The Sanctuary of Vicoforte

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Chapter 8
The Sanctuary of Vicoforte

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Abstract Renowned for its massive masonry oval dome, the largest worldwide, the Sanctuary of Vicoforte has faced significant structural issues, including settlement and cracking. Since the 1980s, a sophisticated monitoring system has evolved, incorporating static and dynamic measurements, supported by geotechnical surveys. Recent advancements include the integration of satellite data. The collection and the analysis of these different kind of data aimed at developing a robust Digital Twin for real-time diagnostics and predictive analysis, paving the way for resilient management of architectural heritage. Temperature-induced behaviors, such as changes in vibration frequencies and crack dynamics, reveal complex interactions between environmental conditions and structural responses. Future upgrades will focus on further integrating remote sensing capabilities to enhance this innovative approach.

Keywords Structural health monitoring · Cultural heritage · Static and dynamic monitoring · Digital twin · Data integration

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8.1 Description

The Basilica “Regina Montis Regalis,” also known as the Sanctuary of Vicoforte, is located near Mondovì in Northern Italy (Fig. 8.1a, b). Construction began in 1596, initially under the direction of architect Ascanio Vitozzi, following a design conceived by Duca Emanuele I di Savoia, who intended the Basilica to serve as the mausoleum for the Savoia’s. The structure is famous for its oval dome, the largest of its kind in the world, with internal dimensions of 37.23 by 24.89 m (Fig. 8.1c). The construction halted for several decades, stopping at the level of the base of the drum of the dome. It was only in the early eighteenth century that Francesco Gallo (1672–1750) resumed the project, overseeing the erection of the high drum and the

