The Study of Burial Depth and Risk Assessment of Submarine Power Cable

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Abstract. In this paper, the determination of submarine cable burial depth and risk assessment method are studied. The main objective of the method is to optimize the burial depth of submarine cable in terms of specifying an economically feasible buried depth which ensures a satisfactory level of protection and by acceptable risk. The risk factors influencing the burial depth of submarine cables were analyzed. The primary risk to which submarine cables are exposed is anchoring, while the environmental factor and the cable itself have relatively smaller impact and cannot be mitigated by burial. Then the calculation method of probability and depth of penetration of anchor deployment near a submarine cable were studied. The method can reduce the protection cost while providing the cable with better protection and to guide the specification of the burial depth of submarine power cables. Compared with traditional methods which relying on operational experience, the probabilistic analysis determines the burial depth based on the water depth and seabed conditions of different sections as well as the vessel traffic of the cable route which is an accurate and quantitative approach.

Introduction

Submarine power cable construction requires a lot of investment [1]. To ensure the return on investment, submarine power cables are generally expected to operate stably and reliably for at least 25 years in the harsh environment of the seabed. Therefore, in addition to the cable core and armor that ensure the normal transmission of power in the long term, consideration should also be given to the additional protection of the cables to avoid damages from the environment where human factors have a great impact. Protection is an important part of submarine cable projects. However, the submarine cables located at the seabed with complicated geological conditions, so the protection is very difficult. It is necessary to make specific studies on the burial depth and risk assessment of submarine cables.

In the early 1980s, cable burial as a protection method began to prevail. The burial depth was set to 0.6m. With the application of the burial technology, the failure rate of submarine cables was greatly reduced. In 1997, Mole et al. proposed the Burial Protection Index (BPI) [2], which was further discussed by Allan [3], to assess the protection given to submarine fiber optic cables in varying seabed conditions and to set appropriate depth of burial for protection from external threats. The BPI has been in use for 20 years and applied to both submarine communications cables and submarine power cables. However, there are many limitations when using this method to determine the burial depth of submarine cables. For example, it only covers anchors of limited sizes; it is conservative with regards to protection from fishing gear and soft clay sea beds. In addition, the BPI ignores water depth, probability of incidents involving anchors, frequency and size of ships in transit, and changes in the seabed profile [4]. In recent years, the depth of burial adopted by general submarine cable projects has been increased to 1.0~1.5 m; the depth of burial in the fishing area is usually 3.0 m; and the depth of burial in busy shipping areas has even reached 5.0~10.0 m [5]. In theory, the deeper a cable is buried, the safer it will be. However, an increased burial depth causes
more difficulties to the burial construction, increases the requirements for burial equipment, significantly drives the construction costs, and makes it more difficult to retrieve and repair the cables. Therefore, it is important to analyze and comprehensively consider the impact of various factors on the burial depth, and to determine a reasonable depth of burial based on the protection level to be achieved. This will not only ensure the safe operation of the submarine cable system, but also reduce the difficulty in burial construction and related costs.

Submarine Cable Burial Depth and Risk Assessment Process

Once cable route is preliminarily determined and inputs are collated and reviewed, the risk assessment is performed. The depth of burial is successively specified based on the outcome of the iterative process and the acceptable risk. The process of burial depth and risk assessment of submarine cables is as follow:

1. Cable route selection
2. Marine survey and data collection
3. Assessment of seabed conditions
4. Identification and assessment of the risks
5. Probabilistic risk assessment
6. Identification of an acceptable risk
7. Specification of the depth of burial

Cable Route Selection

Cable route selection is an effective method for mitigating threats to submarine cables. To determine the cable route, a balance should be maintained between minimizing the cable length and avoiding hazards. It is also recommended to avoid seabed features that might make burial operations difficult, anchorages, or major shipping lanes.

Marine Survey and Data Collation

Marine survey is critical to safeguarding the integrity of submarine cables. The objective of the marine survey is to identify the environmental and human factors that threaten submarine cables as well as the degree of threat. The survey is also designed to acquire various parameters that describe submarine geological and geomorphological conditions, and to understand the topography of the seabed and the characteristics of sediments at a certain depth, which can be referenced by mechanical construction operations. Data required for submarine cable depth and risk assessment are as follow:

1. Project information
   a. Cable route
   b. Cable dimensions and specifications
   c. Authority/stakeholder requirements
2. Preliminary study information
   a. Maps
   b. Met ocean data
   c. Location of existing infrastructure
3. Survey information
   a. Geophysical survey
   b. Geotechnical survey
   c. Sediment mobility
4. Shipping data
   a. Fishing data
   b. Ship AIS data
   c. Vessel incident data
Seabed Condition Assessment

The geological conditions of submarine cable routes affect the burial depth and method. Some unfavorable geological conditions pose a threat to the safe operation of submarine cables. Therefore, with the cable route confirmed and survey data acquired, it is necessary to make a detailed analysis of the seabed conditions along the route [6]. The route should be divided into several sections based on distinct geological and seabed conditions and the penetration of anchors and fishing gear.

