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Modeling thermal behavior of buried subsea power cables: a review of deterministic, data-driven, and hybrid approaches

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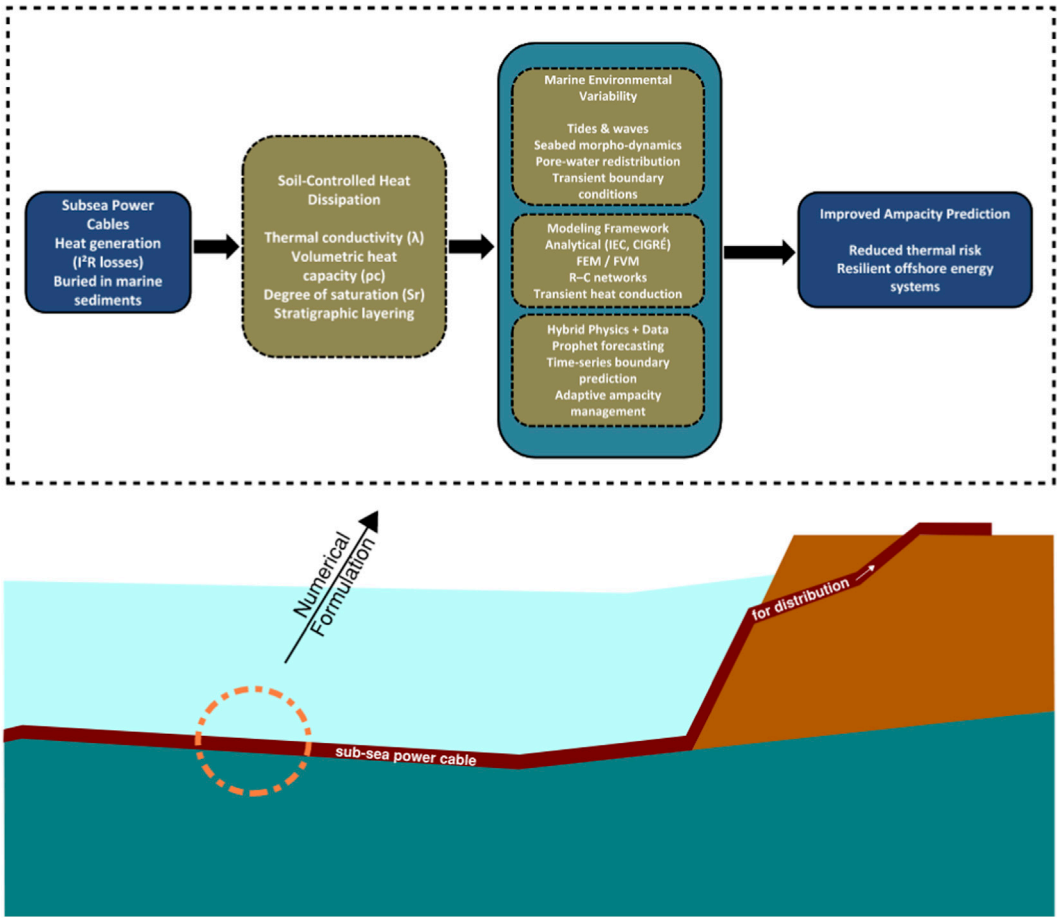
Subsea power cables operate within thermally sensitive seabed environments, where heat dissipation into surrounding marine sediments governs allowable current loading and long-term system reliability. As offshore energy transmission expands, understanding the interaction between cable heat generation, sediment thermal properties, and environmental forcing has become increasingly important for accurate thermal assessment and resilient infrastructure design. This paper presents a critical review of thermal–geotechnical interactions in subsea cable systems, synthesizing literature across electrical cable engineering, marine geotechnics, and environmental modeling. Modeling approaches are organized into a taxonomy comprising deterministic thermal models, coupled thermo-hydraulic formulations, data-driven forecasting techniques, and emerging hybrid physics–data frameworks. The review identifies key limitations in current practice, including insufficient representation of seabed heterogeneity, limited treatment of transient environmental forcing, uncertainty in sediment thermal properties, and challenges in integrating monitoring data into predictive models. Building on these observations, a conceptual hybrid modeling framework is proposed as a future research direction, in which physics-based thermal solvers are complemented by data-driven approaches to capture time-dependent boundary conditions and support adaptive assessment. The findings provide a structured foundation for advancing integrated modeling strategies and developing next-generation thermal assessment frameworks that better reflect the dynamic geotechnical conditions governing subsea cable performance.

KEYWORDS
ampacity, data-driven modeling, heat and mass transfer, marine geotechnics, probabilistic forecasting, prophet forecasting model, soil thermal properties

1 Introduction

Beneath the surface of the world's oceans lies an extensive and largely invisible network of subsea cables that underpins modern society. From an engineering perspective, this network represents a thermally constrained infrastructure system, in which the allowable current-carrying capacity (ampacity) is governed by the efficiency of heat dissipation into surrounding seabed sediments. Offshore wind farms, cross-border power interconnectors, high-voltage direct current (HVDC) transmission systems, and global fiber-optic communication networks rely on submarine cables for reliable energy and data transfer.



GRAPHICAL ABSTRACT

It is estimated that more than 95% of global digital communications and over 1.4 million kilometers of fiber-optic cables are routed across the seabed, while the rapid expansion of offshore renewable energy has led to unprecedented growth in subsea power cable installations worldwide (Carter et al., 2009; TeleGeography, 2023; International Energy Agency, 2022; WindEurope, 2023). The scale and spatial distribution of this infrastructure amplify the importance of accurate thermal assessment, as localized inefficiencies in heat dissipation can translate into significant operational, economic, and reliability constraints at system level. While subsea cable systems are often described in terms of electrical and mechanical design, their performance is fundamentally governed by coupled thermo–geotechnical processes at the cable–sediment interface, where soil properties, environmental forcing, and transient boundary conditions collectively control heat transfer and long-term system behavior.

The global expansion of offshore energy infrastructure has led to a rapid increase in the deployment of buried subsea power cables, whose thermal performance governs allowable current loading (ampacity), operational reliability, and long-term system integrity. Heat generated within the cable, primarily due to conductor resistance and dielectric losses, must dissipate efficiently into the surrounding seabed to prevent excessive temperature rise. This heat transfer process is controlled by a combination of factors, including sediment thermal conductivity, volumetric heat capacity, burial depth, and the thermal boundary conditions at the sediment-water interface. Inadequate heat dissipation can lead to thermal derating, reduced transmission capacity, and accelerated material degradation. Therefore, accurate prediction of cable–soil thermal behavior is essential not only for design optimization but also for operational management and lifecycle performance assessment of offshore energy systems.

Beyond engineering performance, improper or insufficient thermal management of subsea power cables may also have implications for the surrounding marine environment. Localized temperature elevations in seabed sediments can alter thermal gradients, potentially affecting benthic ecosystems, microbial activity, and sediment biogeochemical processes. For example, temperature increases may influence oxygen diffusion rates, nutrient cycling, and habitat suitability for temperature-sensitive organisms. In addition, thermal anomalies associated with cable operation can interact with sediment transport processes, particularly in shallow or mobile seabed regions, where hydrodynamic forcing and sediment mobility are significant. Although the long-term ecological impacts of cable-induced heating remain an area of ongoing investigation, these considerations highlight the importance of integrating environmental sensitivity into thermal assessment and cable

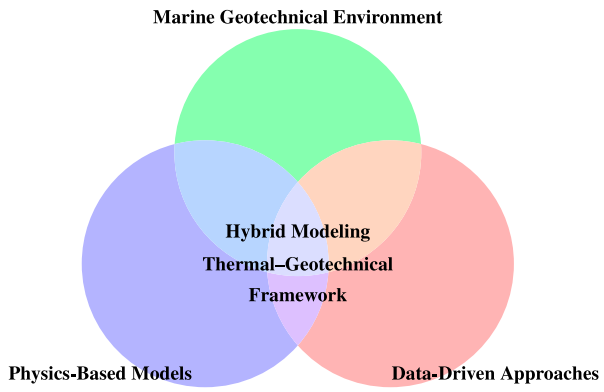


FIGURE 1
Framework illustrating the integration of physics-based models, data-driven approaches, and marine geotechnical processes in subsea cable thermal assessment.

design practices. To provide a conceptual overview of the interdisciplinary nature of subsea cable thermal assessment, Figure 1 illustrates the integration of physics-based modeling, data-driven approaches, and marine geotechnical processes, which together form the basis of emerging hybrid modeling strategies. Unlike terrestrial cable installations, subsea environments introduce additional complexities due to fully saturated conditions, spatial variability in sediment properties, and dynamic boundary forcing associated with ocean currents, tides, waves, and seabed morphology. Marine sediments often exhibit layered structures with varying grain size distributions, mineral compositions, and pore-water characteristics, leading to heterogeneous thermal and hydraulic properties. Furthermore, processes such as sediment heterogeneity, burial depth variability, hydrodynamic-induced cooling, and potential cable exposure due to scour can significantly influence heat transfer mechanisms. The presence of moving water and evolving seabed conditions introduces time-dependent boundary conditions that are not adequately represented in conventional steady-state models. These factors challenge the direct application of terrestrial-based thermal models and necessitate approaches that explicitly account for marine geotechnical and environmental conditions.

A range of modeling approaches has been developed to assess thermal behavior in cable systems, including analytical formulations based on international standards, numerical multiphysics models, reduced-order thermal network representations, and, more recently, data-driven forecasting techniques. Analytical methods, such as those based on IEC standards, provide simplified yet practical solutions for cable rating but often rely on assumptions of homogeneity and steady-state conditions. Numerical models, including finite element and finite volume approaches, enable detailed representation of coupled thermal and hydraulic processes but require significant computational resources and detailed input data. Reduced-order models offer computational efficiency but may sacrifice physical fidelity, while data-driven approaches, including machine learning and time-series forecasting, provide opportunities to capture temporal variability but often lack interpretability and generalizability. Despite these advances, existing approaches remain fragmented, and there is a lack of unified frameworks capable of integrating physical processes with environmental variability and operational data.

