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Front-End Design of Shore Crossings

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ABSTRACT: The design process for cable and pipeline shore crossings is inherently interdisciplinary. It involves assessing the transition of waves from offshore to onshore environments, which determines the hydrodynamic forces affecting both the beachfront and landfall sites. Sediment movement along and across the shore is crucial in establishing the required burial depths for these installations. It is imperative to adhere to environmental standards throughout both the construction and operational phases. This article presents an overview of current best practices for quantifying the impacts of erosion and accretion at the landfall location, sea-level rise, and coastal storms to ensure a resilient shore crossing design.

Keywords: Shore crossing design, Project development study

1 INTRODUCTION

In the energy sector, project development studies proceed through distinct phases leading up to the Final Investment Decision (FID), enabling increasingly precise estimates of the overall development cost at each stage. Upon completion of the Front-End Engineering Design (FEED), a Class 3 estimate—typically ranging from -20% to +30% as defined by the American Association of Cost Engineers (AACE)—is anticipated.

Coastal infrastructure, such as cable and pipeline shore crossings, is particularly vulnerable to severe weather. This necessitates extensive multidisciplinary engineering efforts to produce a dependable cost estimate ahead of the financial close. Shore crossing designs must account for the dynamic behavior of coastal environments, pushing geotechnical engineers to extend beyond conventional considerations such as bearing capacity.

The active and evolutive nearshore zone, refers to the coastal segment extending from the seaward limit of significant wave influence—generally defined by the depth of closure—landward to the shoreline. This region is characterized by intense hydrodynamic activity where incident wave energy undergoes shoaling, refraction, diffraction, and breaking, resulting in substantial sediment mobilization and transport. The interplay between waves, currents, and morphology governs both short-term responses (e.g., storm-induced erosion) and long-term evolution (e.g., profile equilibration, shoreline retreat).

Over the past decades, significant research has been undertaken to understand the processes in the nearshore zone. Dean (1977) introduced an equilibrium profile concept that remains central in coastal morphodynamics. Wright and Short (1984) provided a morphological classification of beach states based on wave energy and sediment characteristics, while Bowen (1980) and Thornton & Guza (1983) advanced the understanding of wave breaking and longshore current generation. More recent numerical models, such as XBeach (Roelvink et al., 2009), have enabled process-based simulations of nearshore sediment transport under both fair-weather and storm conditions.

In this context, engineering solutions for shore crossings require careful integration of this environmental constraints, i.e. short and long-term shoreline evolution, and project-specific requirements (Palmer & King, 2004). Therefore, accurate characterization of wave transformation, seabed mobility, and morphodynamic evolution is essential for optimizing burial depth, stabilizing structures, and ensuring long-term pipeline integrity (DNV, 2021). Previous studies have highlighted the importance of combining detailed numerical modeling with field observations to assess pipeline stability under extreme events (Larsen et al., 2006; Nielsen et al., 2013), but in remote areas, field survey data is generally not available. Moreover, the increasing frequency and intensity of storms due to climate change underscores the need for robust, potentially adaptive designs in this vulnerable coastal interface (Ranasinghe, 2016).

This article aims to highlight key coastal dynamics that geotechnical engineers should consider, even though they fall outside the realm of traditional geotechnical engineering, in order to develop resilient and sustainable designs for cable and pipeline shore crossings.

2 SHORE CROSSING DESIGN CRITERIA

While this article does not focus on detailing design codes and criteria, it is essential for a cable and/or pipeline shore crossing to maintain stability throughout its design life in the face of several key challenges: 1) Coastal erosion, 2) Sea-level rise, and 3) Hydrodynamic forces, including waves and currents.

Energy facilities typically have a design life ranging from 25 to 50 years. Various codes and specifications often mandate that the Top of Pipe (TOP) or Top of Cable (TOC) be buried at least 1 meter deep until reaching a water depth of -10 meters throughout the design life. Additionally, calculations for energy facilities frequently need to consider storm data with a recurrence interval of 100 years.

Numerous shore crossing solutions are available, including horizontal directional drilling, microtunneling, jack and bore, auger boring, and pipe bursting. However, this article focuses on the traditional open trench method, where the trench can be created through excavation or dredging.

