Available online at www.easd.procedia.org
EASD Procedia EURODYN (2026) 1786-1795

EASD Procedia

EURODYN 2026
XIII International Conference on Structural Dynamics
M. Beer, C. Papadimitriou, H. Jensen, J. Chen, M. Broggi, J. Behrensdorf (eds.)
Hannover, Germany, 27.09.–01.10 2026

# OPENBIM-ENABLED MULTI-SENSOR MONITORING AND PRELIMINARY VIBRATION-BASED ASSESSMENT OF THE LNGS UNDERGROUND FACILITY

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**Keywords:** Real-time monitoring system, Multisensor network, openBIM, Digital twin platform

**Abstract.** *The Gran Sasso National Laboratory (LNGS) is an underground research facility dedicated to the study of neutrino and astroparticle physics. To ensure the safety of its experiments, a real-time multisensor monitoring system has been designed and implemented, enabling continuous assessment of structural, hydraulic, and environmental conditions across the underground complex. A key contribution of this work is the adoption of an openBIM-based information model as a common data environment, where sensor locations, metadata, and measurement streams are mapped onto an IFC-compliant model of the facility, enabling interoperable access to monitoring data through standard APIs. Preliminary results from the dynamic instrumentation installed in the Control Room of the Stella experiment demonstrate the system's capability to detect and characterize the structural response under ambient and operational excitations, with dominant frequencies identified at 3.15 Hz, 3.88 Hz, 4.69 Hz, and 5.88 Hz. The openBIM framework is envisioned as the foundational layer of a future Digital Twin platform for LNGS, supporting condition-based maintenance and long-term risk-informed management of the facility.*

ISSN:2311-9020 © 2026 The Authors. Published by EASD Procedia.
Peer-review under responsibility of the Organizing Committee of EURODYN 2026.
doi: 10.47964/1326.10787.557

## 1 INTRODUCTION

Structural Health Monitoring Systems (SHMSs) are widely used in aerospace, civil and mechanical engineering to improve the understanding of the behaviour of complex structures [1, 2]. In underground infrastructures, such as tunnels and research facilities, monitoring becomes particularly critical due to severe environmental conditions, limited accessibility, and strict operational requirements [3]. In these environments, even small variations in temperature, humidity, or vibrations may affect both structural performance and the functionality of sensitive experimental equipment. Advanced tunnel monitoring integrates a variety of sensors and analytical techniques to enhance safety. Recent studies highlight a wide spectrum of approaches (from traditional geotechnical instruments to advanced technologies such as fibre optics, UAVs, wireless IoT networks, acoustic sensing, and artificial intelligence) each offering distinct advantages. However, challenges persist, particularly in the integration of high-density data and the provision of reliable real-time decision support [4, 5]. Underground research facilities represent a particularly demanding context, where structural safety must be ensured together with the continuity and reliability of scientific activities. The Gran Sasso National Laboratory (LNGS) is one of the largest underground research infrastructures worldwide, hosting experiments in neutrino and astroparticle physics within large excavated caverns [6, 7]. The complexity of such systems requires continuous, multi-parameter monitoring capable of capturing the interaction between structural response, environmental conditions, and operational loads. Traditional monitoring approaches based on periodic inspections or isolated sensing systems are often insufficient to fully describe these interactions, due to their limited temporal resolution and the lack of integration between sensor data and geometric or structural information [8]. In recent years, the Digital Twin (DT) paradigm has emerged as a promising approach to overcome these limitations, enabling the integration of monitoring data, geometric models, and analytical tools within a unified digital environment [9]. However, current implementations in civil engineering are often limited to data visualization and aggregation, with reduced interoperability and weak coupling with physics-based models. Interoperability between BIM and Finite Element models has been explored for vibration-based model updating and structural assessment in [10], which highlighted the potential of integrated digital workflows for structural monitoring applications. In this context, openBIM methodologies based on Industry Foundation Classes (IFC) provide a robust and interoperable framework for integrating heterogeneous data sources. While previous work addressed the integration of Building Information Modelling and Life Cycle Assessment for greenhouse gas emission reduction and environmental management of LNGS [11], the present contribution focuses on the structural-dynamic dimension of the Digital Twin, with emphasis on multisensor monitoring, openBIM data integration, and preliminary vibration-based identification of the steel-frame Control Room of the Stella experiment. This paper presents the implementation of a multisensor monitoring architecture for LNGS, its integration within an openBIM-based information model, and preliminary results from vibration-based characterization of the steel-frame Control Room of the Stella experiment.

