Chapter 7
Installation and Protection of Submarine Power Cables

Contents

7.1 Installation

The installation of submarine cables has developed substantially in many respects during the past 20 years. Cable manufacturers are able to deliver very long lengths of submarine power cables, up to 160 km in one piece. Powerful cable laying vessels with more than 6000 t turntables can operate in heavy sea-states using satellite-based navigation systems and modern propulsion systems. A lot of experience from the oil & gas industry can be used also for the installation of submarine power cables. Also, the booming industry of submarine fibre-cables fuelled the technical progress in submarine cable laying. Remote-operated-vehicles (ROV) have developed amazing skills today, which nobody could imagine only two decades ago. Also, the seafloor

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survey can be performed so much easier than it could 20 years ago, today providing a close-up look onto the seafloor and, thus, avoidance of any adverse condition for the cable.

Still, the installation of submarine power cables is not an easy game. Meticulous planning is necessary, taking into account the properties of the cables, the characteristics of the cable route, and the abilities of the installation machinery. The circumstances differ so much from case to case that planning of costs and schedules must provide room for slippage, even if a good knowledge of all prerequisites exists. A successful submarine cable installation requires a carefully selected and integrated assembly of vessels, crews, and auxiliary equipment. An inappropriate cable-laying vessel, undersized equipment on board, or an inexperienced crew have devastated more than one cable laying campaign. Furthermore, a suitable determined installation management must be included. Clear and powerful authorisations for all parties on board should be agreed on.

7.1.1 Cable Laying Vessels

The cable-laying vessel (CLV) is the heart of each cable laying campaign. CLVs are available at all sizes and with all kind of equipment. Worldwide there are a few fully equipped and highly specialised CLVs for large power cables, such as C/S “Skagerrak” and C/S “Guilo Verne” with payloads exceeding 6000 t of cable (Fig. 7.1).

These high-capacity CLVs have a respectable day rate, particularly in times of high demand. There is also a number of cable laying vessels with very large tonnage

Fig. 7.1 C/S “Skagerrak” DP2 vessel with over 6000 t turntable, suitable for all kinds of power cable installation and repair

built for the installation of telecom cables. Most of these vessels are not suited for the installation of power cables as the cable handling equipment onboard is designed for light-weight small-diameter telecom cables. Some of these vessels can be used for power cable installation after considerable refurbishments.

Apart from dedicated CLVs many other vessel types can be temporarily converted for cable laying purposes. Barges and supply vessels can be equipped with suitable gear for cable laying tasks. Barges do not have own propulsion but rely on tug boats for transfer travel. During cable laying, they can be towed by tugs and/or anchors that are carefully placed along the cable route. Barges for this purpose come in all sizes and shapes.

Factors to be considered when selecting a cable laying platform (vessel or barge) are load carrying capability, manoeuvrability properties, deck space for cable handling equipment and jointing shack, crew quarter size, etc. Good sea-keeping properties, i.e. stability of the vessel in wind and waves, are essential for operations in the open sea. The bollard pull is important when a cable plough is to be used.

The barge in Fig. 7.2 has no own propulsion and must be towed to the destination. During cable laying she is pulled by anchor moorings and winches. The following features are visible: Towing chains at the left, central turntable for heavy cables, anchor winches in each corner, blue accommodation containers in three floors, white A-frame in the aft for launching rigid joints and other structures.

The barge in Fig. 7.3 is able to sit on the seafloor during low tides. The cable is coiled into a fixed cable tank. Another, rather unusual barge with a 1700 tonnes-turntable and a 6 m-laying wheel is the “H P Lading” (Fig. 7.4). She is the chopped-off foreship of the once-proud 1930 Exxon tanker “Esso Köbenhavn” after this was broken up in 1963. She has accommodation for 25 people.

Fig. 7.2 Large cable laying barge (Courtesy of Oceanteam Power and Umbilicals, UK)

Fig. 7.3 Flat bottom barge mobilised for cable laying in tidal flats (Courtesy of Oceanteam Power and Umbilicals, UK)

Fig. 7.4 Cable laying barge "H.P. Lading". Tow barge with turntable for up-and-down spooling on the conical hub (Courtesy of NKT Cables A/S)

A new fleet of high-capacity purpose-built CLVs is under construction. Figure 7.5 shows one of the new CLVs. Important features are:

- Turntable with 6000–7000 t cable capacity
- Space aft of the turntable for a jointing house and cable tensioners
- Large wheel or chute on the aft of the vessel for deploying the cable
- High deck strength to add more cable laying facilities or temporary turntables
- Crane over the cable track to handle rigid joints
- Helipad for easy crew transfer.

Fig. 7.5 Latest generation cable laying vessel (under construction). (Courtesy of Oceanteam Power and Umbilicals, UK)

Load capacity. Each laying campaign should transport as much cable as possible to reduce the number of costly and sometimes risky joints at sea. The largest CLVs for power cables have a turntable with an outer diameter of about 30 m and a load capacity exceeding 6000 MT. The load capacity is marginally dependant on the seawater temperature and salinity, i.e. the location and the time of year. Depending on the cable design, volume or weight can be limiting factors when determining the load capacity.

Turntables. The turntable (or carousel) has a vertical axis and is able to store even the largest of power cables, which cannot, due to their torsional stiffness, be stored in a fixed tank by coiling. Most turntables are being loaded in horizontal layers starting from the bottom layer. According to another "school", turntables have a conical inner hub and the cable is wound onto this hub in concentric layers up and down this hub under constant tension. The CLV "H P Lading" and some new vessels are built according to this design. This method requires a continuous cable tension during loading and laying. If the continuous tension is interrupted, this method can cause disorder in the cable turns as they slide down from the center.

Some vessels are or can be equipped with two independent turntables. With this equipment, two cables can be laid simultaneously. If the CLV is equipped with two spaced laying wheels[1] at the stern or bow, the two cables can be laid at a constant distance to each other. Preferentially, the cables are laid closely, bundled to each other. The bundling is accomplished as the cable pair leaves the CLV by means of suitable tape wrapping or cable straps. This is the preferred method for a pair of HVDC cables in shallow waters (up to 250 m water depth.). In the latter case, the pair of cables can be buried later in a single operation.

[1] The laying wheel represents all type of laying gear such as wheels, chutes etc.

Turntables can be divided into an inner and an outer partition. Two cables can be loaded into these partitions independently, either one after the other, or into both partitions at the same time (Fig. 7.6). This method requires a uniform-lay-direction cable armoring. Basically, both cables can be wound into their respective partition of the turntable independently by using individual feeding speeds out from the factory. A better method is, though, to wind up the cable into the outer partition and to coil down the other cable into the inner partition over a hanging coil spreader. Since the turntable is rotating to wind up the first cable, the second cable goes through a semi-coiling where the cable is twisted less than one time per turn. During laying, the process is reversed and the cables can be laid at the same common speed onto the seafloor without residual torsion. The pair of cables can be laid and bundled so that they can be buried in a single run later on. If the cables are not bundled, they might diverge on their way to the seafloor and thus jeopardize the subsequent burial.

For smaller submarine cable projects or repair jobs, small turntables can be mounted temporarily on the decks of barges or supply vessels.

Fixed cable tanks. Circular or oblong holds for cables are common for telecom cables and can be used for power cables, which are not torsion-stiff. The cable is loaded via a coiling spreader that is hung or fixed in considerable height above the tank. While loading, it is important to maintain a minimum inner coiling diameter specified by the cable manufacturer. Supports must be provided to prevent the cable from sliding down from the growing cable stack. A gang of coilers walking on top of the coiled stack must put the cable in place. For the sake of their safety, the coil

Fig. 7.6 Turntable with inner and outer partition for simultaneous laying of two cables. Here, a submarine power cable (outer partition) and a fibre-optic cable (inner partition) are stored on the turntable (Courtesy of ABB, Sweden)

stack should be fenced as it grows in height. The laying is the reverse operation of the loading, and the cable should land on the seafloor without internal torsion. Fixed tanks can be used for cables of moderate diameter with uniform-lay-direction armoring. Single-core cables with single wire armoring are good candidates for the use of fixed tankes. Medium-voltage three-phase submarine cable can also be loaded in a similar technique in oblong holds in vessels.

Cable drums. For many submarine cable projects with short cable length, it is not necessary to employ a dedicated CLV. Submarine cables connecting offshore wind turbines have a length of 400–800 m. They can be installed from barges or supply vessels equipped with cable drum pay-offs and suitable breaking and tensioning engines (Fig. 7.7). Extremely large drums with horizontal axis can be found on some pipeline laying vessels and, basically, may be used for cables.

Positioning. Every cable-laying vessel must be able to position itself very accurately on the prescribed cable corridor and move in desired directions without loosing positioning control. Even slight deviations from the planned position and heading can adventure the health of the cable or the accuracy of cable laying. The cable may end up in a subsea position different from the anticipated one. Maybe the cable goes down beside a pre-dredged trench, outside a licensed corridor, or in a hazardous seafloor area.

Anchoring systems. The classical method to keep the CLV in position is the use of anchoring systems. The CLV, often a propulsionless barge, is manoeuvred between the holds of numerous anchors fanning out in all directions. The anchors are handled by independent AHT (anchor handling tugs). Cable laying barges employ four to

Fig. 7.7 Laying with cable drums on a barge

eight anchors. They are placed some hundred or even thousand metres away from the barge into the water and connected to winches onboard the barge. The barge controls its position, speed, and heading by operating the winches. In very shallow waters it can be advantageous to use flat barges and anchoring methods and tugs because large CLVs often have large draught and protruding propulsion devices. The anchoring method is risky in waters where other cables or pipelines exist. These lines are hooked easily by the numerous anchors, resulting in costly repair jobs. Also, the anchors must not damage the cable already laid. The anchoring method is a tedious and time-consuming method but it avoids the high day-rates of a self-propelled CLV.

Dynamic positioning systems (DP). These systems keep the vessel on a determined position by means of high-sophisticated navigation systems and various ship propulsion devices. DP systems can move the vessel along a pre-determined course over ground. DP systems can also keep the vessel on station with any desired heading. Within certain limits, this is possible even when wind, waves, or currents try to carry the vessel off course. Conventional screw propellers provide forward thrust and, in combination with rudders, also directional control to a certain degree. A number of other propulsion systems are available to provide directional control, even without rudders and at low or no speed. Tunnel thrusters in bow and stern can push the vessel sideway and turn it on the spot. Azimuth thrusters are screw propellers, suspended in pivotable pods under the vessel (Fig. 7.8). They can turn 360° in most cases, and provide excellent manoeuvrability at any speed. Two independent azimuth thrusters can keep the vessel on station or turn it into the required

Fig. 7.8 Azimuth pods (Courtesy of ABB Oy, Marine, Finland)

heading. The pod propellers can be powered mechanically from an engine in the hull (Schottel drive), or with an electric motor in the pod powered from a generator in the vessel hull. Some vessels have retractable azimuths to improve the ability to navigate shallow waters.

Voith-Schneider propulsions consist of rotating vertical blades mounted under the vessel. They can generate thrust in all directions. Azimuth drives and Voith-Schneider propellers provide excellent manoeuvrability and can move the vessel in all directions (back/forth, sideways), which can be necessary during complicated cable laying or repair operations. In contrast to conventional propulsion, they do not need a minimum speed to maintain direction and control. The vessel is able to lay the cable along a well-defined corridor and still to keep the heading into the weather to reduce roll. For stationary jobs such as jointing or ROV operations the vessel is able to keep station and direction also under rough conditions.

DP systems use different navigation systems such as GPS-supported navigation systems, taught wire systems, and acoustic beacons. Most of modern vessels have GPS based systems. They are classified into DP-classes DP0 through DP3 depending on the redundancy of subsystems according to an International Maritime Organisation (IMO) classification. Redundancy requirements include not only propulsion and navigation systems but also features such as independent power generation systems and other auxiliary systems separated by firebreaks. A higher DP class on the vessel increases the safety of the cable operation. The DP class should be carefully selected with respect to the requirements and risk profile of the project. Sometimes, insurance companies require the use of vessels with a defined DP class. Many large submarine cable projects employ DP2 vessels.