3 MULTI-DISCIPLINARY DESIGN

The design of shore crossings demands a multidisciplinary approach, as contributions from multiple fields are vital for sustainable results. Typically, the project management team includes:

1) Civil Engineering: Focuses on infrastructure design and shoreline stabilization while managing coastal erosion.
2) Environmental Engineering: Assesses and mitigates environmental impacts to protect marine ecosystems.
3) Mechanical Engineering: Designs pipelines and systems for resilience against stresses and environmental challenges.
4) Electrical Engineering: Ensures power cables transmit efficiently and adhere to safety standards.
5) Hydrodynamic and Coastal Engineering: Analyzes wave dynamics, currents, and sediment transport's impact on structures.
6) Oceanography: Provides insights into water movement and climate for long-term design and risk management.
7) Regulatory Compliance and Permitting: Ensures project adherence to legal requirements, permits, and stakeholder engagement.

While geotechnical engineering is crucial in shore crossing design, collaboration with these specialized fields is essential for success.

4 HISTORICAL SHORELINE EVOLUTION

During the preliminary and concept phase, sometimes up to dozens different concepts are evaluated. In order to provide a quantified contribution for the selection of the shore crossing location, a study of historical shoreline evolution is done using satellite imagery analysis.

Luijendijk *et al.* (2018) presented a global scale assessment historical shoreline change trends. Once the concept of the possible shore crossing solutions becomes more mature, dedicated studies publicly available, based on low resolution images or commercial high-resolution images; can be performed. Himmelstoss *et al.* (2024) describe one of the possible workflows to follow for reliable results.

Figure 1 presents an anonymized example of a shoreline evolution study conducted by TotalEnergies for one of its developments. The illustration depicts 20 years of shoreline changes along a coastline section stretching just over 23 km. Shoreline erosion and accretion are evaluated at frequent intervals along this 23 km stretch. In Figure 1, shoreline mobility is expressed in meters per year, with positive values indicating accretion and negative values representing erosion. In this example, the shoreline is highly dynamic, exhibiting annual erosion rates of up to 20 meters per year and accretion rates of up to 30 meters per year. Generally, shore approaches are optimally located in stable areas. However, for the final selection, additional factors such as environmental impact, social considerations, and other relevant criteria must also be taken into account. Consequently, an optimal location from the perspective of shoreline stability may not always be the primary criterion.

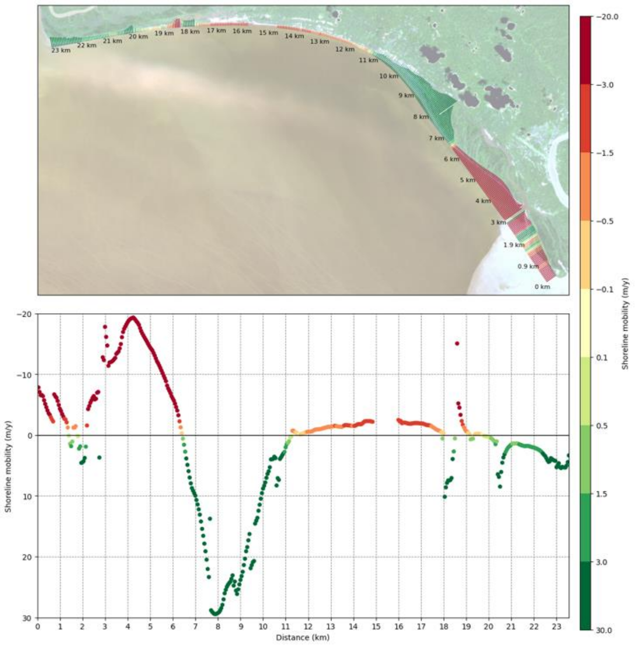

Figure 1: Anonymized example of shoreline mobility based on 20 years of satellite imagery analysis. (Note information on picture to be read from right to left, and graph from left to right.)

This highlights the need to acquire such knowledge of shoreline evolution when choosing a landfall area, in conjunction with expertise and knowledge in the physical processes responsible for such evolution. In this aim, the contribution of numerical models can be decisive (Mangor & al, 2017), as detailed hereinafter.

Moreover, an area that could a priori be selected based on, for example, ecological constraints or optimization in terms of pipeline route length, may be located in a highly evolving area.

The collaborative nature of shore crossing design becomes crucial, underscoring the need for a coordinated effort among various experts to effectively address all aspects of the project.

5 SEA LEVEL RISE

NASA offers an online Sea Level Protection Tool (NASA Sea Level Change Portal), which is informed by the Intergovernmental Panel on Climate Change, 6th Assessment Report (IPCC, 2022). For the sustainable design of energy facilities, projections often adopt conservative scenarios, including high-emissions pathways that anticipate significant warming and associated impacts, such as accelerated sea level rise.

