Advanced Geotechnical Monitoring of Offshore Breakwaters

From Design Hypothesis to Real-Time Validation: The New Genoa Breakwater Experience

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Abstract

The design and construction of **offshore deep water breakwaters** represent one of the most challenging domains in coastal and marine engineering, primarily due to the intrinsic uncertainties associated with seabed characterization and soil–structure interaction mechanisms. Despite the increasing sophistication of numerical modelling tools, the predictive capability of design approaches remains inevitably constrained by partially complete geological knowledge and limited in-situ validation opportunities.

In this context, the present study advocates for a paradigm shift: from a design process based predominantly on assumptions and post-construction verification, toward an integrated methodology centered on **continuous geotechnical monitoring initiated during the earliest phases of construction**.

Drawing upon the large-scale application developed for the **New Genoa Breakwater**, the study illustrates a comprehensive monitoring framework encompassing early-stage instrumentation, multi-sensor integration, underwater wireless communication systems, and advanced digital platforms for real-time data processing.

1. Introduction

In civil engineering practice, the interaction between a structure and its foundation soils constitutes a central theme, governing both performance and safety throughout the lifecycle of the infrastructure. This principle applies with even greater relevance to maritime structures, where environmental loads, construction processes, and geotechnical variability combine to produce highly complex response mechanisms.

Offshore breakwaters, in particular, must be designed to withstand not only static loads induced by their own weight but also dynamic forces generated by waves, currents, and long-term consolidation phenomena. The accurate characterization of the seabed therefore becomes an essential prerequisite for reliable design. However, offshore environments impose severe limitations on the execution of geotechnical and geophysical investigations, often resulting in a partial and uncertain understanding of subsurface conditions.

Consequently, designers are frequently compelled to rely on interpretative models and engineering judgment, awaiting the completion of the structure to validate their assumptions. Although modern computational tools allow for advanced simulations of soil behavior, these remain inherently dependent on the quality and representativeness of input parameters.

It is precisely within this framework of uncertainty that geotechnical monitoring emerges as a strategic instrument, capable of bridging the gap between theoretical design and actual field behavior.

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2. Conceptual Framework and Rationale

The fundamental premise underpinning the proposed approach is that **the behavior of foundation soils cannot be fully anticipated prior to construction**.

Unlike other civil structures, in offshore breakwaters it is extremally complex to carry out a controlled full-scale load tests: the primary loading mechanism—wave action—is inherently stochastic and cannot be fully reproduced under laboratory or field testing conditions.

Furthermore, preliminary trial fields, although useful, provide only localized insights that may not be representative of the entire structure. As a result, the adoption of **distributed, continuous monitoring systems** offers a far more robust strategy for capturing spatial variability and temporal evolution of soil response.

The introduction of real-time monitoring during construction enables:

- Immediate comparison between observed and predicted behavior
- Identification of deviations from expected trends
- Timely implementation of corrective measures (“course corrections”)
- Progressive refinement of geotechnical models

This transforms monitoring from a passive observational activity into a **proactive design validation tool**.

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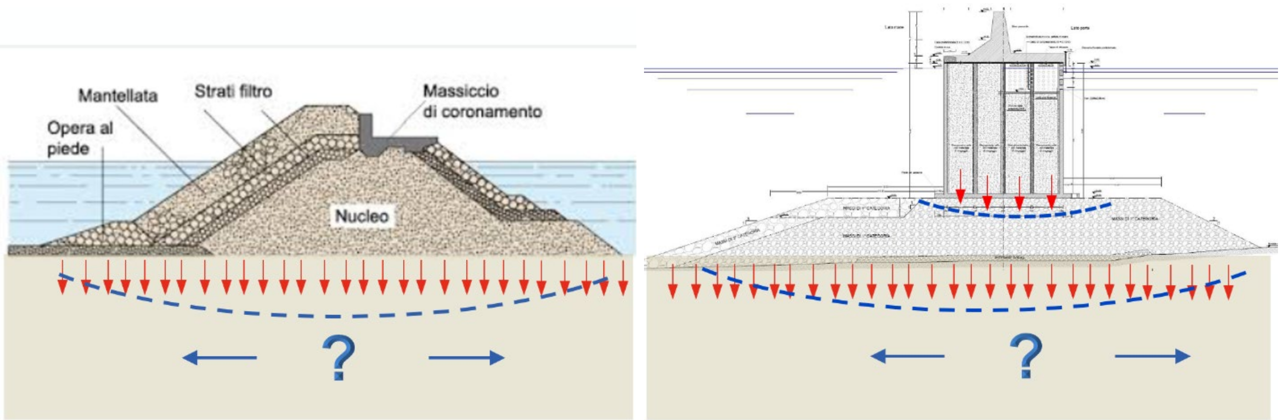
3. Monitoring Objectives and Measurable Parameters