Jointing house. The jointing of submarine power cables can only be performed in specially equipped jointing houses. They must be designed according to the specifications of the jointing company and need to have sufficient size. For a recent submarine power cable project, the on-board jointing house had a size of 4×17 m. The jointing house must be equipped with electric power supply, air condition, and air dryer. It must be fixed sea-worthily on an appropriate place in the cableway on deck. It is of advantage if the jointing house is splitable so it can be removed from the cable after jointing. For safety reasons, the jointing house should have redundant direct radio communication to the vessel bridge, and an alarm bell commanded from the bridge.

Cable tensioners. Also called linear machines, they are necessary for any moving of cables on board and for applying tension during laying. Many linear machines comprise pairs of wheels. The wheel pairs can be opened and closed with controlled pressure to grip the cable. Individual opening is necessary when bulky joints must be deployed. Wheel drive is most often hydraulical. The linear machine in Fig. 7.9 has eight wheel pairs and is installed close to the laying wheel at the vessel stern. The first end of the cable is being passed through the linear machine, which is in pulling mode. When the cable is being deployed into the water, the linear machine can be operated in braking mode. Many machines can be operated in speed- or tension-controlled mode. Linear machines are also available with belts instead of wheels, so called caterpillars. A good friction between the wheels and the cable surface is

Fig. 7.9 Cable tensioner with eight wheel pairs taking grip of the leading cable end

necessary without undue pressure on the cable. Not unlike car tyres, the wheels on the linear machine need to have a sufficient grip for efficient braking/pulling power, and the cable surface must not be too slippery. Some cable layers advocate the use of sand between cable and wheels when the grip slips.

The need for sufficient power in the linear machines must not be underestimated. The cooperation of linear machines, turntables and the vessel must be orchestrated carefully.

Emergency cutter. As described below in the weather chapter, a situation may arise when the cable must be cut in emergency situations. The cutting must be performed rapidly. The preferred solution is a hydraulic cutting head close to the aft wheel with remote control (cf. Fig. 7.10). A simpler device is a movable disc cutter with petrol or electric motor to be operated by a man. The emergency cutting device should be able to cut the cable within 60–90s.

Cableways, rollers, laying and pick-up arms, chutes, and laying wheels are other devices necessary for the cable installation. For each specific installation job, the ensemble of machinery must be selected to meet the requirements and allow for a safe and successful operation. Especially the specified bending radii under defined tension values should be taken into account. It is wise not to try to save money when specifying the equipment for an installation job. Many operations suffered painful delays because of weak cable rollers that have been blown away under heavy loads, or because of too weak linear engines.

It has been discussed to design aft laying wheels or chutes with dynamic heave compensation, in order to facilitate cable installation in higher sea-states. Another

Fig. 7.10 Hydraulic emergency cable cutter

means to reduce the vertical movement of the laying wheel is to arrange it midships, in order to reduce the effects of heave and pitch.

ROV equipment. Many activities in cable laying operations are possible only with the help of ROV (remote operated vehicle, Fig. 7.11). The ROV is a submersible powered tool carrier, which can be equipped with different manipulators and tools. Cameras are valuable to inspect difficult route sections, boulders, outcrops, or man-made leftovers such as wrecks or containers. Also, in easy waters, the ROV can provide valuable data for the as-built documentation. The ROV can handle submarine pick-up operations, inspections of possible damages, and close-ups of questionable areas. ROV are highly complex systems and are available in all sizes. The vessel should have sufficient space for a complete ROV system, comprising the vehicle and its parking space, launch crane, umbilical drum, container for control room and supplies, accommodation for the ROV operating crew, etc.

Helicopter landing pad. For the crew change or transport of specialists like jointers or fault locators a helicopter transfer can be an economic or even the only possible option.

7.1.2 Other Vessels

Apart from the CLV, other vessels are often needed for a submarine cable installation. In strong winds or currents, the CLV may need the assistance of one or more tugs to keep position. During landing operations, a fleet of smaller vessels

Fig. 7.11 ROV with grip manipulators and cameras

is often busy with the handling of pull wires, anchors, floating devices, and the cable. Anchor handling vessels are needed when the cable installation is performed by a propulsionless CLV. For complicated routes, the use of a survey ship during installation can be essential.

For post-lay cable protection a mother vessel for the trenching or jetting equipment is necessary. Before completed protection a fleet of guard vessels is useful to chase away fishing boats and protect the cable from unauthorized access.

Installation jobs far away from the coast require accomodation for the crew. If the CLV does not have sufficient accommodation a separate hotel vessel must be employed. Accommodations must be approved by authorities and insurance companies.

Manned submersible vessels have been used occasionally for cable related jobs [1]. Today, highly sophisticated ROV′'s can perform almost any underwater job without risk.

A 123 kV three-phase cable was installed in 2006 between the two Thai islands of Koh Samui and Kha Nom over a distance of 24 km. Five vessels were participating:

– one laying barge (85×24 m) equipped with 6-point-mooring system, cable tank, LCE, diving spread, jetting spread.
– two AHT (anchor handling tugs)
– one accomodation vessel
– one shallow water jetting sledge support vessel.

7.1.3 Loading and Logistics

Submarine cables with short length can be handled and transported on standard or oversize drums. Most standard and all oversized drums require flatbed trailers making the onshore transport expensive.

When the submarine cable factory is located next to a harbour, the cable drums can be transported to the destination by a cargo vessel. Oversized drums can be shipped in this way avoiding the troublesome and expensive heavy road transports. Some cable manufactures ship long cables in coils laying on a group of rail cars [2], (cf. Fig. 7.12).

The length of in-field cables in offshore wind parks is often in the range of 400–800 m. There are two concepts for the supply of the cables:

1. Supply of pre-cut lengths on drums. Loading and installation require but rather simple machinery and barges with low day rates. However, the correct lengths must already be known in the factory. The requirement of relatively large safety margins in length results in large amounts of scrap cable during installation. Also, the empty drums must be either disposed of or returned, which can be a

Fig. 7.12 Transport of submarine cable on railway cars (Coutesy of NKT Cables A/S, Denmark)

costly activity. Another disadvantage can be a possible client requirement for individual factory acceptance tests on each cable drum.

2. The submarine cable can be shipped in a large coil or on a turntable. On-site, the lengths are cut from the coil as needed during laying. With this concept, less scrap cable and no drums need to be disposed of. However, more complicated equipment is needed both in the factory and on-site.

For the loading of a long cable length, the CLV is mooring directly at the cable factory to take up the cable in one piece. From the factory turntable, the cable runs over cable rollers to the CLV over a laying arm onto the ship turntable. Depending on cable size and equipment capacity, the loading speed is 3–20 m/min. The complicated loading operation requires the synchronised action of turntables and linear machines continuously over days or even weeks. Failures in synchronisation of speed can render kinks, bends, or buckling of the cable. This kind of damages may require costly and time-consuming repairs. Any possible measure to reduce the risk of loss of synchronisation must be considered prior to loading.

Other methods to load long cable lengths manufactured in factories at some distance from the harbour have been used in few cases: Cable roller tracks have been used by a Swedish company, and a British company shipped many drum lengths to a jointing ground at the harbour site. Both methods are tedious and risky.

The loop time for the CLV (load, transfer to site, manufacturing of connecting joint to previously laid cable, laying of the new cable, return to factory harbour) is most often much longer than the laying time. When the installation site is far away from the cable factory, the speed of the transportation vessel can be important. CLVs are relatively slow. Separate cargo vessels can speed up the cable transport, but this scheme requires a transfer of cable from the cargo vessel to the CLV at a port close to the installation site.

The ends of the cable must always be sealed properly to avoid intrusion of water or even humidity. The use of inadequate capping methods or equipment may result in water intrusion, which may require a cut-away of a considerably long length of cable. In the worst case, the cut-away of water-damaged cables requires the use of extra spare cable and extra joints. The end caps are manufactured according to the manufacturer's specifications. Shrink-on end caps often are not appropriate.

The water and humidity barriers in the submarine cable must not be damaged during transport, laying and burying. Too small bending radii, large side wall pressures, shear forces, etc. can destruct metallic laminates and metallic sheathes.

7.1.4 Laying of Submarine Power Cables

Submarine cables on drums, e.g. for in-field cables, can be installed from barges with simpler navigation equipment. A drum pay-off and a linear machine with brake are necessary. The cable runs over a chute or a laying wheel into the water. The chute or wheel must have sufficiently large a diameter to maintain the MBR. The barge normally has no propulsion and must be manoeuvred by tugboats or a set of anchors and winches. Stabilizing the position of a barge requires at least four anchors, one on each corner. Once the anchors are set, the barge can move by hauling in and paying out the anchor lines in an orchestrated manner. The anchors need to be relocated from time to time by specialized anchor handling vessels. To keep the vessel on station at all times, it takes therefore more than four anchors, possibly up to eight or even more. This method is risky to other cables or pipes in the area, and it has actually happened that anchors from the laying barge have damaged cables already installed in the same project. Altogether, this is a very slow method, making 1–2 km a day as a maximum. However, in some waters, the use of barges able to rest on the seafloor at low tides might be the only way to get the job done. In these waters, ROV cameras are often useless as the visibility can be very little or zero.

A linear machine is necessary also for the installation of cables from a turntable. The cable runs from the motorized turntable over a movable pickup arm with cable rollers, through the linear machine, and then over the chute or wheel. The pickup arm normally has the shape of a gooseneck. In the gap between the turntable and the gooseneck, the cable can hang loose. This slack is useful to absorb possible temporary speed differences between turntable and linear engine. The gooseneck is pivotable and often also adjustable in height. Its position is moved according to the point where the cable leaves the turntable. Operators try to keep the slack always in the same curvature. This can turn out difficult, if the turntable drive works depending on load or position of the turntable, or if the linear machine has slippage or wheelspin. The cable runs further towards the laying wheel or chute before departure into the water. Close before the wheel or chute, another linear machine can be installed, working in breaking or pulling mode. For greater laying depth, a Capstan wheel may be used to amplify the cable breaking force from the linear cable engine.

When designing the installation, one of the machines is defined as the "master". This machine defines the laying speed and all other machines, including the vessel propulsion, must follow the master speed.

If the cable would be let down to the sea floor vertically, there would be a risk of looping and instability of the laying direction. The heaving, pitching, and rolling movement of the aft sheave can cause cable damages at the touch down (TD) point, as the cable might be compressed longitudinally. Instead, the cable must be positioned in a well-defined catenary line from the laying wheel to the TD by application of a certain forward tension by means of the vessel. Under these circumstances, the cable hits the sea floor in a flat angle. A fully equipped CLV has the possibility to monitor the catenary parameters. Sensors to monitor the departure angle and the lay tension provide information to calculate the other catenary parameters. Equations relating water depth, bottom tension, top tension, departure angle, and the horizontal distance between aft sheave and TD are given in the Appendix at the end of this chapter.

An inappropriate catenary line or bottom tension can be corrected by a temporary extra pay-out from the turntable, or by a temporary acceleration of the vessel speed. At critical passages of the cable route, the TD should be monitored by ROV.

The bottom tension is considered a critical parameter for the laying. Too low a bottom tension can cause the cable to build loops or to snake, especially if the cable is laid from a fixed tank, which generates twisting in the cable. Many cable laying "pilots" consider that a high bottom tension results in a cable on the seafloor carrying a highly residual tension. The residual cable tension is thought to impede later burying for protection. Figure 7.28 in the Appendix of this chapter shows the main parameters of the catenary line.

Misalignment of the various speeds (vessel, turntable, linear machines, tensioners, etc.) can cause a cable kink, loops or damages of the deck equipment. Submarine power cables that break out from their roller guides during laying may cause serious damages and hazards for the deck crew.

