supported by Andrulewicz *et al*., 2003, who published an article on environmental effects of the installation and functioning of the submarine *SwePol* Link HVDC transmission line in the Polish marine area of the Baltic Sea. Significant changes in zoobenthic species composition, abundance or biomass which could have been clearly related to cable installation had not been observed.

Emu Ltd (2004) also tried to make generalisations in relation to the sensitivity of ecology likely to be found on different seabed types. In summary, faunal communities populating exposed bedrock, chalk, gravel, coarse sand, silty sand and intertidal mudflats were identified to be potentially prone to long-term (> 6 months) damage. Fauna supported by seabed types like stiff clay, sands of high mobility and clay was considered less at risk.

Disturbance of species is most obvious if biogenic habitat structures like mussel beds, sea grass beds, *Sabellaria* reefs or maerl beds are affected. 'Maerl' is a collective term for several species of calcified red seaweed. Maerl beds are mixed sediments built by a surface layer of slow-growing, unattached coralline algae creating a habitat for rich fauna. The high sensitivity of maerl beds is explained by the slow growth and poor recruitment of maerl species. Sabellarian reefs (*Sabellaria spinulosa*) are considered to be less prone to destruction by physical damage (e.g. due to shrimp fishery gear). Provided that the worms are not killed or removed from their tubes, the natural growth and capacity for repair is such that they can rebuilt destroyed parts of their dwellings within a few days (Gruet 1971 in Vorberg 2000). In case of sea grass occurrence in the course of a planned subsea cable route sea grass rhizomes had to be cut (Kerite company 2001). Sea grass monitoring accompanying the cable laying at Nysted offshore wind farm (Denmark) revealed that shoot density of eelgrass and the biomass of rhizomes were reduced close to the trench as a combined effect of excavation and back filling and temporary burial below sediment deposited alongside the cable trench (Birklund 2003).

4.6.3 Water quality effects (turbidity)

Water quality effects may affect benthic fauna and flora in a wider range if sediment is redistributed during cable burial or removal. Increased suspended sediment concentrations and changes of the oxygen level, for example, influence the submarine light absorption as well as environmental factors for benthic and pelagic organisms. The species´ mechanisms of filtration could be at least temporarily obstructed (Söker *et al*., 2000). Possible turbidity of the seawater can affect growth of the macrobenthos for a certain time. Coverage with soil may have a lethal effect on some macrobenthos species.

Könnecker (1977) in an article on epibenthic assemblages as indicators of environmental conditions presumes that water turbidity and sediment precipitation exert a major control on epifaunal distribution patterns, especially so in case organisms are particularly prone to clogging of their incurrent canals. The author reports tunicates to be immune to sedimentation whilst hydroids and bryozoans seem to be able to cope. Maurer *et al*, 1986 reported that epifaunal or deep-burrowing siphonate suspension feeders were unable to escape burial by more than 1 cm of sediment whereas infaunal non-siphonate feeders tolerated burial by 5 cm but less than 10 cm (in Hiscock *et al*., 2002). As pointed out by Baker (2003) the relative impact of sediment redistribution will be controlled by the amount of redistribution (the thickness of the layer of resettled sediment), its variance from the existing material (introduction of mud onto a sand sediment is expected to have a more substantial effect than mud settling on mud) and the sensitivity of the species or community. The area affected by plumes and smothering depends on the amount of excavated and dumped sediment, on the depth of the seabed and the dispersal in the water column; finer particulates remain in suspension longer than larger particulates and can potentially disperse over a wider area (Hiscock *et al*., 2002. TNU (2005) report based on the results by GSX PL (2001) that suspended fine and medium sands require about 9 h for resettlement whereas silty sediments remain in suspension up to 4 days.