## 2 GRAN SASSO NATIONAL LABORATORIES

The Gran Sasso National Laboratory (LNGS), managed by the Italian National Institute for Nuclear Physics (INFN), is the largest underground research center in the world dedicated to the study of neutrino and astroparticle physics. Located beneath approximately 1,400 m of rock inside the Gran Sasso massif in central Italy, the Laboratory benefits from a natural shielding that dramatically reduces cosmic radiation, creating ideal conditions for highly sensitive physical

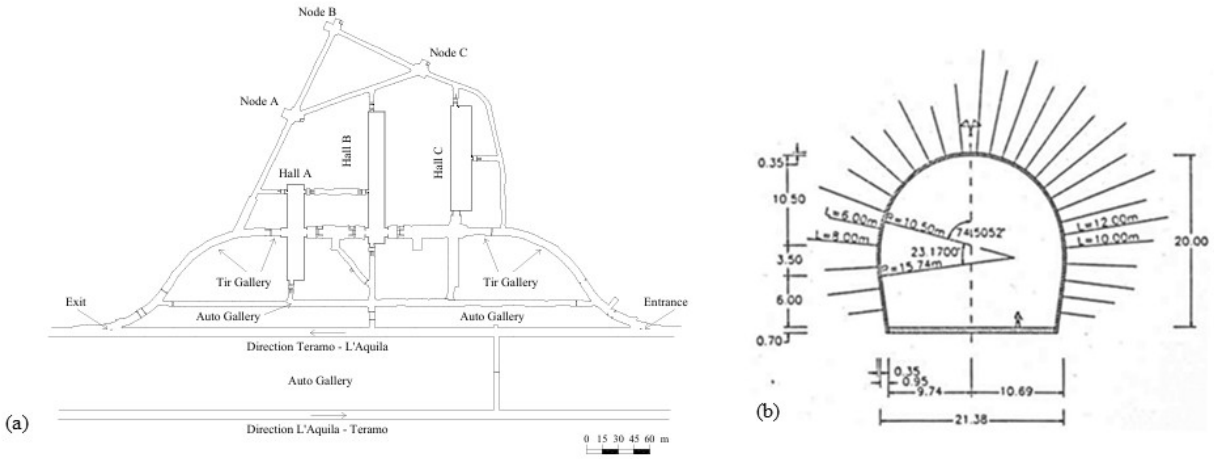



Figure 1: (a) Plan view of the underground Gran Sasso National Laboratory; (b) Cross-sectional view of the gallery, showing the rock bolts reinforcement system [6, 7].

experiments [6, 7]. The underground complex comprises three large experimental halls (Hall A, Hall B, and Hall C, Figure 1a) connected by an extended network of service tunnels, covering a total area of approximately 18,000 $m^2$. The halls are characterised by large spans, quasi-cylindrical cross-sections, and internal lining systems designed to ensure long-term structural stability [7]. From a structural standpoint, the surrounding rock mass is primarily composed of brittle limestone, which is susceptible to fracturing under mechanical stress. The excavation of the large caverns induced significant redistribution of the in-situ stress state, increasing the risk of localised cracking and instability. To ensure long-term stability, a combination of passive rock anchors, steel bolts, and sprayed concrete (spritz-beton) was adopted (Figure 1b). A critical design constraint was the minimisation of construction materials, particularly those introducing radiological impurities, which required careful optimisation of reinforcement systems to balance structural safety with the ultra-low-radiation requirements of the experiments [6]. The operational environment imposes additional structural and dynamic demands. Sensitive experiments require strict control of vibrations, temperature variations, and humidity levels, as even minor fluctuations may affect both structural performance and experimental reliability. Steel-frame structures, such as the Control Room of the Stella experiment located in Hall B, represent secondary structural systems whose dynamic behaviour is directly influenced by operational excitations, including crane movements and ventilation systems. Limited accessibility and the continuity requirements of ongoing experiments make periodic inspections insufficient, and justify the implementation of a continuous automated monitoring system, as described in the following section.