The monitoring strategy is structured around a clear identification of key physical quantities governing soil behavior. In particular, the focus is placed on:

- **Vertical deformations (settlements)** of the foundation soil
- **Horizontal displacements**, indicative of potential instability mechanisms

- **Pore water pressures**, which control consolidation processes and effective stress evolution



By systematically correlating these parameters with:

- The magnitude and distribution of applied loads
- The sequence of construction activities
- The temporal evolution of the structure

it becomes possible to derive **empirical behavioral laws** describing the response of the soil–structure system.

Such correlations are of paramount importance not only for validating design assumptions but also for developing predictive frameworks applicable to future projects.

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4. Monitoring Strategy and Instrumentation System

4.1 General Philosophy

A crucial aspect of the proposed methodology lies in the timing of instrumentation deployment. Unlike traditional monitoring approaches, which typically begin after the structure becomes partially emergent, the present strategy requires that the system be installed **prior to the placement of construction materials on the seabed**.

This allows the capture of the **entire deformation history**, from the initial disturbance of the natural soil state to the final operational conditions.

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5. Case Study: The New Genoa Breakwater

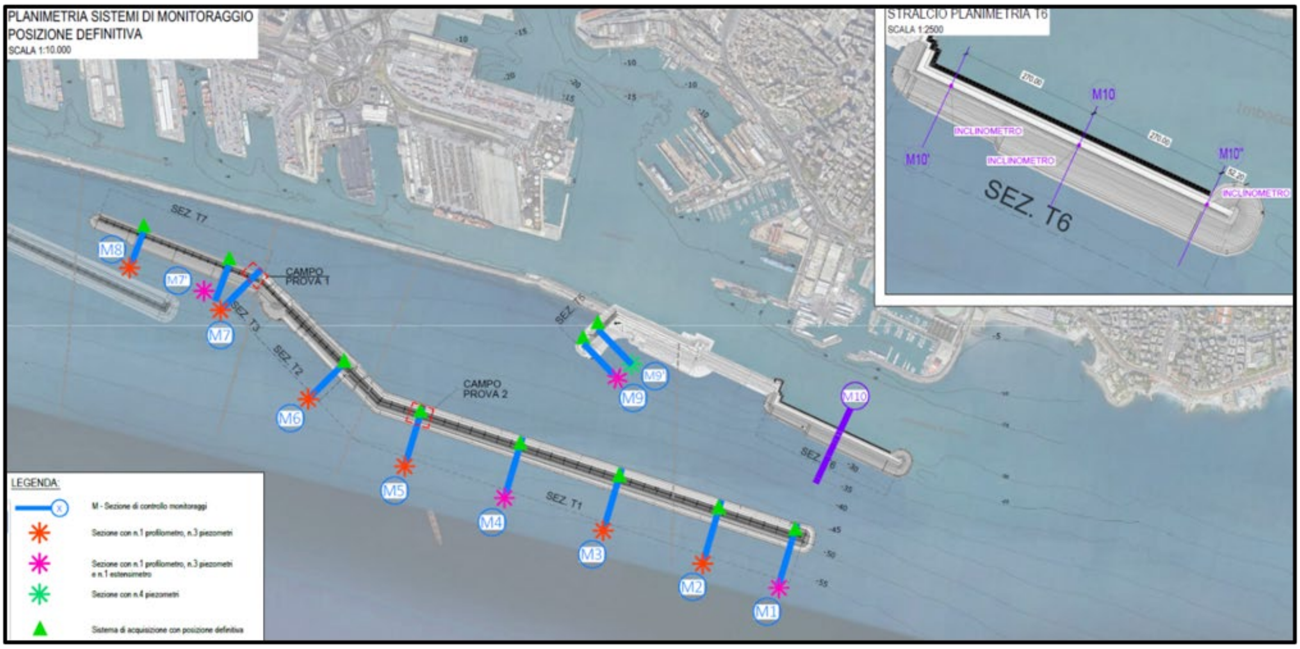
The New Genoa Breakwater provides a unique opportunity to validate the proposed monitoring approach at full scale.

