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ABSTRACT

Active volcanic areas are exposed not only to eruptive hazards but also to prolonged unrest phases, during which ground deformation and repeated seismicity may persist for months or years. In these contexts, buildings experience a non-stationary structural demand that differs fundamentally from conventional design scenarios based on short-duration extreme events.

The Campi Flegrei (Naples, Italy) provides a representative example. Recent bradyseismic phases have been characterized by progressive uplift and recurrent low-to-moderate magnitude earthquakes distributed over extended time intervals. Under such conditions, structural damage may accumulate gradually through the interaction between slow deformation and repeated dynamic excitation, rather than resulting from a single destructive event.

This long-duration exposure shifts the monitoring paradigm. The objective extends beyond identifying immediate failure mechanisms to detect progressive changes in structural response, stiffness degradation, crack evolution, and differential displacement patterns. Volcanic unrest must therefore be interpreted as a persistent loading regime requiring integrated structural and geophysical observation.

Monitoring volcanic environments operates under practical constraints. Resource limitations, access restrictions, and evolving unrest conditions may affect installation density and data continuity. Within the broader research framework underlying these Guidelines, implementation was influenced by such constraints, limiting the number of instrumented buildings and occasionally affecting data availability.

In Campi Flegrei, intensified seismic phases further increased operational complexity, highlighting the need for resilient acquisition systems and structured data management. These conditions support a central methodological choice: the present Guidelines adopt a principle-based, architecture-oriented framework rather than relying on extensive site-specific calibration. The approach is designed to remain valid under partial datasets and evolving operational capacity.

These Guidelines provide a transferable framework for the design, implementation, and interpretation of building monitoring systems in volcanic areas affected by precursor activity. They integrate structural engineering principles with operational experience from the multiparametric monitoring system implemented in Campi Flegrei. The document aims to:

- define monitoring objectives consistent with volcanic precursor physics;
- identify vulnerability drivers under prolonged unrest;
- establish scalable and resilient monitoring architectures;
- structure data management and interpretation to support engineering and civil protection decisions.

Although Campi Flegrei is used as an application case, the framework is conceived to be generalizable to other volcanic environments characterized by deformation and repeated seismicity.

The Guidelines address structural and geotechnical engineers, civil protection authorities, public administrators, and researchers working at the interface between engineering and volcanology, promoting interoperability between structural and volcanic monitoring networks. These Guidelines provide a transferable framework for the design, implementation, and interpretation of building monitoring systems in volcanic areas affected by precursor activity. They integrate structural engineering principles with operational experience derived from the multiparametric monitoring system implemented in Campi Flegrei.

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4.1 Volcanic Precursor Phenomena and Structural Effects

Ground deformation is one of the most characteristic manifestations of volcanic unrest. It may result from magma intrusion, pressurization of shallow reservoirs, or hydrothermal processes, producing uplift, subsidence, horizontal displacement, and local tilting. Although deformation can extend over large urban sectors, its spatial gradients may vary significantly at the building scale.

In the Campi Flegrei caldera, bradyseismic phases have been marked by progressive uplift reaching decimetric scales over multi-year intervals, accompanied by measurable horizontal displacement. Even when expressed as moderate rates (e.g., millimeters per month), cumulative deformation may induce structurally relevant strain. From a mechanical perspective, differential vertical displacement Δw over a characteristic building length L induces curvature:

$$\kappa \approx \frac{\Delta w}{L^2}$$

which generates tensile and compressive strains in structural elements. Brittle materials such as masonry are particularly sensitive to such curvature, while reinforced concrete structures may experience stress redistribution and secondary effects due to differential settlements.

The structural significance of deformation is governed less by absolute displacement than by spatial gradients, acceleration of deformation rate, and interaction with pre-existing vulnerabilities. In Campi Flegrei, accelerating bradyseismic phases have reinforced the need to interpret deformation trends dynamically rather than statically.

Volcanic seismicity differs from tectonic earthquakes in its temporal pattern. Instead of isolated high-magnitude events, unrest phases often generate clusters of low-to-moderate magnitude earthquakes over extended periods.