## 3 STRUCTURAL HEALTH MONITORING SYSTEM

The Structural Health Monitoring project involves the implementation of an integrated monitoring system at the underground Gran Sasso National Laboratory (INFN). The primary objective is the continuous surveillance of the stress–strain state of the lining covering the galleries, together with the characterization of the environmental conditions within the laboratories and the identification of the dynamic behaviour of the steel-frame Control Room of the Stella experiment. The infrastructure is based on a sensor network designed to automatically provide real-time measurements of structural, hydraulic, and environmental parameters, with historical

data analysis and trend tracking supported by a SCADA-based supervisory system. Table 3 provides an overview of the complete multisensor network.

| Domain | Sensor type | No. |
|---|---|---|
| Structural | Toroidal load cells (rock bolts) | 23 |
| | Flat jacks and strain gauges | 51 |
| | Biaxial inclinometers | 12 |
| | Rod extensometers | 82 |
| | Triaxial accelerometers (force-balance) | 8 |
| | Triaxial accelerometers (piezoelectric) | 3 |
| | Laser sensors | 11 |
| Hydraulic | Flow meters | 2 |
| Environmental | Humidity and temperature sensors | 36 |
| | Differential pressure sensors | 18 |
| | Electromagnetic field sensors | 3 |
| | Radon gas detectors | 3 |
| | Sound level meters | 3 |
| | Infrared camera | 1 |

Table 1: Overview of the LNGS multisensor monitoring network.

### 3.1 Structural and Geotechnical Monitoring

Stresses acting on tunnel linings in the halls and adits are monitored through toroidal load cells installed on existing rock bolts, flat jacks, and extensometer bars applied directly to the shotcrete lining. Stability of crane-supporting pillars in the experimental halls is controlled through biaxial inclinometers and coupled extensometer bars.

### 3.2 Dynamic Monitoring

Triaxial accelerometers are installed on the Control Room of the Stella experiment to support: identification and continuous monitoring of the main modal frequencies; monitoring of operational vibrations induced by truck passages or work activities; and updating of the numerical model representative of the structural dynamic behaviour.

### 3.3 Hydraulic and Environmental Monitoring

The drainage network is monitored through automatic flow meters integrated within infrastructure pipelines. Environmental parameters include radon gas concentration and acoustic pollution levels. Microclimatic conditions — temperature, relative humidity, and atmospheric pressure — are continuously acquired throughout the underground complex.

## 4 LNGS OPENBIM MODEL AND MONITORING SYSTEM

This section describes the openBIM-enabled digital and monitoring framework implemented for the LNGS underground facility. The adoption of openBIM methodologies, based on the Industry Foundation Classes (IFC), enables a structured and interoperable representation of the

infrastructure, supporting the integration of geometric, semantic, and monitoring data within a unified environment. In parallel, a preliminary real-time multisensor monitoring system is being developed, providing the basis for data acquisition and visualization within a Digital Twin-oriented framework.

### 4.1 OpenBIM Model of LNGS

The Building Information Model (BIM) of the Gran Sasso National Laboratory (LNGS) provides a digital representation of the underground research infrastructure, integrating geometric, material, and system-related information. The model was developed using commercial BIM software based on available technical drawings and construction documentation, enabling a consistent reconstruction of the laboratory configuration.

Within the openBIM framework, the model is structured according to IFC standards, allowing interoperability between different software environments and facilitating the integration of heterogeneous data sources. The LNGS facilities are characterized by large-scale experimental halls with longitudinal layouts, quasi-cylindrical cross-sections, and internal lining systems designed to protect structural components.

The model includes both structural and non-structural elements, such as insulation systems, steel support structures, and service installations, reflecting the operational configuration of the Laboratory. Due to the experimental nature of LNGS, internal layouts are subject to continuous modifications; therefore, the openBIM model serves as a stable geometric and informational reference capable of representing evolving conditions [11], as illustrated in Fig. 2.