The implemented system includes:

- **12 geotechnical monitoring stations**, distributed along the entire breakwater alignment
- Continuous data acquisition during both **construction and operational phases**
- Integrated monitoring of deformation and pore pressure fields

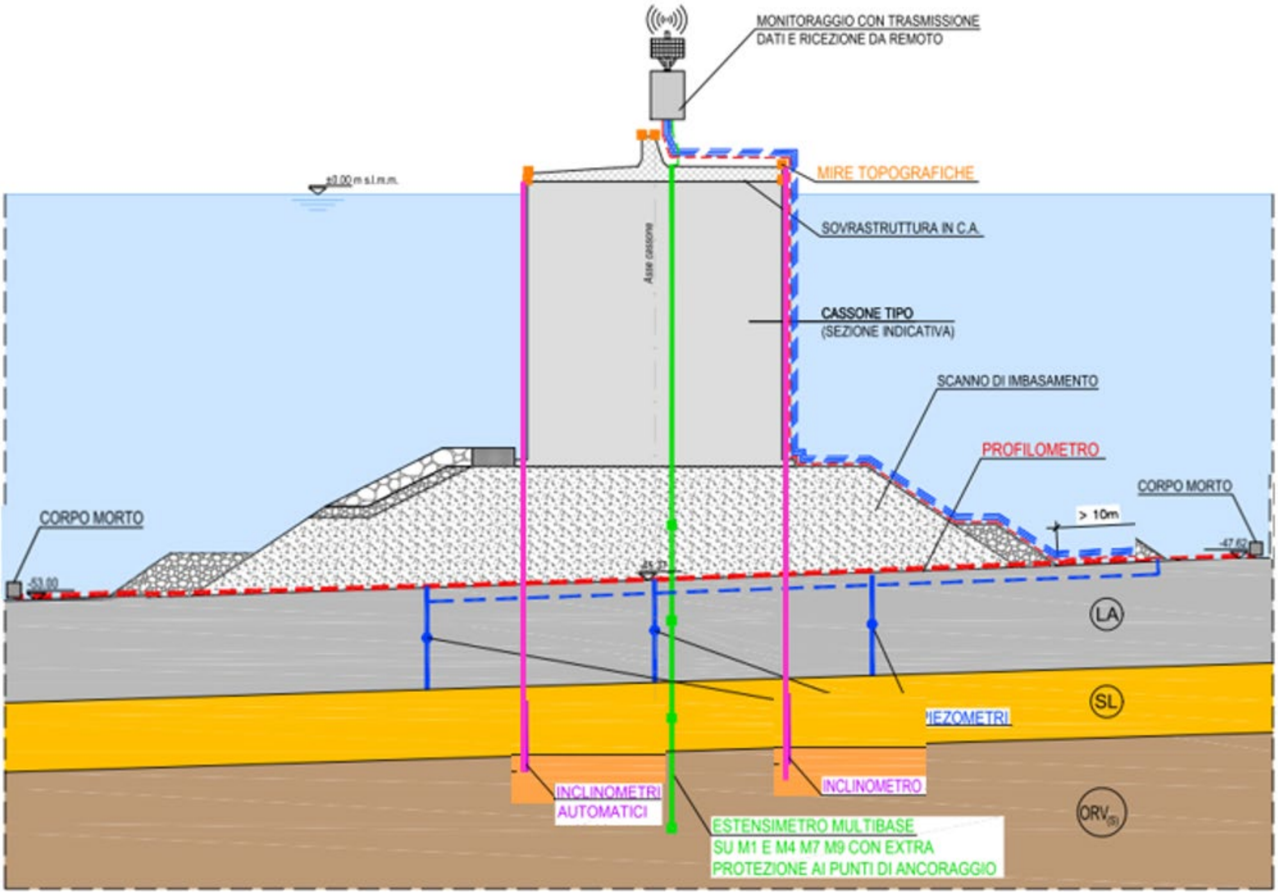
The combination of distributed instrumentation and continuous acquisition has enabled:

