

Review

Installation of XLPE-Insulated 400 kV Submarine AC Power Cables under the Dardanelles Strait: A 4 GW Turkish Grid Reinforcement

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Abstract: This paper describes the 400 kV AC submarine link under the Dardanelles Strait composed of 12 submarine armoured single-core cross-linked polyethylene (XLPE)-insulated cables (plus a back-up power cable). The link consists of two parallel-operated double-circuit links named Lâpseki-Sütlüce I and Lâpseki-Sütlüce II. The transmissible power is 4000 MW (1000 MW per circuit) and the average length for a single-core cable is about 4.6 km: the submarine cables are part of overhead lines. This paper gives a wide account of the cable installations and, chiefly, of the cable protections on the seabed: different protection choices were extensively used (i.e., water jetting and mattresses).

Keywords: submarine single-core armoured cables; submarine cross-linked polyethylene insulated cables; cable protections

1. Introduction

The Turkish high voltage (HV) transmission grid is highly modern. In the first years of HV electrification (around 1968), the Turkish grid was constituted by 154 kV overhead lines supplying only the most important cities: in those years, the load peak was about 1.5 GW. Nowadays, the load peak is about 47.5 GW with an energy demand of about 250 TWh. The modernization and reinforcement of the Turkish grid have been witnessed by Professor Francesco Iliceto in his consultant activity and in his papers [1–4].

The transmission network is composed of about 21,000 km of Extra High Voltage (EHV) lines (400 kV) and 39,000 of HV lines (154 kV). The power plants have a rated power of about 81 GW (almost equally shared between hydroelectric, coal thermoelectric, and turbo-gas plants). A great achievement of the Turkish transmission system operator (TEİAŞ) is the interconnection with the ENTSO-E grid. Turkey is interconnected with the Bulgarian and Greek grids by means of three 400 kV A.C. overhead interties. The synchronous parallel is strongly helped by the use of Special Protection Systems (with acronym SPSs) also called System Integrity Protection Schemes. These SPSs are installed in the two Turkish interconnection substations (with the aforementioned Greek and Bulgarian grids). The active powers flowing through these three interties are measured and updated every 50 ms. These measurements are then sent to the SPS computing system which sums them and computes the time derivative and its average value every 1.5 s. If this average value and the above-mentioned algebraic sum exceed prefixed thresholds (expressed in MW/s and in MW) along with a sign indicating that the power import is increasing, SPSs control the load shedding of 12 substations (154/34.5 kV) for a total of 1200 MW.

2. Description of the Link

In this scenario, the installation of the cable systems and the erection of the associated 400 kV overhead lines were economically justified in order to transmit a large power amount generated by the power plants (located along the Southern coast of the Marmara Sea) to Istanbul, via the Western corridor (Trakya) [5]. The cable systems link the Lâpseki substation (Asian side) with the Sütlüce one (European side) across the Dardanelles Strait. The land and submarine cables are shown in Figure 1, whereas Table 1 gives all their geometrical characteristics. With regard to Lâpseki–Sütlüce I [5], the cable system consists of a proper submarine part (about 3850 m) and two land stretches (the Lâpseki part about 600 m and the Sütlüce part about 150 m). The submarine part is operated in solid bonding (with acronym SB), whereas the two land parts are operated in single-point bonding (with acronym SPB) as shown in Figure 2.

As already mentioned, the cable lines are part of a mixed or hybrid line (cascade connections of overhead–cable–overhead lines), as shown in Figure 3, which renders these links extremely interesting from an electrical engineering research standpoint [6–21].