From a geotechnical perspective, subsea cables are embedded within dynamic marine sediments that evolve under hydrodynamic forcing, sediment transport, and seabed morphology. These conditions are influenced by waves, tides, currents, and anthropogenic activities, introducing spatial and temporal variability that directly affects cable performance and reliability (Cao et al., 2021; Mir Tamizdoust and Ghasemi-Fare, 2020).

Recent cable failures and thermal derating incidents have highlighted that electrical and mechanical design alone are insufficient to guarantee long-term serviceability in such environments. For instance, operational experience from offshore wind export cable systems in the North Sea has shown that sections installed in low-conductivity clay-rich sediments can experience elevated conductor temperatures, leading to localized thermal derating and reduced transmission capacity (Dong et al., 2023). Similarly, in several HVDC interconnector projects, burial depth variability and post-installation seabed mobility have altered heat dissipation pathways, resulting in higher-than-anticipated thermal resistance and operational constraints.

Thermal behavior is governed not only by cable properties but also by sediment thermal conductivity, volumetric heat capacity, degree of saturation, and stratigraphic layering. In addition, cyclic pore-pressure variations, gas inclusions, and sediment disturbance during installation can alter the effective thermal properties of the surrounding soil over time. Seabed morphodynamics such as scour, sediment mobility, and cable exposure further complicate heat dissipation pathways, potentially leading to localized thermal hotspots or changes in boundary conditions during operation (Unsworth et al., 2023). These processes introduce uncertainties that are not adequately captured by simplified or static modeling approaches.

Thermal behavior is governed not only by cable properties but also by sediment thermal conductivity, volumetric heat capacity, degree of saturation, and stratigraphic layering (Lu et al., 2007; Dong et al., 2015; Li and Wang, 2024). In addition, cyclic pore-pressure variations, gas inclusions, and sediment disturbance during installation can alter the effective thermal properties of the surrounding soil over time (Hughes et al., 2015; Zhou et al., 2022). Seabed morphodynamics such as scour, sediment mobility, and cable exposure further complicate heat dissipation pathways and modify thermal boundary conditions, particularly through interactions with seawater temperature and flow variability (Ma et al., 2024). These coupled processes introduce spatial and temporal variability and associated uncertainty in thermal response, which are not adequately captured by simplified or static modeling approaches (Yan et al., 2025).

In this context, this paper presents a critical review and perspective on thermal–geotechnical modeling of buried subsea power cables. The study synthesizes existing literature across electrical engineering, marine geotechnics, and environmental modeling, and organizes modeling approaches into a structured taxonomy comprising deterministic thermal models, coupled thermo-hydraulic formulations, data-driven techniques, and emerging hybrid physics–data frameworks. Key limitations and knowledge gaps in current methodologies are identified, with particular emphasis on subsea-specific processes, uncertainty in

sediment properties, and the integration of monitoring data into predictive models. Building on this synthesis, a conceptual roadmap for hybrid modeling is proposed as a future research direction to support adaptive, data-informed thermal assessment of subsea cable systems. This review contributes to advancing reliable, efficient, and environmentally responsible subsea cable design, which is essential for supporting global energy transition goals while minimizing ecological impacts in marine environments. Despite these advances, several critical interdisciplinary gaps remain unresolved. Existing deterministic models inadequately capture seabed heterogeneity and evolving thermo-hydraulic conditions, while transient environmental forcing such as tidal and seasonal variability is rarely incorporated into conventional thermal rating approaches. Data-driven methods, although effective in capturing temporal patterns, often lack integration with governing physical processes and therefore have limited interpretability in engineering design. Furthermore, the absence of unified frameworks that combine physics-based modeling with real-time or observational data restricts the ability to perform adaptive and site-specific thermal assessment. This review addresses these challenges by proposing a hybrid modeling framework that integrates physics-based thermal solvers with data-driven forecasting techniques, enabling improved representation of environmental variability, parameter uncertainty, and dynamic boundary conditions.

2 Review methodology

This study adopts a structured literature review approach to synthesize existing research on thermal–geotechnical modeling of subsea power cable systems. The objective is to systematically identify, classify, and critically evaluate modeling approaches reported across electrical engineering, marine geotechnics, and environmental modeling domains, while maintaining sufficient flexibility to incorporate interdisciplinary contributions.

2.1 Literature search strategy

A comprehensive literature survey was conducted using the Scopus database, complemented by targeted searches in Web of Science and Google Scholar to ensure broad coverage of peer-reviewed publications. The search was performed in January 2025 and included publications from 2005 onward, with emphasis on recent advances over the past decade. The search strategy combined keywords related to subsea cables, thermal behavior, and geotechnical processes, including: *"subsea cable," "submarine power cable," "thermal behavior," "ampacity," "marine sediment," "seabed soil," "thermal conductivity," "heat transfer,"* and *"offshore energy transmission."*. The temporal distribution of publications related to thermal–geotechnical behavior of subsea power cables is presented in Figure 2.

The observed trend reflects the growing recognition of thermal–geotechnical interactions as a critical factor in subsea cable design and operation. The increase in publications in recent years also highlights the emergence of advanced modeling approaches, including numerical multiphysics simulations and data-driven techniques, as well as increased availability of field monitoring data. This trend supports the need for a structured synthesis of existing methodologies, as undertaken in this review.

Boolean operators were used to refine the search queries, and multiple combinations of keywords were tested to ensure comprehensive retrieval of relevant studies. Reference lists of key articles were also screened to identify additional sources not captured in the initial database search.

The initial database search yielded approximately 320 records across Scopus, Web of Science, and Google Scholar. After removal of duplicate entries, 245 unique records remained. A preliminary screening based on titles and abstracts resulted in the exclusion of studies not directly related to thermal behavior, cable systems, or geotechnical interactions, reducing the dataset to 128 publications. Subsequently, these studies were subjected to full-text review to

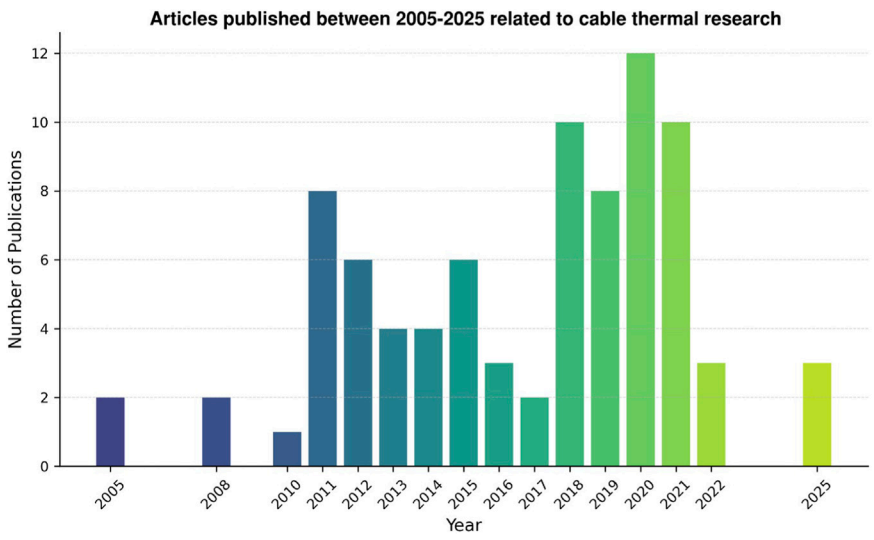


FIGURE 2
Temporal evolution of peer-reviewed publications addressing thermal–geotechnical behavior of subsea power cables and marine sediment interaction (2005–2025).

assess methodological relevance and applicability to subsea environments, leading to a final selection of 67 publications included in this review. Of these, 22 studies focused on deterministic and analytical approaches, 18 on numerical and thermo-hydraulic modeling, 15 on data-driven methods, and 12 on hybrid or integrated frameworks.

2.2 Inclusion and exclusion criteria

To ensure relevance and quality, the following inclusion criteria were applied:

- Peer-reviewed journal articles published in English;
- Studies addressing thermal behavior, heat transfer, or ampacity of power cables;
- Research involving soil, sediment, or environmental interactions relevant to cable thermal performance;
- Studies presenting analytical, numerical, experimental, or data-driven modeling approaches.

The following exclusion criteria were applied:

- Conference papers, editorials, and non-peer-reviewed reports;
- Studies focused exclusively on electrical or insulation design without consideration of thermal–soil interaction;
- Duplicates or studies with insufficient methodological detail.

Given the limited availability of subsea-specific studies, selected terrestrial cable studies were included where their methodologies were considered transferable or informative for subsea applications. These studies were critically evaluated with respect to their applicability under marine conditions.

2.3 Screening and classification

The initial search yielded a broad set of publications, which were screened based on titles, abstracts, and keywords to identify relevant studies. Full-text review was then conducted for selected articles to assess their methodological contribution and relevance to subsea thermal–geotechnical processes.

The selected studies were subsequently categorized into four primary modeling groups:

1. Deterministic thermal models (analytical and standards-based approaches);
2. Coupled thermo-hydraulic and multiphysics numerical models;
3. Data-driven and statistical forecasting approaches;
4. Hybrid physics–data modeling frameworks.

This classification enables a structured comparison of modeling approaches in terms of physical representation, data requirements, computational complexity, and applicability to subsea environments.

To further understand the structure of existing research, a thematic network analysis was performed on the selected studies. Figure 4 illustrates the relationships among publications based on thematic similarity, with nodes representing individual studies and edges indicating conceptual or methodological connections.