A power cable stored in a fixed cable tank can be paid-out using a fixed or movable pick-up arm over the tank. During loading in the factory, the cable has captured one torsional turn for each turn it was laid around the cable tank. This residual torsion is now released when the cable enters the fixed cable guide on the vessel. The rest of the laying from a fixed tank is equal to laying from a turntable.

Single-wire armored cables are not torsional-balanced. As the cable tension at the laying wheel and the bottom tension are unequal, there will be a resulting torsion in the cable as it goes down to the seafloor. At great depths especially, this may lead to cable loops. The catenary of these cables should be monitored by ROV – if possible – to detect any irregularities.

When a pair of cables is installed simultaneously, the cables can be stored in two independent turntables. A double set of cable handling equipment transports the cables to the laying wheel. Before departing, the cables are bundled together using steel straps, tape wrapping heads, or something similar. Bundled cables can be buried later in a single run. For the Cross Sound and the Estlink HVDC projects, the two HVDC cables and a fibre-optical cable were bundled and laid simultaneously.

For cables stored on inner and outer partitions of a turntable, different pay-off equipment is necessary. Most often, the outer cable has been spooled onto the turntable in the cable factory without torsion. It will be taken up as described with a movable pick-up arm, and paid out. The inner cable must reach the laying wheel with the same speed as the outer cable. Independent from the turntable speed, it will be taken up with a gooseneck and pulled by a tensioner with a speed that corresponds to the laying speed of the outer cable. However, as the turntable is actually turning to pay out the outer cable, only part of a torsional turn is released in the inner cable for each turn it is uncoiled from the turntable. For this, the method is called "semi-coiling".

There is a large difference in cable laying complexity, if a plain feature-less seafloor allows for a "simple" reel-out of the cable, or if the seafloor structure requires that the cable be laid between and around obstacles such as boulders, rocks, or outcrops. Free spans should be avoided under all circumstances. Sometimes, ROV-supported monitoring is necessary in order to direct the cable into the best possible line between the obstacles. This is also valid for pipe and cable crossings. Sometimes, special laying techniques must be developed and engineered for critical cable routes.

ROV monitoring of the TD is recommended even for other reasons:

1. An inappropriate TD angle can damage the cable seriously. Using ROV on-line monitoring can alert suitable action at an early stage.
2. Equipped with positioning device the ROV can supply very precise position data of the cable route for the as-built documentation.

7.1.4.1 Laying of Cable Around a Curve

When laying the cable around a bend with too small a bending radius, the residual bottom tension tends to drag the cable laterally over the seafloor. The minimum required bending radius can be calculated as

$$R_s = L_s = \frac{FT_H}{W_s \mu} \tag{7.1}$$

where (cf. Fig. 7.13)

F, Safety factor (suggested: 2.0);
T_H, Horizontal bottom tension;
W_s, Cable unit weight in water;
μ, lateral friction coefficient cable-soil.

After passing an obstacle, a straight line of length L_s should be laid before the curve is initiated. This is to avoid the cable being dragged against the obstacle as a result of lateral displacement. For cables with smooth extruded outer sheath, the following friction coefficients μ may be assumed: clay 0.2, sand 0.6, and gravel 0.8 [3]. Slightly higher values can be used for cables with yarn serving.

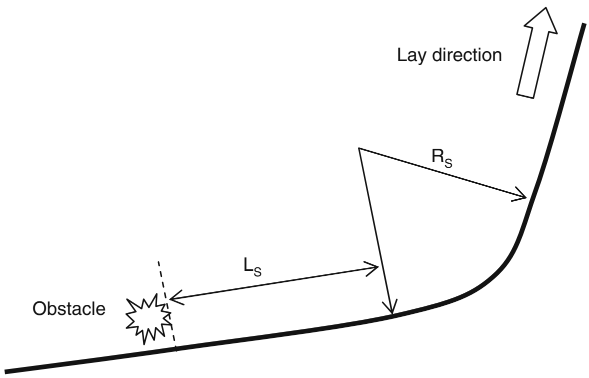

Fig. 7.13 Laying the cable in a curve

7.1.5 Landing of Submarine Cables

The landing of submarine power cables sometimes requires the most engineering, the most equipment and often the most time of all efforts of the cable project. The majority of all submarine cable projects have at least one landing point. Regularly, the laying operation is started here. A number of methods for the cable landing have been used, but new projects may require new methods. The method to be used depends much on the shore conditions, equipment abilities and authority requirements. In cable installation jargon the coastline is called beach even if nobody wants to spend a single day of vacation there.

Sometimes it is possible to establish an open trench through the beach. The entrance point can be stabilised by cofferdams. The open trench goes from the sea entrance to the most appropriate land site for the joint pit between the submarine cable and the connecting land cable, called beach joint. The beach joint can be located inside the real sand beach, behind a dike, or as far away as some kilometres from the beach (e.g. the Baltic Cable project). The trench routing should be as straight as possible in order to avoid undue pulling forces and curves. During pull-in, the cable is guided on roller guideways inside the trench or outside; in the latter case, the cable will be pushed into the trench afterwards. The trench profile must be engineered with respect to thermal properties. Despite the fact that dikes along the European North Sea coast are very sensitive areas and normally must not be penetrated under any conditions, the NorNed cable could be landed through the Dutch protection dike system in open trench thanks to a well prepared operation (Fig. 7.14). Only one year after the operation the dike appears in pristine conditions.

In some areas, the only acknowledged method to cross the beach zone is the use of closed pipes. The method of choice is Horizontal Directional Drilling (HDD), where a drilling station is erected on the land side of the dike or beach. The drilling station drills a hole with a pre-determined curvature under the beach area and/or dike into the open water. The drilling path can be controlled in all directions. After drilling, the hole is lined with steel or plastic pipes for the later pull-in of cables. The pipe sections must be welded without leaving any internal welding beads, which could obstruct the cable pulling through the pipe. The longest possible length for

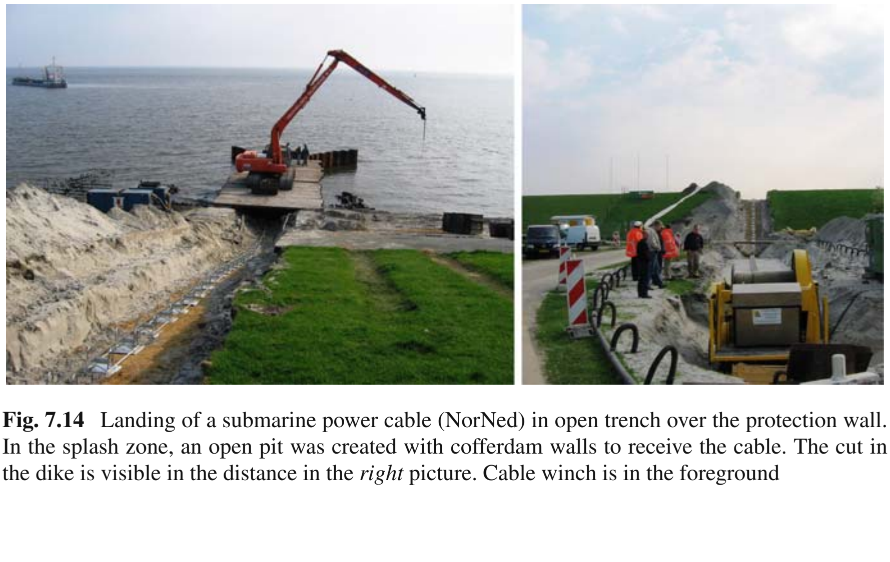

Fig. 7.14 Landing of a submarine power cable (NorNed) in open trench over the protection wall. In the splash zone, an open pit was created with cofferdam walls to receive the cable. The cut in the dike is visible in the distance in the *right* picture. Cable winch is in the foreground

HDD for cable applications is today in the range of 1400–1800 m. The length is limited not only by the drilling technique but also by the maximum pulling length of cables. The latter depends on:

- cable properties like weight, stiffness and maximum allowed pulling forces
- friction coefficients
- bending radii
- lubrication methods
- possibility of employing cable pushing, e.g. at river crossings.

The risk of failure increases more than linearly with the pulling length. For long pull length, the internal diameter of the pipe should be 2.5 times the cable diameter, for a short pull length, a factor of 1.5 is sufficient. Pulling two or three cables in the same pipe increases the pulling forces substantially and is recommended for very short length only (e.g. road crossings). The necessary pulling force for a straight pipe can be estimated by the following equation:

$$\text{Pulling force} = \text{cable weight} \cdot \text{friction coefficient} \tag{7.2}$$

With a pulling length of 400 m, a cable weight of 400 N/m and a friction coefficient of 0.4, the necessary pulling force is 64 kN (~6.4 MT). This is valid for a straight pipe without internal obstructions such as weld beads. The maximum pulling force can be decreased when the pipe is water-filled to obtain bouyancy for the cable. Proper choice of materials for cable sheath and pipe walls can decrease the friction coefficient. Friction coefficients for various material pairings are depending on the explicite composition of the polymeric materials. Tabulated values are of little use in practical life as the properties often are influenced by temperature and dirt on the cable surface. For engineering purposes, the friction coefficient can be set to 0.4 for unlubricated cable pulls, and 0.25 for lubricated cable pulls. Lubricating agents can be mineral slurries, gels, or bio-degradable oils. A slight bend, such as a gentle curve under a river crossing, does not change the figure very much. However, pipe bends increase the necessary pulling force substantially and should be avoided with all methods. Any bend contributes strongly to the resulting pulling force, especially if the bend is located close to the target end of the pulling route. If possible, cable pulling always starts from the difficult bends.

When all land preparations are concluded, the CLV approaches the landing spot as close as possible and stays there by means of its DP system. On shore, a winch is installed and a pull wire from the winch is transported to the CLV and connected to the cable end. The power cable can now be paid out over the laying wheel or the chute. Floating devices (air-filled bags) are being attached to the cable, while more cable is being paid out. Water currents e.g. due to tidal changes and wind may interfere strongly with this operation. The curvature in the cable in Fig. 7.15 was caused by tidal longshore currents.

Fig. 7.15 Floating of a submarine power cable during landing (NorNed). Crew members wear safety harness

Auxiliary boats may be necessary to keep the cable in position, while the shore winch hauls in the pull wire and the power cable to the beach and further to its destination. When the cable end has reached the destination on shore, it can be anchored there and the air-bags can be removed starting from the beach. The cable is now sinking down to its predetermined position. The maximum pulling length on land is much depending on the route. The Baltic Cable, a 450 kV HVDC cable, was pulled for about 5 km from the beach onto land, using a large number of small synchronised cable pulling machines along the route. The above-mentioned methods can be applied for the starting end of the cable. After landing the cable with the above-mentioned method, the CLV can start laying the cable. At the destination beach, different methods must be employed. There, the CLV arrives with the end piece of the submarine cable, which must be brought onto land. The CLV would move towards the beach as close as possible. From now on, the cable would be equipped with floating devices such as air cushions. Then the CLV would turn into a heading in parallel to the beach or even back. It is important that the floating devices are attached to the cable before the CLV starts changing its direction. The CLV now pays out the remainder of the cable, or at least as much as is necessary to reach the beach jointing pit. Since many cables are produced with spare or excess length there will be a remainder of cable onboard the vessel. A pulling eye is attached to the properly cut tailing end of the cable when it leaves the CLV. The floating cable can now be pulled from a shore pulling winch, when necessary assisted by working vessels. Cable layers, pray to your God that it is long enough!

Should weather conditions get worse, threatening the finalization of the destination beach approach, the CLV may reel out the remaining cable quickly in parallel to the shore line and put the cable end on the seafloor with suitable capping. In a later operation, it would recover the cable and complete the installation within a suitable weather window.