- Detailed tracking of soil response during each construction phase
- Direct comparison between observed and predicted settlements
- Improved understanding of soil–structure interaction mechanisms



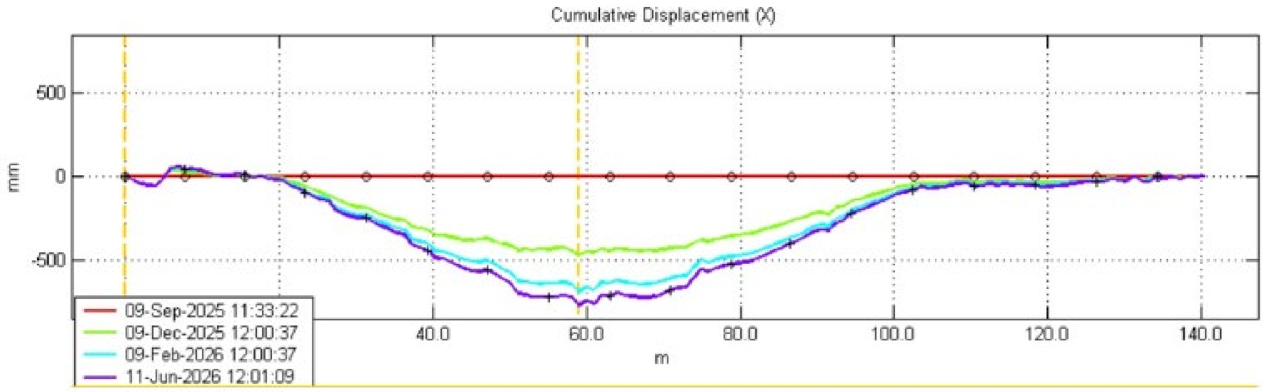
5.1 Instrumentation Components

The complexity of soil behavior necessitates the integration of multiple complementary instruments, each providing specific insights into the system response.



Horizontal Profilometers

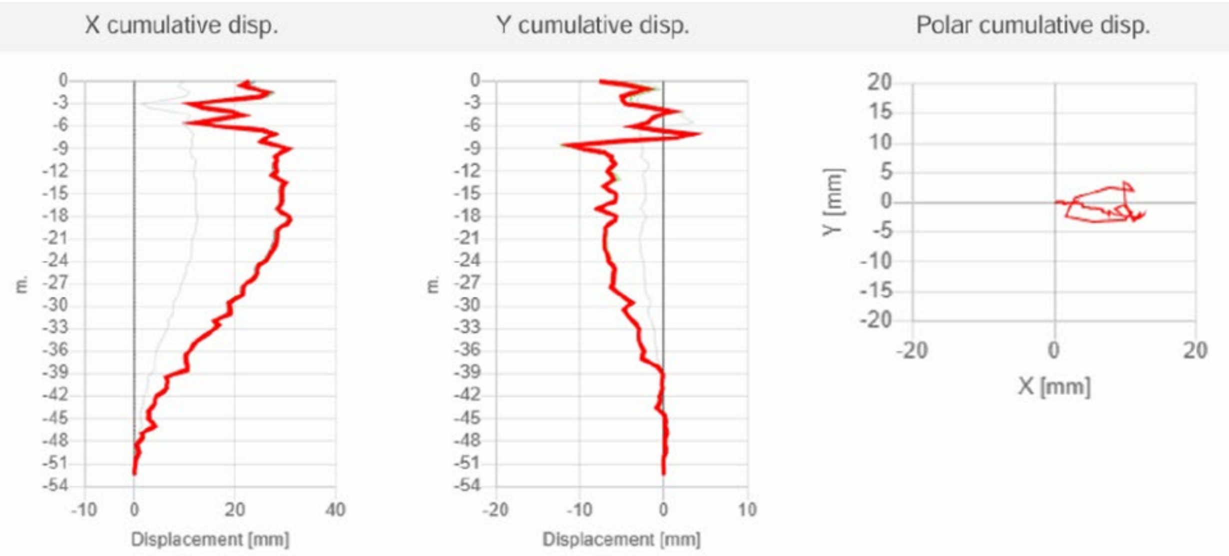
These instruments consist of articulated chains of inclinometers installed at the interface between natural soil and embankment materials. Their function is to reconstruct the deformation profile along a horizontal plane, enabling the identification of settlement gradients and differential movements.