The network reveals the presence of distinct research clusters, broadly corresponding to (i) cable ampacity and electrical performance studies, (ii) soil–cable thermal interaction and geotechnical processes, and (iii) subsea and submarine cable applications. The relatively dense interconnections between clusters suggest increasing overlap between electrical, geotechnical, and environmental domains, reflecting the interdisciplinary nature of subsea cable research.

At the same time, the presence of identifiable clusters highlights a degree of fragmentation in the literature, where different modeling approaches and disciplinary perspectives are often developed in parallel. This observation supports the need for integrated modeling frameworks that can bridge these domains, as discussed in subsequent sections.

While Figure 2 highlights the rapid growth of research activity, the thematic network shown in Figure 3 illustrates the structural organization and fragmentation of the field.

2.4 Scope and limitations

It is important to note that this review is not intended as a fully systematic meta-analysis with quantitative synthesis, but rather as a structured critical review that integrates insights across multiple disciplines. While efforts were made to ensure comprehensive coverage, the selection of studies may be influenced by database indexing and keyword selection. Furthermore, due to the interdisciplinary nature of the topic, certain relevant studies from adjacent domains may not be exhaustively captured.

Despite these limitations, the adopted methodology provides a transparent and reproducible framework for organizing existing knowledge and identifying research gaps in thermal–geotechnical modeling of subsea power cables.

3 Thermal-geotechnical processes in subsea environment

Heat dissipation from a buried subsea power cable is governed by the transfer of internally generated heat from the conductor to the surrounding marine environment. This process occurs predominantly through radial heat conduction across a sequence of material layers that include the conductor, electrical insulation, metallic sheaths, external protection, engineered backfill, and native seabed sediments (Dong et al., 2023). Among these components, the surrounding sediment typically constitutes the dominant thermal resistance and therefore controls the rate at which heat is removed from the cable system (De Lieto Vollaro et al., 2011). The seabed thus functions as a three-dimensional thermal sink whose effectiveness depends on the intrinsic thermal properties of the soil–water matrix. Refer to Table 1 for nomenclature and symbols used in this manuscript.

The thermal response of marine sediments is primarily governed by thermal conductivity (λ) and volumetric heat capacity (ρc), which together control both the magnitude of temperature rise and the rate of thermal equilibration (Lu et al., 2007; Dong et al., 2015).

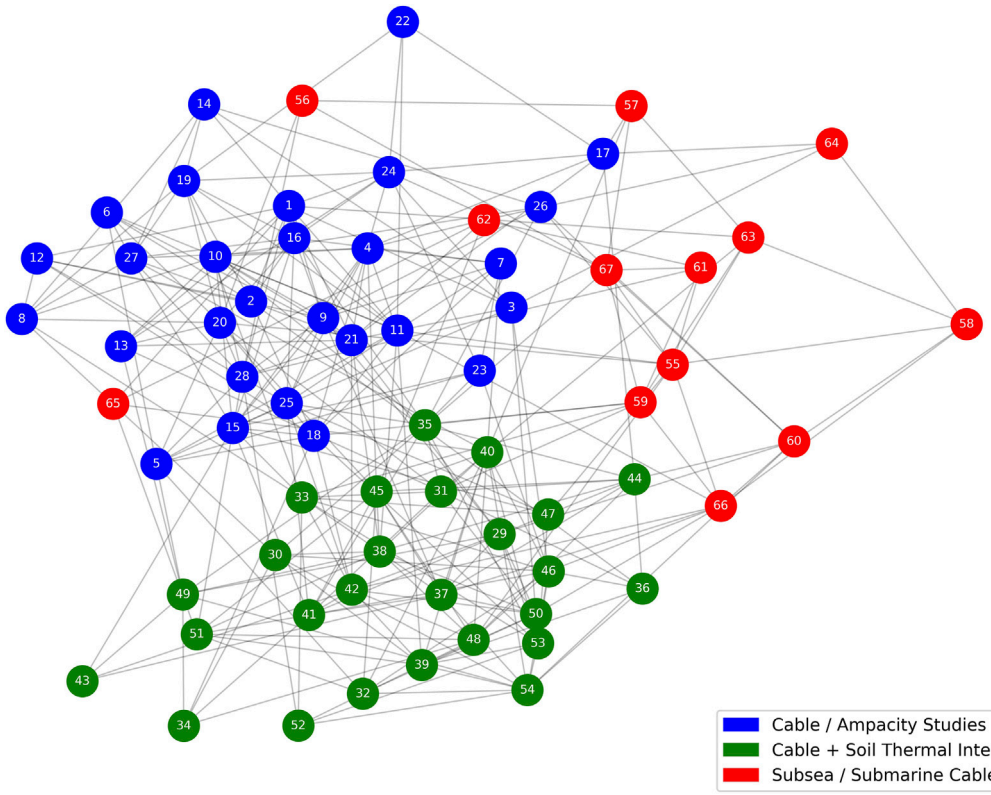


FIGURE 3
Thematic network of selected subsea cable studies. Nodes represent individual publications and are labeled numerically for identification purposes only; node size is uniform and does not reflect citation count or network centrality. Colors indicate research focus, and edges represent thematic similarity. The network highlights the interdisciplinary and partially fragmented nature of existing research.

In coarse-grained, fully saturated sands and silts, heat transfer is relatively efficient due to the interconnected pore-water network, which enhances conduction (Zhou et al., 2022). In contrast, fine-grained sediments or partially desaturated soils exhibit markedly lower effective thermal conductivity. The presence of entrapped gas or air-filled voids introduces low-conductivity phases that disrupt heat-flow paths, producing localized thermal bottlenecks around the cable (Hughes et al., 2015). Consequently, porosity (n) and degree of saturation (S_r) exert first-order control on the radial temperature gradients that develop in the vicinity of the cable.

At the continuum scale, the coupled thermal behavior of the soil–cable system is described by the transient heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q' \tag{1}$$

where T denotes temperature, $\lambda(\theta)$ represents moisture-dependent thermal conductivity, and Q corresponds to internal heat generation within the conductor. This governing (Equation 1), provides the theoritical provides the theoretical foundation for both classical analytical cable-rating formulations and modern numerical approaches such as finite-element and finite-volume modeling (De Lieto Vollaro et al., 2011; Dong et al., 2023). Although analytical solutions often assume constant soil properties and steady-state conditions, the equation itself is inherently transient and capable of representing time-dependent behavior when appropriate material descriptions and boundary conditions are applied.

In marine environments, conductive heat transfer rarely occurs in isolation. The seabed is subjected to continuous hydrodynamic forcing from tides, waves, and currents, which can induce oscillatory pore-water flow within shallow sediment layers. This pore-fluid motion introduces advective heat transport that may augment or counteract conductive heat dissipation, particularly in permeable sands (Zhou et al., 2022). In practice, CFD-based workflows are often used to quantify flow resistance and loss characteristics that underpin convective parameterization, and similar approaches can support near-bed convection estimates for exposed or partially exposed cable segments (Haroon et al., 2017). Although advective effects are often neglected in simplified design models, they can modify near-cable temperature fields and contribute to temporal variability in thermal performance.

At the sediment–water interface, heat exchange with the overlying seawater imposes an additional, time-dependent boundary condition on the system. This interaction is commonly represented through a convective heat-flux relationship, shown in Equation 2:

$$-\lambda \frac{\partial T}{\partial z}|_{z=0} = h(t)\,[T(z=0,t) - T_{sw}(t)] \tag{2}$$

where $h(t)$ is the convective heat-transfer coefficient and $T_{sw}(t)$ is the seawater temperature. Both parameters vary over time due to

TABLE 1 Nomenclature and symbols used in this manuscript.

Symbol	Description
T	Temperature (K or °C)
q'	Volumetric heat generation within the cable (W m^{-3})
λ	Effective thermal conductivity of soil or sediment (W m^{-1} K^{-1})
λ_h	Horizontal thermal conductivity of layered or anisotropic sediment ($Wm^{-1}K^{-1}$)
λ_v	Vertical thermal conductivity of layered or anisotropic sediment ($Wm^{-1}K^{-1}$)
ρ	Bulk density of soil or sediment (kgm^{-3})
c	Specific heat capacity of soil or sediment ($Jkg^{-1}K^{-1}$)
ρc	Volumetric heat capacity of soil or sediment ($Jm^{-3}K^{-1}$)
S_r	Degree of saturation of soil or sediment (–)
n	Porosity of soil or sediment (–)
z	Vertical coordinate measured from seabed surface (m)
t	Time (s)
T_{sw}	Seawater temperature at the sediment–water interface (K or °C)
h	Convective heat-transfer coefficient at sediment–water interface ($Wm^{-2}K^{-1}$)
FEM	Finite element method
FVM	Finite volume method
R–C	Thermal resistance–capacitance network model
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
DTS	Distributed temperature sensing
PINN	Physics-informed neural network
LSTM	Long short-term memory neural network
GRU	Gated recurrent unit
SVR	Support vector regression
GPR	Gaussian process regression

hydrodynamic forcing, including current velocity, stratification, storm events, and seasonal temperature variability, which govern heat exchange at the sediment–water interface (Mir Tamizdoust and Ghasemi-Fare, 2020; Unsworth et al., 2023). Recent numerical analyses of submarine cable systems demonstrate that seawater velocity and burial configuration significantly influence conductor temperature, with temperature reductions stabilizing beyond approximately 1 m/s current velocity and burial depth governing the transition from convective to conduction-dominated regimes (Zhang et al., 2020). For shallowly buried cables, fluctuations in this upper boundary condition can propagate into the sediment and influence the thermal regime surrounding the cable on timescales ranging from hours to months.