Söker *et al*., 2000, estimate that laying of the cable may disturb a two meter wide sector on the ground on both sides, and water will be troubled some meters around the site of construction. The same authors expect the effect on water to be diminished after some hours whereas effects on the sea floor will be observable for some weeks. At Nysted offshore wind farm, Denmark, a backhoe was used to excavate a 1.3 m wide, 1.3 m deep and 10.300 m long cable trench. Excavation work took one month (Birklund 2003). The excavated sediment was placed alongside the trench and later used for the back filling. The total volume of seabed material excavated was approximately 17 000 m^3. The sediment spill was estimated to be 0.5 – 1 % of the amount excavated. Inspection of the trench after the back filling showed that the surface of the trench was below the surrounding seabed due to an inadequate filling of the trench. In addition, the lowered seabed acted as a trap and the trench was filled with detached macrophytes. At some stations close to the trench the silt/clay content of the sediment was higher after the earthwork and this increase was probably caused by a local sedimentation of fine sediment spilled during dredging and back filling. The structure of the benthic fauna had changed significantly at the impact stations close to the trench. Whereas the abundance of the benthic fauna was reduced by 10 % at the control stations abundance at the impacted stations decreased to 50 %. According to the author all effects were confined to a narrow zone close to the cable trench (Birklund 2003). Fast recovery of the benthic community was expected at the stations close to the cable trench. Within the trench the accumulation of macroalgae was assumed to delay or prevent a re-colonisation of the sediment by the local fauna. However, in regard to the area affected the impact on the offshore environment was considered negligible.

For a wind farm development site in Great Britain, the Inner Dowsing offshore wind farm (Greater Wash Strategic Area), it has been predicted that 90 % of resuspended sediments from cable laying re-settle within 1 km of the construction corridor (Offshore Wind Power Ltd. 2002 in Baker 2003). The amount of resuspended material was regarded insignificant in comparison with baseline conditions.

The study of Cook Cove Cable 5 Submarine Cable Replacement Project reports a turbidity intensity of 21 NTU (Nephelometric Turbidity Unit; ≈ 21 $mg*l^{-1}$) in a distance of 15 m from the jet trench (from EBA 2004 cited in BCTC 2006). Such intensities are regarded as a slight increase in waters with naturally low turbidity.

The environmental impact report for the proposed Trans Bay Cable Project (URS Corporation 2006) refers to experiences from other cable laying projects and concludes that by use of a hydro plow or equivalent technologies 10 to 20 % of the fluidized sediments would be dispersed.

Estimation of sediment deposition and suspended sediment concentration in connection with the Cape Wind Energy Project was undertaken by modelling (Galagan *et al*., 2003). Results are presented in Figure 4.20 and Figure 4.21. Effects are clearly a function of range. Sediment deposition is predicted to occur in a maximally 90-120 m wide corridor (depending on the sediment type). Water quality effects might occur at a distance of more than 0.9 km from the site. Results of the prediction are again summarized in Table 4.7 and Table 4.8. The model assumption of Galagan *et al*., 2003, contains a part of 30 % suspended sediments of the total sediment volume and a relocation of the remaining 70 % of the sediment volume within the trench. Increased sediment concentrations are expected to last only a few minutes to less than one hour.

Table 4.7 Intensity and extent of sedimentation caused by using a hydro plow at sandy conditions (after Galagan *et al*., 2003)

Area	Sedimentation range
cable trench	ca. 19 - 24 mm
15 m distance from hydro plow	ca. 11 - 17 mm
30 m distance from hydro plow	ca. 2 – 5 mm
45 m distance from hydro plow	up to ca. 1 mm
60 m distance from hydro plow	low

Table 4.8 Intensity and extent of turbidity disturbance caused by using a hydro plow at sandy conditions (from Galagan *et al*., 2003, amended by IfAÖ)

Area	Minimum	Average	Maximum
cable trench	ca. 35 mg/l	ca. 65 mg/l	ca. 120 mg/l
60 m distance from hydro plough	< 5 mg/l	ca. 35 mg/l	ca. 78 mg/l
150 m distance from hydro plough	none	ca. 15 mg/l	ca. 38 mg/l
300 m distance from hydro plough	none	ca. 10 mg/l	ca. 20 mg/l
450 m distance from hydro plough	none	none	ca. 10 mg/l