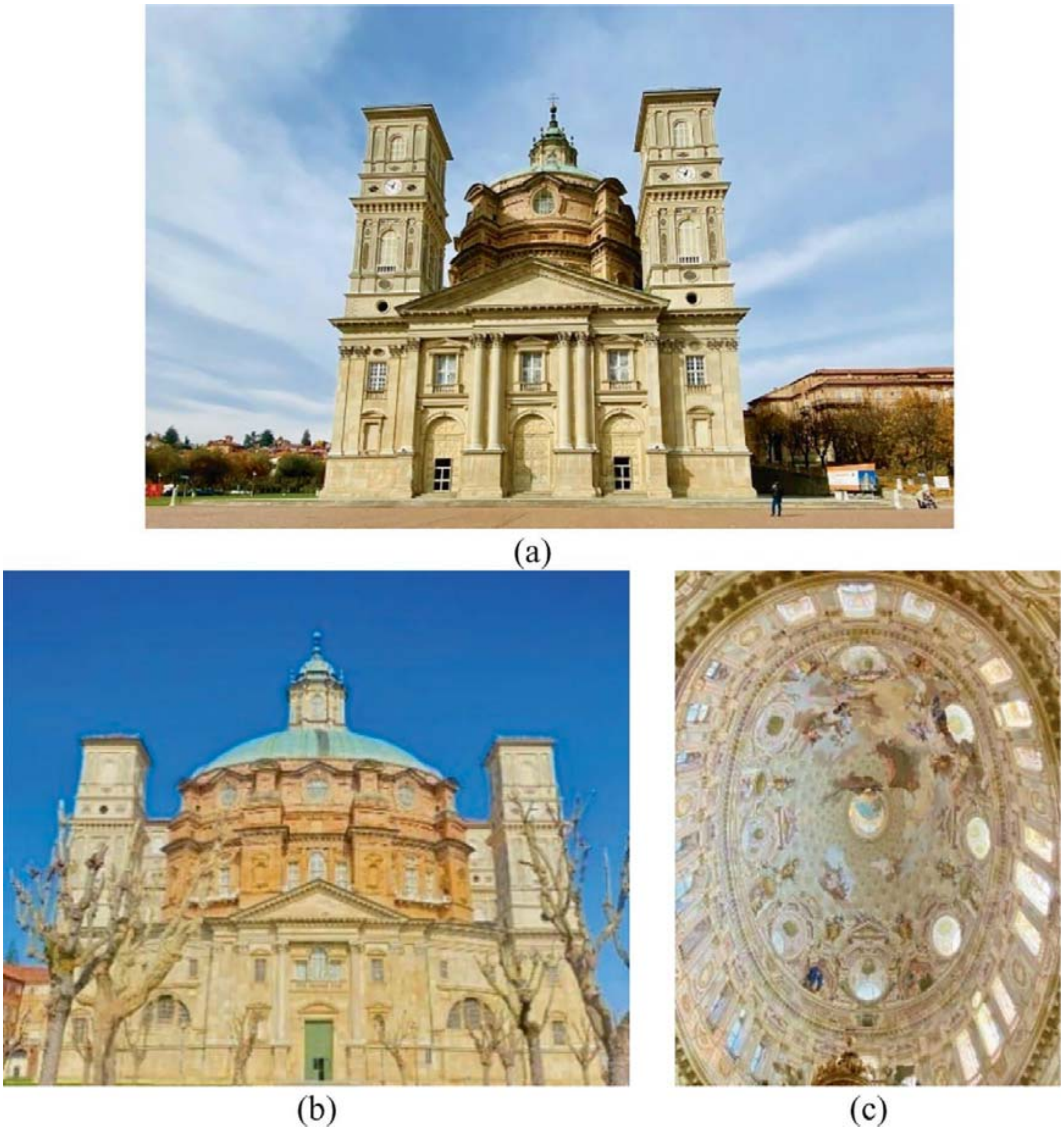
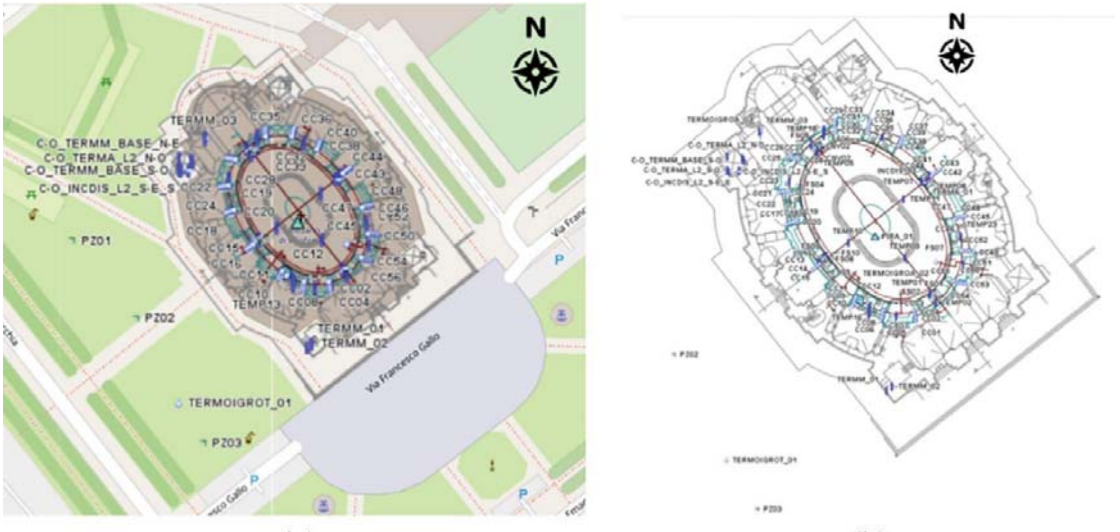


Fig. 8.1 The Sanctuary of Vicoforte: (**a**) Top view, (**b**) façade, and (**c**) internal view of the oval dome

majestic dome. Gallo also incorporated a system of iron rings, consisting of three rings with a total section of approximately 140 cm^2, designed to absorb some of the horizontal thrust. The dome was disarmed in 1732 (Cozzo et al., 2017), and the lantern was completed in 1735, marking the Basilica inauguration. Over time, the dome and drum system experienced significant structural challenges, largely due to ongoing settlements and the daring structural configuration of the dome. In 1983, severe concerns regarding settlement and cracking led to detailed inspections, monitoring, and strengthening interventions. From 1985 to 1987, an extensive survey gathered comprehensive data on the foundation conditions, dome geometry, and geotechnical aspects. In parallel, previous structural investigations had begun in the late 1960s, notably following surveys by engineer Martino Garro in 1962. In the 1970s, the scientific community began to systematically investigate the structural health of the Sanctuary, which ultimately informed restoration efforts focused on maintaining its stability.