The effective thermal conductivity of marine sediments is further influenced by saturation state and pore-fluid composition. Microstructure-sensitive numerical approaches such as lattice element formulations have been used to model effective thermal conductivity in modified geomaterials, offering insight into how contact topology and inclusions alter conductive pathways (Rizvi et al., 2018). A commonly adopted conceptual expression represents λ as a function of porosity and saturation shown in Equation 3:

$$\lambda_{\text{eff}} = (1-n)\lambda_s + nS_r\lambda_w + n(1-S_r)\lambda_a \tag{3}$$

where λ_s, λ_w, and λ_a denote the thermal conductivities of the solid mineral skeleton, pore water, and air, respectively (Lu et al., 2007; Dong et al., 2015). While simplified, this formulation illustrates the pronounced sensitivity of heat dissipation to even modest reductions in saturation. Such changes may arise from cyclic thermal loading, pore-pressure redistribution under hydrodynamic forcing, or disturbance of the sediment fabric during installation and post-installation seabed evolution (Hughes et al., 2015; Zhou et al., 2022). Field-relevant analyses show that temperature fields around buried power cables differ markedly between static and cyclic heating regimes, with implications for near-field gradients and thermal risk envelopes (Ahmad et al., 2021; Ahmad et al., 2026).

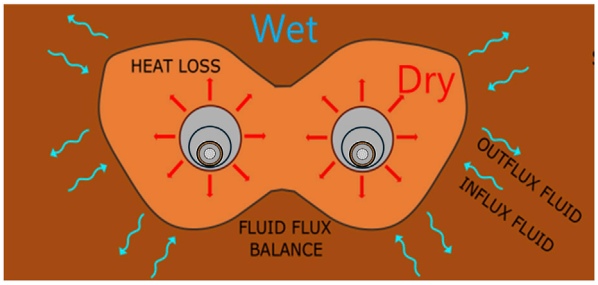


FIGURE 4
Conceptual representation of thermo–hydraulic interaction around buried subsea power cables under cyclic thermal loading. Heat dissipation induces moisture redistribution, leading to the development of locally desaturated zones with reduced degree of saturation (S_r) and thermal conductivity (λ). Fluid influx and outflux govern the dynamic balance between wet and dry regions, influencing long-term ampacity and thermal reliability.

Taken together, these mechanisms define the soil–cable system as a coupled thermo-hydraulic domain in which thermal performance depends not only on intrinsic sediment properties but also on environmental forcing and subsurface variability (Unsworth et al., 2023). This coupling implies that soil thermal parameters cannot be treated as static inputs but must instead be understood as evolving quantities influenced by both operational and environmental processes. Establishing this physical foundation is essential for interpreting the limitations of conventional steady-state cable-rating approaches and for motivating the advanced numerical and data-driven frameworks reviewed in subsequent sections of this paper.

3.1 Influence of soil properties and stratigraphy

Marine sediments are rarely uniform. Layered sequences of sand, silt, clay, and organic material lead to spatially variable thermal properties along the cable route. Fine-grained clays, although rich in water, often exhibit lower thermal conductivity (0.8–1.2 $W\,m^{-1}\,K^{-1}$) compared to coarse sands (1.5–2.5 $W\,m^{-1}\,K^{-1}$). Transitions between these layers can cause abrupt changes in thermal resistance, producing "hot spots" where local temperature rises exceed design assumptions. Furthermore, the volumetric heat capacity (ρc) of clays is high, meaning that they store rather than dissipate heat efficiently; this can delay cooling during load fluctuations and extend the time to reach thermal equilibrium. Salinity, mineralogy, and pore-water chemistry also modify λ by influencing ionic conduction within the pore fluid, making *in situ* thermal characterization a nontrivial task.

Beyond intrinsic properties, structural factors such as burial depth, backfill geometry, and compaction influence the effective heat path. A shallow burial depth exposes the cable to higher convective losses but less conductive confinement, while over-burial within low-λ sediments can trap heat and raise steady-state conductor temperature. The thermal performance of a subsea cable is thus controlled by a multi-parameter interaction between soil type, saturation, and burial configuration parameters that are inherently geotechnical.

3.2 Failures and thermal challenges with geotechnical roots

Post-installation inspections, forensic analyses, and long-term monitoring of subsea power cables increasingly demonstrate that a substantial fraction of thermal and mechanical degradation originates from geotechnical processes within the surrounding seabed rather than from intrinsic electrical defects. Although modern cable systems are designed with conservative thermal limits and robust insulation materials, their long-term performance is fundamentally constrained by the evolving ability of the seabed to dissipate heat. Environmental forcing, sediment mobility, and operational loading interact to modify soil thermal properties over time, often in ways not captured by conventional design assumptions. The most critical geotechnically driven mechanisms affecting thermal performance are discussed below.

3.2.1 Saturation loss and dry-out

Cyclic thermal loading associated with variable power transmission can induce progressive moisture redistribution in the immediate vicinity of a subsea cable. In fine-grained backfill materials and low-permeability marine sediments, repeated heating promotes vapor migration away from the cable surface along thermal gradients. Even under globally saturated seabed conditions, this process may lead to localized partial desaturation in the near-field zone surrounding the cable. Because the thermal conductivity of air is orders of magnitude lower than that of water, small reductions in degree of saturation (S_r) can result in disproportionate decreases in effective thermal conductivity (λ). This initiates a positive feedback mechanism whereby reduced heat dissipation elevates conductor temperature, further enhancing moisture migration and accelerating desaturation. The strong nonlinearity between saturation and effective conductivity is consistent with pore-network connectivity concepts demonstrated in lattice-based studies of unsaturated granular composites (Shrestha et al., 2019). The coupled interaction between radial heat dissipation, moisture redistribution, and pore-fluid flux balance in adjacent cable systems is conceptually illustrated in Figure 4. Over extended operational periods, such feedback can produce persistent thermal bottlenecks that are not reversible during cooling cycles. Laboratory investigations and numerical studies have shown that repeated heating–cooling cycles can significantly alter moisture distributions in fine-grained soils, leading to long-term degradation of thermal performance even in the absence of external drying (Dong et al., 2015; Lu et al., 2007). Laboratory-scale cable backfill experiments under steady and cyclic thermal loading further confirm that thermal cycling can drive measurable performance shifts in the surrounding geomaterial, especially through moisture redistribution and evolving effective conductivity (Ahmad et al., 2019; Ahmad et al., 2025a). These observations underscore the limitations of assuming fully saturated and thermally stable soil conditions in subsea cable rating.

3.2.2 Sediment heterogeneity

Marine sedimentary environments are inherently heterogeneous, with spatial variability in grain size distribution, mineral composition, fabric, and organic content occurring over short lateral and vertical scales. Along a subsea cable route, transitions between sands, silts, clays, and mixed deposits introduce abrupt contrasts in thermal conductivity that strongly influence heat dissipation. Low-conductivity clays and organic-rich sediments may act as thermal barriers, concentrating heat within localized sections of the cable. Numerical simulations and field observations indicate that such heterogeneity can produce temperature differentials exceeding 10–15°C relative to adjacent higher-conductivity zones (De Lieto Vollaro et al., 2011; Dong et al., 2023). These localized hot spots are particularly problematic because they may not be detected through averaged soil characterization or uniform thermal design parameters. Furthermore, sediment heterogeneity complicates post-installation monitoring and interpretation of temperature data, as measured thermal responses may reflect local geological conditions rather than global loading changes. From a design perspective, neglecting heterogeneity may lead to underestimation of peak conductor temperatures and premature insulation aging in thermally unfavorable segments.

3.2.3 Scour and exposure

Seabed mobility poses a long-term threat to both the mechanical protection and thermal stability of subsea power cables. Processes such as bedform migration, current-induced scour, anchor drag, fishing activity, and interaction with nearby offshore foundations can progressively reduce burial depth or fully expose sections of a cable. Loss of sediment cover fundamentally alters the dominant heat-transfer mechanism from conduction through soil to convection with the surrounding seawater. While convective heat exchange may enhance cooling under certain steady conditions, exposed cables are subject to rapid thermal cycling driven by fluctuating seawater temperatures, currents, and operational loads. Such thermal cycling accelerates thermo-mechanical fatigue, promotes differential expansion of cable components, and increases the rate of insulation degradation (Mir Tamizdoust and Ghasemi-Fare, 2020; Unsworth et al., 2023). In addition, repeated burial and re-exposure due to migrating sediments can produce complex thermal histories that are difficult to capture using static models. These effects highlight the need to consider seabed morphodynamics not only as a mechanical risk but also as a critical factor in thermal reliability assessment.

3.2.4 Cyclic hydrodynamics

Marine sediments experience continuous hydrodynamic forcing arising from tides, waves, and episodic storm events, which induce cyclic pore-pressure fluctuations within the seabed. These fluctuations can modify effective stress, porosity, and degree of saturation in and around cable trenches. In permeable sediments, oscillatory pore-water motion may temporarily enhance advective heat transport, while in fine-grained soils it can alter thermal contact conditions between the cable, backfill, and native sediment. Short-term changes in saturation state and fabric can result in transient variations in effective thermal conductivity by factors of two or more (Zhou et al., 2022). Although individual cycles may be short-lived, their cumulative influence over thousands of tidal and storm cycles can contribute to long-term variability in thermal performance. Such variability complicates the interpretation of distributed temperature sensing data and challenges the assumption of steady thermal boundary conditions commonly adopted in design practice.