Their contribution is particularly valuable in distinguishing between **global settlement trends** and **localized deformation phenomena**, thus providing a refined understanding of soil response.

Vertical Inclinometers

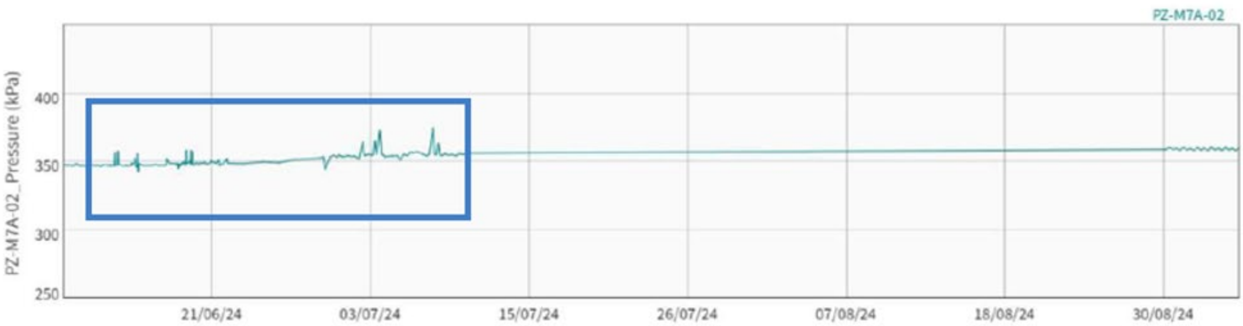
Vertical inclinometer chains are designed to capture lateral displacements within the soil mass. By measuring angular variations along depth, they allow reconstruction of displacement profiles and identification of potential shear zones.



The correct functioning of these instruments requires anchoring in a stable reference layer, ensuring that measured movements reflect true soil deformation rather than instrument drift.

Piezometers

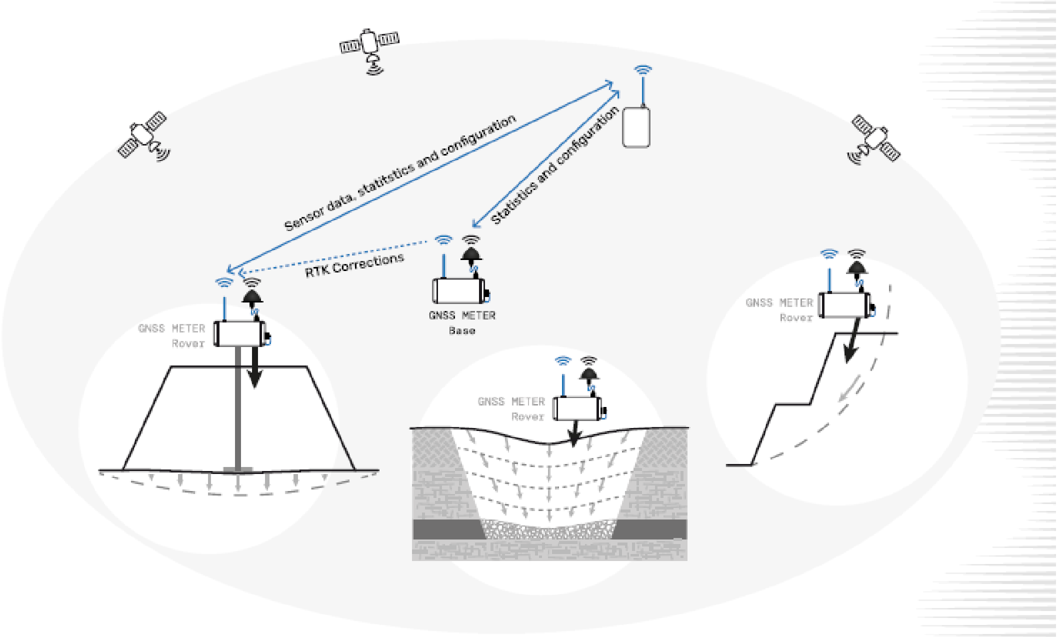
Piezometers play a fundamental role in monitoring pore pressure evolution, a key parameter governing consolidation and effective stress redistribution.