In Campi Flegrei, recent unrest has produced hundreds of local earthquakes capable of generating perceptible shaking. While individual events may not exceed conventional design thresholds, their repetition introduces cumulative cyclic demand. Structural degradation under repeated excitation can be interpreted through stiffness variation. The fundamental frequency of a structure is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

A progressive reduction in effective stiffness k, due to cracking or damage, produces measurable frequency shifts. Monitoring the relative variation Δf_n / $f_{n,0}$ therefore provides an indirect indicator of structural modification under repeated moderate shaking.

In volcanic contexts, repetition and clustering often govern structural consequences more than peak intensity. Monitoring strategies should therefore prioritize longitudinal comparison across events rather than single-event assessment.

In active calderas such as Campi Flegrei, deformation and seismicity interact. Deformation may pre-stress structural components and initiate cracking, while subsequent shaking propagates damage and accelerates stiffness degradation.

Damage evolution under these conditions is cumulative and trend-driven. It may remain subcritical for long periods before affecting serviceability or safety. The dominant mechanism is progressive response modification rather than sudden collapse. For this reason, monitoring should focus on the temporal evolution of displacement, crack growth, modal frequency variation, and coherence among multiple indicators. The Campi Flegrei experience confirms that structural effects during prolonged unrest are best interpreted through trend analysis rather than isolated exceedance of deterministic thresholds.

4.2 Building Vulnerability in Volcanic Contexts

The structural impact of volcanic precursor phenomena is strongly conditioned by building typology, material properties, and global configuration. In prolonged unrest environments such as Campi Flegrei, vulnerability must be interpreted not solely in terms of ultimate collapse capacity, but in relation to sensitivity to differential deformation, cyclic demand, and progressive stiffness modification.

Urban sectors within the Campi Flegrei caldera include heterogeneous building stocks composed primarily of:

- unreinforced masonry (URM) structures,
- reinforced concrete (RC) frame systems of different construction periods,
- mixed structural configurations.

This heterogeneity produces differentiated response mechanisms under similar geophysical forcing.

4.2.1. Unreinforced masonry (URM)

URM buildings are intrinsically vulnerable to differential ground movements due to their low tensile strength, limited ductility, and brittle failure mechanisms. Even moderate curvature induced by non-uniform uplift or settlement may generate tensile stresses exceeding material capacity, leading to crack initiation in walls, vaults, and arch systems.

Under bradyseismic deformation, crack patterns often develop gradually and may initially manifest as distributed microcracking rather than localized structural distress. However, progressive crack propagation can reduce wall stiffness, alter load transfer paths, and increase susceptibility to out-of-plane mechanisms.

Repeated moderate seismic events, such as those documented during recent unrest phases in Campi Flegrei, may further propagate existing cracks. While individual earthquakes may not reach severe intensity levels, their cumulative effect can progressively weaken masonry panels and diaphragms.

In URM buildings, vulnerability is therefore governed by:

- curvature sensitivity due to differential displacement,
- crack propagation under cyclic loading,
- limited energy dissipation capacity,
- interaction between vertical and horizontal structural components.

Because degradation may evolve slowly, early stages are not always readily detectable through visual inspection alone, reinforcing the importance of monitoring dynamic and deformation-sensitive parameters.

4.2.2. Reinforced concrete (RC) frame structures

Reinforced concrete structures exhibit different vulnerability patterns. While generally more ductile than URM systems, their response under volcanic unrest is influenced by design age, detailing quality, and structural configuration.

RC buildings constructed prior to modern seismic codes may present limited confinement, insufficient reinforcement detailing, or irregular stiffness distribution. Under repeated moderate seismic excitation, cracking in beams, columns, and infill panels may progressively reduce effective stiffness without producing immediate visible damage.

The interaction between differential ground deformation and frame behavior may induce additional stress redistribution. Foundation rotations and settlements can modify boundary conditions, generating secondary bending moments and altering load paths within the structural system.