3.2.5 Thermally enhanced backfill degradation

Thermally enhanced backfills (TEFs) are increasingly used to improve subsea cable heat dissipation by increasing the effective thermal conductivity of the surrounding medium. These materials often rely on optimized grain-size distributions, high solid–fluid contact efficiency, or the inclusion of conductive additives. While TEFs can significantly improve initial thermal performance, their long-term stability under marine conditions remains uncertain. Cyclic hydrodynamic loading, installation-induced disturbance, chemical interaction with seawater, and biological activity may induce particle segregation, loss of fines, or changes in fabric over time. Such degradation processes can reduce contact efficiency and progressively diminish λ, eroding the intended thermal benefits of the backfill (De Lieto Vollaro et al., 2011). From a lifecycle perspective, the performance of TEFs should therefore be evaluated not only at installation but throughout the operational lifespan of the cable.

Collectively, these mechanisms operate over seasonal to decadal timescales, demonstrating that soil thermal properties surrounding subsea cables are dynamic rather than static. Models that assume fixed values of λ and ρc risk under- or over-estimating ampacity and may fail to capture the onset of progressive thermal overstress. Recognizing and quantifying these geotechnically driven processes is essential for the development of adaptive thermal models and resilient subsea cable design strategies.

3.3 Need for geotechnical thermal modeling

Conventional cable-rating frameworks, such as IEC 60287 and CIGRÉ 601, represent the seabed as a static, homogeneous medium characterized by a single, time-invariant thermal resistivity. This idealization has proven adequate for many terrestrial installations where soil conditions are relatively stable and well constrained. In marine environments, however, these assumptions are increasingly incompatible with field reality. Subsea cables are embedded within sediments that are spatially heterogeneous, hydraulically active, and continuously influenced by hydrodynamic forcing, sediment transport, and pore-fluid migration. As a result, the thermal environment surrounding a subsea cable is neither uniform nor stationary, and its evolution cannot be captured using simplified steady-state representations.

Marine seabeds exhibit pronounced variability in sediment type, stratigraphy, porosity, and saturation state over both lateral and vertical scales. These variations directly affect thermal conductivity (λ) and volumetric heat capacity (ρc), which govern the dissipation and storage of heat generated by cable operation. Moreover, environmental processes such as tidal cycling, wave loading,

storm events, and long-term morphodynamic change can modify burial depth, sediment fabric, and degree of saturation (S_r) over time. Together, these processes introduce temporal variability into soil thermal properties that is fundamentally inconsistent with the fixed-parameter assumptions embedded in traditional cable-rating methods.

A growing body of recent research demonstrates that incorporating site-specific and depth-dependent thermal properties into thermal analyses can substantially alter predicted temperature fields and allowable current ratings. Studies that account for measured profiles of λ, ρc, and S_r report deviations in predicted conductor temperature on the order of 20%–30% relative to conventional design approaches. Such discrepancies are not merely academic; they have direct implications for ampacity estimation, insulation aging, and long-term reliability. Overly conservative assumptions may lead to unnecessary derating and economic inefficiency, while unconservative assumptions risk progressive thermal overstress and premature failure.

These findings have motivated a paradigm shift away from purely electrical design philosophies toward integrated thermal–geotechnical modeling frameworks in which the seabed is treated as an active component of the cable system. Within this perspective, soil properties are no longer treated as fixed boundary conditions but as evolving state variables influenced by environmental forcing and operational history. Geotechnical thermal modeling enables explicit representation of sediment heterogeneity, saturation dynamics, burial configuration, and seabed exposure, thereby providing a physically consistent basis for evaluating temperature evolution under realistic conditions.

Adopting a geotechnical thermal framework offers several tangible benefits. It allows engineers to quantify the influence of sediment stratigraphy and moisture state on heat dissipation, to evaluate the thermal consequences of burial depth and backfill selection, and to assess the impact of seabed mobility and hydrodynamic variability on long-term performance. Importantly, such models also provide a foundation for probabilistic and adaptive design approaches, in which uncertainty in soil properties and environmental forcing can be explicitly considered rather than absorbed into conservative safety factors.

Ultimately, the performance of subsea power cables is constrained not by conductor efficiency alone but by the capacity of the surrounding seabed to dissipate heat. The heterogeneity of marine sediments, their evolving saturation state, and their exposure to cyclic hydrodynamic loading render the thermal response of the seabed inherently geotechnical in nature. Recognizing and modeling these soil-controlled mechanisms is therefore a prerequisite for the development of resilient, efficient, and future-ready subsea power transmission systems.

4 Current practice and limitations

The engineering design of subsea power cables has historically been driven by electrical and mechanical criteria, with geotechnical input limited to burial feasibility and protection. In practice, the thermal behavior of the seabed, although critical for cable reliability, is often simplified or represented through constant parameters. A closer inspection of standard design workflows reveals both the strengths and the deficiencies of the present approach from a geotechnical perspective.

4.1 Present design workflow

Design procedures generally follow three stages: (i) geotechnical and geophysical site characterization, (ii) burial and backfill design, and (iii) thermal performance assessment:

(a) Site investigation and soil classification High-resolution geophysical surveys, complemented by cone penetration tests (CPT), vibracores, and grab samples, define the stratigraphy, shear strength, and soil type along the route. These parameters guide trenching method selection but rarely include *in situ* measurements of thermal conductivity or volumetric heat capacity. Thermal properties are typically inferred from empirical correlations or laboratory measurements on disturbed samples, introducing uncertainty in representative field values. Recent soft- and hard-computing approaches for estimating effective thermal conductivity from soil descriptors provide an additional pathway to reduce uncertainty when direct *in situ* measurements are sparse (Rizvi et al., 2020b).

(b) Burial and backfill design The target burial depth is determined by balancing mechanical protection requirements, against trawling, anchors, and hydrodynamic exposure with constructability constraints. Depending on the trenching method (jetting, ploughing, or mechanical excavation), the backfill may consist of native sediment or a thermally enhanced material (TEF) designed to increase λ. In most cases, the backfill is assumed to remain homogeneous and saturated throughout the cable's service life, despite known changes in density and moisture over time.

(c) Thermal rating analysis Steady-state analytical formulations, most commonly the IEC 60287 standard or its CIGRÉ equivalents, are used to estimate ampacity. The cable and its environment are idealized as concentric cylindrical layers, each with assigned thermal resistivity. The soil is represented as a semi-infinite homogeneous medium with a constant λ and a fixed ambient temperature (T_∞). The resulting temperature rise is linear in the logarithm of radial distance, and the maximum allowable current is obtained by limiting the conductor temperature below its design threshold (typically 90 deg. C for XLPE systems).

4.2 Limitations of the conventional approach

Although effective for preliminary design, these assumptions diverge from field reality in several respects:

- Static soil properties: The IEC model assumes constant λ and ρ c, whereas *in situ* values vary dynamically with saturation,

TABLE 2 Comparison of current subsea cable design practices, limitations, and emerging geotechnical opportunities.

Aspect	Current practice	Limitations/Technical gaps	Geotechnical opportunities
Soil characterization	Focused on strength and stratigraphy; thermal properties are seldom measured	Thermal properties inferred from correlations or laboratory tests on disturbed samples	Incorporate *in situ* thermal conductivity (λ) and volumetric heat capacity (ρc) testing with CPT; correlate λ with degree of saturation (S_r), porosity, and grain-size distribution
Backfill selection	Native or thermally enhanced backfill (TEF) specified primarily by electrical design criteria	TEF behavior under cyclic loading, segregation, and salinity effects remains poorly constrained	Conduct laboratory and field-scale evaluation of TEF–sediment mixing and long-term evolution of λ
Thermal modeling	IEC 60287 steady-state analytical formulations	Static λ, uniform burial depth, constant seabed temperature	Develop transient FEM/FVM models with spatially variable λ and time-dependent boundary conditions
Boundary conditions	Fixed ambient seabed temperature	Neglects tidal, diurnal, and seasonal temperature variability	Apply data-driven forecasting approaches (e.g., prophet) for dynamic thermal boundary inputs
Monitoring	Limited to electrical load and conductor temperature	Absence of soil temperature, moisture, or pore-pressure feedback	Integrate distributed temperature sensing (DTS) and pore-pressure sensors for coupled thermal–hydraulic monitoring
Post-installation evolution	Assumed constant burial depth and stable soil conditions	Scour and sediment mobility alter heat dissipation pathways over time	Couple morphodynamic and thermal models to predict cable exposure and associated temperature rise

temperature, and compaction. Repeated heating–cooling cycles may desaturate the soil, reducing λ by up to 50 percent.

- Simplified boundary conditions: The upper boundary is taken as isothermal at T_∞, ignoring tidal and seasonal temperature variations. In shallow waters, the sediment–water interface may fluctuate by 5–10 deg. C daily, influencing the upper thermal gradient.
- Neglecting layering and anisotropy: Real seabeds exhibit stratification and anisotropic thermal conductivity ($\lambda_h \neq \lambda_v$). One-dimensional analytical models cannot capture lateral heat spreading or localized hot spots induced by low-λ sediment layers.
- No coupling with hydrodynamics: Pore-water advection induced by tides and waves can transport heat; this is not represented in purely conductive frameworks.
- Limited post-installation feedback: Once installed, most systems lack soil instrumentation, preventing calibration of model predictions or adaptive operation based on measured thermal behavior.
- These simplifications lead to conservative ampacity estimates, often resulting in overdesign, or, conversely, to unrecognized risks of overheating when soil properties degrade.

4.3 Toward geotechnically informed thermal design

A geotechnical perspective reframes the seabed not as a passive boundary but as an active component of the cable system. Incorporating measured soil parameters and environmental variability into design models enables more realistic and site-specific ampacity evaluations. The integration of distributed temperature sensing (DTS) and *in situ* thermal testing (e.g., needle-probe or thermal response tests) can close the data gap between assumed and actual conditions.

Table 2 summarizes the contrast between current industry practices, their inherent limitations, and the emerging opportunities for improvement through geotechnical characterization and data-driven methods.