The landing of submarine cables to offshore platforms (or offshore wind-turbines, OWT) is somewhat different. Offshore structures with fixed foundations usually carry J-tubes that reach from the seafloor up to the top-side of the platform. The J-tubes are made from steel or polymeric materials. Above the top opening of the J-tube, there is a winch to be used for cable pull-in. The lower opening of the J-tube is bellmouth-shaped and points away from the platform or OWT foundation. The opening may be at, under, or above seafloor level. To install the start end of the submarine power cable, the CLV would approach the J-tube until it reaches a distance corresponding to the water depth or more. A pulling wire is sent from the topside winch down through the J-tube, and further on to the cable end onboard the vessel. The cable is paid out from the stationary vessel, while the pulling wire is hauled in. Ideally, the cable approaches the bellmouth horizontally. The pull-in of the submarine power cable is only successful when some conditions are fulfilled:

- The bending radius of the J-tube must be sufficiently high. It is most advisable to design the J-tube with a bending radius substantially larger than the MBR of the cable in order to avoid undue friction and high tensional loads on the topside winch
- The J-tube interior must be clear of obstacles and welding beads. The J-tube should be camera-inspected before cable pull-in. The internal diameter of the J-tube should be 2.5 times the cable diameter
- The winch is sufficiently strong
- An ROV or a diver shall be provided to camera-monitor the bellmouth.

The landing of the second end of the cable at the next OWT or platform can be performed in a similar way. The difference to the fore-end is that the tail of the cable must be taken off the CLV and parked somewhere, before it can be pulled into the J-tube. The "parking-lot" should be as close to the receiving J-tube as possible to reduce the length of pulled cable. The parked cable can rest on the seafloor when the water depth is in the range of 10–30 m and the seafloor is free of boulders, outcrops, and other obstacles. The parked cable can then be pulled into the J-tube from its "parking-lot" on the seafloor. In greater depths, or when movement over the seafloor is being hindered, the cable end must be parked with floating devices.

7.1.6 Jointing of Submarine Power Cables

Although modern cable laying vessels can store and handle enormous lengths of cable, it is sometimes unavoidable to joint cables on open sea because the length of the cable route cannot be covered with a single shipload of cable. Other applications of submarine cable joints include the jointing of different cable designs along the route. The design of submarine cable joints is treated in Chap. 4.

The assembly of submarine power cable joints on open sea is a challenge that requires meticulous planning, suitable and reliable equipment, and a highly specialised and well-trained crew. With these preconditions, and a sufficiently long period of favorable weather, the joint can be manufactured and deployed safely. The manufacturing of the joint inside the jointing shack is described in Chap. 4. Here, the positioning of cables before jointing and deployment of the completed joint is to be discussed. The deployment of a manufactured joint on the seafloor can be a complicated operation, as the two jointed cables must be handled simultaneously with the joint. No overbending or overtensioning must occur, nor must the cable arrangement get stuck in A-frames or other structures on board. The cable laying circumstances decide which type of sea joint can be used.

Power cable joints must be prepared in purpose-built jointing houses onboard the CLV. A simple tent might be acceptable for the jointing of medium-voltage cables in calm waters. The jointing of high-voltage submarine cables requires jointing houses with air-conditioning, air-drying facilities, hoisting, and cable handling equipment. Outside the jointing house, additional space might be required for the air-conditioning units, storage, and waste boxes.

When laying long lengths of submarine cables in subsequent campaigns it is sometimes not possible to joint the next length immediately to the previous length. It is possible to sink a cable end into the water for an indefinite time and later recovery if the cable end is capped carefully according to the manufacturer's instructions. The use of inadequate methods or equipment may result in water intrusion, which requires a cut-away of a considerably long piece of cable. In the worst case, the cut-away of water-damaged cables requires the use of extra spare cable and extra joints.

7.1.6.1 In-Line Joints

In the simplest laying scheme, the CLV is laying cable **A** first. The end of Cable A is provided with a cable seal with pulling eye, a ground wire, and a hooking arrangement before it is lowered to the seafloor. The hooking arrangement should be ROV friendly for later recovery. Buoyancy links at the end of the ground wire can be useful, should sediment movements bury the ground wire.

After the first laying campaign, the vessel returns to port to fetch the next length, Cable B. The CLV returns to the cable route at the end of cable **A**. The ground wire of cable **A** is hooked with an ROV or a grapnel and pulled onboard over the laying wheel to a jointing shack onboard the vessel. There, the second cable length, which is still onboard the vessel, is jointed to the first cable. If the joint is a flexible joint (cf. Chap. 4), the completed joint can now be transferred through the ordinary laying equipment of the vessel, and passes over the stern laying wheel down into the water. The vessel is keeping a suitable cable tension and layback in order to preserve the joint from undue bending at the touchdown point. The jointed new

Cable B is following, and the laying operation can be continued. This arrangement requires that the complete second cable runs through the jointing shack unless the shack is a split design and can be removed after jointing. If the joint design is rigid, it cannot be pulled through the ordinary cable route and over the stern wheel. Instead, the rigid joint body must be hauled over carefully with cranes. At the same time, sharp bends of the cables must be avoided where they are connected to the rigid joint body. A carefully orchestrated operation of deck cranes, vessel positioning, and winches is necessary to deploy the joint, bring Cable B fully into the cable laying machinery, and lay the joint correctly onto the seafloor. It should be avoided that the joint position on the seaflor is affected by sharp bends, boulder fields, and free spans.

In-line joints are comparatively easy to handle, particularly if flexible joints can be used. The cables lie straight on the seafloor and can later be buried in a single uninterrupted run (precaution is needed when a rigid joint body is too bulky for the trenching equipment). However, the method requires a long period of good weather for the jointing operation and the subsequent laying of Cable B.

A different approach is to lay Cable B without jointing it to cable A in the first place. Cable A and B will later be connected by a so-called hairpin joint.

7.1.6.2 After-Installation Joints

Sometimes it is necessary to lay down both Cables A and B onto the seafloor without jointing. A possible reason might be a short weather window not allowing for both jointing and subsequent laying in one go. Also, it can be less costly to use the high day-rate CLV only for laying, and use a cheaper vessel for the jointing job. The post-lay jointing can be done in different configurations. One post-lay cable configuration is depicted in Fig. 7.16. Both Cable ends A and B are lying on the seafloor with straight overlap, each hopefully equipped with seal, pulling eye, ground wire, and ROV-friendly hooking devices.

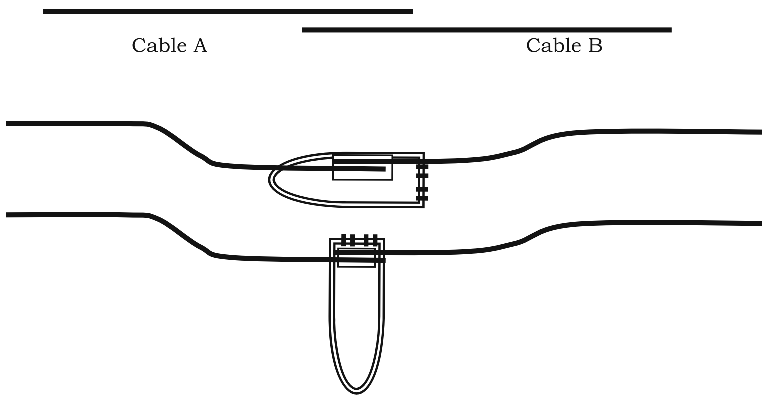

Fig. 7.16 Two cables laid with overlap, and positioned in a jointing shack (symbolized by a rectangle on the vessel) parallel to the bulkward or across the aft deck

For the final jointing, the two cable ends can be pulled up to a jointing shack arranged along the deckside and the bulkward. The ground wires of the cable ends are hooked by ROV or grapnel, pulled up and guided to the jointing shack over wheels, chutes, and suitable cable guides. The length of the overlap in Fig. 7.16 must be two times the water depth, plus the length of the desired catenary lines during jointing, plus 100–150 m depending on the length of the cable guides on-board. It can be prudent to have an extra length to provide cable for a second try if the first joint must be redone.

Another similar set-up is to have the jointing shack transversely across the aft deck of the jointing vessel (cf. lower part of Fig. 7.16). The Cables A and B would be pulled up over chutes or wheels protruding laterally from the vessel, and guided into the jointing shack using winches, linear machines, or other suitable equipment. The ends are positioned inside the jointing shack with overlap according to the joint manufacturer's instructions. The cables must be secured firmly outside the jointing shack so they cannot move under any conditions.

The vessel must keep station during the subsequent jointing operation. If the DP system cannot keep the vessel on station in difficult weather tug boats can assist to stabilize the position of the CLV. After jointing the jointing shack must be removed or opened so that the jointed cables can be deployed into the water.

Another configuration for a post-lay jointing is shown in Fig. 7.17.

The cable ends are laid departing from the straight cable route. The distance between the two cables in the spur route may range between 5 and 20 m. The length of the spur route must be sufficient in order to keep the cable in a stable position on the seafloor even if the CLV keeps pulling in order to maintain a proper catenary line during the jointing. The minimum length L_S for stability is given in Eq. 7.1 in this chapter. Further allowance must be made for 100–150 m on board of the CLV. If provisions shall be made for a second try of joint manufacture, the spur cable

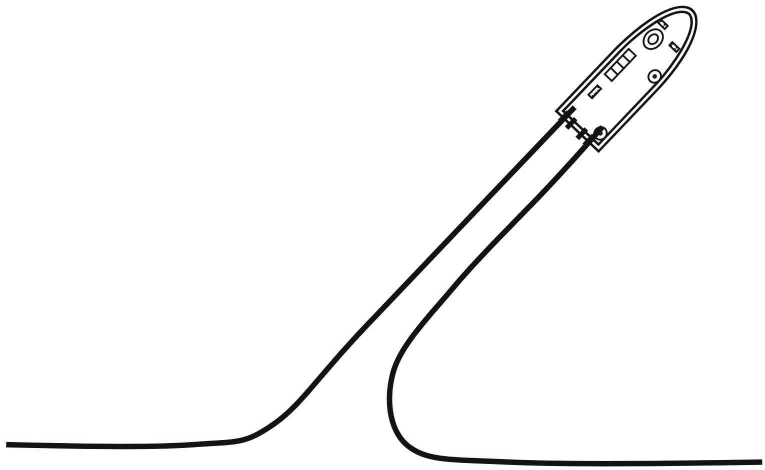

Fig. 7.17 Two cables laid for a hairpin joint

length must be even longer. The spur cable route may be laid in a sharper angle to either side in order to provide an advantageous CLV heading into the waves for the jointing operation to come.

For the preparation of the hairpin joint, both cable ends are pulled up to the vessel aft deck simultaneously, while the CLV travels backwards along the spur route. One cable is being pulled up over the ordinary stern wheel, the other over a provisional wheel or chute. Well onboard the vessel, both cable ends are guided to the jointing shack using winches, linear machines, or other suitable equipment. The ends are positioned inside the jointing shack with overlap according to the joint manufacturer's instructions. The cables must be secured firmly outside the jointing shack in a way that they cannot move under any conditions. The CLV must keep station during the subsequent jointing operation. After jointing the jointing shack must be removed or opened so that the jointed cables can be moved. The jointed cables **A** and **B** form a loop or hairpin-shaped open bend which now must be deployed into the water. The deployment of the joint is possibly the trickiest part of the operation. The excess length of the two jointed cables must be organized to form gentle curves on the seafloor. A welded steel arc ("quadrant") is used to support the cable in the loop and provide the correct bending radius (cf. Fig. 7.18, and the description of an example repair operation in Chap. 7). During the deployment, the vessel moves along the spur route to maintain suitable cable tension.

In the trade, the hairpin that is deployed on the seafloor is also known as "loop", "omega", or "final bight". More nicknames are probably being used.