Their readings provide direct insight into the rate at which excess pore pressures dissipate, thereby influencing settlement rates and long-term stability.

GNSS Monitoring Nodes

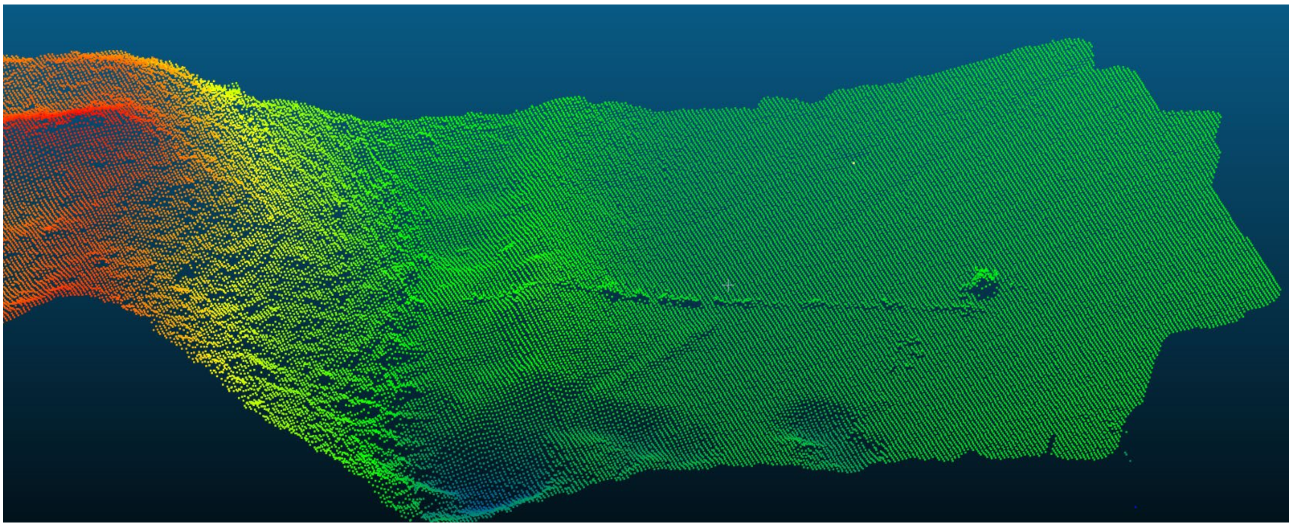
Once structural elements emerge above sea level, GNSS nodes are employed to track global displacements with high temporal resolution, including during extreme events such as storms.



The nodes, on each caisson, and the GNSS base and gateway of the topographic system are indicated in the plan below.

Multibeam Targets and Settlement Gauges

Complementary systems such as multibeam targets (concrete blocks) and extensometers provide additional measurements of absolute settlement and stratigraphic compression, contributing to a comprehensive monitoring framework. See below a typical multibeam 3D representation showing a target (concrete block).