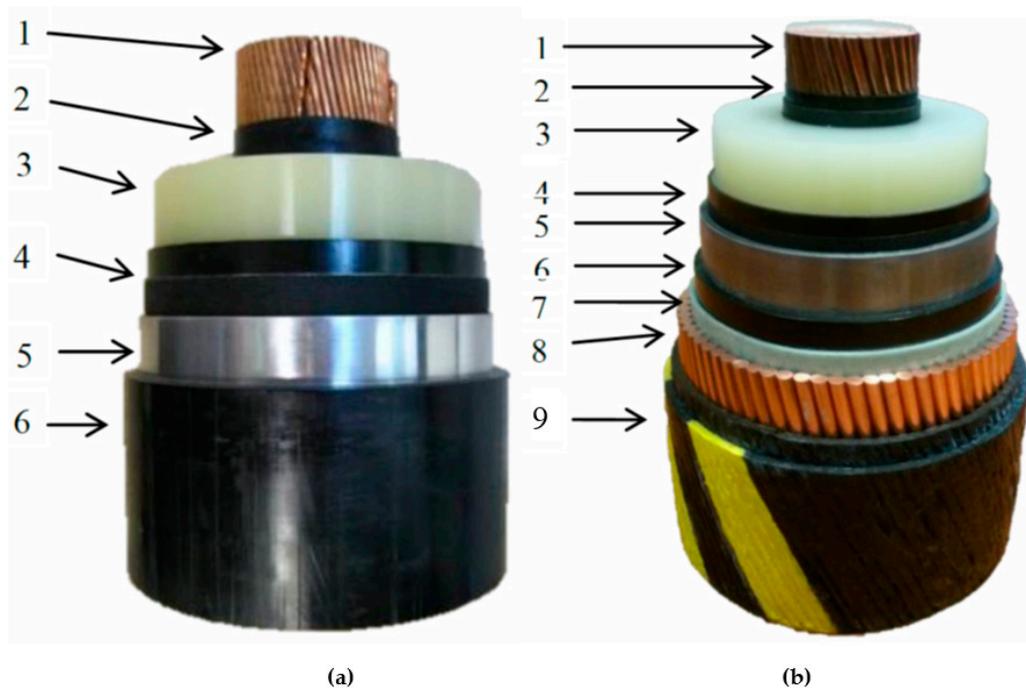


Figure 1. (a) Land Milliken-type cable; (b) Submarine armoured single-core cable [5].

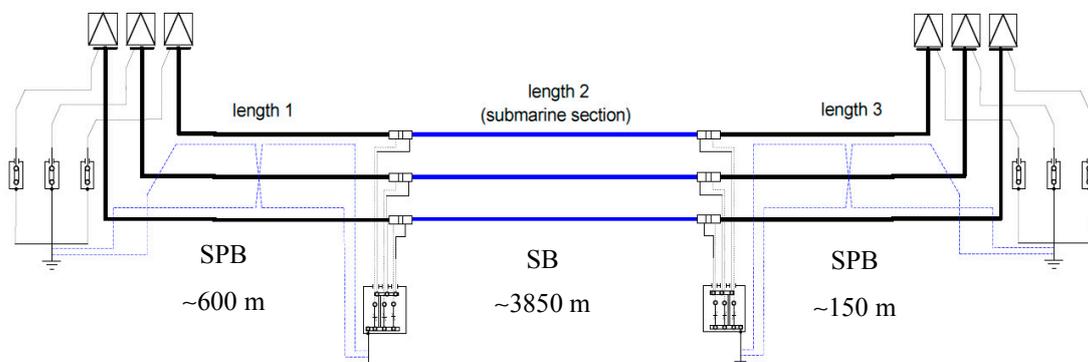
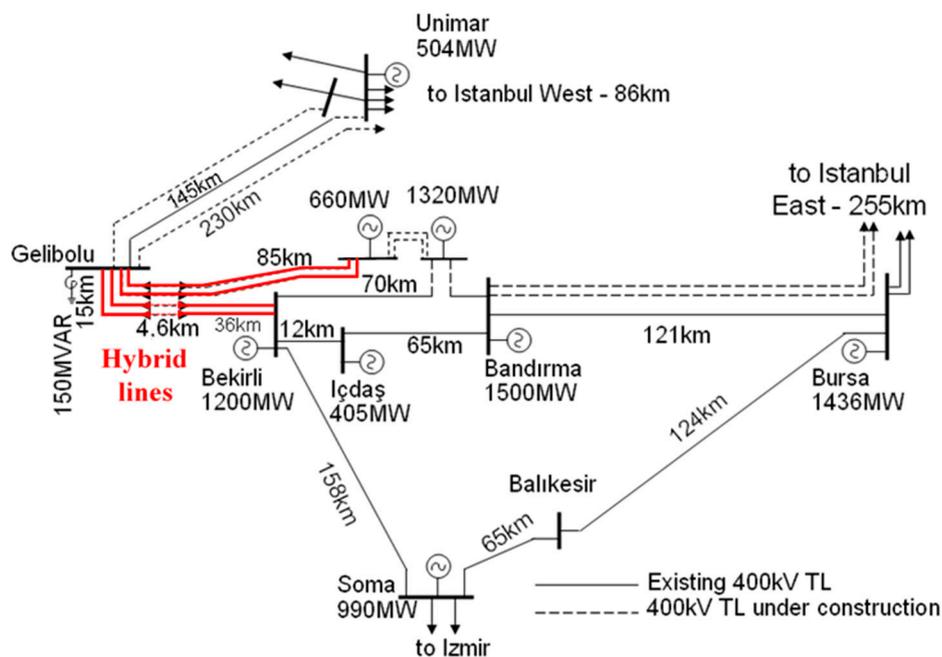


Figure 2. Screen bonding arrangements for the Lâpseki–Sütlüce I cable system.

Table 1. Land and submarine cable geometrical characteristics (XLPE: cross-linked polyethylene; PE: polyethylene).

Land Cable			Submarine Cable		
N	Description	Nominal Diameter mm	N	Description	Nominal Diameter mm
1	Copper conductor M-type watertight	58	1	Copper conductor with aluminium central rod watertight	52.6
2	Conductor Screen	61.6	2	Conductor Screen	55.6
3	XLPE insulation	116.7	3	XLPE insulation	112.6
4	Insulation Screen	119.8	4	Insulation Screen	115.6
5	Longitudinally Welded Al screen	124	5	Extruded lead screen	124.1
6	PE outer sheath	137.4	6	PE sheath	131.1
	-		7	Bedding	133.1
			8	Copper round wires armour	144.9
			9	Serving	153

**Figure 3.** Single-line diagram of the Southern Marmara Sea 400 kV network (hybrid lines Gelibolu–Berkili are highlighted in red).