Suitable vessel equipment provided, a hairpin joint can be installed with both flexible and rigid cable joints. The advantage of hairpin joints is that it can be pro-

Fig. 7.18 The quadrant, a steel support frame, goes into the water (Courtesy of ABB, Sweden)

duced independently of the cable laying operation, maybe on a later occasion with more favorable weather. The hairpin joint can also be manufactured using a different vessel with appropriate equipment for the operation. This vessel can have a lower dayrate than a top-of the-line CLV. A hairpin joint provides no straight cable corridor and post-lay trenching must take special measures to protect the spur route and final bight.

7.1.7 Weather

Weather is the cable crew's worst enemy. Countless are the hours during which an armada of cable laying vessels and working boats has been rolling idly in waves and wind for hours, days, or even weeks until useful weather appeared from the skies. Weather can demolish any working plan and any schedule. Neptune is still invincible if it were with the fanciest technology. Waiting on weather ("WoW") is a very costly way of doing nothing.

Unfortunately, it is almost impossible to list weather limits for a safe laying operation. Neither wind nor waves per se constitute obstacles for cable laying. What matters is only the movement of the laying wheel when the cable is hanging down from it. This movement is caused by waves, which in turn are caused by winds. Each step in this causal chain involves statistical relations and local parameters making things difficult.

7.1.7.1 Winds

Wind generates waves. The wind distribution can be very different for different places and is subject to strong seasonal variations, which may create weather windows of different length for the cable laying. The wind speed is given in the classical Beaufort scale or other speed units such as km/h, m/s or knots (1 kn = 1852 m/h). Relations are listed in Table 7.1 together with the characteristics of related sea-states.

7.1.7.2 Wave Properties

Waves originate from wind blowing over a water surface. Fresh wind waves usually have a short time period and can be rather steep. The longer the length of the route where wind can attack the water ("fetch") the higher the waves can build up. In parts of the North Sea, westerly winds have a longer fetch and build up much higher waves than easterly winds. In the Baltic Sea, parts of the Mediterranean, and other marginal seas the fetch is limited and the wave height is often smaller than with similar wind forces over the Ocean.

The size of waves that wind of a given strength can generate depends also on the wind duration and the water depth. Empirical formulae for the calculation of wave characteristics from wind speed are given in [4] for the Baltic and North Sea. Table 7.2 summarizes some of the results with the condition of constant wind speed in constant direction over the entire area.

Table 7.1 Wind speed and sea-states

Beaufort	Wind speed Kn	km/h	m/s	Description	Sea conditions
0	0	0	0–0.2	Calm	Flat
1	1–3	1–6	0.3–1.5	Light air	Ripples without crests
2	4–6	7–11	1.6–3.3	Light breeze	Small wavelets. Crests of glassy appearance, not breaking
3	7–10	12–19	3.4–5.4	Gentle breeze	Large wavelets. Crests begin to break; scattered whitecaps
4	11–15	20–29	5.5–7.9	Moderate breeze	Small waves
5	16–21	30–39	8.0–10.7	Fresh breeze	Moderate longer waves. Some foam and spray
6	22–27	40–50	10.8–13.8	Strong breeze	Large waves with foam crests and some spray
7	28–33	51–62	13.9–17.1	Near gale/ Moderate gale	Sea heaps up and foam begins to streak
8	34–40	63–75	17.2–20.7	Fresh gale	Moderately high waves with breaking crests forming spindrift. Streaks of foam
9	41–47	76–87	20.8–24.4	Strong gale	High waves with dense foam. Wave crests start to roll over. Considerable spray
10	48–55	88–102	24.5–28.4	Whole gale/storm	Very high waves. The sea surface is white and there is considerable tumbling. Visibility is reduced
11	56–63	103–119	28.5–32.6	Violent storm	Exceptionally high waves
12	64–80	120	32.7–40.8	Hurricane	Huge waves. Air filled with foam and spray. Sea completely white with driving spray. Visibility greatly reduced

The values given here serve for an approximate overview and must not be taken for engineering purposes. It is highly recommended to use wave spectra for the actual location of a proposed submarine cable project.

Waves generated by winds can travel a far way over the oceans. Travelling over hundreds of miles, the waves become less steep, having longer periods, but can

Table 7.2 Wave height at different wind speeds

	Wind speed			
	20 kn 10.3 m/s 37 km/h 5 Bft	30 kn 15.4 m/s 56 km/h 7 Bft	40 kn 20.6 m/s 74 km/h 9 Bft	46 kn 23.7 m/s 85 km/h 10 Bft
Baltic Sea				
Significant wave height H_s, m	1.6	3.3	5.3	6.3
Highest of 100 waves $H^{1/100}$, m	2.4	5.0	8.0	9.5
North Sea and Mediterranean (west of 21°E)				
Significant wave height H_s, m	1.9	4.8	8.6	10.3
Highest of 100 waves $H^{1/100}$, m	2.9	7.2	13.0	16.0

conserve much of the wave height. These waves, which are generated far away are called "swell", and may prevail for days after they have been generated. Travelling waves can be reflected from coastlines. In some spots, travelling waves from different origins can interfere and build up to larger wave heights than those from each contributing wave train. Refraction and interference of waves can build up complicated wave patterns particularly between coastal islands and the mainland, or in waters where sand banks can impact wave train directions [4]. For this reason, the waves at a certain location are composed of waves with different characteristics and height. Wave direction can be different from and even opposite to wind direction. Waves can be existent in the absence of wind, as a result of earlier winds/storms.

Each sea-state comprises a spectrum of waves with different wave height. The wave height distribution is often described as a Raleigh distribution. In many sea-state forecasts the term "significant wave height" is used. The significant wave height H_s is defined as the average wave height of the highest third of all waves [5, 6]. In practice, one would measure the height of 10,000 subsequent waves and take the average of the highest 3333 waves to obtain H_s. The definition of H_s is independent of the statistical distribution of the wave heights. If the Rayleigh distribution is used the probability of various wave heights can be related to H_s:

$H^{1/10}$ (one wave out of ten in the upper third) $= 1.27 \cdot H_s$
$H^{1/100}$ (one wave out of hundred in the upper third) $= 1.67 \cdot H_s$
$H^{1/1000}$ (one wave out of thousand in the upper third) $= 1.86 \cdot H_s$
H^{max} (Max wave height expected) $= 2 \cdot H_s$

Figure 7.19 shows Raleigh-distributed wave heights for a significant wave height of 4.4 m (indicated by a vertical line).

Other researchers prefer other statistical distributions (e.g. Gauss distribution) to represent the wave spectrum. This disagreement reflects the fact that the wave spectrum differs between locations. A comprehensive treatment of wave theories and a related bibliography can be found in [7]. Freak waves (also called "monster

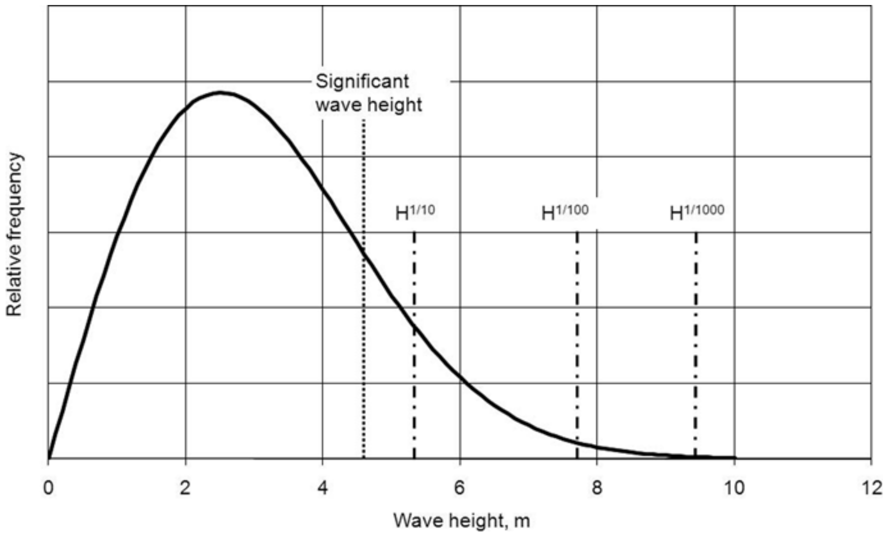

Fig. 7.19 Wave height of a Rayleigh-distributed wave spectrum. Significant wave height is indicated by a *vertical line* at 4.4 m

waves" or "rogue waves") are not part of these statistics. Today the existence of freak waves is widely acknowledged [4, 8].

For the cable installation engineer, it is important to know that the maximum wave height can be roughly twice the significant wave height given in sea-state forecasts, and that waves with $2{\cdot}H_s$ are expected to occur a few times in each eight-hour interval. As the accuracy of sea-state forecasts decreases for longer forecast horizons, the cable installation engineer should consider increasing the safety margins for cable installation operations with long duration.

7.1.7.3 Vessel Movement

The next question is how different vessels react to a given wave spectrum. The response is not only depending on vessel size but also on its design and equipment. For each CLV a RAO (Response Amplitude Operator) can be established that takes into account an individual vessel's size, mass distribution and other parameters reflecting the seakeeping properties of the vessel.

The movement of a cable laying vessel (CLV) has six degrees of freedom (Fig. 7.20):

The RAO (Response Amplitude Operator) for the vessel in question translates wave characteristics to vessel movements. In particular, the heading of the waves with respect to the vessel is an important factor to determine the vessel heave, pitch, and roll from the wave characteristics. For laying operations, pitching and heaving have the largest influence on the vertical movement of the laying wheel. Still, rolling cannot be totally neglected if the aft laying wheel is off the vessel centre line.

Lateral movements	Heave (up and down) Surge (back and forth) Sway (right-to-left)
Rotational movements	Roll (rotation around the longitudinal axis) Pitch (rotation around the beam axis) Yaw (rotation around the vertical axis

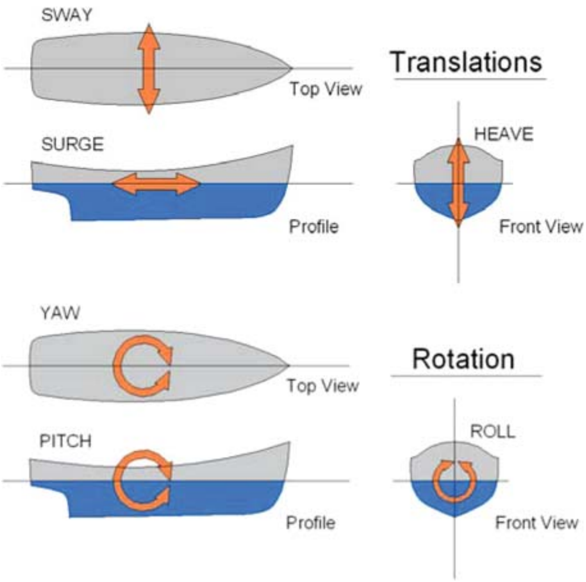

Fig. 7.20 Six basic movements of a ship. Source: Wikipedia, http://en.wikipedia.org/wiki/Ship_motions

Figure 7.21 shows the RAO factor for a specific cable-laying vessel in the 6000 t payload class. The period time of the (sinusoïdal) wave is represented on the *x*-axis. The *y*-axis is the RAO factor for heave. The factor is given in m/m, and describes the relations between the resulting heave amplitude to the causing wave amplitude. A RAO heave factor of 0.6 means that the heave of the vessel is 0.6 times the wave height. Seven curves are given for different wave headings related to the vessel. 180° means head-on waves, 90° are beam waves. Some interesting observations can be deducted from Fig. 7.21:

- The vessel response on waves is very much depending on the wave direction and the wave period time.
- Waves with short period time usually do not cause large heave since the wave length is smaller than the vessel length.
- Beam waves can cause large heave even at relatively short period time.
- In very short and very long waves the wave direction is less critical for the heave.