Infill panels—frequently present in RC frame buildings in Campi Flegrei—play a critical role in dynamic response. Progressive cracking or detachment of infills can significantly modify global stiffness and modal properties, leading to measurable frequency variation even in the absence of primary structural element damage. For RC structures, vulnerability under volcanic unrest is therefore primarily associated with:

- stiffness degradation rather than immediate strength loss,
- cumulative cracking under repeated moderate shaking,
- interaction between infills and structural frame,
- alteration of dynamic characteristics over time.

4.2.3. Structural configuration effects

Beyond material typology, global configuration influences response. Irregular plan layouts, soft-story conditions, torsional eccentricities, and discontinuities in stiffness may amplify the effects of both deformation gradients and dynamic excitation.

In volcanic contexts characterized by spatially variable uplift, such as Campi Flegrei, buildings located across deformation gradients may experience differential demands even within short urban distances. Configuration-sensitive amplification mechanisms may therefore concentrate damage in specific structural zones.

Vulnerability assessment must consequently integrate material, detailing, and configuration parameters rather than relying on typological classification alone.

4.2.4. Soil–structure interaction under bradyseismic deformation

Soil–structure interaction (SSI) represents a key vulnerability amplifier in caldera environments. Bradyseismic uplift and subsidence rarely occur uniformly at the building scale. Spatial variability of ground movement interacts with foundation systems, modifying effective structural demand.

The displacement observed at the structural level reflects both free-field ground movement and additional deformation induced by foundation compliance. Flexible or heterogeneous soil conditions may amplify rotations, settlements, and stress redistribution.

In Campi Flegrei, where deformation fields exhibit spatial heterogeneity, SSI effects are particularly relevant for interpreting monitored behavior. Buildings founded on compressible soils may display amplified tilt or displacement relative to neighboring structures subjected to similar regional uplift.

SSI also influences dynamic response by altering effective boundary stiffness. Changes in foundation conditions can modify global stiffness–mass interaction, affecting natural frequencies and damping characteristics. For this reason, monitoring configurations that include both foundation-level and upper-level measurements provide more reliable insight into structural amplification and stiffness evolution.

4.2.5. Progressive and time-dependent vulnerability

A defining characteristic of structural vulnerability under volcanic unrest is its time-dependent nature. Unlike conventional hazard scenarios dominated by single extreme events, unrest conditions impose repeated and interacting demands that may progressively alter structural properties.

In Campi Flegrei, repeated moderate earthquakes combined with ongoing deformation have demonstrated that structural modification may occur without abrupt collapse. Instead, gradual stiffness reduction, crack propagation, and boundary condition changes accumulate over time.

Vulnerability must therefore be understood as an evolving property. A building initially exhibiting acceptable performance may become increasingly sensitive as stiffness degrades and pre-existing defects interact with new loading cycles.

Monitoring systems are essential precisely because they allow detection of such temporal evolution. The identification of progressive modal frequency shifts, accelerating displacement trends, or coherent multi-parameter variation provides early insight into changing structural conditions before critical thresholds are reached. The Campi Flegrei experience confirms that under prolonged unrest, vulnerability is governed less by instantaneous demand and more by cumulative structural response.

4.3 Monitoring Objectives and Conceptual Principles

4.3.1. Monitoring as an adaptive decision-support framework

In volcanic unrest environments, building monitoring cannot be conceived as a purely diagnostic or research-oriented activity. Its primary function is to support technical evaluation and risk-informed decision-making under evolving and uncertain conditions.

In contexts such as Campi Flegrei, where deformation and seismicity may persist and fluctuate over extended periods, structural response must be interpreted dynamically rather than episodically. Monitoring is therefore positioned at the interface between:

- structural engineering assessment,
- volcanic process evolution,
- civil protection management.

The objective is not the mere accumulation of measurements, but the detection of meaningful deviations from reference conditions and the identification of progressive structural modification.

Monitoring outputs acquire operational relevance only when translated into interpretable indicators, such as:

- temporal variation of modal properties,
- acceleration of displacement trends,
- coherent evolution across independent parameters.

This perspective shifts the focus from isolated exceedance values to structured, trend-based interpretation.

4.3.2. Baseline definition and anomaly recognition

A reliable baseline condition represents the cornerstone of monitoring under volcanic unrest. Without baseline characterization, it becomes difficult to distinguish between pre-existing structural features, environmental variability, and unrest-induced changes.