Risks Affecting Cable Burial Depth

Fig. 1 shows the causes of submarine cable damages [7]. As is shown in the figure, human activities causes account for 63.4%, natural causes 22.6%, and cable hardware causes only 12.9%. Apparently, the most important contributor to submarine cable damages is human activities. Most of the cable failures are caused by anchor and trawl.

To specify the depth of burial, consideration should be given to the risks that are mitigated by means of cable burial and that affect the burial of cables. There are two types of hazards, namely natural and human activities, as listed below:
1. Natural
   a. Sediment mobility
   b. Seismic activity
   c. Submarine landslide
2. Human activities
   a. Trawl
   b. Anchor
   c. Dredging/drilling
   d. Other cables, pipelines

Benthic Fishing

For protection from damage by common fishing gear, it is generally required that the burial depth of submarine cables in fine sand is 0.5m, and in silty clay is 2.5m. Work by Linnane et al. (2000) indicates that fishing gear penetration is limited to a maximum of 0.3m penetration even in soft sediment [8]. Therefore, this level of protection is too conservative. A pragmatic approach suggests considering 0.3 m as the effective maximum penetration depth of benthic fishing gear. Site specific fishing activity should be investigated to ensure the applicability of the above statement. If no other risks are present, by applying for example a factor of safety of 2, the burial depth of submarine cable can be 0.6 m.
Ship Anchoring

Grounding of ships in shallow water may present a hazard to submarine cables, but according to statistics, errant or emergency anchoring is the most significant threat to submarine cables from shipping. Errant anchoring is not considered, because it is complex to assess the probability of human error with a standardized approach. Moreover, in the case of errant deployment of anchors, it is unlikely that the anchors will exert their ultimate holding capacity thus reaching their maximum penetration depth. Consequently, only emergency anchoring is considered in the probabilistic risk assessment, but accounting for the maximum penetration depth from a given anchor is a conservative approach.

Probabilistic Risk Assessment

To determine a cost effective and practically achievable depth of burial that provides an appropriate level of protection, it is important to assess the risk of anchoring with a systematic, accurate and quantitative approach. By assuming that the anchor is a threat once deployed near the cable, a conservative approach is adopted to specify the probability of anchor deployment:

\[ P_{\text{Strike}} = P_{\text{Traffic Risk}} \sum_{n} \frac{D_{\text{Ship Drag}}}{V_{\text{Ship}} \times 8760} P_{\text{Incident}} P_{\text{WD}} \]  

where \( P_{\text{Traffic Risk}} \) is the probability modifier based on the tolerable level of risk; \( D_{\text{Ship Drag}} \) is the distance travelled by the anchor; \( V_{\text{Ship}} \) is the ship speed when the anchor is deployed; \( P_{\text{Incident}} \) is the probability of incident requiring the deployment of an anchor; \( P_{\text{WD}} \) is the probability modifier for nature and depth of seabed; and \( n \) is the number of ships crossing the cable route.

Eq. 1 only identifies the probability of an anchor deployment near a cable that could result in an anchor strike. It should be noted that the deployment of an anchor will not necessarily result into an anchor strike. Similarly, an anchor strike will not necessarily result in an immediate cable failure. The reason lies in that additional armor provides a certain level of protection from external aggression. It could occur that a cable is struck several times without sustaining critical damage. However, this could lead to internal weaknesses (especially in the insulation) which will eventually develop in failures. This paper, therefore, uses a conservative way and assumes that any anchor deployment is a hazard.

Probability Modifier and Acceptable Risk

The probabilistic risk assessment approach is intended to be iterative. To specify a burial depth which results in a tolerable residual risk, the value of \( P_{\text{Traffic Risk}} \) is modified as follows:

1. Calculate the value of \( P_{\text{Strike}} \) for all ships;
2. Calculate the value of the return period corresponding to this value of \( P_{\text{Strike}} \);
3. Agree an acceptable return period with the involved stakeholders;
4. Calculate the value of \( P_{\text{Strike}} \) that satisfies the acceptable return period;
5. Calculate the value of \( P_{\text{Traffic Risk}} \) which achieves the tolerable level of the \( P_{\text{Strike}} \);
6. The value of \( (1-P_{\text{Traffic Risk}}) \times 100\% \) is the percentage of ships for which cable burial is required for protection;
7. The anchor/ship size required for this percentage of ships is taken from the appropriate distribution curve;
8. The required burial depth is derived. If the burial depth is considered impractical, the acceptable level of risk should be reconsidered.