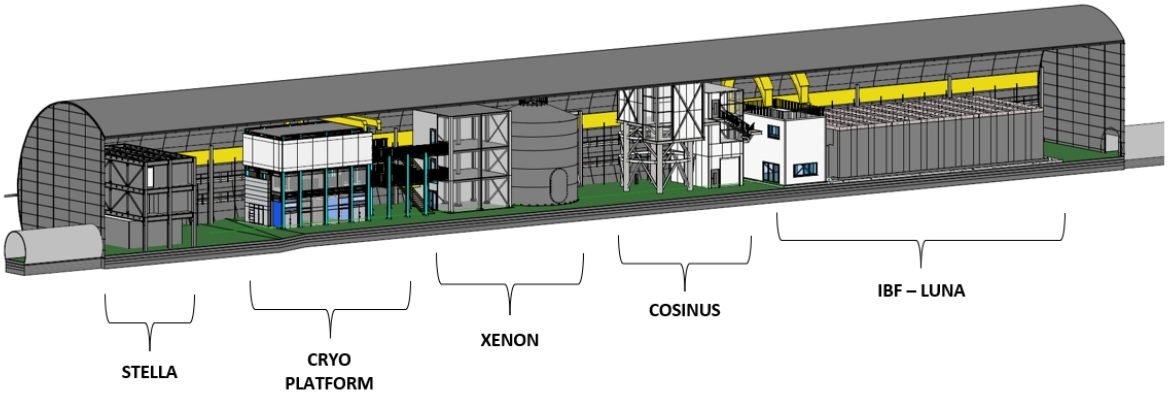



Figure 2: openBIM model of the LNGS underground Hall B, illustrating the geometric representation of the experimental facilities and structural layout, with experiment names annotated.

### 4.2 OpenBIM-Based Monitoring System and Data Integration

In parallel with the openBIM model development, a monitoring system is being implemented across selected areas of the LNGS infrastructure to acquire structural, environmental, and operational data. The system consists of a distributed network of sensors, including force balance and piezoelectric triaxial accelerometers for structural dynamic measurements and environmental sensors for complementary data acquisition. The monitoring architecture is based on a distributed framework in which data are collected, pre-processed, and transmitted through gateway devices to a centralized Data Processing Center (DPC). High-frequency accelerometric data are recorded in binary format and subsequently processed, while environmental data are

acquired through gateway systems and integrated into the monitoring platform. The collected data are stored in time-series databases, supporting both real-time monitoring and historical analysis. Within the openBIM framework, each sensor is modelled as a geometric family in the BIM authoring environment and exported as an `IfcSensor` entity within the IFC-compliant model. This representation associates each sensor with its physical location, type, and metadata directly within the geometric model of the facility. Sensor identifiers are linked to the corresponding time-series database entries, enabling the mapping of measurement streams onto the three-dimensional environment. The resulting platform supports both dashboard-based visualization and three-dimensional spatial contextualization of sensor metadata and time-series data within the openBIM model, as illustrated in Fig. 3 [12]. The monitoring strategy is based on ambient vibration testing, allowing the identification of structural dynamic characteristics under unknown natural excitation. Sensor placement was guided by preliminary modelling to support the observation of dominant structural behaviour. At the current stage, the system supports data acquisition, storage, and visualization; advanced analysis procedures, including automated modal identification and model updating, are planned as future developments.

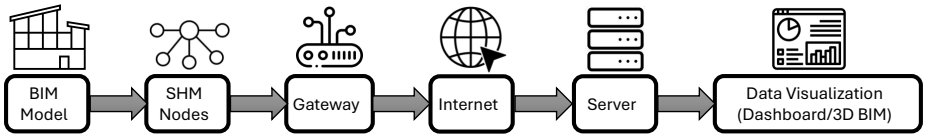



Figure 3: Reference architecture of the SHM-based monitoring system integrated with the openBIM model of the LNGS infrastructure.

### 4.3 Preliminary vibration-based monitoring information

In this section some preliminary results about the vibration monitoring system installed in the Control Room of the Stella experiment will be shown. It is a steel frame structure located in Hall B. It consists of three levels interconnected by an external staircase anchored both to the ground and to the structure itself via beams. Each level contains rooms dedicated to the execution and study of physical phenomena related to the experiments conducted within the Laboratory. The structure, measuring approximately 13.00 m $\times$ 6.40 m in plan, is supported by six columns (three for each short lateral side (Y-direction), Figure 4a) that are anchored to the ground using bolts. Each floor is composed of a slab system with a thickness of 0.25 m realized by steel grating resting on secondary beams. Structural rigidity is ensured by bracing located along the long side (X-direction), at the second and last floor levels, and also on the short lateral planar frames (Y-direction). Further stiffening has been implemented at the beam-column joints by inserting brackets into the web and flanges of the columns. The structure is enclosed by external cladding made of very thin sandwich panels. Figure 4 shows the BIM model of the Control Room with both a three-dimensional view and a plan view. Two triaxial accelerometers have been installed at diagonal points on the roof ($A_1$ and $A_2$, Figure 4) and another one at one corner of the second floor ($A_3$, Figure 4). The sensors are force-balance type, enclosed in an aluminium casing with corrosion-resistant treatment, with the following characteristics: standard sensitivity 5 V/g, full scale $\pm 2$ g, inertial mass 15 g. The continuous