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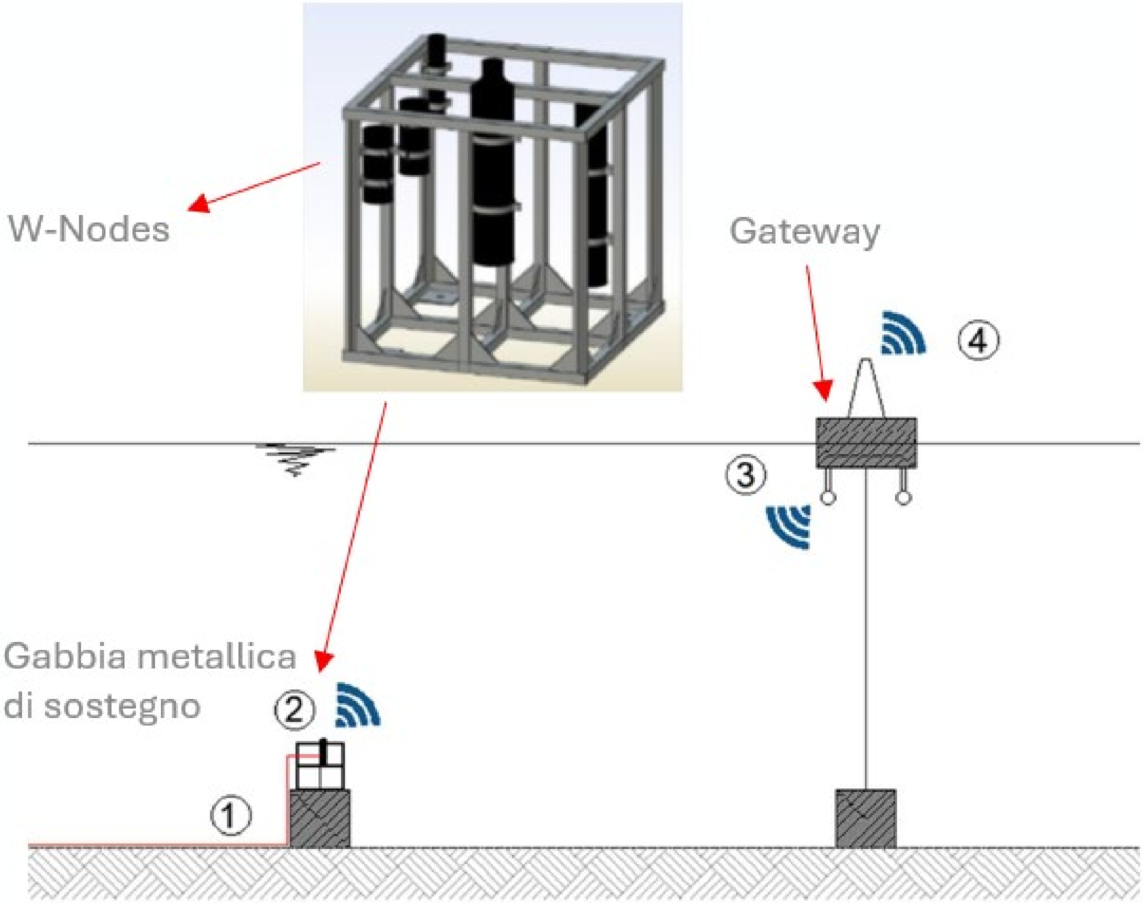
6. Technological Innovation in Data Acquisition

One of the most remarkable aspects of the Genoa Breakwater monitoring system is the implementation of the **W-Sense underwater wireless network**, representing a significant advancement compared to traditional cabled systems.

The system architecture is based on:

- Submerged acquisition units (W-Nodes)
- Acoustic communication between nodes
- A surface gateway installed on a buoy
- Radio-frequency transmission to onshore facilities



This hybrid configuration enables reliable data transmission even in deep-water environments, while significantly reducing installation complexity and vulnerability to mechanical damage.