If the cable burial depth exceeds the expected penetration depth of the largest anchor identified for a ship in transit along the cable route, then the probability of a strike is zero. Similarly, if no shipping is anticipated in the area, the probability of a strike is zero. If the cable is not buried, the results of the assessment represent the worst case scenario for the cable being subject to risk from
any anchoring ship. If very limited shipping traffic is anticipated, further analysis to assess the risk from anchors may be redundant.

The acceptable risk depends on the risk appetite of the involved stakeholders. Due to the lack of relevant standards on the acceptable return period, the engagement with all the project stakeholders is strongly recommended for the definition of the acceptable level of risk for submarine cables.

**Water Depth**

Water depth is an important factor affecting the risk of submarine cables. It influences the navigation of ships and their behavior in emergency situations, thus the likelihood of anchor deployment. Fig. 2 shows the failure frequency against the depth at the points of failures. It shows that the majority of failures are recorded at the proximity of the terminal points and they become less frequent as the depth of the sea increases.

![Figure 2. Failure frequency against the depth at the points of failures.](image)

During emergencies involving loss of control of a ship, captains typically consider two kinds of risks before deploying an anchor: the risk of the ship hitting an obstacle and the risk of the ship going into very shallow water, thus the risk of grounding. It is recommended that the probability modifiers should be project specific and be developed based on the water depth, potential obstacles and the vessel traffic. For example, at some locations along the cable route, the water depth may be great enough to prevent the use of an anchor, reducing the probability of damage to a cable to 0; however, at the locations close to an anchorage, a modifier of 1 might be used. Table 1 lists the probability modifiers in various situations for three ship sizes. In the actual submarine cable project, local conditions of the cable route should be thoroughly assessed to develop the modifiers.

<table>
<thead>
<tr>
<th>Water depth[m]</th>
<th>Probability Modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DWT 2000 t</td>
</tr>
<tr>
<td>&gt;50</td>
<td>0</td>
</tr>
<tr>
<td>30–50</td>
<td>0.0</td>
</tr>
<tr>
<td>10–30</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Ship Velocity and Anchor Drag Distance**

$V_{\text{Ship}}$ and $D_{\text{Ship Drag}}$ determine the exposure of the cable to a ship deploying its anchor per year. $V_{\text{Ship}}$ and $D_{\text{Ship Drag}}$ vary for each ship type and size.

$V_{\text{Ship}}$ is the velocity with which the ship drifts while it is deploying an anchor. Due to personnel and equipment safety requirements, $V_{\text{Ship}}$ is typically less than 1 knot, while for smaller ships its maximum could even be 2 knots. For the largest ships, $V_{\text{Ship}}$ is considerably less than 1 knot. However, it should be highlighted that the deployment of the anchor may occur at a higher ship velocity e.g. in close proximity of an obstacle.

$D_{\text{Ship Drag}}$ is the distance travelled by the anchor when deployed to exert its holding capacity and immobilize the ship. $D_{\text{Ship Drag}}$ can be estimated based on the ship's weight, drifting speed, anchor holding capacity, water speed and hull resistance, as shown in the following equation [9]:

\[
D_{\text{Ship Drag}} = \frac{W_{\text{Anchor}} \cdot g}{S_{\text{Anchor}} \cdot V_{\text{Ship}} \cdot r_{\text{Skin}}}
\]
\[ D_{\text{Ship Drag}} = \frac{m V_{\text{Ship}}^2}{4 \cdot UHC} \]  

(2)

where \( m \) is the ship displacement; \( V \) is the ship speed when the anchor is deployed; and \( UHC \) is the Ultimate Holding Capacity of the anchor.

A more pragmatic approach suggests the use of empirical data from anchor trials where the drag distance of various anchor types may be measured in various soil conditions.

**Probability of Incident**

\( P_{\text{Incident}} \) is the probability of an incident requiring the deployment of an anchor and has the greatest influence on the outcome of the probabilistic assessment. The selection of \( P_{\text{Incident}} \) must not be over-conservative or under-estimated. However, developing an accurate value for the probability of an incident is complex, and the availability of information varies significantly from location to location. In some locations, the availability of incident data from National Authorities allows assessment of the number of incidents for a certain ship type or class. When statistical data on the number of incidents is not available, figures from the literature can be used, and local failure rates can be estimated based on the local vessel traffic.