3. A Brief Overview of the Submarine Cable Protection Techniques

It is worth mentioning that the first submarine cable for telegraphic purpose, installed between England and France in 1850, was inadvertently cut by a French fisherman within the first 24 h of operation [22]. In 1858, the first transatlantic cable (always for telegraphic purposes) between Ireland and Newfoundland was just a little bit luckier and failed after 26 days of operation. Many submarine cables were installed unprotected on the seabed in shallow water stretches until the 1980s and 1990s. Without cable protections, third-party damages are a frequent reality. The engineering community has always felt this issue so strongly that a paper [23] dated 1938 and emblematically entitled “Protection of Submarine Cable by Placement Underground” stated that:

“a plow has been devised by engineers of the Western Union Telegraph Company which when pulled along the ocean bottom is expected to cut a furrow, drop the cable into it, and back fill over the cable”.

When suitable subsea burial tools (e.g., jetting, trenching, and dredging machines) became available in the 1980s, the burial and covering protections of more and more longer cable stretches

became a common engineering practice. However, in 1986, only a small portion of submarine power cables was externally protected [24]. Today, almost all submarine power cables are externally protected by burial or covering (e.g., by means of mattresses or tubular products, or rock dumping) (see Figures 4 and 5).

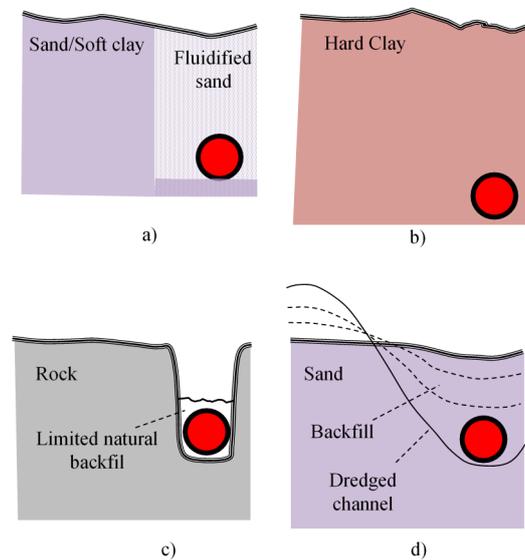


Figure 4. Protection of cable through burial: (a) jetting and fluidification; (b) ploughing; (c) mechanical cutting; (d) open-trench dredging.

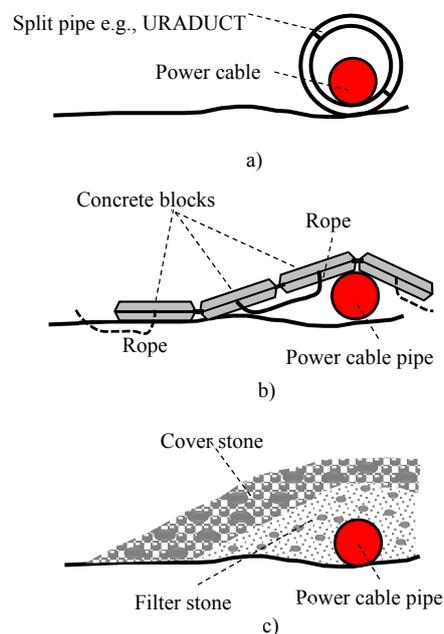


Figure 5. Special cable protections: (a) tubular product; (b) mattress covering; (c) rock dumping.

It is worth remembering that these protections play also a key role in order to avoid possible sabotages. Figure 6 shows the suitability of different burial techniques depending on the seabed conditions [25]. The scales for cohesive and cohesionless soils are approximately reported on the x-axis. The suitability of the different tools is reported on the y-axis.

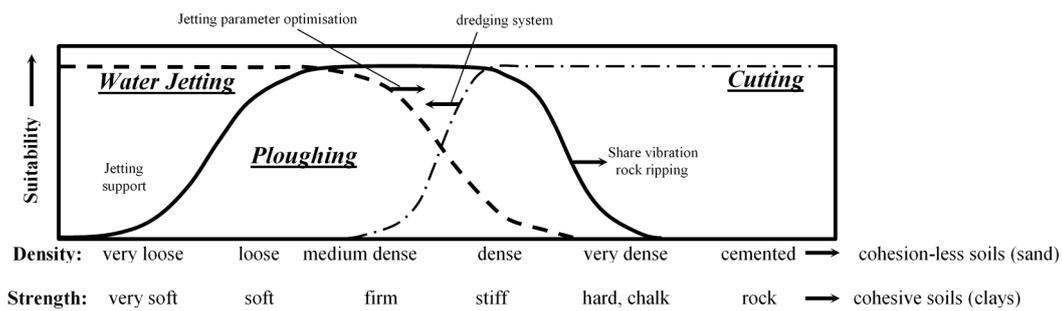


Figure 6. Indicative burial tool suitability in different ground conditions.