4.4 Implications for design and research

The recognition of these limitations has motivated a shift toward more comprehensive thermal modeling that merges geotechnical data with environmental forcing. Future design standards are likely to include variable (λ) and ρ c profiles, transient seabed temperature boundaries, and uncertainty analyses reflecting natural variability. Such integration will require closer collaboration between electrical engineers, marine geotechnical specialists, and data scientists.

By embedding soil thermal characterization within the cable design process, the industry can transition from empirical safety factors to predictive, site-specific models that better represent the true coupled behavior of subsea cable–soil systems.

4.5 Thematic structure of cable thermal research

To better understand the structural organization of the field, a thematic network analysis was conducted on 67 cable-related studies. The resulting graph highlights three dominant research clusters: (i) conventional cable ampacity studies, (ii) cable–soil thermal interaction research, and (iii) subsea and submarine cable investigations (see Figure 2). The visualization demonstrates that while ampacity modelling forms the dense core of the literature, thermo-hydraulic soil coupling and subsea applications remain

comparatively fragmented. The full list of analyzed studies is provided in the Supplementary Material.

5 Numerical and data-driven modeling approaches

The prediction of temperature evolution around subsea cables requires models capable of representing both the physics of heat transfer and the variability of the marine environment. Traditional analytical methods have provided practical tools for steady-state rating, but the growing complexity of offshore projects, ranging from deeper water to variable backfill and layered sediments, demands more comprehensive numerical and hybrid approaches. From a geotechnical standpoint, these models differ in how they treat soil parameters, boundary conditions, and environmental forcing. Three major families of approaches can be distinguished: deterministic (physics-based), data-driven (statistical or machine-learning), and hybrid coupling frameworks that combine the two.

5.1 Deterministic (physics-based) models

Deterministic methods explicitly solve the governing heat conduction equation. As shown in Equation 4, these models describe transient heat transfer within the soil–cable system by directly solving the conservation of thermal energy based on the governing physical properties of the surrounding medium.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q' \tag{4}$$

where T is the temperature field, λ is thermal conductivity, ρc is volumetric heat capacity, and q' is the volumetric heat source. These models rely on material properties measured or assumed from geotechnical data and provide spatially resolved temperature fields around the buried cable.

5.1.1 Analytical and semi-analytical formulations

The most common standard, IEC 60287, represents the soil as a homogeneous half-space with steady-state heat conduction. Its solution, though mathematically simple, assumes constant λ and a fixed boundary temperature T_∞. CIGRÉ extensions include multi-layer and transient adjustments, but the core framework remains axisymmetric and limited to conduction-only processes. Analytical solutions are valuable for design screening, sensitivity studies, and validation of more complex numerical models.

5.1.2 Finite element and finite volume models

Finite Element Method (FEM) and Finite Volume Method (FVM) models solve transient, anisotropic, or heterogeneous soil problems. Beyond continuum solvers, discrete and lattice-based formulations have also been used to represent heterogeneous geomaterials and evolving fabric effects, offering a complementary route for capturing localized behavior in cemented or structured media (Rizvi et al., 2020a). The maturity of FEM-based geotechnical simulation is also evidenced across underground and subsurface stability applications, supporting its transferability to seabed and trench-scale thermal analyses when appropriate constitutive and boundary representations are adopted. Implementations in tools such as COMSOL Multiphysics, PLAXIS Thermal, and FLAC3D allow the incorporation of:

- Depth-dependent λ and ρc profiles derived from geotechnical logs;
- Time-varying surface temperature or convective boundaries at the sediment–water interface;
- Coupled thermo-hydraulic formulations where saturation or pore pressure evolves with temperature.

Such models capture localized phenomena including trench backfill contrasts, rock berms, and seabed morphology. Their main limitation is computational cost and the need for detailed soil data, often unavailable during early project phases.

5.1.3 Thermal resistance–capacitance (R–C) networks

To reduce computational complexity, R–C network models approximate each layer (insulation, backfill, sediment) as a lumped element with equivalent thermal resistance and capacitance. The transient heat transfer is described by ordinary differential equations representing energy balance between nodes. R–C models can reproduce both steady and cyclic thermal behavior and are particularly useful for system-level simulations where fast iteration is required (e.g., operational ampacity management).

5.2 Statistical and AI-Based models

Data-driven modeling approaches offer an alternative to purely physics-based thermal analyses by learning empirical relationships between environmental forcing and observed soil or cable temperatures. Rather than explicitly solving the governing heat conduction equation, these methods infer system behavior directly from historical data. Data-driven assessment frameworks have also proven valuable for predicting degradation and risk in soil-embedded infrastructure systems, motivating analogous learning-based strategies for subsea cable condition, thermal risk, and operational decision support (Ahmad et al., 2025b). Their primary advantage lies in situations where long-term monitoring records are available but subsurface thermal properties, boundary conditions, or hydrodynamic interactions are uncertain or poorly constrained.

In marine environments, seabed temperature and saturation are influenced by multiple interacting processes, including tidal cycles, seasonal seawater temperature variation, sediment permeability, and burial depth evolution. Capturing such variability using deterministic models alone can be challenging, particularly when input data are sparse or spatially heterogeneous. Statistical and AI-based models therefore provide a complementary framework for identifying dominant temporal patterns and forecasting future thermal states under operational and environmental uncertainty.

5.2.1 Time-series forecasting models

Classical time-series models such as Autoregressive Integrated Moving Average (ARIMA) and its seasonal extension (SARIMA) represent observed temperature records as combinations of autoregressive terms, moving averages, and periodic components (Box et al., 2015). These models are computationally efficient and have been widely applied in hydrology, climatology, and coastal engineering for forecasting temperature and water-level fluctuations. However, their applicability is limited by assumptions of linearity and stationarity, which may not hold under changing environmental or operational conditions.

The Prophet model extends traditional time-series approaches by decomposing a signal into additive components representing long-term trends, multiple seasonalities, and discrete event effects (Taylor and Letham, 2018). Unlike ARIMA-type models, Prophet is designed to handle irregular sampling, missing observations, and abrupt changes in trend, features commonly encountered in offshore monitoring datasets due to sensor downtime or maintenance interruptions. Its transparent structure allows individual components to be interpreted in physical terms, such as seasonal seabed temperature cycles or step changes associated with storm events or cable reburial. These characteristics make Prophet particularly suitable for forecasting seabed temperature or saturation time series used as boundary inputs in thermal analyses.

5.2.2 Machine-learning and neural network models

More advanced machine-learning methods are capable of capturing nonlinear relationships between environmental drivers and thermal response. Techniques such as Support Vector Regression (SVR), Random Forests, and Gradient Boosted Trees have been used to model complex interactions between metocean variables, including tidal elevation, current velocity, wave height, and seabed temperature (Hastie et al., 2009). These models are well suited to multivariate datasets and can identify dominant predictors without explicit physical assumptions.

Neural network architectures designed for sequential data, particularly Recurrent Neural Networks (RNNs), offer further advantages for thermal forecasting. Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) networks incorporate internal memory states that enable them to represent long-term temporal dependencies (Hochreiter and Schmidhuber, 1997). This capability is essential for marine environments where short-period tidal cycles are superimposed on seasonal and interannual temperature trends. LSTM-based models have been successfully applied to coastal temperature prediction, groundwater level forecasting, and soil moisture estimation (Kratzert et al., 2019).

Despite their predictive power, neural networks are often criticized for limited interpretability. The learned relationships are not explicitly linked to physical soil properties such as thermal conductivity or heat capacity, which complicates their use in design-oriented analyses. Consequently, these models are most effective when used as forecasting tools rather than standalone substitutes for physics-based thermal simulations.

5.2.3 Gaussian process and probabilistic methods

Gaussian Process Regression (GPR) and Bayesian modeling frameworks provide a probabilistic alternative to deterministic and purely data-driven approaches. GPR treats temperature evolution as a stochastic process defined by a covariance function, yielding both mean predictions and associated uncertainty bounds (Rasmussen and Williams, 2006). This feature is particularly valuable in marine geotechnical applications where soil properties and boundary conditions are uncertain or spatially variable.

Bayesian approaches allow prior knowledge, such as expected seasonal behavior or physically plausible parameter ranges, to be combined with observational data. The resulting posterior distributions enable risk-informed evaluation of thermal performance, including probabilistic estimates of exceedance of allowable conductor temperatures. While computational cost can limit scalability for large datasets, probabilistic models provide critical insight into confidence levels associated with thermal predictions, supporting more robust design and operational decision-making.

5.3 Hybrid coupling frameworks

Hybrid modeling frameworks integrate the physical consistency of deterministic thermal solvers with the adaptability of data-driven forecasting models. Rather than replacing physics-based analysis, machine-learning components are used to supply time-dependent inputs or to update uncertain parameters, creating a dynamic interaction between data and governing equations.

5.3.1 Data-driven boundary forecasting

In hybrid frameworks, statistical or machine-learning models are commonly employed to forecast boundary conditions that are difficult to prescribe deterministically. Time-dependent seabed temperature $T_{sw}(t)$, pore-water pressure, or degree of saturation $S_r(t)$ can be predicted from historical metocean records using models such as Prophet or LSTM networks. These forecasts are then imposed as boundary conditions in transient finite element or thermal resistance-capacitance (R–C) models.

This approach allows thermal solvers to account for realistic environmental forcing without explicitly modeling hydrodynamics or sediment transport. By separating environmental prediction from heat transfer computation, the framework reduces model complexity while retaining sensitivity to key external drivers.

5.3.2 Physics-informed learning

Physics-informed neural networks (PINNs) represent a growing class of hybrid models in which physical laws are embedded directly into the learning process (Raissi et al., 2019). In thermal applications, the heat conduction equation is incorporated into the loss function, constraining predictions to satisfy conservation of energy. This structure improves extrapolation beyond the training dataset and reduces dependence on large volumes of labeled data.