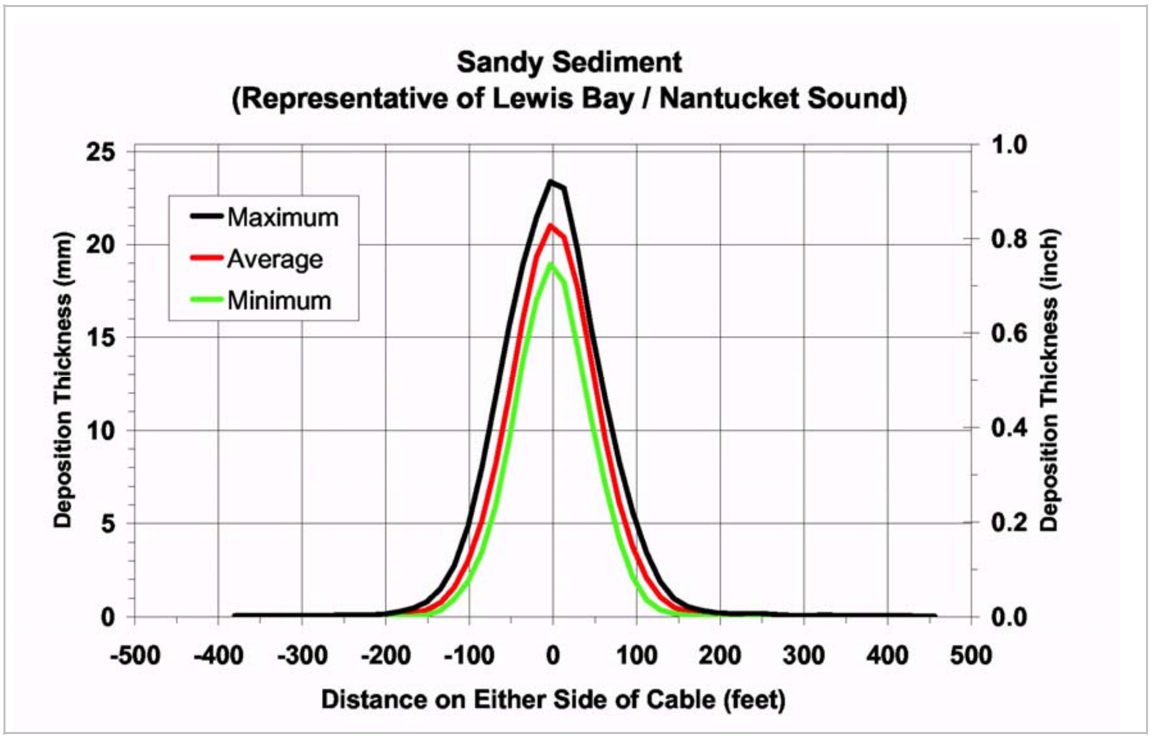


Figure 4.20 Sediment deposition thickness as a function of distance in sandy sediment in Lewis Bay for the Cape Wind Energy Project (Galagan *et al*., 2003)