Table 2 reports a comparison among different burial techniques [25], and the text highlighted in grey regards situations of a certain importance for the Lâpseki–Sütlüce installation.

Table 2. Comparison of Burial Techniques [25] (for the assessment see (1)).

Factor	Hydro Jetting	Ploughing	Mechanical Cutting
Range of suitable soil conditions	M	H	M
Uneven bathymetry	H	M	L
High currents	L	H	H
Low underwater visibility, high turbidity	L	H	L
Very shallow water	L ⁽²⁾	H	M
Simultaneous lay and burial (SLB)	M	H	L
Post-lay burial (PLB)	H	L ⁽³⁾	M ⁽³⁾
Manoeuvrability	H	L	M
Multipass capability	H	L ⁽⁴⁾	M ⁽⁴⁾
Ability to bury bundled cables	H	M	M
Ability to bury loops or repair joints	M	-	-
Safety of cable during burial operation	H	L ⁽⁵⁾	M
Suitability in close proximity to infrastructure	H	L	M
Backfill quality	M	H	L
Environmental benignity	M	H	M
Rate of progress	M	H	L
Availability of suitable vessels	H	M ⁽⁶⁾	H
Mobilisation layout flexibility	H	L	M
Ease of catenary/tow line management	H	M	H

(1) Assessment: H = High/more favourable, M = Medium/neutral, L = Low/less favourable, - = not applicable;

(2) Requires water supply. Typical minimum water depths are 5 to 10 m for ROV based systems; (3) Requires subsea loading of cable if start and end points are offshore; (4) Single pass only, except for pre-lay trenching operations;

(5) A cable manufacturer may recommend not using ploughing as a burial technique; (6) Large bollard pull required. Due to size and weight of plough, generally launched over stern, not side.

Of course, the real installation or laying phase is only the last step of a long and precise process, which foresees, at least, the following milestones:

- A route cable survey comprising of geophysical and geotechnical portions;
- A marine survey, which could include an extraction of samples from the seabed.

The milestones are not sequential, e.g., information will have to be gathered so the route can be evaluated, but a tentative route must be chosen before a submarine survey can be done [26–33]. In any case, geotechnical investigations (meant as a direct measurement of the seabed and subsoil physical properties, e.g., by in situ sampling with laboratory analysis [29]) and ground ones (commonly including geotechnical investigations, geological studies, and geophysical surveys) must be performed before the installation begins. It is worth noting that, as wholly demonstrated by the Cigré technical

brochure # 398 [26], mechanical damages by human activities (cables damaged by natural events, e.g., landslides and earthquakes are less than 9% of cable faults) are the most common cause of cable failure. The chief causes of submarine cable failure are:

- Fishing activity;
- Ship anchoring (chiefly in shallow water).

In general, relatively a small depth of cover is adequate for protection from fishing activities (for many years the standard burial depth was 0.6 m). Fishing activities, which pose a threat, include trawling by both beam and otter boards (there are other fishing techniques which can be dangerous for cable integrity, like shellfish dredging and stow net fishing).

It is now common practice to bury cables up to a water depth of 1 km, however, cable damage associated with fishing has been reported at depths of 1.2 km. In order to take this fact into account, the cable industry is now being asked to achieve, on some projects, burial in water depths up to 1.5 km. This is not the case of Lâpseki–Sütlüce I and II, since the maximum depth of the Dardanelles Strait reaches about 0.1 km. Therefore, burial and protection of the 13 single-core cables were mandatory.

4. Assessment of Lâpseki–Sütlüce Optimal Burial Depth

The nature of the seabed soils clearly plays an important role in the depth into which anchors and fishing gear could penetrate. Figure 7 shows that, with regard to fishing gears, a cover depth equal to 0.6 m gives good guarantees, even in soft soil, to avoid cable damages [26].

With regard to the anchor penetration depth into the seabed, it depends upon both the seabed type and the anchor weight. It is rather impressive [26] that in soft seabed a 30 t anchor (see Figure 8) can penetrate 5 m inside the seabed! With regard to the Lâpseki–Sütlüce I and II installations in the Dardanelles Strait, an optimal burial depth $h_{opt} = 1.5$ m (brown line in Figures 7 and 8) is a very good measure to avoid anchor and fishing gear damages (with a minimum cover depth $h_{min} = 1$ m).

In order to compare this choice with other meaningful submarine installations [33], in the Oslofjord project [34], the cables were mostly buried 1 m below the seabed in order to provide general cable protection. This target was particularly important in the trawling areas. Cable and Wireless Global Marine have developed the concept of a Burial Protection Index (BPI) [29], as shown in Figure 9. This recognises the resistance of different seabed soils to penetration by anchors and fishing gears. It is based on typical soil types encountered during cable installations; however, it must be remembered that such soil mechanics is not an exact science.