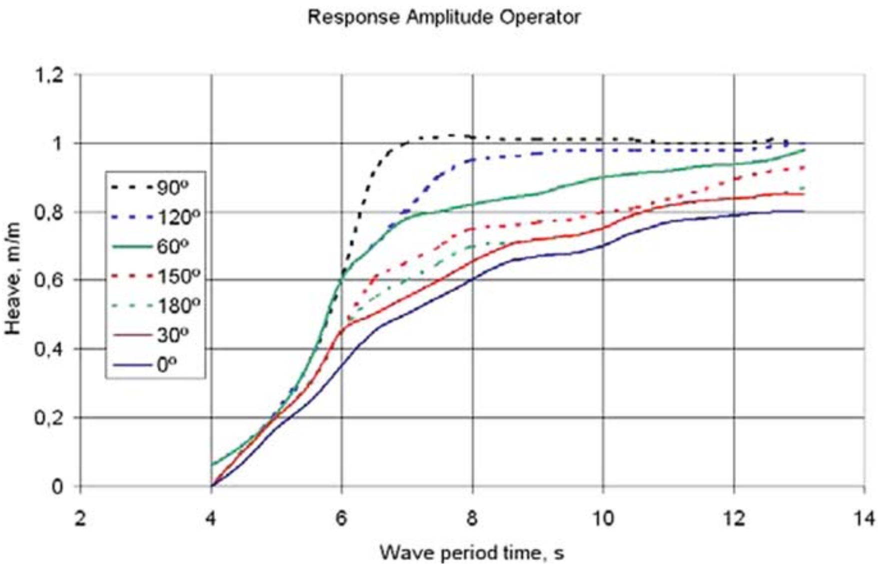

Fig. 7.21 RAO for heave for a 6000 t payload CLV

During cable laying, the vessel heading is dictated by the cable route. If the cable route is S–N and the prevailing winds are NW, the CLV receives the waves from a quarterly direction, which often results in the most onerous movements.

The cable that is hanging down from the laying wheel in a catenary line is subjected to a number of forces. Let us first consider a simple case when the cable hangs down almost vertically. Assume that the cable has a weight w per meter in water (that is the weight in air minus the cable's buoyancy). The water depth is D. The vessel stands still. The weight of the hanging cable is now

$$F = D \cdot w \tag{7.3}$$

Now, we assume that the laying wheel is moving up and down in response to waves. To make it easy, we assume that the vessel floats on the waves like a wine cork, i.e. the laying wheel movement is identical to the wave movement. The movement has a sinusoidal shape. The movement amplitude (measured peak to peak) is h, and the movement period (time between subsequent upside peaks) is T. The laying wheel movement can now be described as:

$$y = h/2 \cdot \sin(2\pi/T \cdot t) \tag{7.4}$$

The largest acceleration of such a movement can be found by twofold derivation with respect to time and amounts to:

$$a_{\max} = h/2 \cdot (2\pi/T)^2 \tag{7.5}$$

As an example, a vertical laying wheel movement with 4 m peak-to-peak and a 6 s period time reaches a maximum acceleration of about 2.2 m/s^2. The maximum force on the hanging cable is now

$$F_{\max} = F + m \cdot a_{\max} \tag{7.6}$$

where m is the mass of the hanging cable. Since the force due to acceleration is an inertia phenomenon, the cable mass must be used for the calculation rather than the weight in water or air.

Actually, this value can be larger still. Especially high waves with short period can cause substantial acceleration values. In addition, waves can interfere, which leads to sudden vertical movements. Stowing guidelines published by the International Maritime Organization (IMO) and International Labor Organization (ILO) of 02.05.1997 state that vertical acceleration of up to 1 g (=9.81 ms^{-2}) can be observed at the aft and bow of a vessel [9]. However, these high acceleration values are encountered on vessels under speed into head waves, which results in shorter wave periods. The speed of CLVs is rather low (mostly under 1 kn) so the contribution of vessel speed can mostly be neglected. Still it is prudent engineering to consider an appreciable vertical acceleration when estimating the cable tension.

During cable laying with a departure angle of 25°–30°, the suspended cable length is considerably higher than the water depth. The entire cable must be accelerated following the vertical movements of the laying wheel. The cable portion far away from the wheel, close to the TD, is moving up and down with, in comparison to the laying wheel, lower amplitude. The necessary force to accelerate the cable must be vertical. The cable can only transmit forces along its own direction. For this reason, large tensions along the cable have to be transmitted to create the vertical forces for the cable acceleration close to the TD.

The tensional forces on the cable are results of waves with a statistically distributed wave height. Even if the significant wave height of the weather forecast seems to be harmless, only a few waves of exceptional amplitude can cause tensions big enough to damage the cable.

7.1.7.4 Other Impacts of Wind and Waves

Vessel movements can introduce adverse effects on cable laying beyond the tensional force on the cable:

Crew work ability. Many seamen suffer from seasickness. In heavy weather, 10–30% of the crew might be sick and unable to work [10]. The healthy part of the crew might be unable to work for safety reasons.

Danger to the crew. The cable jointing crew inside the jointing shack can be subjected to danger from moving equipment. All equipment in the jointing house must be lashed to the walls or the floor, and working can be very difficult when the jointers need one hand to secure themselves all the time. The power cable must be anchored firmly on board to keep it in place. The greatest danger comes from the cable in the jointing shack. In very strong heaves, the cable hanging in the water is exposed to forces so strong that it might be overtensioned. The grip of cable tensioners might slip or the cable securing devices on board might break.[2] The situation is out of control, when the heavy cable starts now moving unfastened in the jointing shack and over deck areas. This is seriously dangerous for the crew, the equipment, and the vessel. It calls for immediate crew clearance of the area and possibly emergency cut of the cable in order to save health or life of the deck crew. Emergency cutting is a safety measure and causes normally large economic losses in form of costly repair operations and schedule slippage. Should the Master or the charterer of the vessel, in order to save consequential costs, put the crew's safety at risk, he can be subject to criminal prosecution.

Loss of position. The CLV keeps station by means of thrust engines. In heavy weather, the thruster capability can be overwhelmed by side winds, strong currents and/or waves. The vessel is driven from its determined position. The cable is still in its hanging position and may act as an anchor chain. It can be subject to additional tensional strength and also to other forces, when the direction of drift is not along the cable route. This has happened in a number of cable installation projects. When the CLV is been driven back over the cable, there is a risk of twisting and kinking of the cable.

7.1.8 Organisation

In 1964, a report on a submarine cable laying operation declared: "Captain and crew of the boats shall be cooperative with the cable laying work and, if possible, having experience in cable handling" [11]. The insight behind this statement was not new. However, more than one project manager wished that everybody had read this report. Today, the installation of a major submarine link is a considerable industrial construction project. Only with meticulous planning, appropriate resource allocation and thorough contingency preparedness the project can succeed.

A number of different companies can be engaged in a cable installation such as the following parties:

- The client, represented by the client rep on board
- Nautical crew of the vessel from Master to maid
- Cable laying and handling crew onboard, perhaps from another company
- Cable manufacturer representative

[2] Cable tensioners must never be used alone to secure the cable during jointing.

- Survey company responsible for staying in the cable corridor, making fresh in-situ surveys, and preparing the as-built documentation
- Owners and operators for the ROV equipment, guard vessels, auxiliary vessels
- Insurance companies.

These companies can be contracted independently by the client, or can have a subcontractor hierarchy, or anything in-between. In many projects, the different tasks of the cable laying operation are organised by a single contractor who is using subcontractors. The single contractor is the only interface to the client, and the coordination responsibility is put on the single contractor. This is a convenient structure for the client as he has only one contractor to talk to. It is fair, when the single contractor is claiming extra compensation for his efforts of interface coordination and increased risk exposure.

In a different business plan, the client goes shopping for all different supplies and services in separate contracts. This gives the client the opportunity to procure the best offer for each of the contracts and to avoid paying coordination surcharges to a general contractor. In this case the interface coordination is an effort to be performed by the client (or an external company hired for that purpose).

In any case, there must be clearly defined responsibilities, order flow and mandates, and communication paths between the participating parties.

It can be of advantage for the client to hire contractors who have been working together successfully in previous projects.

Coordination and planning meetings involving the parties should be conducted repeatedly and long before the operation starts. Flaws in the project organisation or/and the installation equipment can be detected during these personal meetings. People meet, people accept the other's roll, and people know whom to talk to. The importance of a mutual understanding of the role and competence of each party can't be overestimated. Costs for early coordination meetings pay back manyfold.

During the cable installation, daily operation meetings are conducted involving representatives for all relevant parties. Apart from the HSE (Health, Safety, Environment) topics, the progress of the last 24 h and the planned work for the next 24 h are to be discussed then and there. In separate tool-box-meetings, the details of certain work activities are organized with the relevant crew.

7.2 Protection of Submarine Power Cables

Submarine cables are precious assets and need to be protected from external hazards. The 1986 Cigré study [14] presents a comprehensive compilation of submarine cable faults and protection methods. The protection constitutes a considerable part of the total investment.

There are four principle steps of submarine cable protection:

1. selection of a suitable cable route
2. design of suitable cable armoring
3. protection on the seafloor e.g. by burying
4. active after-installation protection.

It is widely accepted that a well-designed cable protection enhances the reliability and, hence, the availability of the cable system. The operational costs for repair and maintenance can be reduced by a proper protection.

7.2.1 Selection of a Suitable Cable Route

After a desktop study a provisional cable route can be selected. As far as possible, hazardous areas should be avoided, such as:

- Shipping lanes, anchorages, harbour entrances
- Fishing grounds
- Boulder fields, outcrops, submarine canyons and steep slopes
- Wrecks, ammunition-dumping grounds, debris
- Areas with strong water currents.

Shipping lanes should be avoided because the presence of heavy ship traffic can impose restrictions on the installation operations. Also, the risk of anchor damages is higher where ships travel. If shipping lanes have to be crossed somewhere, it is advisable to do this at right angle to keep the interference low. Anchorages, ammunition-dumping grounds, and military exercise areas are strict no-go's for submarine cable installation.

Fishing grounds exercise a direct threat to the cable's health. Not only fishing nets but also ancillary gear such as mooring points can do harm to the cable.

Landing points for the cable link must be selected carefully. Shorelines have very different characters and are sometimes stable in their position, sometimes very volatile and prone to changes. The shoreline and the adjacent bathymetry may change rapidly due to tidal current, longshore currents, wave patterns, seasonal storms, and more. Even if many coastal communities try to preserve the coastline as it is by various costly measures, there are voices advocating the acceptance of natural changes of the shorelines.

Shorelines may also be disturbed by man-made interference such as breakwaters, harbour entrances, beach protection, etc. When selecting a cable route, also future near-shore developments should be taken into account.

Electric stray currents from on-shore activities (electric trains, welding, etc.) have reportedly caused cable damages. Therefore, the route selection should also include possible effects from onshore activities.

Many other obstacles may be hidden in the water or even under the seafloor. The following list has a few of these, and many more different things have been found by the survey crews: ship wrecks, abandoned cars and trucks, lost containers, dumped construction materials, active or defunct subsea installations, military installations, garbage dumps, intake or outflow pipes, etc. Most often it is not possible to avoid the crossing of cables and pipelines but one should select suitable crossing points at a distance from shore.

OWP installations define a safety zone of 500 m for their own protection but it is strongly recommended to keep away from OWP at least 2000 m, unless the cable in question runs to that OWP. This is to enable possible future repair activities, which may require some space outside the cable corridor. Also, future OWP must be taken into account. The laws of the High Seas do not grant a safety zone around the submarine cable.

Great care should be devoted to the selection of the best seafloor topology and morphology for the cable route. Not only boulder fields, outcrops, submarine canyons, and steep slopes threaten the cable or call for trouble during installation. A smooth sandy seabed might seem suitable for laying and installation, but there might be a ridge of rock just some feet below, making the subsequent trenching very difficult.