Sea level rise potentially causes the entire coastal profile to shift landward. This concept, introduced by Bruun (1962) and known as Bruun's Rule, describes the relationship between sea-level rise and shoreline retreat in coastal engineering.

Figure 2 illustrates an anonymized cross-shore profile, with the blue line representing the current profile, the green line indicating projected erosion over 40 years, design life, based on historical evolution rate, and the red line showing the impact of sea level rise and erosion. In this example, the shoreline is projected to shift approximately 80 meters landward due to erosion, with an additional 15-meter shift expected from projected sea level rise. A resilient pipeline terminus must be strategically buried, taking into account the projected shoreline position over its design life of 40 years, as exemplified in this study.

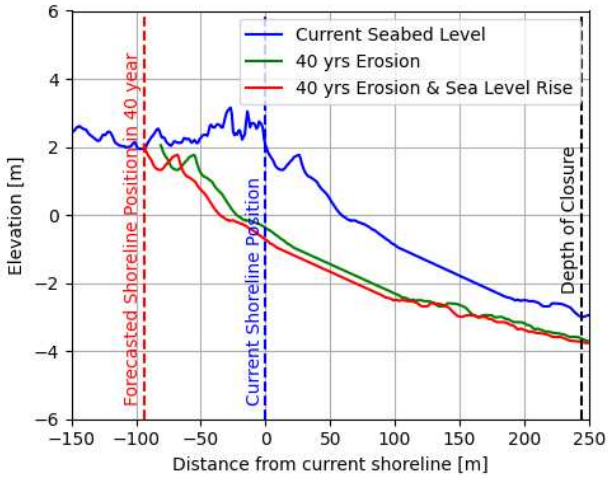

Figure 2: Example of impact of 1) 40 years erosion and 2) 40 years sea-level rise on shoreline position for the anonymized study location.

6 WAVE TRANSFORMATION

In designing a pipeline shore crossing, understanding the impact of storm-generated waves on the shoreline is essential. To accurately quantify hydrodynamic forces on a beachfront, it's necessary to assess how waves propagate from deep water into shallower coastal zones. Booij *et al.* (1999) developed a widely regarded third-generation wave transformation model, which serves as a benchmark in the field.

A comprehensive wave transformation study typically considers factors like refraction, diffraction, reflection, dissipation and shoaling, each influencing wave characteristics due to seabed bathymetry and water depth.

By modeling 100-year recurring storm conditions, engineers can predict potential beach erosion or sediment deposition patterns, thereby enhancing the resilience of pipeline infrastructure against coastal storms.

Figure 3 illustrates the omnidirectional extreme wave conditions for an anonymized location offshore of the study site, indicating a 4.19-meter extreme wave height expected to occur once every 100 years. Generally, wave transformation models require calibration against local measurements to ensure robust and accurate predictions.

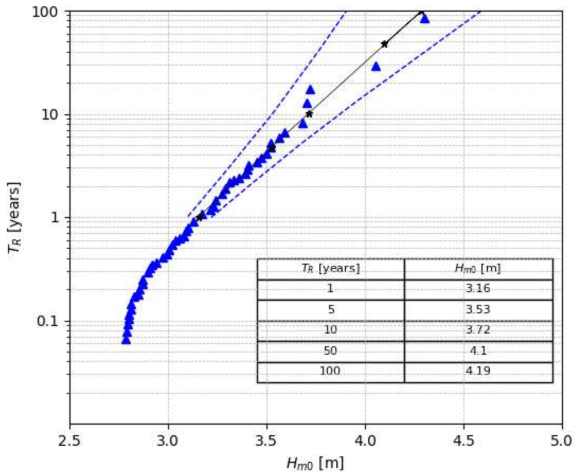

Figure 3: Example of omnidirectional extreme offshore wave conditions for anonymized study location.

7 BEACH RESPONSE TO STORMS

To gain a comprehensive understanding of hydrodynamic processes and sediment transport in a broader coastal area, numerical models are typically set up and calibrated using local measurements.

A coastal storm can be considered as a “short term” event (few hours) when dealing with shoreline evolution. For such short-term event, it is generally assumed that the beach profile development is mainly due to cross-shore transport.

In the example given here, the coastal response is studied using advanced software such as LITPROF from MIKEbyDHI software suite. This approach allows for the analysis of multiple storm events and enables quantification of the beach profile following a storm.