The meaning of the BPI is:

- BPI = 0 Assumes that the cable is surface laid;
- BPI = 1 Depth of burial consistent with protecting a cable from normal fishing gear only;
- BPI = 2 Depth of burial gives protection from anchors up to approximately 2 t. This may be suitable for normal fishing activity, but would not be for larger ships (e.g., large container ships, tankers);
- BPI = 3 Depth of burial sufficient to protect from anchors of all but the largest ships.

It is worth noting that this approach is not general, and consequently it must be used with due care.

In any case, if the majority of the seabed in the part of Dardanelles Strait where the cables have been laid is “coarse sand with gravels and cobbles” and the depth of cover ranges between $h_{min} = 1$ m and $h_{opt} = 1.5$ m, the BPI ranges between about 1.5 and 2: this should guarantee from fishing activities and anchors up to 2 t. Subsequently, where it was not possible to reach h_{min} , the use of further protections has been necessary.

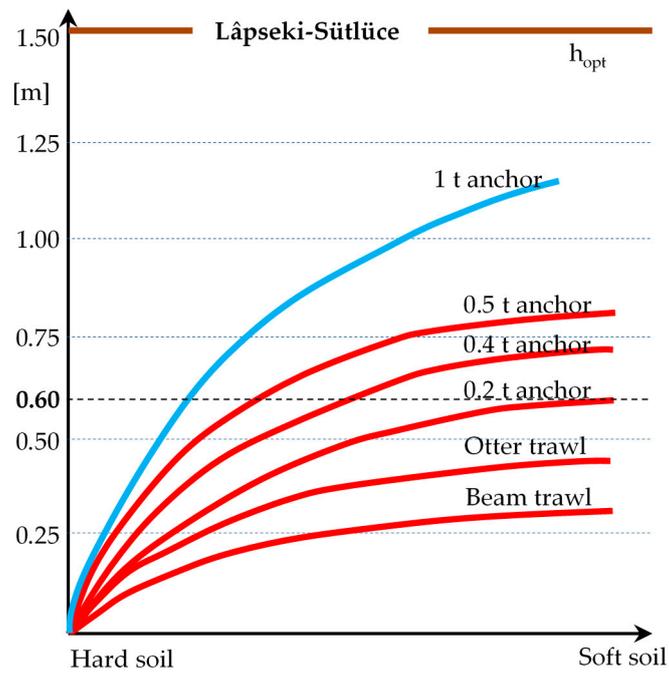


Figure 7. Penetration of smaller anchors and fishing gears versus soil hardness.

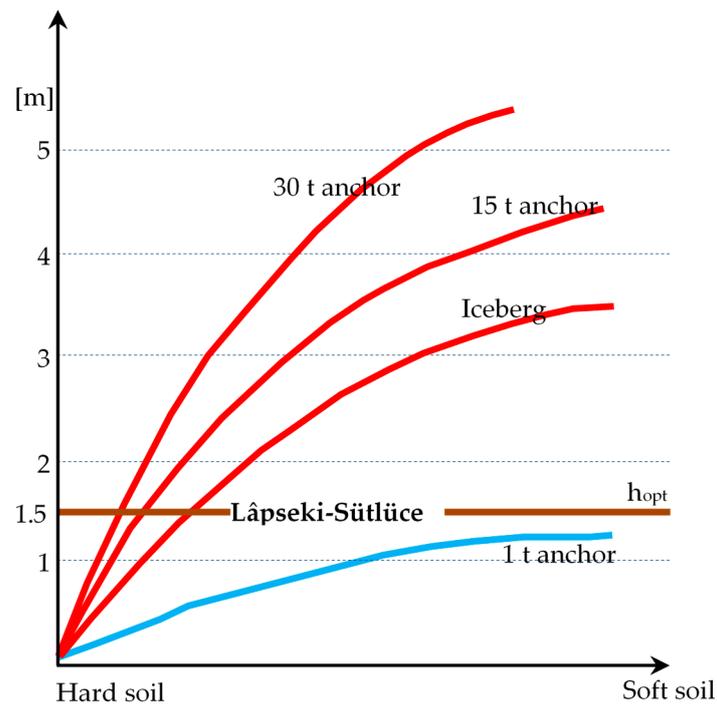


Figure 8. Anchor penetration versus soil hardness.