8.2 Static and Seismic Monitoring

In the early 1980s, a hooping system was installed to prevent the widening of cracks, primarily concentrated in the dome-drum system. The system consists of four high-strength steel bars arranged in each of the 14 tangential directions. Steel frames connect the ends of the bars in two adjacent stretches. The tie bars, slightly prestressed to 50 kN using jacks, were retensioned in 1997 to compensate for physiological load losses (Chiorino et al., 2008). Geological and geophysical investigations, conducted between 1976 and 2008, confirmed that the subsoil of the Sanctuary is composed of different materials (Scandella et al., 2011). A marl layer slopes downwards from the northeast to the southwest, while a clay layer exists beneath the rest of the building, causing serious cracking patterns. Monitoring of the Vicoforte Sanctuary began in 1983 with the installation of instruments to investigate crack pattern evolution. Since then, the static monitoring system has undergone several updates, culminating in 2004 with an automated data acquisition system; this system was comprised of 133 instruments specifically placed on the dome-drum structure (Ceravolo et al., 2017). The system continuously operated from 2004 to 2015, after which it was restored and reactivated in November 2023. Today, the static monitoring of the Vicoforte Sanctuary consists of 56 load cells, 2 laser distance meters, 2 distance meters, 12 crack meters, 28 thermometers, 1 barometer, 1 pyranometer, 3 thermo-hygrometers, and 3 piezometers (Fig. 8.2). In 2015, a dynamic monitoring system was added, consisting of 12 accelerometers (Ceravolo et al., 2016) (Fig. 8.3) distributed at different heights to monitor the overall structural behaviour, which also underwent adjustments and updates in 2023. The dynamic acquisition system at the Sanctuary of Vicoforte records data based on two criteria: time and threshold. The time criterion involves recording for 20 min every hour to limit data storage, while the threshold criterion records data when ground horizontal acceleration exceeds 0.042 g, in line with Italian seismic hazard



(a) (b)

Fig. 8.2 Layout of the low-rate system of the Sanctuary and the mixed monitoring system of the West bell tower

regulations. This ensures the dynamic response of the structure during seismic events is captured.

Finally, in 2023, a mixed monitoring system was installed in the West bell tower, including 2 MEMS triaxial accelerometers, 2 inclinometers combined with biaxial laser distance meters, 6 thermometers, and 4 strain gauges.

8.3 Results and Discussion

The data collected by the dynamic monitoring system are automatically processed to determine the main frequencies and modal shapes of the Sanctuary. In these automatic identification processes, a cluster analysis is applied to group the potential physical modes into uniform sets that represent the same mode (Pecorelli et al., 2020). The analysis of the static and dynamic monitoring data of the Sanctuary, including correlations with environmental data, showed that both types of behavior are strongly influenced by changes in ambient temperature. At the moment, no significant correlation was found with other environmental factors, such as humidity or rainfall. The study revealed that temperature increases lead to corresponding rises in the internal masonry temperature, with delays of 10–30 days due to thermal inertia. This also causes cracks at the balcony level to widen and the load on the bars to decrease, as steel expands more than masonry under heat. Furthermore, the first vibration frequencies of the structure were found to increase with rising temperatures, except for low temperatures where a bilinear behavior was observed. This may be linked to the stiffening effect of ice on the structure. Interestingly, an unexpected relationship was identified between dynamic and static data: higher temperatures led to both increased vibration frequencies and more significant crack