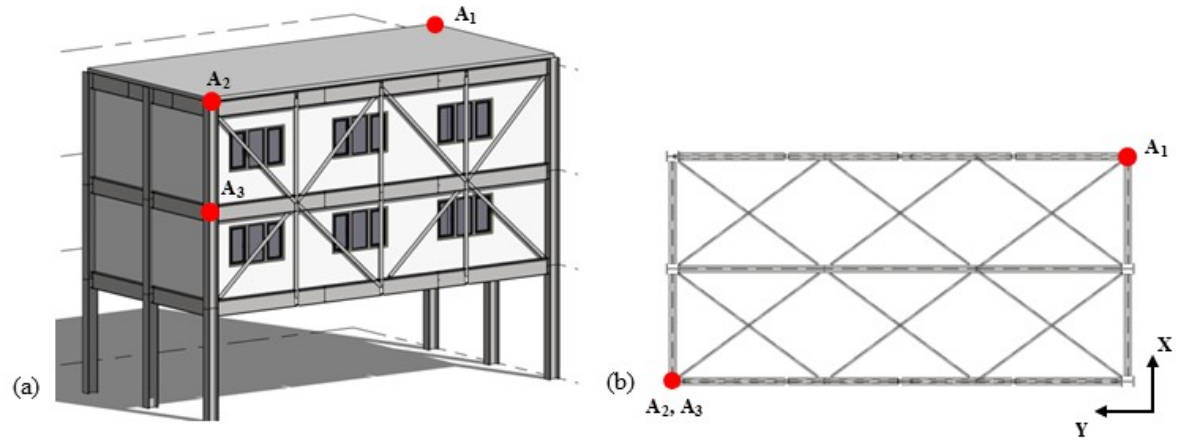



Figure 4: BIM model of the Control Room of the Stella experiment: (a) three-dimensional view of the steel-frame structure; (b) plan view with layout of the installed accelerometers ($A_1$ and $A_2$ at roof level; $A_3$ at the second floor level).

monitoring of these accelerations, started some months ago, will provide information useful for: (1) evaluating the fluctuation of modal features due to environmental parameters (temperature and humidity) or noise induced by work activities (e.g. crane movements) and ventilation; (2) updating the computational model of the Control Room; (3) detecting possible damage trends; (4) evaluating the reliability and vulnerability of the monitored structure. Figures 5, 6, 7 present representative time histories along with their corresponding Power Spectral Densities (PSDs), recorded on 20 November 2025. The time histories span a total duration of 30 minutes and were acquired at a sampling frequency of 100 Hz. The measured standard deviations are notably low, ranging from 0.0011 m/s$^2$ to 0.0017 m/s$^2$. Despite the low amplitude of the recorded signals, the high sensitivity of the sensors allowed the identification of the main structural frequencies, clearly visible in the corresponding PSDs (Figures 5(b,d), 6(b,d), 7(b,d)). In particular, from the comparison of all PSDs reported in Figure 8, the frequencies 3.15 Hz and 4.69 Hz are tentatively associated with the two principal bending modes along the Y- and X-directions, respectively. The peak at 5.88 Hz shows higher amplitude in the Y-direction than in X, suggesting a possible second bending mode in the Y-direction or a coupled bending-torsional mode. A further spectral peak at 3.88 Hz is visible in the X-direction PSD of sensor $A_3$, located at the second-floor level, but does not appear as a dominant feature in the roof-level sensors $A_1$ and $A_2$, nor in the global comparison of Figure 8; this peak may be associated with a secondary bending mode of the structure. The physical interpretation of all identified peaks will be confirmed through mode shape extraction, modal identification procedures, and comparison with numerical predictions from a finite element model of the Control Room. Modal features will additionally be tracked on a daily basis using measurements acquired during morning and night hours, to assess the influence of environmental and operational variability.