Sand waves on the seafloor might constitute considerable risks for the cable life. Sand waves can move on unpredictable paths creating unexpected patterns through the years. As a result, the cable can be buried much deeper than previously expected, or the cable can ly exposed and without protection in the valleys between the sand waves. In worst cases, free spans may be generated, or the exposed cable may be sand-blasted by the sand-loaded current.

It can be more economic to run the cable in a detour rather than spend money for a higher degree of other protection in a dangerous area.

Route selection also includes fine adjustment during cable laying where ROV can monitor the detailed cable route and helps laying the cable between rocks rather than over them. In a Norwegian project, the cable was allowed to follow the “valleys” between seafloor elevations, rather than a “blind” straight laying (Fig. 7.22). Actually, hiding the cable between natural elevations might give it a good protection without burying it, but it requires meticulous control of the cable touchdown during laying.

7.2.2 Design of a Suitable Cable Armoring

The armoring of submarine cables (power or telecom) must be designed to meet the tensional forces during laying and the protection requirements during the lifetime of the cable. The telecom submarine cable industry has developed an armoring

Fig. 7.22 The initially planned route (*straight line*) would have implied several ridge/valley crossings with risk for free spans. Detailed route survey enabled to lay the cable along the *curved* route avoiding strong undulations [12] (Courtesy of Submarine Telecom Forum)

philosophy according to Table 7.3. According to this philosophy, the shallow water cables are protected with heavy armoring against external violence, while the deep-sea cables have a lighter armoring because there is little threat from human activities down there.

Submarine power cable projects in the 1950–1980s have often followed a similar concept providing a heavier armoring for the beach section as external dangers are

Table 7.3 Types of cable armoring for submarine telecom cables [13]

Water depth	Armoring	Characteristics
< 200 m	Rock Armor (RA)	Double armor with short lay in the outer armoring layer, improved impact resistance and better flexibility to follow seafloor undulations
<500 m	Double Armor (DA)	Protected cable for areas with little or no burial depth
<1500 m	Single Armor (SA)	Used for areas with limited burial depth

expected to be more frequent in shallow waters and in the splash zone. The open sea cable was covered with a lighter protection. The principle is very easy: more massive steel wire armoring provides a better protection against fishing gear and anchors.

As submarine power cable dimensions and weight have grown considerably during the last two decades, manufacturers are less keen to provide extra heavy armoring for the beach zone. In many cases, the armoring is designed only to meet the requirements of tensional forces during laying. As most power cables are installed in shallow to moderate depths (< 300 m), the armoring can be designed rather simple. Often, this allows for a thin-wire armoring, which is not prepared to cope with external threats. Unfortunately, the protection against damages is sometimes neglected when manufactures try to submit the lowest bid. However, there are good examples as well. The Channel Island cable between France and Jersey/Guernsey was equipped with an extra-strong steel wire "rock armor" in 2000. A double-layer counter-helical armoring provides a much better protection against external violence than a single-layer armoring. In many encounters of submarine power cables with installation gear, anchors, etc., the outer wire layer was damaged but not the inner layer.

It should be considered carefully if the circumstances of the cable route (shipping lanes, fishing grounds, etc.) or the installation method may call for additional reinforcement of the cable. Often, the manufacturer can offer armoring with higher protection level as an option.

The choice of the appropriate armoring is a difficult balance between up-front capital costs and expected (better: feared) costs of future cable damages including repair and income losses. The initial costs for extra heavy armor are known but the future costs can only be projected estimates. It should be taken into account that the armoring cannot be upgraded after a few years of project experience.

Shorter parts of the cable can be equipped with additional protection by attaching plastic shells during laying of the cable (cf. Fig. 7.23). This method is often used to strengthen the protection at cable and pipeline crossings.

7.2.3 External Protection

Many submarine cables have been laid unprotected on the seafloor except for the immediate beach zone until the 1980s and 1990s. Until then, it was almost taken as inexorable fate that submarine power cables are being damaged from time to time. When appropriate subsea burial equipment became available in the 1980s, the burial protection of longer cable stretches became more common. Existing cables such as the Baltic Cable were buried afterwards to upgrade the protection level. When the Cigré study on mechanical damages to submarine cables [14] was compiled in 1986, only a small fraction of submarine power cables were externally protected. The study also accounts for the fate of the Kontiskan link between Denmark and Sweden. The first cable there was laid unprotected in 1964, designed to withstand all what was known of fishing gear at that time. Fishing gear grew heavier with time, and during the early 1970s, the cable was damaged too many times by trawls. It was

Fig. 7.23 Protective plastic shells are attached to two HVDC cables and an FO cable before the cable group leaves the vessel (Courtesy of ABB, Sweden)

decided to replace a piece of the cable by a cable with heavier armoring, and to bury the new cable piece. The new cable piece had no failures until the report was written, while the remaining unburied cable suffered another 14 failures during the same time.

Today, almost all submarine power cables have an external protection (burial or covered). This protects the cable not only against accidental damages but also against sabotage. For over 100 years, submarine cables have been the target of war-related assaults; today evil forces might try to attack unprotected submarine power supply. Having this in mind, the insurance companies would probably reward suitable protection efforts with a lower premium, or even require complete cable protection prior to issuing an insurance policy.

7.2.3.1 Trenching

The most common protection method today is trenching, i.e. the burial of the cable under the seafloor.

There is a variety of different trenching methods, and new equipment is being developed as the amount of submarine infrastructure increases.

Ploughing down submarine cables has been known and practised for many decades. A underwater cable plough has a horizontal framework that can travel over the seafloor either on four sledges, one in each corner, or on wheels, or caterpillars (Fig. 7.24). In the centreline of the frame there is a plough share reaching down into the seafloor. In contrary to an agricultural plough, the cable burying plough is not designed to turn over the soil but to cut a narrow slit with as little resistance as possible. While the ploughshare is cutting this slit the cable is guided down directly behind the ploughshare or through a hollow slot inside the ploughshare. The ploughshare must have a shape and inclination such that it is not pressed upwards

Fig. 7.24 Cable plough. The tiltable plough share to the right is now horizontal, ready for tilting down to the vertical position (Courtesy of IHC Engineering Business Ltd., UK)

over the seafloor while moving. The backward inclination of the ploughshare adds vertical forces that keep the plough in the soil [15].

Ploughs are towed after the surface vessel and can require high tow forces. In deeper water, the plough requires long heavy tow cables and the position control of the plough becomes difficult [16].

More sophisticated plough systems employ vibration or water jets to support the ploughing process. These systems require power supply from the surface. The plough depth is up to 3 m depending on the seafloor stiffness.

The ploughing has some inherent risks when the plough meets rocky soil conditions. Rocks and boulders encountering the course of the plough are sometimes able to derange the heading direction and misalign the plough with respect to the cable. This has the potential to squeeze and damage the cable. Another risk is that boulders or debris can enter the entrance bellmouth together with the cable and develop enormous side impacts on the cable.

Rocks and boulders may misalign the plough in relation to the cable that in some cases can be damaged. In soft seafloor soils (sand, silt, mud, clay) a plough can be used to open a temporary furrow into the seafloor.

Ploughing down cables is a brute force method suitable for soft to medium strong soils and shallow waters. Many ploughs are passive systems with a fairly good reliability, which makes ploughing to one of the most economic cable burial methods.

7.2.3.2 Jetting Methods

Another group of burial equipment relies on water jetting action. A sword carrying a row of water nozzles is pushed down into the seafloor (Fig. 7.25). The high-pressure

Fig. 7.25 Cable jetting device. The sword carrying water nozzles is visible to the *right*, tilted up (Courtesy of LD Travocean, France)

water flow from the nozzles fluidises the seafloor (Fig. 7.25). While the water-jetting unit is moved along the cable, the cable sinks down into the slurry. Soon after, the slurry re-solidifies. Often, there are two swords travelling on each side of the power cable. Different carrier systems are available for the water-jetting unit. The simplest carrier is a sledge that slides on the seafloor much similar to a plough. A support vessel tows the sledge. These machines often feature a combination of plough and water jetting. Submersible pumps mounted on the sledge can create a water flow of 1100 m^3/h at 5.5 bar pressure. One particular sledge carries six of these powerful pumps, plus a long row of monitoring instruments.

The water-jetting unit can also be assembled into a purpose-built ROV with own propulsion. This ROV is a large truck crawling on the seafloor on wheels or caterpillars. The vehicle carries high-power water pumps to create large water flows at high pressures, the jetting swords, wheel drives, cable tracking equipment, process monitoring sensors, and positioning systems. Other water-jetting ROV are free-flying over the seafloor. An umbilical cable connects the ROV to the surface vessel in order to provide power supply and data communication. The ROV-based water-jetting system is complex and requires auxiliary systems (power supply, crane, deck space, control cubicle, etc.).

7.2.3.3 Simultaneous or Post-Lay Burial?

Ploughs and water-jetting equipment can be used for simultaneous laying and burial of the cable, or for post-lay burial (PLB). A PLB operation can be performed at convenient occasion after the cable has been laid by the CLV. A smaller vessel can be hired at lower day rates for the burial operation. In a PLB operation the burial equipment (plough or water-jet of any kind) moves along the cable route, guided by joystick in an on-board control room. ROV cameras provide an overview over the situation to take measures in case not only the cable but also rocks or debris are going to enter the cable entrance of the equipment, which could lead to damages on the cable. The cable is, however, at risk in the time window between laying and protection. Despite the deployment of guard vessels patrolling the cable route to chase away fishing boats, it has happened that submarine cables waiting for burial protection have been hooked.

In a simultaneous laying and burial operation, the plough or water-jetting would follow the CLV immediately. The cable can be fed into the burial equipment directly from above, which leads to a better cable guiding and reduced risk for encounters with rocks. Also, the guiding of the burial equipment on the seafloor is fairly easy. A simultaneous laying and burial operation slows down the laying operation considerably because the burial equipment is the slowest of the entire spread. This is particularly costly when a high day-rate specialized CLV must be used for the laying operation. Also, the weather window for the slow operation must be much longer than for the laying operation without simultaneous burial. Many cable installation specialists advocate the opinion that the cable should be brought into the water as quickly as possible without the retarding effect of simultaneous trenching.

The economic situation is different when the laying is performed with a less expensive laying barge. The progress of a laying barge is much slower than that of a CLV due to the time-consuming anchor handling procedures of the laying barge. Therefore, the simultaneous use of trenching gear would not have the same retarding effect as with a self-propelled CLV.

Laying barges are often used to install cables in shallow waters or tidal flats, where large CLV cannot operate. In these cases, the operation of the trenching equipment can be synchronised better with the laying equipment. The trenching gear (plough or jet) can be towed equidistantly behind the barge as she moves. Another solution would be the laying of cable during high tides when the barge can swim and the subsequent trenching at low tides when the barge lies on belly and can serve as hold point for the trenching equipment.

Another method developed for the installation of pipelines in tidal flats is the "bathtub" method [17]. A dredger prepares a wide flotation ditch for the laying vessel, which follows directly after the dredger. The laying vessel can float all the time in the ditch regardless of the tides. The laying vessel is directly followed by another floating barge, which refills the ditch. The leading dredger pumps its excavation soil by pipe to the tailing refill barge. The cable-laying vessel has always a pond of water to swim in.

7.2.3.4 Trenching Depth

There is always a discussion about the ideal trenching depth providing sufficient protection at reasonable cost. While it is obvious that a deeper trenching provides a better cable protection, the relationship between trenching depth and protection level is not linear, though. In some cases, the protection level would not increase below a certain trenching level.

While a large burial depth can offer a better protection (up to a certain degree), it comes with some important disadvantages.

Slower process, need for heavier equipment, considerably higher costs, higher risk for equipment failure and cable damage, less efficient cable cooling, larger difficulties when the cable must be retrieved for repair, or decommissioning.

The optimum burial depth can vary considerably along the cable route depending on protection requirement and soil conditions. A mathematical model for the detailed planning of the degree of protection for cable route sections with different properties and risk patterns is suggested in [18]. The burial depth is discussed further in Chap. 8. It should be noted that the designed trenching depth not always can be achieved. Unexpected sub-bottom soil conditions can render the chosen trenching equipment insufficient.