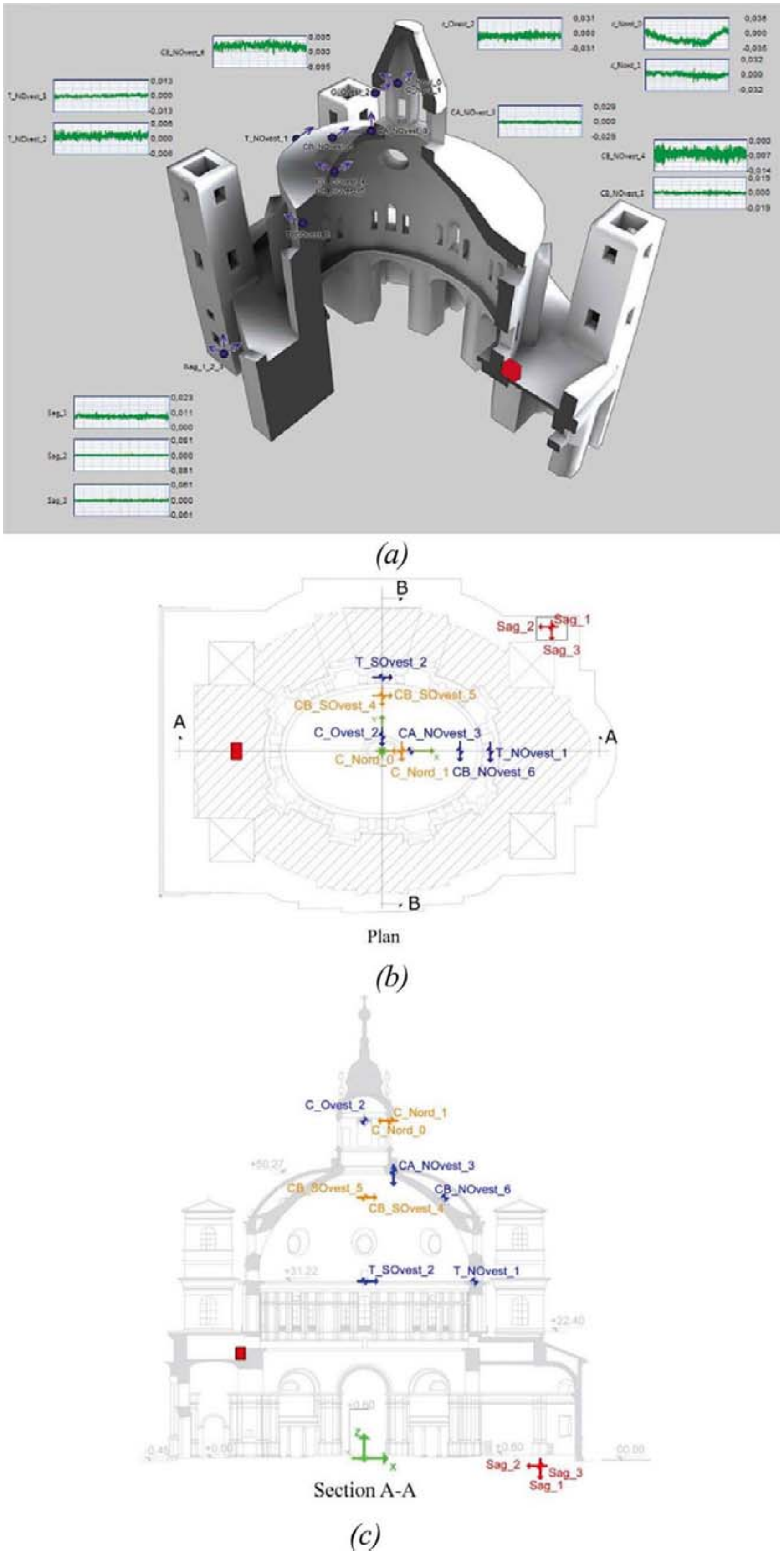


Fig. 8.3 Dynamic monitoring system of the Sanctuary of Vicoforte: (**a**) Dynamic monitoring system software interface, (**b**) Layout of the configuration the accelerometers, and (**c**) Section A-A of the configuration of dynamic monitoring system

openings, as well as reduced bar tension. This suggests additional, unmodeled phenomena, such as micro-cracks or soil seasonal cycles, particularly affecting the first vibrational modes. A plausible interpretation concerns the effect of ice, which is known to significantly increase structural rigidity (Peeters & De Roeck, 2001) (Fig. 8.4).