## 5 CONCLUSIONS

This paper presented the design and implementation of a real-time multisensor monitoring system for the Gran Sasso National Laboratory (LNGS), one of the most complex underground research infrastructures worldwide. The proposed framework integrates a network of structural, hydraulic, and environmental sensors within an openBIM-based information environment, establishing a common data infrastructure grounded on IFC standards. The adoption of an openBIM

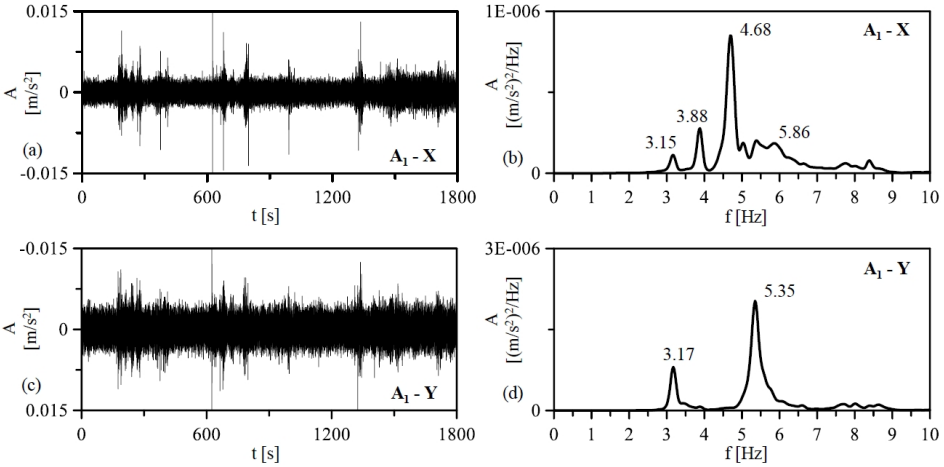



Figure 5: Example of 30 minutes of acquisition (20 November 2025): time history (a),(c) and corresponding Power Spectral Densities (b),(d). Sensor $A_1$ in Figure 4.

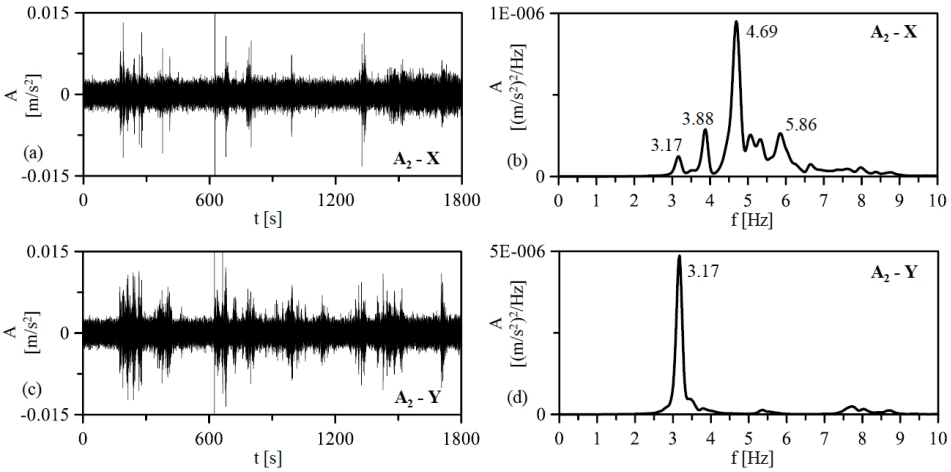



Figure 6: Example of 30 minutes of acquisition (20 November 2025): time history (a),(c) and corresponding Power Spectral Densities (b),(d). Sensor $A_2$ in Figure 4.

backbone proved effective in enabling interoperable access to heterogeneous monitoring data, linking sensor metadata and measurement streams to a geometric and semantic representation of the underground facility. Preliminary results from the dynamic instrumentation installed in the Control Room of the Stella experiment demonstrated the system's capability to acquire continuous ambient vibration data under low-amplitude excitation, with measured standard deviations ranging from 0.0011 m/s$^2$ to 0.0017 m/s$^2$. Despite the low signal levels, the high sensitivity of the force-balance accelerometers allowed the identification of dominant spectral peaks at 3.15 Hz, 4.69 Hz, and 5.88 Hz, tentatively associated with the two principal bending modes along the Y- and X-directions, respectively. The peak at 5.88 Hz, stronger in the Y-direction, suggests a second bending or coupled bending-torsional mode, to be confirmed through modal identification. A further peak at 3.88 Hz, observed in the X-direction PSD of the second-floor sensor $A_3$ but absent in the roof-level sensors, may be associated with a secondary bending mode of the structure, to be confirmed through modal identification and numerical predictions. The openBIM framework established in this work is envisioned as the foundational layer of a future Digital Twin platform for LNGS, capable of supporting condition-based maintenance, scenario