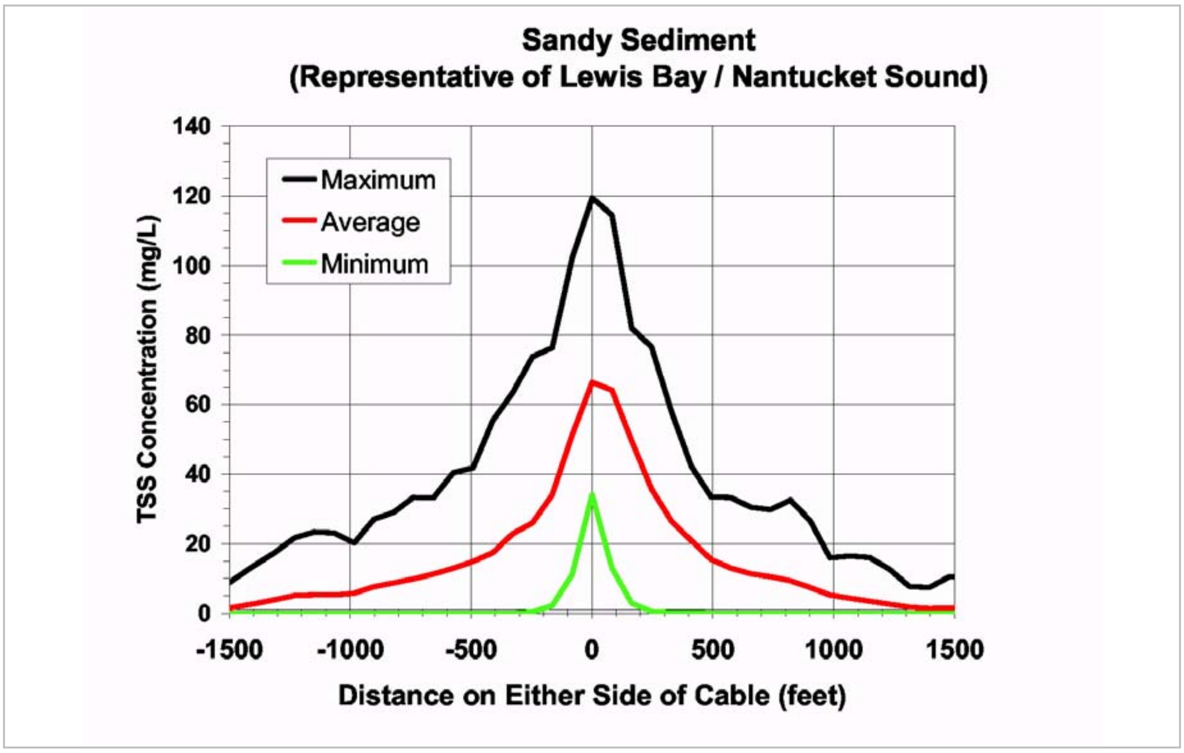


Figure 4.21 Suspended sediment concentration as a function of distance from the cable route in sand-sized sediment in Lewis Bay for the Cape Wind Energy Project (Galagan *et al*., 2003).

In the scope of the Vancouver Island Transmission Reinforcement Project an estimation of the volume of sediment disturbed at English Bluff has been made. Assuming that 1) each cable will be buried to, or removed from, a depth of 1.0 m, 2) the width of the disturbed area is 1.0 m for cable burial and 0.6 m for cable removal, 3) the total length of cable to be buried within Canadian jurisdiction is 2,040 m, including all intertidal trenching; and 4) the total length of cable to be removed within Canadian jurisdiction is 2,730 m, a total volume of 1 103.4 m³ has been estimated to be suspended due to cable installation/removal (BCTC 2006). This estimate was based on the assumption that 70 % of the disturbed material settles back immediately or remains within the trench. The authors also provide information on settling velocities of unhindered discrete particles (theoretical and laboratory determined) reported by Hitchcock *et al*., 1999 (Table 4.9).

Table 4.9 Settling velocities of unhindered discrete particles (from BCTC 2006, according to Hitchcock et al. 1999), characteristics of the receiving environment (water depth, salinity, density, tidal current etc.) not taken into account.

Particle description	Size	Settling velocity [cm*s-1]
Sand	0.2 mm	2.1417
	0.1 mm	0.67
Silt	0.05 mm	0.1816
	0.02 mm	0.0298
	0.01 mm	0.00749
Clay	5 µm	0.00187
	1 µm	0.0000748

A factor influencing the extent of water quality effects is the use of appropriate cable installation techniques. The width of seabed that is directly disturbed during cable burial can vary between ploughing, trenching and jetting. For example, the actual width of seabed directly disturbed during cable burial in connection with the Basslink project, Australia, was estimated to range from approximately 0.5 m (ploughing) to about 1 m (jetting) (National Grid 2000). Northeast Utilities Service Company (2002) regard a hydraulic jet plow to create a relatively narrow trench.

Anthropogenic turbidity effects due to trenching and burying of cable have to be assessed against the background of **naturally induced turbidity** by tides, wave, currents etc. Under normal conditions suspended matter in seawater from the open North Sea has values of < 3 mg/l and coastal waters of < 20 mg/l. River estuary and silty coastal waters like the Wadden Sea often contain high concentrations of suspended matter (Table 4.10, Figure 4.22, Figure 4.23). Results of field measurements conducted during extreme situations such as storms were not available. Results of a simulation of storm event in the North Sea are shown in Figure 4.24. Christiansen et al. (2006) mention for an area at Danish Wadden Sea concentrations of suspended matter for a storm situation of 100 - 300 mg/l compared with medium averages of < 50 mg/l.

Table 4.10 List of total suspended matter (TSM) in European coastal waters (Ferraria et al. 2003)

Site	**Period**	**Number of Sampling**	**TSM (mg/l)** (average; max and min values)
Loire plume	May-1998	9	1.91; 0,86-2.3
Seine plume	May-1998	9	2.73; 1.2-4.31
Thames plume	May-1998	7	5.6; 0.77-20.9
Rhine plume	May-1998	10	3.5; 1.87-7.63
Humber plume	May-1998	8	2.53; 0.76-8.22
German Bight	May-1998	17	1.55; 0.6-6.7
Plymouth - English Channel	September-1998	51	1.05; 0.4-3.13
Texel North Sea	September-1998	33	8.9; 1.17-70.1
Wilhelmshaven - German Bight	September-1998	32	10.1; 1.2-38.9
Heringsdorf - Baltic Sea	September-1998	51	3.2; 0.51-5.98