Then, the data acquired from the monitoring system can be used for the updating of the Finite Element Model (FEM) of the Sanctuary. The first model updating of the Sanctuary was based on the results of a dynamic test campaign conducted in 2008 (Chiorino et al., 2011). Successively, in order to consider the structural, typological and historical peculiarities of each component of the structure, a more accurate FE model was built that consisted of 9 homogeneous macro-elements: 7 for the building (lantern, dome, drum, basement, but-tresses, belltowers and iron ties) and 2 for the soil (marl and clay). Then a thermo-elastic updating was performed using multiphysics data, including the thermal analysis to obtain the temperature distribution of the drum-dome system as related to the forces acting in the tie-bars (Ceravolo et al., 2020). This distribution was determined by applying local temperature measurements to the thermal FE model.

The update of the FEM model (Fig. 8.5) through experimental data allows the model to be as close as possible to reality, enabling it to accurately reflect the actual behaviour of the structure while always considering the uncertainties inherent in its nature. The more types of data are used to enrich the model and study the behaviour of the structure (Figs. 8.4 and 8.6), the greater the fidelity of the model to its real-world counterpart. Thus, it was decided to equip the Sanctuary of Vicoforte with instruments capable of characterizing its behaviour from multiple perspectives. In addition, when dealing with SHM, it is essential to consider the influence that the environment and the soil can have on the structure response. For this reasons, the Sanctuary of Vicoforte presents a complex monitoring system (Table 8.1) that

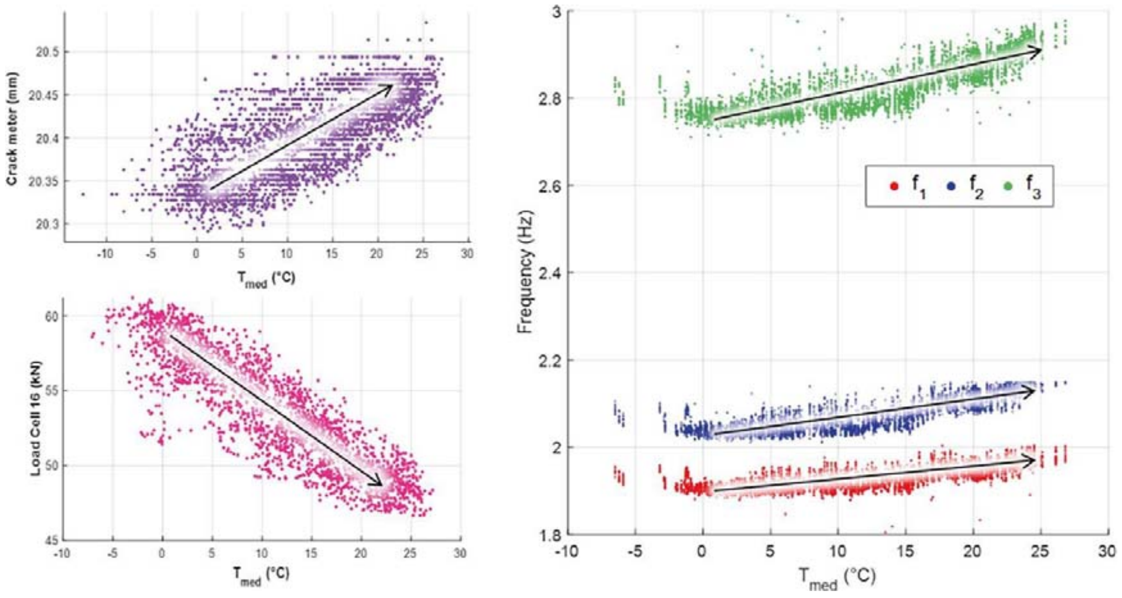


Fig. 8.4 Comparison of the results coming from the static and the dynamic monitoring systems