TABLE 3 Comparison of modeling approaches for subsea cable thermal analysis.

Model type	Strengths	Limitations	Typical use case
Analytical/IEC	Simple, fast, widely standardized	Steady-state assumptions, homogeneous soil representation	Preliminary design, screening studies
FEM/FVM	Captures heterogeneity, anisotropy, and transient behavior	High data demand and computational cost	Detailed thermal assessment, research and design verification
R–C network	Computationally efficient transient approximation	One-dimensional simplification, parameter calibration required	Operational monitoring and real-time ampacity control
ARIMA/SARIMA	Simple temporal forecasting, low computational cost	Linear structure, limited non-stationary handling	Seasonal seabed temperature trend analysis
LSTM/GRU	Captures nonlinear and long-term temporal dependencies	Large training data requirements, limited interpretability	Long-term environmental and thermal forecasting
Prophet	Interpretable structure, robust to missing data and irregular sampling	Limited spatial representation without coupling	Forecasting boundary temperatures or saturation states
Hybrid (physics + AI)	Combines physical consistency with data adaptability	Implementation complexity and integration effort	Digital twin development and adaptive thermal modeling

For subsea cable applications, PINNs offer a promising pathway to integrate sparse temperature measurements with governing thermal equations, enabling estimation of spatial temperature fields and effective soil properties simultaneously. Although still an emerging research area, physics-informed learning provides a systematic means of reconciling data-driven flexibility with geotechnical realism.

5.3.3 Real-time and digital-twin integration

As offshore monitoring systems expand, hybrid models increasingly support real-time decision-making through digital twin implementations. A digital twin represents a continuously updated virtual replica of the cable–soil system, combining deterministic thermal models with real-time data assimilation. Bayesian updating, Kalman filtering, or sequential Monte Carlo methods are commonly used to adjust model parameters as new observations become available (Beck, 2021).

Within such a framework, forecast models provide near-term environmental predictions, while the thermal solver estimates conductor temperature and ampacity under anticipated conditions. This integration enables adaptive operation, early detection of anomalous heating, and proactive maintenance planning, shifting subsea cable management from static design verification toward continuous performance assessment.

5.4 Comparative assessment

The modeling approaches discussed above occupy distinct positions along a spectrum defined by physical interpretability, data requirements, and computational cost. Deterministic models offer clear physical insight but require detailed soil characterization, whereas data-driven methods excel in pattern recognition but lack explicit linkage to soil physics. Hybrid frameworks combine these strengths by embedding environmental intelligence into physically consistent thermal solvers. The relative advantages and limitations of these approaches are summarized in Table 3 providing guidance for selecting appropriate modeling strategies at different stages of subsea cable design and operation.

5.5 Computational taxonomy of subsea cable thermal models

The modeling approaches used for subsea cable thermal assessment can be categorized according to their computational structure, governing physics, dimensionality, and coupling complexity. Although numerous studies have addressed cable ampacity and temperature prediction, the computational assumptions and solution strategies vary significantly. To provide clarity, existing methods are classified into four principal categories: analytical steady-state models, numerical finite element models, coupled thermo-hydraulic formulations, and data-driven predictive models.

Analytical approaches, including IEC-based formulations, typically assume one-dimensional steady-state heat conduction with simplified boundary conditions. These methods offer computational efficiency but do not capture transient loading or sediment heterogeneity. Finite element models extend the formulation to two- or three-dimensional domains by solving the transient heat diffusion equation, as expressed in Equation 5.

$$\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q \tag{5}$$

where T is temperature, λ is thermal conductivity, and Q represents internal heat generation. While spatially resolved, many implementations neglect moisture migration and pore-scale hydraulic effects. Thermo-hydraulic models introduce coupled heat and fluid transport mechanisms by incorporating Darcy flow and moisture-dependent thermal properties. The computational characteristics and capabilities of the principal thermal modeling approaches discussed in this section are summarized in Table 4. These formulations improve physical realism but introduce

TABLE 4 Computational classification of subsea cable thermal modeling approaches.

Model type	Dimensionality	Transient capability	Hydro-thermal coupling	Computational cost
IEC analytical	1D	No	No	Low
Finite Element Method (FEM)	2D/3D	Yes	Partial	Moderate-high
Thermo-hydraulic coupled	3D	Yes	Yes	High
Data-driven/ML	0D/Statistical	Yes	No	Low-moderate
Hybrid framework (proposed)	Multi-scale	Yes	Partial	Adaptive

TABLE 5 Comparison of forecasting models for subsea thermal prediction.

Model	Advantages	Limitations	Suitability for marine geotechnics
ARIMA/SARIMA	Simple, interpretable, captures linear seasonality	Restricted to stationary assumptions, limited handling of multiple cycles	Short-term seabed temperature forecasting under stable environmental conditions
LSTM/GRU	Captures nonlinear and multivariate temporal dependencies	Large data requirements, computationally intensive, limited interpretability	Long-term coupled hydrodynamic–thermal forecasting
Gaussian process regression	Probabilistic predictions with uncertainty quantification	Poor scalability for long or high-frequency datasets	Risk-based thermal assessment and confidence interval evaluation
Prophet	Handles multiple seasonalities, interpretable structure, robust to missing data	Assumes additive effects, limited spatial generalization	Boundary temperature and moisture forecasting for hybrid geotechnical models

significant parameter sensitivity and computational demand. More recently, data-driven and statistical forecasting models have been explored to predict transient seabed temperature variations and dynamic cable rating. These approaches reduce computational burden but lack physical interpretability when applied independently. This classification highlights the absence of an integrated framework capable of combining physics-based modeling with adaptive data-driven correction for subsea environments.

5.6 Relevance to marine geotechnics

From a geotechnical viewpoint, these modeling approaches represent complementary methods of understanding how soil properties and environmental processes control heat dissipation. Deterministic models quantify conduction through stratified media, while data-driven methods infer the time-varying influence of hydrodynamic and climatic forcing. The integration of both offers a path toward predictive geotechnical frameworks where thermal behavior is continuously updated from field measurements, allowing adaptive management of subsea cable ampacity.

6 Hybrid physics-data modeling approaches for subsea cable systems

Building on the limitations identified in existing modeling approaches, hybrid physics–data modeling frameworks have emerged as a promising direction for subsea cable thermal assessment. These frameworks aim to integrate physics-based thermal models with data-driven techniques to capture both mechanistic processes and time-dependent environmental variability. A comparison of forecasting models for subsea thermal prediction is provided in Table 5. In the context of subsea cable systems, such frameworks provide a pathway for combining deterministic heat transfer models with real-time monitoring data and statistical inference methods. The following discussion outlines the key components and structure of a representative hybrid modeling framework, synthesizing concepts reported in the literature.

The preceding review highlights the fragmented nature of current modeling strategies for subsea cable thermal assessment. Deterministic models provide physical interpretability but are computationally intensive when extended to fully coupled thermo-hydraulic formulations. Data-driven approaches enable rapid forecasting yet lack embedded geotechnical physics. To address this gap, a hybrid computational framework is proposed that integrates physics-based solvers with adaptive statistical correction layers.

6.1 Governing thermo-hydraulic formulation

The thermal evolution of seabed sediments surrounding a cable may be described by the transient heat equation:

$$\frac{\partial T}{\partial t} = \nabla \cdot (\lambda(\theta)\nabla T) + Q \tag{6}$$

where T denotes temperature, $\lambda(\theta)$ represents moisture-dependent thermal conductivity, and Q corresponds to internal heat generation from the conductor. Coupled fluid flow effects may be represented through Darcy's law and mass conservation equations governing pore water migration. These coupled

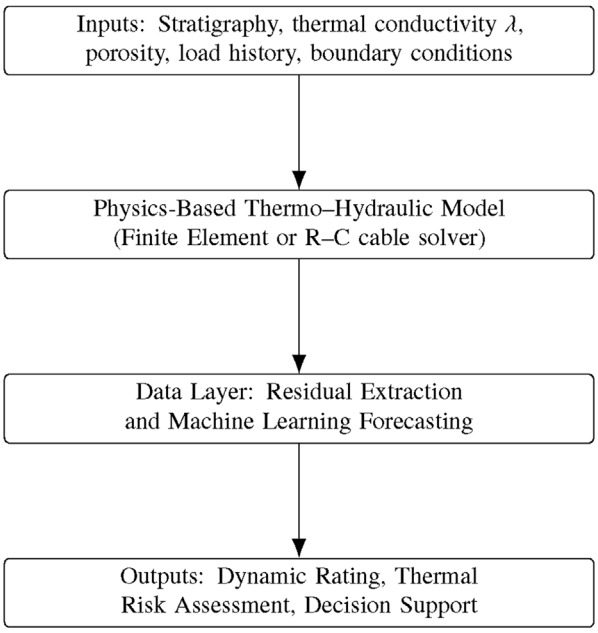


FIGURE 5
Hybrid computational architecture integrating deterministic thermo–geotechnical modeling with machine learning correction layers for adaptive ampacity estimation of subsea cable systems.

processes influence both transient response and effective thermal impedance.

6.2 Data-driven residual correction layer

While physics-based models capture governing processes, parameter uncertainty and environmental variability introduce prediction residuals. A statistical correction layer can be introduced:

$$\hat{T}(t+\Delta t) = T_{\text{physics}}(t+\Delta t) + f_{\text{ML}}(r_t) \tag{7}$$

where f_{ML} represents a forecasting model (e.g., Prophet or neural networks) trained on residuals r_t between observed and modeled temperatures. This enables adaptive refinement without abandoning physical consistency.