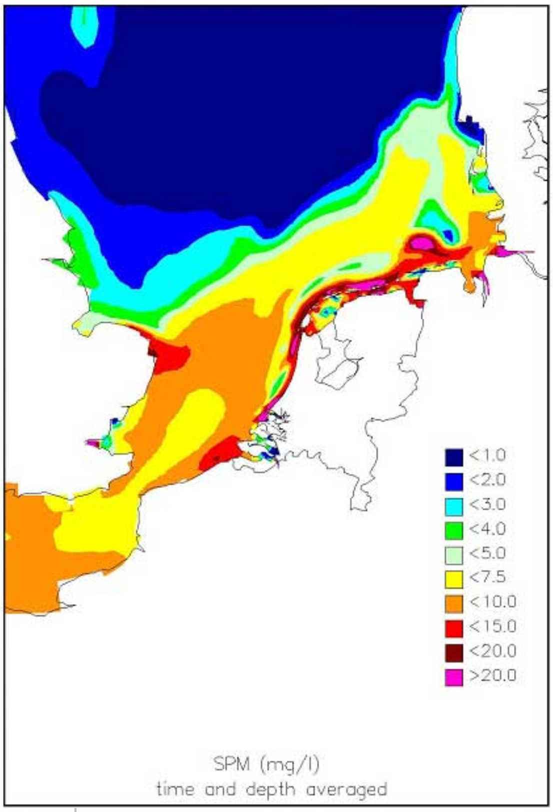


Figure 4.22 Modelling of suspended particulate matter (SPM) in the North Sea with the 3D hydrodynamic model Delft3D-SED (http://www.wldelft.nl/rnd/intro/topic/transport-of-suspended/index.html).

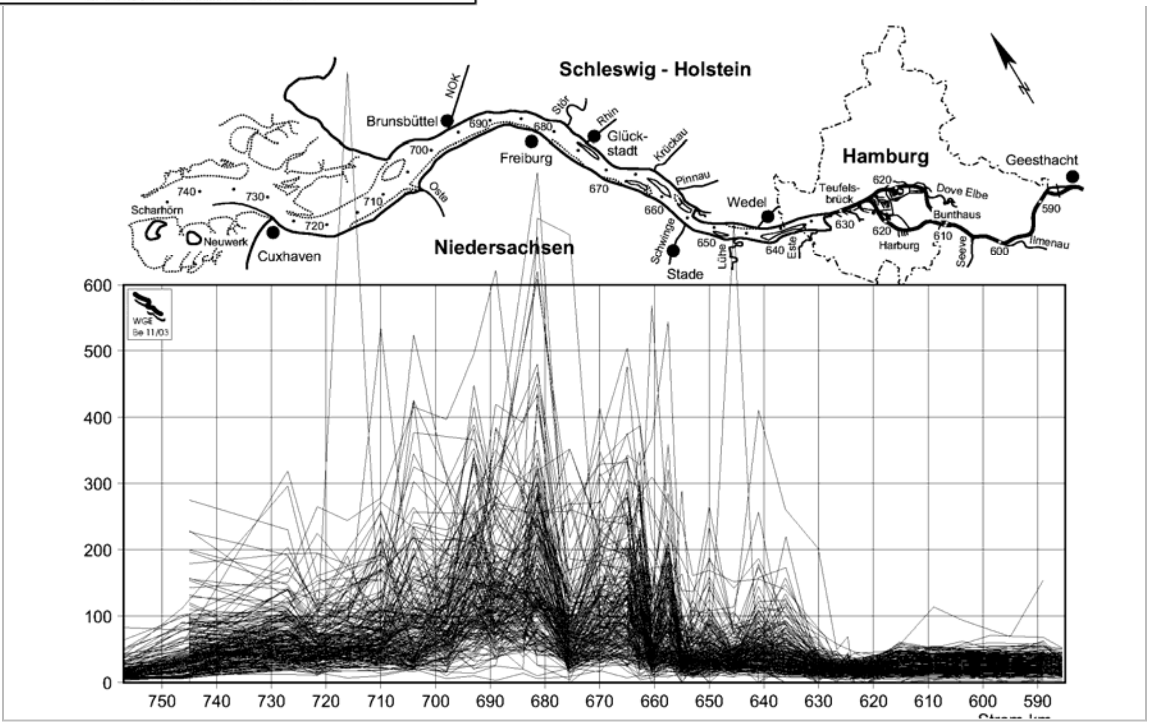


Figure 4.23 Transect of suspended solids at tidal Elbe – 1979-2003 (Bergemann 2004).