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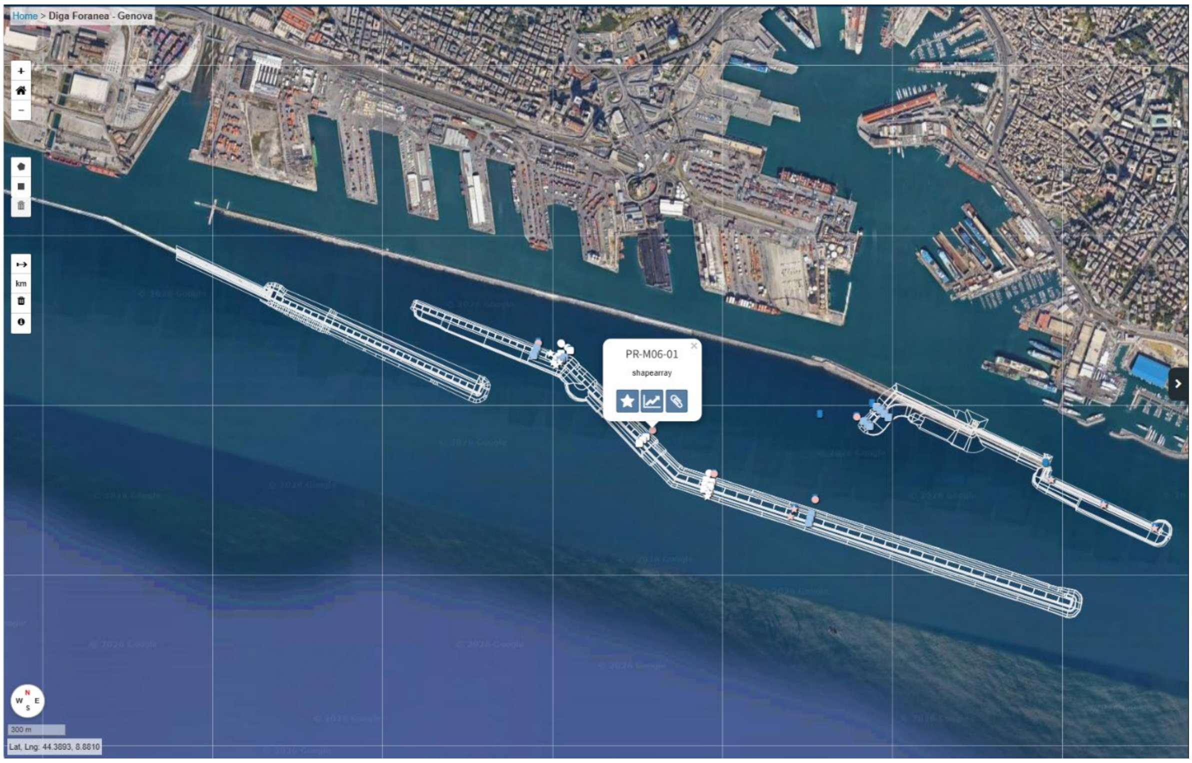
7. Data Processing and Interpretation Platform

The monitoring system is complemented by the **SDD platform**, a web-based digital environment designed for data management, visualization, and interpretation.

Through intuitive graphical interfaces and real-time updates, the platform allows engineers to:

- Visualize deformation trends and pressure evolution
- Identify anomalous behavior patterns
- Perform rapid comparative analyses
- Support data-driven decision-making



8. Discussion

The results obtained from the Genoa Breakwater highlight the transformative potential of advanced geotechnical monitoring.

In particular:

- Monitoring initiated at early construction stages provides invaluable insights into soil behavior
- The integration of multiple instruments allows a **multi-dimensional understanding** of deformation processes
- Digital technologies enhance the accessibility and usability of data

More broadly, the approach contributes to the development of a **feedback-based design philosophy**, in which observations continuously inform and refine engineering decisions.

9. Challenges of Offshore Monitoring

The implementation of geotechnical monitoring systems in offshore environments, however, introduces significant technical challenges:

- Increased installation complexity with increasing water depth
- High risk of damage due to construction activities (e.g., rock dumping, boat anchoring, etc.)
- Limitations in data transmission and power supply
- Stringent requirements for durability and robustness

Furthermore, instruments must be installed prior to material placement, exposing them to extreme mechanical stresses and making replacement virtually impossible once buried.

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10. Conclusions and Perspectives

Geotechnical monitoring in offshore breakwaters should no longer be regarded as an optional or secondary activity, but rather as a **fundamental component of the design and construction process**.

The experience gained from the New Genoa Breakwater leads to the following recommendations:

- Monitoring systems should be incorporated **from the earliest design stages**
- Dedicated financial resources must be allocated for installation and long-term operation
- Industrial developments should focus on:
    - Robust and durable instrumentation
    - Simplified installation procedures
    - Integrated and autonomous monitoring systems

Looking forward, the increasing integration of digital technologies, real-time data analytics, and predictive modelling is expected to further enhance the role of monitoring, paving the way toward more resilient and adaptive offshore infrastructures.