- Baseline definition typically includes:
- initial modal frequencies and damping ratios,
- normal displacement variability,
- stable crack patterns,
- response under low-intensity seismic excitation.

An anomaly should not be defined solely as a deviation from a nominal value, but as a persistent or accelerating variation relative to baseline variability. In practice, relative frequency variation

$$\frac{\Delta f_n}{f_{n,0}}$$

often provides a sensitive indicator of stiffness modification.

In Campi Flegrei, the availability of repeated, standardized event recordings enables longitudinal comparison under comparable excitation levels, strengthening anomaly recognition through consistent datasets.

Anomalies must always be interpreted within their temporal context. Transient deviations may reflect environmental or measurement variability, whereas persistent and accelerating trends carry greater diagnostic weight.

4.3.3. Multiparametric integration

Volcanic precursor processes generate coupled mechanical effects. No single monitoring parameter can capture structural condition comprehensively.

Displacement and tilt measurements reflect quasi-static deformation; crack evolution captures material-level response; modal properties reveal global stiffness variation; ground-motion records quantify input demand.

Interpretative reliability increases when independent indicators exhibit coherent evolution. The multiparametric monitoring architecture implemented in Campi Flegrei—integrating accelerometric, velocimetric, and GNSS sensors—demonstrates how structural and ground processes can be jointly interpreted within a unified framework.

Multiparametric integration therefore reduces interpretative ambiguity and limits overreliance on isolated indicators.

4.3.4. Scalability and resilience

Monitoring systems deployed in volcanic environments must remain functional under fluctuating operational conditions. Unrest intensity, logistical access, and resource allocation may evolve over time.

A scalable framework allows progressive adjustment of sensor density, acquisition frequency, and analytical depth. During stable phases, simplified evaluation may suffice; during intensified unrest, higher-resolution acquisition and rapid interpretation may become necessary.

Resilience is equally critical. Data continuity cannot always be guaranteed, particularly during seismic swarms or infrastructure disruptions. The Campi Flegrei implementation demonstrates the importance of automated event harvesting, standardized processing, and structured archiving in preserving interpretability even under partial data conditions.

Scalability and resilience ensure that monitoring remains scientifically coherent and operationally useful throughout evolving unrest phases.

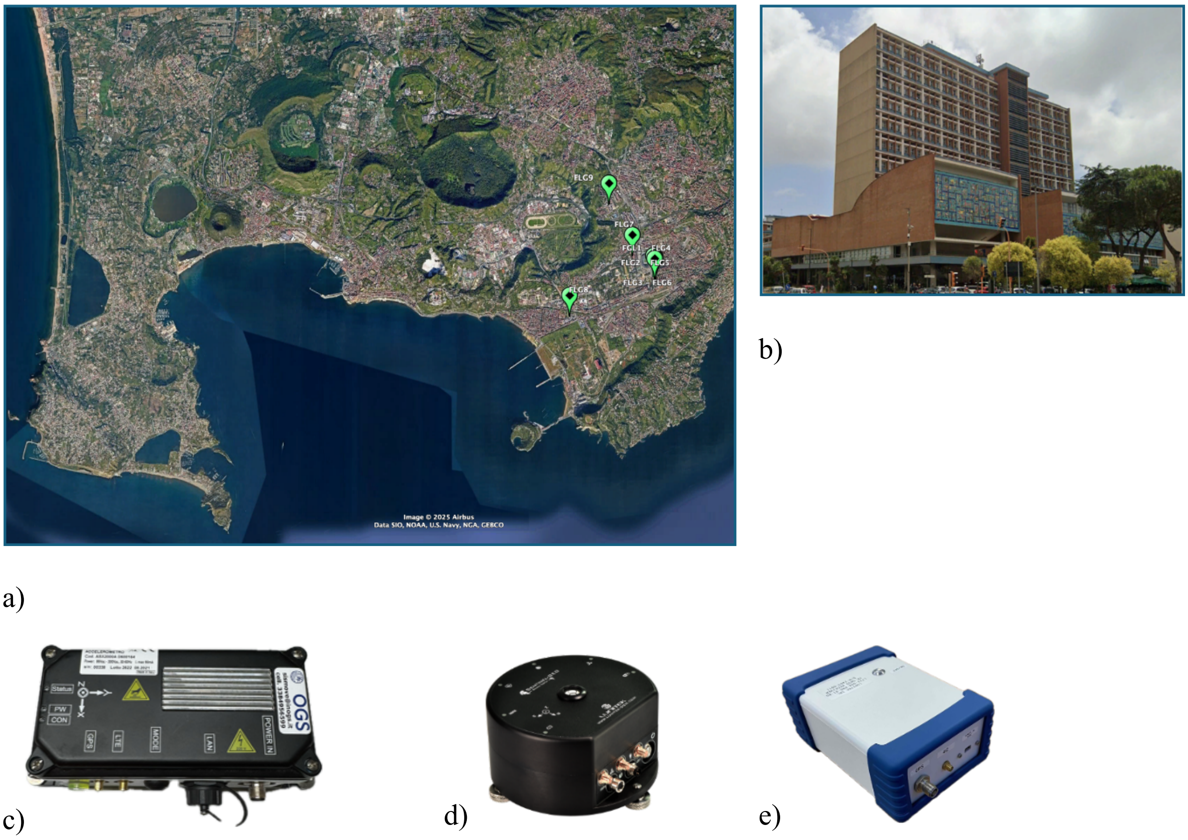
4.4 Monitoring Architecture Design Framework