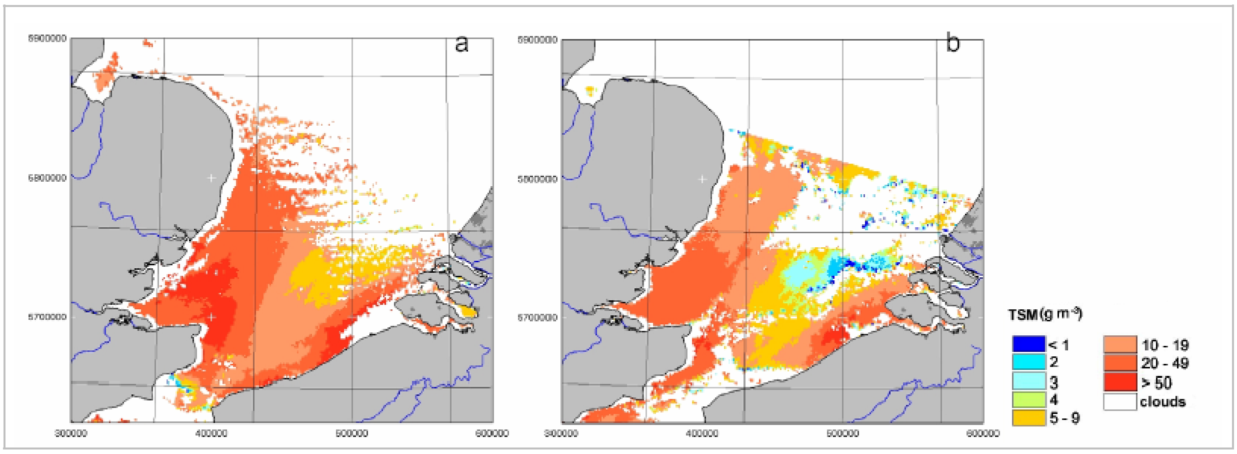


Figure 4.24 Example for sediment settling after storm at southwestern North Sea (simulation); a: High sediment concentrations during storm (28 December 2001); b: The system is restoring three days after the storm (Eleveld *et al*., 2004)

4.6.4 Physical alteration to the seabed

A last point to be discussed under ´disturbance effects` is physical alteration to the seabed. It was already mentioned that cable protection may be applied in form of rock-mattress covers, cast iron shells, cable anchoring, ducting or rock dumping. Other examples for protection measures are the use of special backfill materials for cable burial, reinforced concrete slabs or steel plates. All these protection measures lead to physical alteration of the seabed. The use of any backfill material rather than local sediment may attract non-local fauna. The introduction of artificial hard bottom into an environment dominated by sand will certainly support the settlement of non-local hard bottom fauna. Changes in the structure of the local sand communities in the immediate vicinity of such ´artificial reef` could be expected. Such processes were described as 'reef effect' and extensively discussed in literature (see e.g. Wenner *et al*., 1983, Buckley & Hueckel 1985, Ambrose 1994, Reimers & Branden 1994, Hiscock *et al*., 2002, Birklund & Petersen 2004, Joschko *et al*., 2004, Biowind 2005, Leonhard & Pedersen 2005). The submarine cables themselves if not buried/covered along the seafloor will provide a solid substrate for a variety of species. The larvae of sessile encrusting organisms (encrusting corals, sponges, anemones) have been observed settling on and colonizing the cable surface (Figure 4.25). Numerous other species would also be attracted to the area for camouflage and predation purposes. Studies specifically investigating such effects for subsea cables could not be found.

Figure 4.25 Subsea power cable, in place for approximately 50 years, covered with sessile encrusting organisms at Vancouver Island (BCTC 2006).

4.6.5 Conclusions in regard to disturbance

Disturbance effects related to submarine cables are in general expected to be temporary and localised. It seems that technical standards and modern equipments today guarantee that suspended sediment concentrations which occur during cable burial or removal do not exceed those occurring under natural conditions. Areas along the cable route affected by coverage with protective structures will usually be restricted to a narrow strip along the cable. The potential for introduction of non-local fauna by the application of such protective cover (artificial hard bottom) into soft sediment areas exists. Effects on the local fauna related to that will in most cases be very localized although long-term.

In environmentally sensitive areas physical disturbance, damage, displacement and removal of flora and fauna might turn out to be a significant impact. Avoidance of such areas would be an appropriate mitigation measure.

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