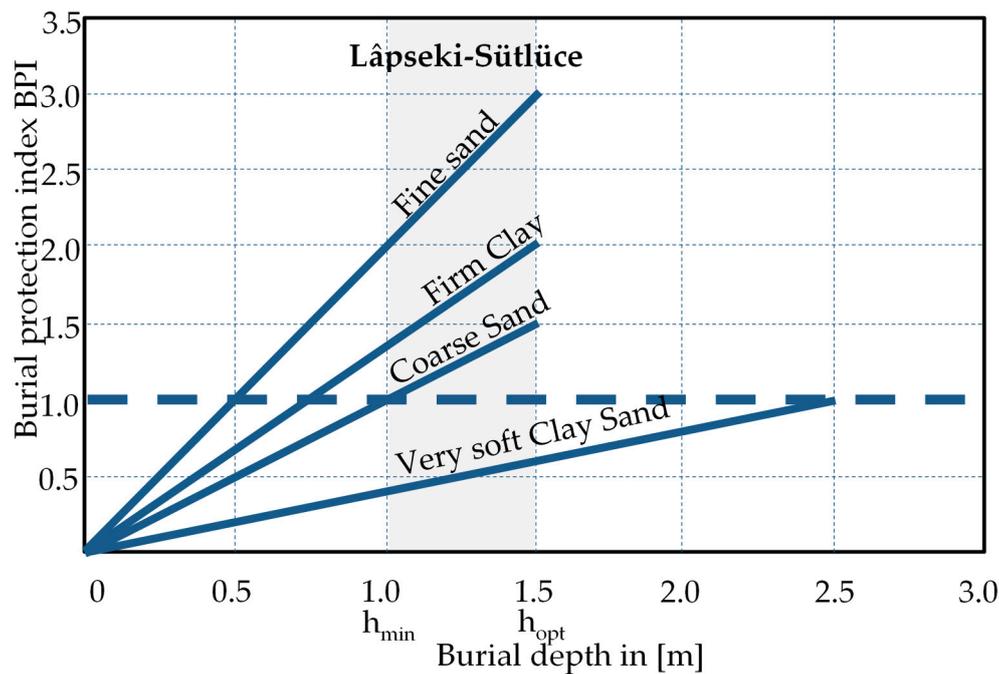


Figure 9. Burial protection index as a function of burial depth for different seabed types [29].

5. Verification of the Consistency of the Installation Choices of Lâpseki–Sütlüce

The marine survey conducted by Prsymian and Teiaş in order to define the final cable routes and to gather information for the burial assessment survey (BAS) was wide, detailed, and comprehensive. The work consisted of:

- A desktop study;
- A topographic survey at both landings from the shoreline to the sea/land joint bay area;
- A near-shore bathymetric survey;
- AN offshore marine survey.

Moreover, it was decided to enlarge the marine survey to 5 additional vibrocoreing and to 3.5 km offshore marine survey by a Remotely Operated Vehicle (ROV) for additional route development. Ambient conditions (like seawater temperature and salinity) ought to be taken into account. One of the route objectives is to avoid possible abrasion and damage caused by waves, tide, sea current, moving sea bottom, etc. As fully demonstrated by the Sorgente–Rizziconi submarine part [11], it is often necessary to select a cable route that may not be the shortest alternative. A distance between parallel single-core cables (or multiple three-core ones) of 100–200 m (or twice the water depth) will significantly lower the risk of damage to more than one cable due to one accident. In fact, the choice of maximum spacing in Lâpseki–Sütlüce I between the seven single-core cables (meant as the spacing between two adjacent cables) is about 250 m in correspondence to the maximum water depth of 100 m (spacing/water depth \cong 2.5). This should reduce the risk of multiple cable damage and guarantee some available room for possible cable repair. The target is to find a seabed as smooth as possible and to avoid:

1. Rough sea bottom, which may cause free spans, abrasion, or sidewall pressure on the cable;
2. Steep slopes (less than 15–20% is recommended);
3. Natural obstacles like boulders or even human past activities as wrecks, scrap, etc;
4. Areas where waves, high water currents, high tidal range, soil movements, or ice may cause problems (it is not the case of the Lâpseki–Sütlüce submarine link);

5. Cable crossings and other cables or services nearby (as it is the case of the Lâpseki–Sütlüce submarine cables);
6. Too shallow water depth for cable laying, protection, and repair;
7. Too hard or too soft seabed;
8. Areas of existing and future marine activities like shipping channels, fishing areas.

Another merit of this detailed survey has been that the final selected routes were shorter than the reference routes with a saving in the project costs. Seabed shows a terraced morphology with few morphological steps with a slope locally greater than 15° . With regard to the burial assessment survey (BAS), the typologies of the seabed were categorized as in Table 3. It is worth noting that in the P category seabed only surgical or micro trenching was foreseen. These seabed categories are also shown in Figure 10 without reference to A, B, C, D, and P letters of Table 3.