6.3 Integrated workflow architecture

The proposed hybrid framework operates in four computational stages:

1. Deterministic thermo-hydraulic simulation for baseline prediction
2. Residual extraction from monitoring or synthetic datasets
3. Machine learning-based correction or forecasting
4. Dynamic rating update and real-time thermal risk assessment

This architecture supports multi-scale modeling and forms a foundation for digital twin implementation in offshore energy systems.

The computational workflow of the proposed hybrid framework is illustrated in Figure 5. The architecture integrates environmental monitoring data, statistical forecasting, and deterministic thermal–geotechnical modeling to enable adaptive ampacity estimation and real-time decision support.

6.4 Computational advantages

The hybrid strategy balances interpretability and adaptability. Physics-based modeling ensures thermodynamic consistency, while data-driven layers improve robustness under uncertain sediment properties, cyclic loading, and seasonal variability. Such integration is particularly relevant for marine geotechnical environments characterized by heterogeneous stratigraphy and dynamic boundary conditions.

7 Prophet model for marine geotechnical applications

The increasing availability of long-term environmental monitoring data has motivated the use of statistical forecasting tools capable of representing non-stationary behavior, multiple seasonalities, and irregular sampling. Among these tools, the Prophet model, developed by Facebook's Core Data Science team, has emerged as a robust and interpretable framework for time-series forecasting. Unlike many black-box machine-learning approaches, Prophet decomposes observed signals into physically interpretable components, making it particularly suitable for marine geotechnical applications where statistical trends can be linked to identifiable environmental and seabed processes.

In subsea power cable systems, key thermal boundary conditions such as seabed temperature, degree of saturation, and near-bed hydrodynamic forcing exhibit pronounced temporal variability driven by tidal cycles, seasonal seawater temperature fluctuations, and episodic storm events. These variations strongly influence heat dissipation into the surrounding sediment and, consequently, cable ampacity and long-term reliability. Prophet provides a structured mechanism to forecast such boundary conditions while preserving interpretability, allowing statistical components to be directly associated with geotechnical phenomena. As such, Prophet functions as an intelligent forecasting layer that complements, rather than replaces, physics-based thermal models.

7.1 Model structure and mathematical formulation

Prophet represents an observed time series $y(t)$ as the additive superposition of four components:

$$y(t) = g(t) + s(t) + h(t) + \varepsilon(t) \tag{8}$$

where each term captures a distinct contribution to the observed signal.

The trend component $g(t)$ represents the long-term, non-periodic evolution of the system and is modeled as a piecewise linear or logistic growth function with automatically detected changepoints. In marine geotechnical contexts, this term can

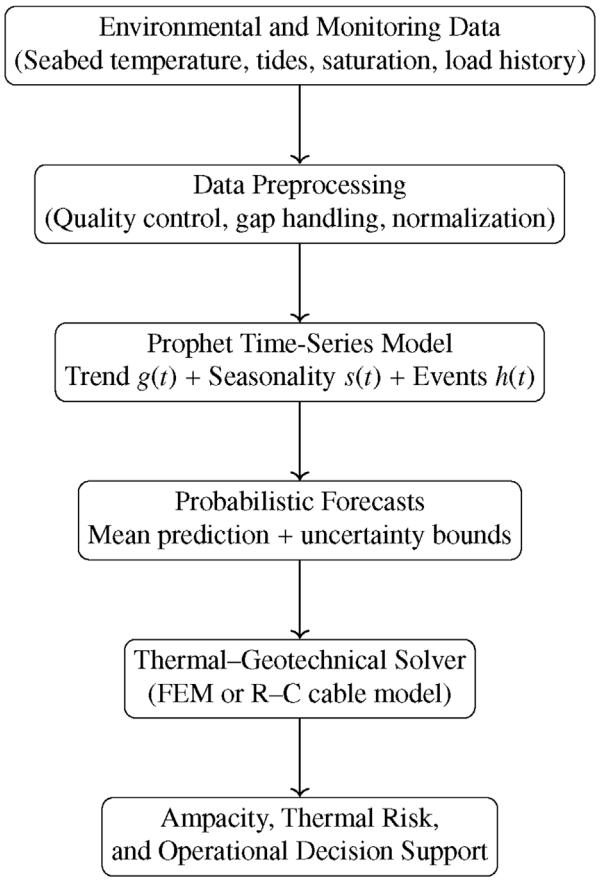


FIGURE 6
Integrated workflow for applying the Prophet forecasting model as a dynamic boundary-condition generator in marine geotechnical thermal analysis of subsea power cables.

reflect gradual seabed temperature drift due to climatic forcing, progressive burial depth changes, or long-term alteration of sediment thermal properties.

Seasonal effects are represented by the term $s(t)$ using truncated Fourier series, enabling the simultaneous capture of multiple periodicities:

$$s(t) = \sum_{n=1}^{N}\left[a_n \cos\left(\frac{2\pi nt}{P}\right) + b_n \sin\left(\frac{2\pi nt}{P}\right)\right] \quad (9)$$

where P denotes the period of the seasonal cycle. This formulation allows representation of semi-diurnal and diurnal tidal signals, seasonal seawater temperature variation, and longer-term climatic oscillations influencing seabed thermal conditions.

The event or forcing component $h(t)$ accounts for discrete disturbances such as storms, extreme tides, seabed mobility, or operational changes in cable loading. These effects are introduced as indicator functions over specified time intervals, enabling their localized thermal influence to be isolated and quantified. The residual term $\varepsilon(t)$ represents measurement noise, sensor uncertainty, and short-term variability not explicitly captured by the model.

All model parameters are estimated within a Bayesian framework implemented using the Stan probabilistic programming language, yielding posterior distributions for each component and enabling probabilistic forecasting with uncertainty bounds.

7.2 Implementation for subsea cable thermal analysis

The implementation of the Prophet model for marine geotechnical applications follows a structured workflow, schematically illustrated in Figure 6. Environmental and operational time-series data are first assembled for variables of interest, including seabed temperature, seawater temperature, pore-water pressure, or degree of saturation. Data gaps caused by sensor outages or maintenance are retained rather than interpolated, as Prophet naturally accommodates irregular sampling. A piecewise linear trend is typically specified to capture long-term thermal drift while allowing changepoints associated with major environmental or operational transitions. Multiple seasonal components are then defined explicitly, commonly including tidal (semi-diurnal or diurnal) and annual cycles. The Fourier order is selected based on the expected complexity of the thermal response and the temporal resolution of the data.

Known external disturbances such as storms, extreme wave events, or burial disturbance are incorporated as event regressors, allowing their transient thermal impact to be quantified separately from background variability. Model calibration is performed using historical data, with validation carried out through rolling-origin or cross-validation schemes to assess forecasting robustness.

Once calibrated, Prophet generates forward predictions of environmental variables with associated uncertainty bounds over horizons ranging from days to months. These forecasts are subsequently supplied as time-dependent boundary conditions or material-property modifiers (e.g., $T_{sw}(t)$ or $S_r(t)$) within finite element or thermal resistance–capacitance models. This coupling enables physics-based thermal solvers to account for realistic environmental forcing without explicitly modeling hydrodynamics or sediment transport processes.

7.3 Role within hybrid and digital-twin frameworks

Within hybrid modeling frameworks, Prophet serves as a forecasting interface between environmental monitoring systems and deterministic thermal solvers. When combined with real-time data assimilation techniques such as Bayesian updating or Kalman filtering, the approach supports digital twin implementations of subsea cable systems. In such configurations, forecasted boundary conditions and continuously updated thermal models enable proactive ampacity management, early detection of anomalous heating, and risk-informed operational decision-making.

Overall, the Prophet model provides a transparent and computationally efficient means of incorporating environmental intelligence into marine geotechnical thermal analyses, bridging the gap between long-term monitoring data and physically consistent heat transfer modeling.

7.4 Implications for marine geotechnics

The adoption of Prophet in marine geotechnical analysis provides a bridge between observational data and mechanistic modeling. By forecasting temperature, saturation, and convective boundary variations, the model enables dynamic coupling between environmental conditions and the soil's thermal response. This capability enhances the predictive accuracy of ampacity assessments, supports early detection of anomalous heating, and provides a foundation for adaptive design strategies. In doing so, the Prophet model transforms geotechnical analysis from a static design exercise into a continuously updated, data-informed process.

8 Conclusion

This study presented a structured synthesis of thermal–geotechnical modeling approaches for buried subsea power cable systems, integrating deterministic formulations, coupled thermo–hydraulic models, and data-driven techniques. The review showed that while physics-based models provide consistent representation of heat transfer, they rely on simplified assumptions regarding soil properties and boundary conditions, whereas data-driven approaches capture temporal variability but lack direct physical interpretability.

Key gaps identified in current practice include the treatment of seabed sediments as homogeneous and time-invariant media, limited representation of transient boundary conditions at the sediment–water interface, and the absence of systematic integration between monitoring data and predictive models. These limitations contribute to uncertainties in ampacity estimation, thermal derating under evolving seabed conditions, and long-term reliability assessment.

The proposed hybrid modeling framework addresses these gaps by coupling physics-based thermal solvers with data-driven correction and forecasting layers, enabling adaptive thermal assessment under variable environmental and geotechnical conditions. In practical terms, this requires (i) incorporation of depth-dependent and spatially variable soil thermal properties derived from *in situ* characterization, (ii) implementation of transient boundary conditions at the sediment–water interface using metocean data, and (iii) integration of monitoring systems such as distributed temperature sensing (DTS) for model calibration and real-time updating. Despite this advancement, challenges remain in quantifying spatial variability of sediment properties, representing coupled thermo–hydraulic processes under cyclic loading, and obtaining long-term field datasets for model validation. Addressing these challenges is essential for advancing predictive, performance-based design and operation of subsea cable systems.

Author contributions

SA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. ZR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. FW: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – review and editing.

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Conflict of interest

Author SA was employed by Kiewit Corporation.

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Supplementary material

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