The best protection for the cable is sub-bottom burial out of the reach of fishing gear. A burial depth of 1–1.5 m is a good protection against most of fishery threats. Trawling and fish dredging equipment do seldom reach depths exceeding 1 m. However, as sea bottoms can be volatile, a good sand cover might disappear after years or even months leaving the cable exposed and vulnerable for fishing gear aggression.

The choice of trenching depth might be influenced by the knowledge of future developments in the cable route such as planned harbour dredging, ship lane dredging, or future pipe installation.

7.2.3.5 Other Protection Methods

There are also pre-laying trenching methods using dredging or excavating. The cable trench is prepared before the laying vessel brings the cable. The necessary furrow in the seafloor can be prepared by different machinery. Cutter-suction dredgers can work in a wide range of soils from mud to soft rock [17]. They can even cut an access ditch for themselves in shallow waters or mudflats. Here, also backhoes mounted on a small barge can operate.

If the seafloor is rocky or otherwise too hard for ploughing/jetting, the cable trench can be prepared before laying by cutting wheels, cutting chains, or other mechanical disintegrators. This is costly, slow, and only suitable for limited length of the cable route (Fig . 7.26).

In many cases, none of the methods mentioned here is feasible for one of the following reasons:

- Long rocky stretches which cannot be avoided
- Crossing of the cable over other cables or pipes
- The sand layer is too thin to achieve the specified burial depth
- Beach area does not allow for access with large vessels.

Fig. 7.26 Wheel cutter for rocky seafloor. Cable trench cut into calcarite seafloor (Courtesy of LD Travocean, France)

For these cases, some other protection methods have been developed: an artificial cover protects the cable. The cover can consist of:

– Cast iron half pipes to be assembled onto the cable after laying. Mostly used in near-shore waters and applied by divers
– Concrete slabs
– Cement bags or mattresses
– Rock dumping.

Concrete slabs, cement bags, and mattresses can be applied from the sea level though for some projects purpose-built ROV have been developed to deploy mattresses over longer lengths.

Rock dumping is a technology well-known from protection of submarine pipelines of any kind and size. Purpose-built vessels carry a shipload of rocks over the laid cable and discharge the load. On some barges, the rocks are simply pushed over the side of the barge (side-dump). In a bottom-door vessel or split-barge the hold is opened underneath, and the load of rocks is falling down altogether. For the protection of cables, this method is simple and quick but wasteful. Better control and a more beautiful protection job can be achieved with discharge through a flexible fallpipe. Modern rock-dumping vessels are equipped with high-sophisticated control and monitoring instrumentation, e.g. DP systems.

A peculiar protection method was used for the 1967 SACOI HVDC cable between Italy and Corsica. After too many encounters with fishing gear, a number of heavy steel ropes were run next to the cable, resting on blocks at a certain height above the seafloor [14]. Their purpose was to prevent fishing gear from entangling with the power cable.

The strangest heard-of protection method, the alignment of scrapped busses along an Istanbul submarine power cable, could, however, not be confirmed.

7.2.4 After-Installation Protection

Even after the successful and completed installation of submarine power cables, the protection can be maintained and improved by active measures. Unfortunately, the after-installation protection measures are neglected in many submarine power cable projects.

Since the overwhelming majority of cable damages are caused by human activity, it is a good idea to keep people away from the cable. This is an information task. People must be told that there is a cable, and that it is dangerous or at least inconvenient to get in touch with it.

Beach warning signposts should be erected where applicable. Also, information on the cable position must be given to all issuers of sea charts, be it national marine agencies, fishing authorities, etc. National sea chart authorities would issue “Notices to Mariners” alerting on newly installed submarine cables. It is important to entry the submarine power cable into any sea chart and registry imaginable. The cable information should be disseminated to pipeline operators, harbour authorities, meteorological, and hydrographical agencies. Military authorities should be informed in any case even if their present operational zone does not include the cable route. London-based “International Cable Protection Committee” (www.iscpc.org) keeps cable registers mainly for the telecom cable industry but would also include submarine power cables into their charts.

The dialogue with fishermen and their organisations is crucial. Fishery authorities and fishermen’s professional organisations are usually willing to help to spread information on submarine power cables. Every fisherman and mariner should know that it is a bad idea to try to recover an entangled gear or anchor from a cable by brute force. Mariners should know that it could be very dangerous to encounter a submarine power cable. The loss of at least three fishing vessels and several men of their crew has been attributed to hooking of submarine cables [19]. Every fisherman should also know that the cable owner would happily compensate him for a lost fishing gear rather than to repair a cable that has been damaged when the fisherman tried to recover that gear. It is also advisable to circulate information and education to fishing exhibitions and schools for fishermen and future mariners. In less developed areas, it can be profitable to provide local fishermen with easy-to-understand charts, free of charge, showing the position of the cable.

The Long Island Power Authority has hired local fishermen to guard their cable installation works. By this the local fishing community got aware of the cable existence.

Another way to protect the cable after laying is to monitor ship movements close to the route. The Vessel Monitoring System (VMS) specially designed for fishing vessels, or the AIS for all vessels, provide live data on ship identity and movements. By action of a marine authority or a specialized security company, the vessel can be warned upon approach to the cable corridor. Active ship movement monitoring can also be incorporated into harbour surveillance and other systems. Position and movement data may even be used in court proceedings when cable damages are dealt with. Many useful tips for the after-laying protection of submarine cables are given in [20].

Sea and air patrol of the cable route are efficient methods to keep possible hazards out. At least at times, the Cook Straight HVDC cable and other cable routes have been guarded regularly by sea patrols. Still, this service is expensive. Instead of establishing an own patrol service, the cable operator might enrol on other existing patrol services. Possible offenders can be identified and warned prior to cable damage. In case of damage, the offender can be identified for further claiming.

7.3 Appendix: The Catenary Line

When the CLV lays cable in calm waters with constant speed over a horizontal seafloor, the cable is following a catenary line from the exit point on the laying wheel down to the touchdown (TD) point on the seafloor. Actually some more simplifications are necessary to achieve a catenary line:

1. The cable has no bending stiffness
2. The cable does not experience any drag while moving through the water
3. The cable has a uniform weight per meter.

The bending stiffness of submarine power cables can be neglected in most cases except for very shallow waters. Given the slow laying speed the drag forces exerted onto the cable may also be neglected (in contrast to telecom cables, which are paid out at much higher speed).

In the coordinate system of Fig. 7.27 the catenary line can be expressed as:

$$y = a \cosh\left(\frac{x}{a}\right) \tag{7.7}$$

where a is the catenary parameter

In Fig.7.28, the real laying situation is included in the diagram. Note that the seafloor is not at y=0 but at the vertical coordinate y=a. The angle ϕ is expressed by the derivative of Eq. 7.7:

$$\cot\varphi = \frac{\partial y}{\partial x} = \sinh\left(\frac{x}{a}\right) \tag{7.8}$$

The coordinates of the point where the cable leaves the laying wheel are x=L and y=H+a. From Eq. 7.7 follows:

$$y = H + a = a \cosh\left(\frac{L}{a}\right) \tag{7.9}$$

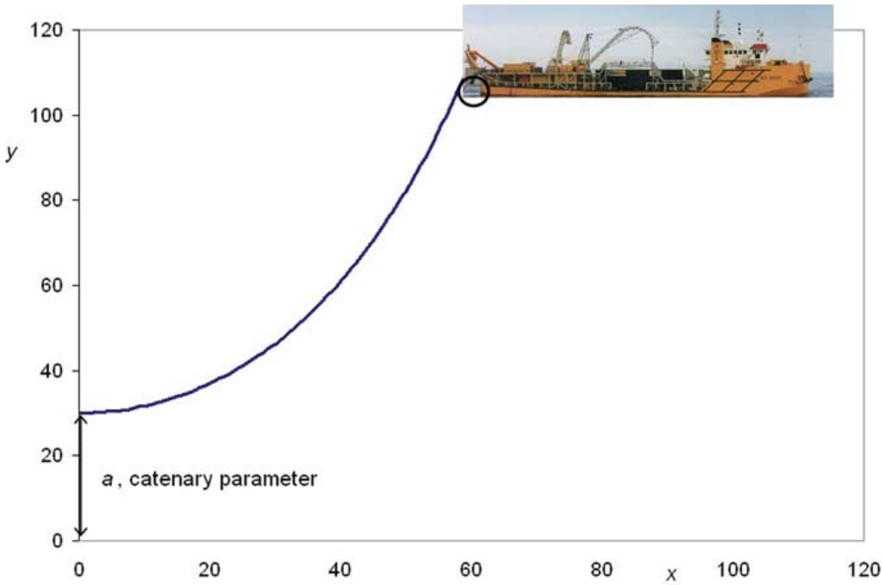

Fig. 7.27 Catenary curve of the cable under the laying vessel. Here the catenary parameter *a* has the value *a*=30

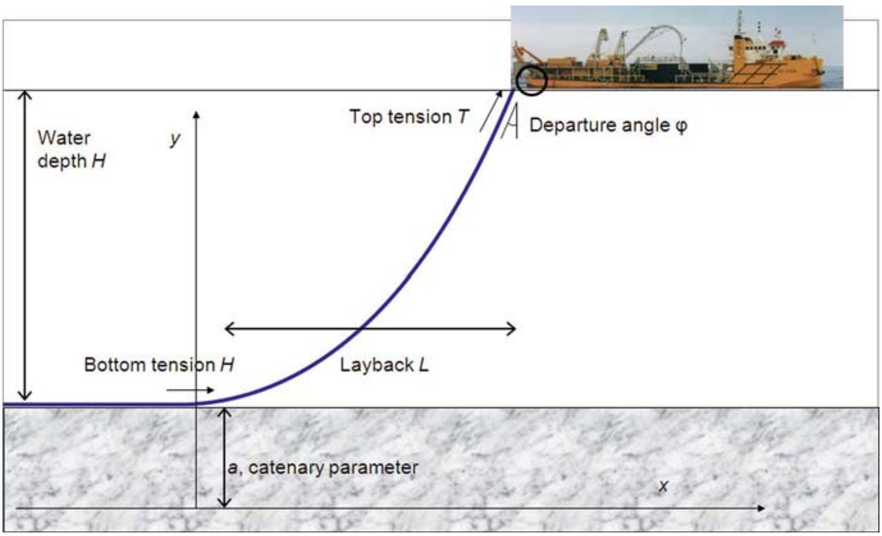

Fig. 7.28 Catenary curve of the cable under the laying vessel

The inclination of the curve at the same place is equal to the departure angle ϕ. During laying of the cable, the departure angle ϕ can be monitored and the water depth *H* is known. In the following we calculate all relevant entities from the known values. From Eq. 7.7 follows:

$$\cot\varphi = \sinh\left(\frac{L}{a}\right) \text{ or } \frac{L}{a} = \operatorname{arcsinh}(\cot\varphi) \tag{7.10}$$

That means that *L/a* can be calculated from the observed departure angle. Now, we put *L/a* into Eq. 7.9 and solve for *a*:

$$a = \frac{H}{\cosh\left(\frac{L}{a}\right) \quad - 1} \tag{7.11}$$

Now, the catenary parameter *a* is calculated, and we can continue calculating the other important entities.

$$T_0 = w \cdot a$$

where T_0 is the bottom tension and *w* the cable weight per metre in water. The layback *L* can be calculated from Eq. 7.10. The total length *s* of the suspended cable (from wheel to touchdown) is:

$$s = a \sinh\frac{L}{a} \tag{7.12}$$

The important top tension *T* is:

$$T = \sqrt{T_0^2 + w^2 s^2} \tag{7.13}$$

Finally the bending radius at touchdown is:

$$R_o = a \cosh^2\frac{L}{a}. \tag{7.14}$$

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