Figure 4 illustrates a series of beach responses to various storm conditions. It shows a typical storm induced erosion on the top of the beach and the dune, and the creation of sand bar systems on the lower part of the profile. This illustration depicts the envelope of cross-shore responses to coastal storms. The blue line represents the current seabed profile, while the gray lines indicate the disturbed seabed conditions caused by storm activity. The red line denotes the lower limit, which indicates the resilient burial depth of sediments.

When designing a shore crossing, the most conservative scenario (representing the lower limit) must be considered.

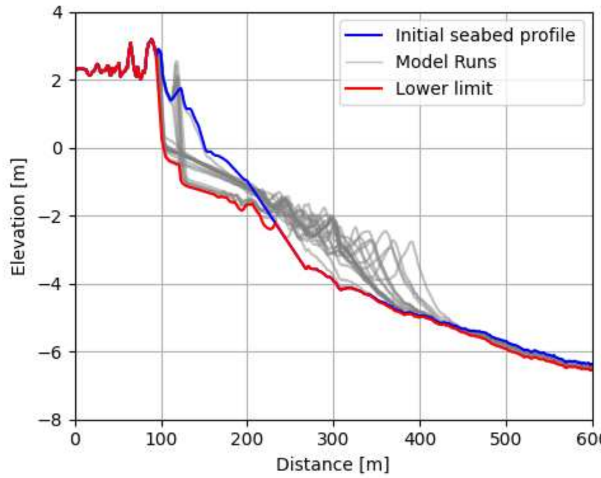

Figure 4: Example of envelope of cross-shore response to coastal storms for the anonymized study location.

8 BURIAL DEPTH AND EXECUTION WORKS

Figure 5 illustrates the burial criteria for a cable or pipeline, taking into account: 1) Erosion, 2) Sea-level rise, 3) Beach response to storms, and 4) A local specification burial requirement of 1-meter for an anonymized location.

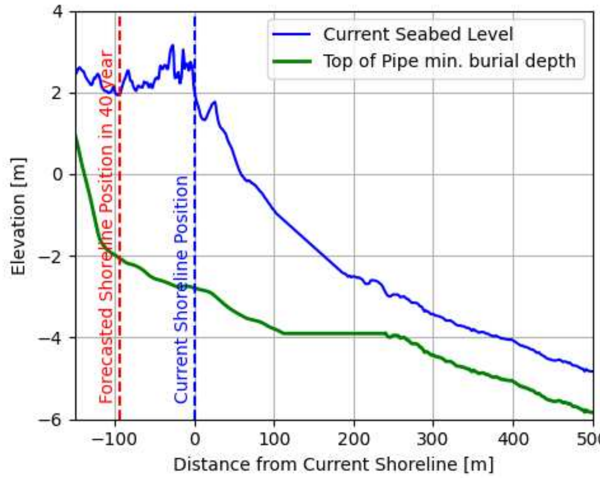

Figure 5: Example of minimum burial depth requirement for an anonymized study location, ensuring resilience against: 1) Erosion, 2) Sea-level rise, 3) Storm response, and 4) A local-specific burial depth of 1 meter.

It is crucial to emphasize that determining the minimal burial depth depends heavily on high-quality geophysical and geotechnical surveys that cover the entire coastal zone, including the shore front and back, extending up to the depth of closure.

Once the minimum burial depth is established, traditional geotechnical engineering processes can commence. Several installation methods may be considered, including the use of a cofferdam—grounded in established design principles familiar to geotechnical engineers—or the implementation of an open trench design.

Additionally, the feasibility of execution methods must be thoroughly evaluated. For instance, Warren *et al.* (2011) demonstrated the negative impacts of interrupting a littoral drift during the construction phase.

Indeed, including a temporary hard structure along the shore can result in significant shoreline accretion on the updrift side of the structure and consequently significant shoreline erosion downdrift. Such impact can be estimated using dedicated software such as LITLINE or Shoreline Morphology from MIKEbyDHI software suite and GENESIS.

9 CONCLUSIONS

This article has emphasized the importance of both stepping beyond and returning to traditional geotechnical engineering principles to ensure resilient designs for cable and pipeline shore crossings. Disregarding established best practices can lead to overestimation, inflating initial construction costs, or underestimation, potentially resulting in a terminus that incurs significant maintenance over its operational lifespan.

Each shore crossing has its unique characteristics, and the guidelines presented here may assist in identifying some of the challenging processes involved in the design. Ultimately, effective shore crossing design necessitates a combination of in-situ measurements and modeling work.

AUTHOR CONTRIBUTION STATEMENT

All Authors: Data curation, Formal Analysis, Writing- Original draft.

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