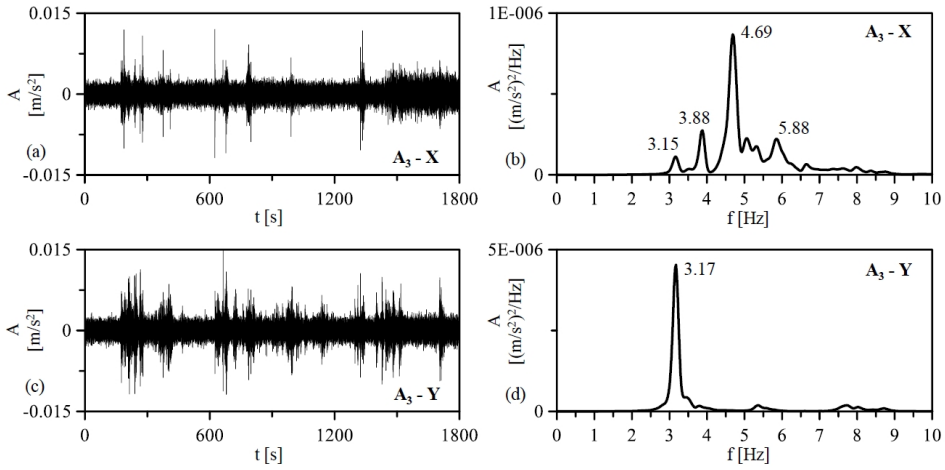



Figure 7: Example of 30 minutes of acquisition (20 November 2025): time history (a),(c) and corresponding Power Spectral Densities (b),(d). Sensor $A_3$ in Figure 4.

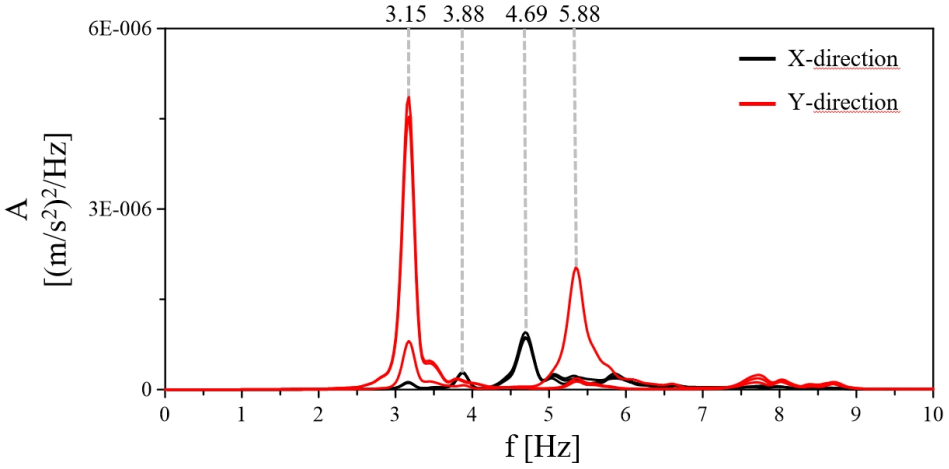



Figure 8: Comparison of Power Spectral Densities from sensors $A_1$, $A_2$, and $A_3$ in X- (black lines) and Y-direction (red lines). Dashed vertical lines indicate the dominant spectral peaks at 3.15 Hz, 4.69 Hz, and 5.88 Hz.

analysis, and risk-informed management of the facility. Future developments will focus on the coupling of monitoring data with numerical models for model updating, the extension of the dynamic monitoring system to additional areas of the underground complex, and the integration of physics-informed data interpretation strategies.

## 6 ACKNOWLEDGEMENTS

The authors would like to thank the Italian Project TECNODIGIT - Call BANDO A CASCATA PROGETTO ECS ROMETECHNOPOLE - SPOKE 1 E 6 funded by PNRR M4C2 Dalla Ricerca all'Impresa Investment 1.5 and Italian Project PRIN 2022 AID-STRU "AgeIng and Degradation in the performances of STRUctures: model- and data-driven tools embedded in digital-twins".

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