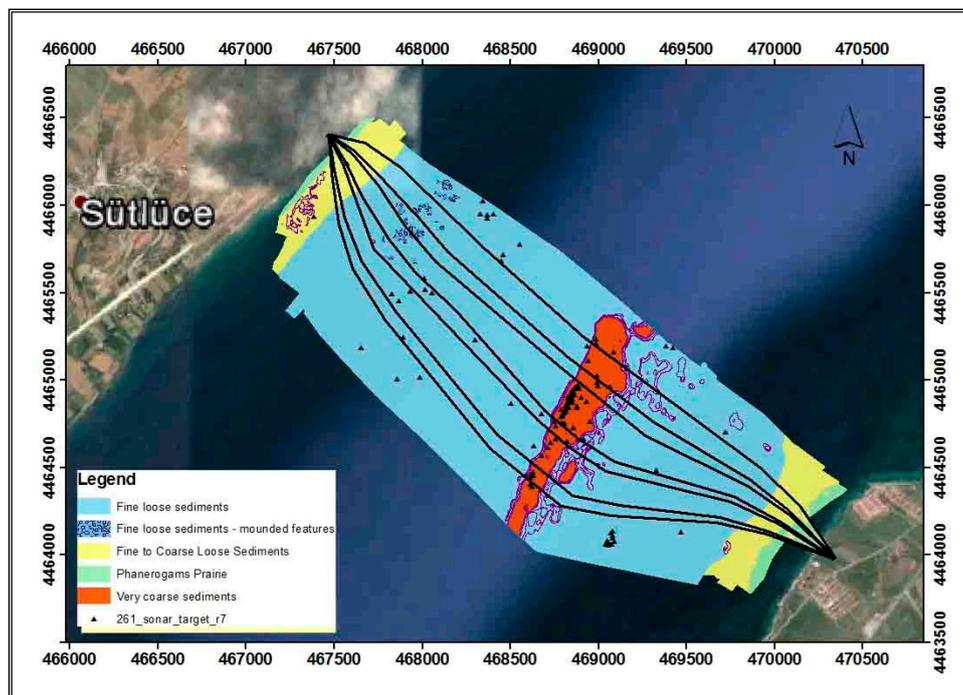


Figure 10. Seabed categories encountered by the cables of Lâpseki–Sütlüce I.

Table 3. Seabed categories encountered in the cable route.

Category	Cover Depth (m)	Seabed Conditions	Protection
A	>1.50	fine sediments (soft clay/silt) and/or coarse sediments (loose to dense sand) with thickness >1.65 m	
B	1.00–1.50	fine sediments (soft to firm clay/silt) and/or coarse sediments (loose to dense sand/fine gravel) with thickness 1.15–1.65 m	<i>jetting</i>
C	0.75–1.00	fine sediments (soft to firm clay/silt) and/or coarse sediments (loose to dense sand/fine gravel) with thickness 0.90–1.15 m	
D	<i>variable</i>	<i>Subcropping/outcropping very coarse sediments (loose gravel/pebbles/cobbles/possible boulders)</i>	<i>jetting attempt + other protection</i>
P	approx. 0.50	<i>Cymodocea nodosa prairie</i>	<i>microtrenching</i>

The spare cable route encounters the D category seabed (whose definition is “vener of loose coarse sediments, SAND/fine, GRAVEL over loose very coarse sediments, coarse

GRAVEL/PEBBLES/COBBLES/possible boulders, subcropping/outcropping very coarse sediments”) for a total length of 200 m. The D soil category is visible in orange in Figure 11 and it intersects the two circuits for an almost equal length (for the northern circuit, including the spare phase, from 200 to 250 m, and for southern circuit from 110 m to 160 m). For this D category seabed, a given number of vibrocore samples were extracted from the seabed (see Figure 12). The position of the vibrocore sample with code VBC_27 is visible inside the orange zone and besides the spare cable in Figure 11.

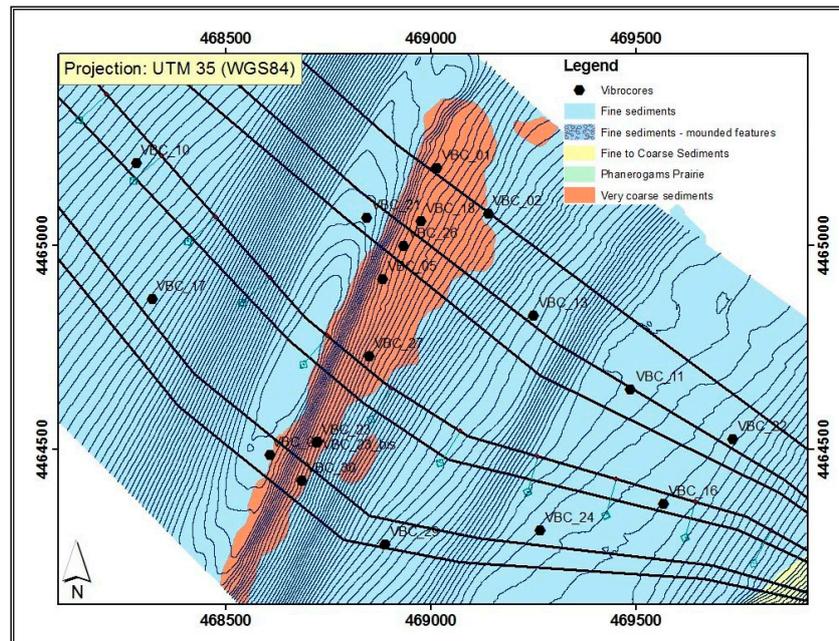


Figure 11. Shallow geology model, Asia Side for Lâpseki-Sütlüce I.



Figure 12. Very coarse gravel in VBC_27 sample.