**Anchor Penetration**

The depth that an anchor penetrates the seabed can be calculated using the following steps:

1. Determine the final velocity of the anchor;
2. Specify the terminal kinetic energy of the anchor;
3. Specify the energy absorbed in the gravel;
4. Specify the penetration depth of the anchor.

The final velocity of an anchor is expressed by the following equation [10]:

\[ (m - V \rho_{\text{water}}) g = \frac{1}{2} \rho_{\text{water}} C_d A v_T^2 \]  

(3)

If an anchor with a weight of \( m \) falls into water freely without having a windlass to reduce the chain velocity, the maximum velocity at which the anchor reaches the seabed or its final velocity is as follow:

\[ v_T = \left[ \frac{2 mg (1 - \rho_{\text{water}} / \rho_{\text{anchor}})}{A \rho_{\text{water}} C_d} \right]^{1/2} \]  

(4)

where \( v_T \) is the final velocity through the water; \( m \) is the mass of the anchor; \( g \) is the gravitation acceleration of the anchor through the water; \( A \) is the projected area of the anchor in the flow direction; \( \rho_{\text{anchor}} \) is the density of the anchor; \( \rho_{\text{water}} \) is the density of water; and \( C_d \) is the drag coefficient.

The final velocity of the anchor before it reaches the seabed can be specified by the above equation. It can then be used to calculate the kinetic energy and momentum generated when the anchor reaches the seabed, and thus the depth of the anchor penetrating into the seabed. The final kinetic energy and momentum are given by the following equations:

The kinetic energy is:

\[ E_T = \frac{1}{2} m v_T^2 \]  

(5)

The momentum is:

\[ P_T = m v_T \]  

(6)

In addition to the final energy, the effective energy in an impact also includes the energy of added hydrodynamic mass, which should be given appropriate consideration. Therefore, the effective impact energy \( E_E \) for a falling anchor is calculated by:
\[ E_E = E_T + E_A = \frac{1}{2} (m + m_a) v_T^2 \]  

where \( m_a \) is the added hydrodynamic mass calculated by:

\[ m_a = \rho_{\text{water}} \cdot C_a \cdot V \]  

where \( C_a \) is the added mass coefficient.

The added mass coefficient \( C_a \) and drag coefficient \( C_d \) depend on the geometry of the object. Typical values are given in Table 2.

<table>
<thead>
<tr>
<th>Description</th>
<th>( C_a )</th>
<th>( C_d )</th>
</tr>
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<tbody>
<tr>
<td>Flat/long shaped</td>
<td>0.1-1.0</td>
<td>0.7-1.5</td>
</tr>
<tr>
<td>Box shaped</td>
<td>0.6-1.5</td>
<td>1.2-1.3</td>
</tr>
<tr>
<td>Round shaped</td>
<td>1.0-2.0</td>
<td>0.6-2.0</td>
</tr>
</tbody>
</table>

The energy absorbed in the gravel can be described as:

\[ E_P = 0.5 \gamma' D N_p A_p z + \gamma' N_q A_p z^2 \]  

where \( \gamma' \) is the effective unit weight of the soil; \( D \) is the diameter of the cable; \( A_p \) is the potential impact area of the cable; \( z \) is the penetration depth of the anchor; and \( N_p \) and \( N_q \) are the bearing capacity coefficients.

Make \( E_E = E_P \) to calculate the depth that an anchor penetrates the seabed.

### Specification of Burial Depth

At this stage the following should have been identified:

- The penetration depth of external hazards against which mitigation is required;
- Eventual constraints from natural hazard;
- Other constraints.

Based on the above and with the application of a suitable FoS, the depth of burial can be specified. The cable route designers should choose a FoS based on the project-specific acceptable risk profile, the local conditions and engineering judgement. Care should be taken to specify a FoS which results in an economically achievable target burial depth. The selection of the FoS should aim to optimize cable protection without resulting in unjustified conservativism and an overly high cost.

### Conclusions

This paper studied the determination of burial depth and risk assessment of submarine power cables. It is aimed to reduce the protection cost while providing the cables with better protection and to guide the specification of the burial depth of submarine power cables.

1. The primary risk to which submarine cables are exposed is anchoring, while the environmental factor and the cable itself have relatively smaller impacts and cannot be mitigated by burial. Therefore, anchoring should be particularly considered for burial depth selection.
2. Compared with traditional methods, the probabilistic analysis determines the burial depth based on the water depth and seabed conditions of different sections as well as the vessel traffic of the cable route, not relying on operational experience or general definition.
3. The probabilistic analysis method requires reliable data on vessel traffic along the cable route, so it is important to collate the traffic data on all types of ships crossing the cable route.

### Acknowledgement

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References