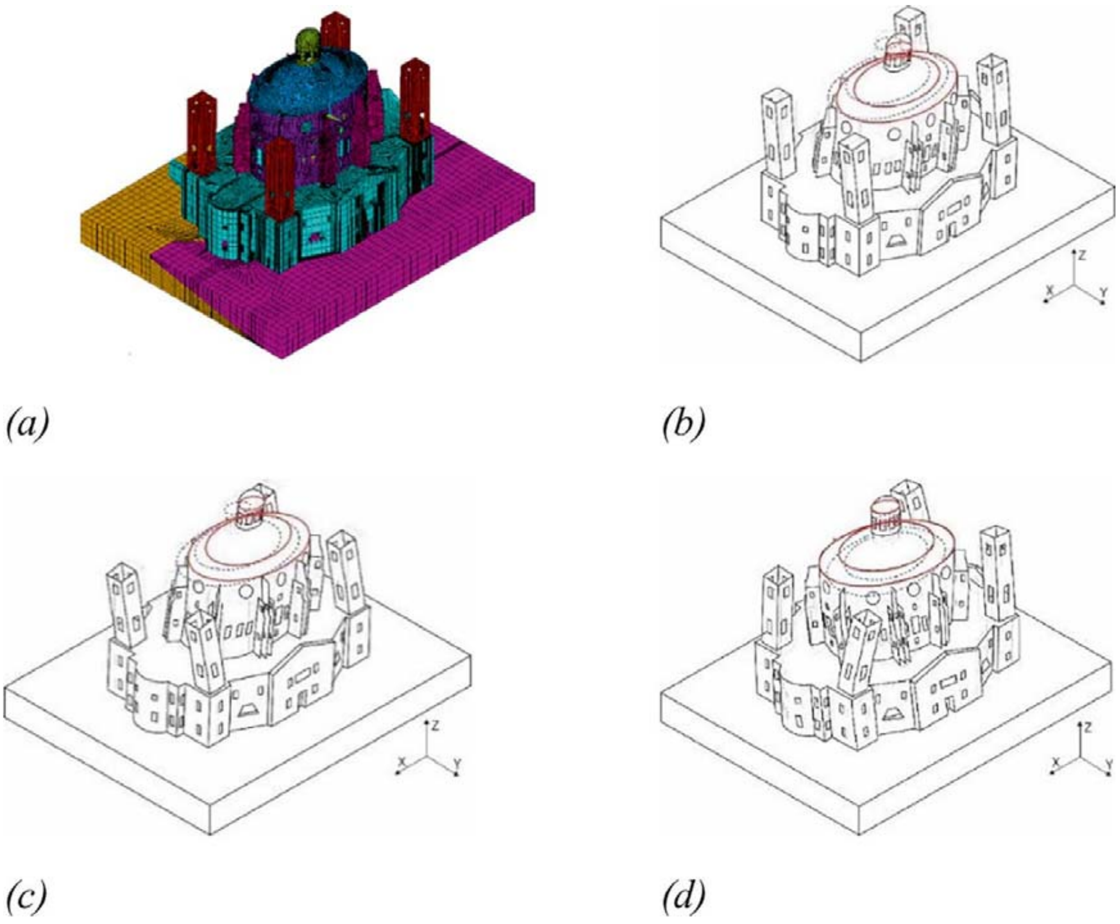


Fig. 8.5 (**a**) FEM of the Sanctuary of Vicoforte, (**b**) first modal shape (longitudinal along Y direction), (**c**) second modal shape (longitudinal along X direction), and (**d**) third modal shape (torsional)