Seabed samples collected in the D area show the occurrence of thick levels of very coarse gravel with cobbles (see Figure 12), in some cases accompanied by levels of clayey and silty sands. The gravel is, at places, outcropping, as revealed by the ROV video inspection of Figure 13. The submarine survey document reports that in D area boulders and blocks are present. The nature of the category D seabed is also confirmed by other vibrocore samples extracted in the same area.

The intersection of the two circuits in the D category seabed occurs at the crossing with the in-service (with acronym IS) telecommunication cable [35] named ITUR (see Figure 14).

The common practice of submarine cable installation considers a minimum safe distance from IS cable crossings of 100 m on both sides, while, for jetting works, this safe distance is reduced up to

20 m, if the soils and cable configuration allow. The unlucky occurrence that the category D seabed is in correspondence to the IS ITUR and Mednautilus cables rendered the cable protection extremely delicate and difficult.



Figure 13. Very coarse gravel in the D category seabed.

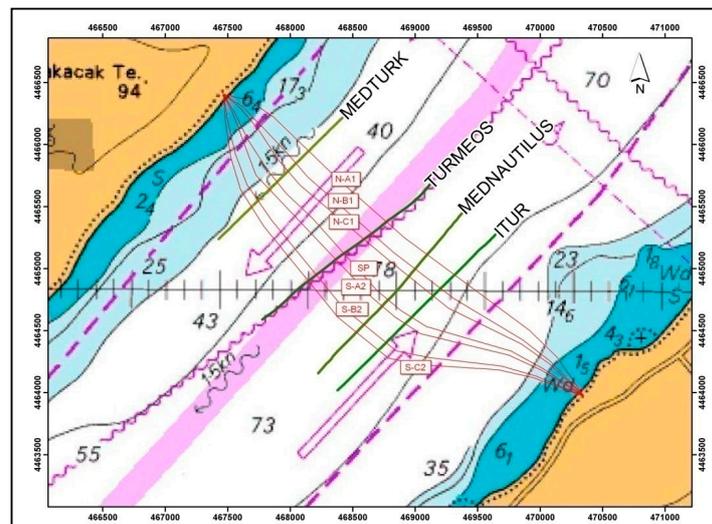


Figure 14. Plan view of cable crossings due to the in-service telecommunication cables (ITUR, MEDNAUTILUS, TURMEOS, and MEDTURK).

Prysmian tried several jetting passes (see Figure 15 for the employed jetting machine) and used mattress covering when the cover depth was less than h_{\min} . All the installation steps are summarized in the flowchart of Figure 16.

In the Lapseki–Sütlüce installation, ASSOMAT II was used to perform mattress covering (see Figure 17). AssoMat II is a self-propelled autonomous installation frame.

Due to its dimensions (5.5 m × 2.9 m) along with four thrusters, AssoMat II can operate at high water depths with adverse local conditions like high currents. Its control system allows an accurate positioning of the mattresses along the protected route and a proper alignment of the sequence of mattresses.

In Lâpseki-Sütlüce, it was used when the h_{min} had not reached 1 m after several passes of jetting activity in the stony seabed.



Figure 15. Some photos of the real jetting ROV used in the Lâpseki-Sütlüce installation.

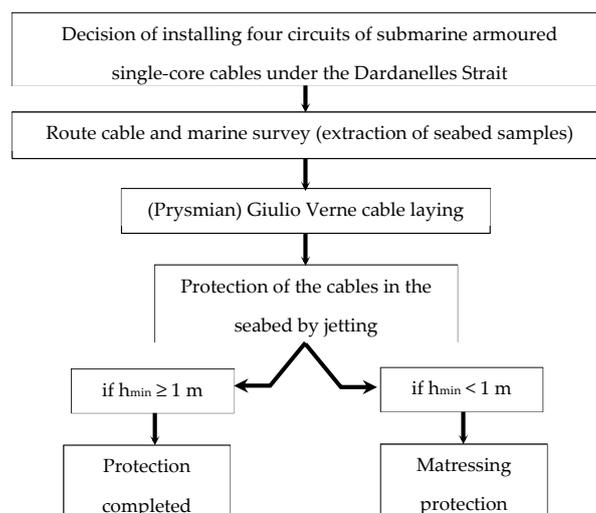


Figure 16. Flow-chart of the installation steps.



Figure 17. Assomat II used in the Lâpseki–Sütlüce installation.

6. Conclusions

This paper presents some technical features and installation characteristics of the 4 GW AC EHV submarine link under the Dardanelles Strait. This link is one of the very few EHV AC submarine cable systems with extruded insulation worldwide. Special attention was paid to the cable protection on seabed against third-party injuries due to the high maritime traffic on the Dardanelles Strait. Protection of the 400 kV cables was achieved by water jetting burial at 1.5 m in most of the routes. The 13 single-core cables have overcrossed four pre-existing in-service fibre optic cables laid on the sea bottom along the Strait. At the crossings, plastic separation sleeves were placed over the fibre optic cables, and concrete mattresses over the power cables.

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Conflicts of Interest: The authors declare no conflict of interest.

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