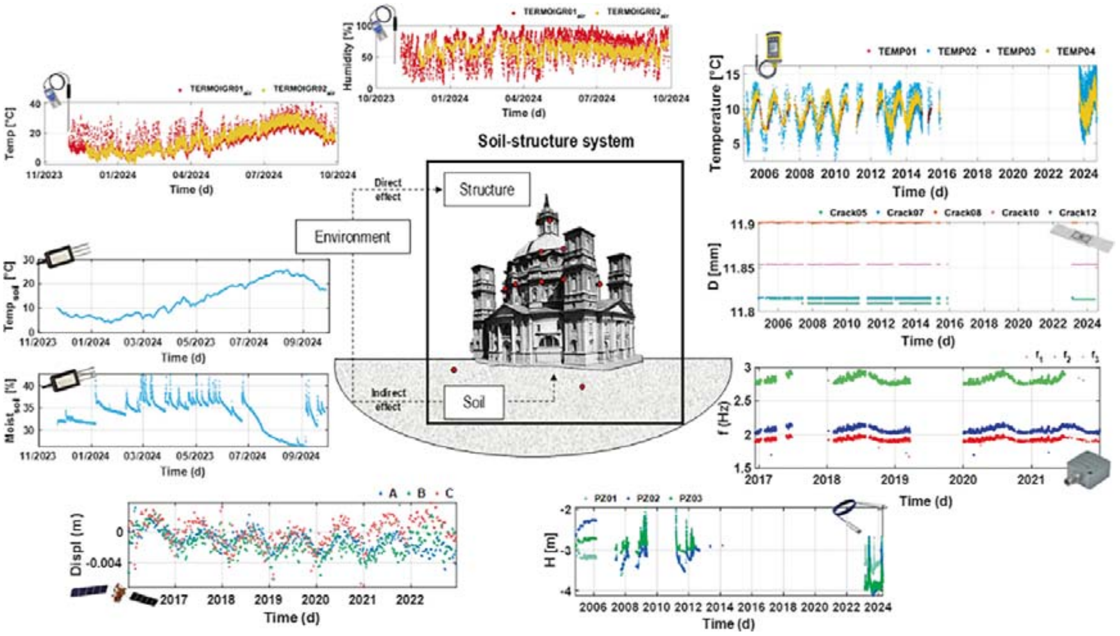


Fig. 8.6 The Sanctuary of Vicoforte with some time series obtained from in situ sensors (static and dynamic) and remote sensors

Table 8.1 Output and instruments

Type of monitoring	Static, environmental and seismic
Outputs	Updated multiphysics Finite Element Models Structural safety levels Seismic vulnerability indices Crack patterns Soil parameters and settlements
Instruments	Monitoring system of the structure Low rate (static and environment system): 1 barometer 56 load cells 2 laser distancemeters 2 distancemeters 12 crackmeters 28 thermometers 1 pyranometer 5 thermo-hygrometers 3 piezometers High rate (dynamic system): 12 accelerometers West bell tower monitoring system (low and high rate): 2 MEMS triaxial accelerometers 2 inclinometers combined with laser distance meters (biaxial) 6 thermometers 4 strain gauges

provide useful information to complete the global overview of its health state. In addition to data obtained directly from sensors installed on-site, data collected through satellite surveys, such as displacement data (DInSAR), are also added. This supplementary data is valuable for gathering information that may not be available from the installed sensors (Fig. 8.6).

8.4 Future Works

In conclusion, the Sanctuary of Vicoforte currently benefits from an extensive array of sensors that facilitate a comprehensive characterization of its structural behaviour (Fig. 8.6). The data obtained are essential for validating the numerical model, enhancing its accuracy, and enabling real-time tracking of structural changes while accounting for inherent uncertainties. This development has culminated in an effective Digital Twin capable of not only monitoring current structural conditions but also predicting future behaviours. Looking ahead, the installation of corner reflectors on the four towers will enhance the system's capabilities by enabling continuous data collection through satellite remote sensing, specifically utilizing CosmoSkyMed (ReLUIS, 2023) acquisitions. This upgrade will provide valuable additional data regarding the structure's integrity. Moreover, the integration of these displacement measurements with data from in-situ sensors will allow for comprehensive correlations and validations. This approach not only bolsters the reliability of the Digital Twin but also represents a significant advancement in the application of satellite data for structural monitoring, paving the way for more resilient and informed management of heritage structures.

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