A monitoring system for buildings exposed to volcanic precursor activity must be conceived as an integrated architecture rather than as a collection of independent instruments. Sensor configuration, acquisition strategy, and data management must directly reflect the physical mechanisms described in Sections 2 and 3.

In volcanic contexts such as Campi Flegrei, where long-term deformation and repeated seismicity act simultaneously, the monitoring architecture must capture both quasi-static and dynamic structural response within a unified interpretative framework.

- The system can be conceptually described as a layered structure composed of:
- a sensing layer (physical measurements),
- an acquisition layer (data transmission and storage),
- a processing layer (calibration and standardization),
- an interpretative layer (engineering analysis and decision support).

The strength of the architecture lies in the coherence between these layers, ensuring that measurements are immediately usable for structural interpretation.



a) b) c) d) e)

Figure 1. *Overview of the monitoring installation in the Campi Flegrei area. (a) Location map of the instrumented buildings; (b) Engineering building at Piazzale Tecchio (UNINA); (c) ADEL*

accelerometric sensor; (d) Lunitek velocimeter; (e) LZERO GNSS receiver used for co-located deformation measurements.

4.4.1. Sensor integration and spatial configuration

Sensor selection must be guided by structural mechanics requirements. Because volcanic deformation induces slow differential movements while seismic swarms generate repeated dynamic input, monitoring must integrate:

- deformation-sensitive measurements (e.g., GNSS or displacement sensors),
- dynamic response measurements (accelerometric and/or velocimetric sensors).

In Campi Flegrei, the deployed multiparametric configuration integrates accelerometers, short-period velocimeters, and GNSS receivers within an urban building context. This configuration enables simultaneous observation of:

- ground deformation velocity,
- foundation-level ground motion,
- structural response at upper levels.

The spatial arrangement of sensors is critical. Where feasible, instrumentation at both foundation and superstructure levels allows separation between input motion and structural amplification, facilitating modal tracking and stiffness evaluation over time.

4.4.2. Acquisition chain and system robustness

The effectiveness of monitoring architecture depends not only on sensor configuration but also on the reliability of the acquisition chain.

Volcanic unrest environments may impose operational stress on monitoring systems due to increased seismic activity, access limitations, or communication disruptions. For this reason, acquisition design must ensure:

- continuous waveform streaming,
- automated event detection and harvesting,
- standardized calibration procedures,
- structured data storage.

In Campi Flegrei, automated event harvesting and deterministic archiving reduce latency between seismic occurrence and data availability, enhancing both scientific usability and operational responsiveness.

System robustness should be considered a scientific requirement rather than merely a technical feature. Fragmented or inconsistent datasets severely limit interpretability under evolving unrest conditions.

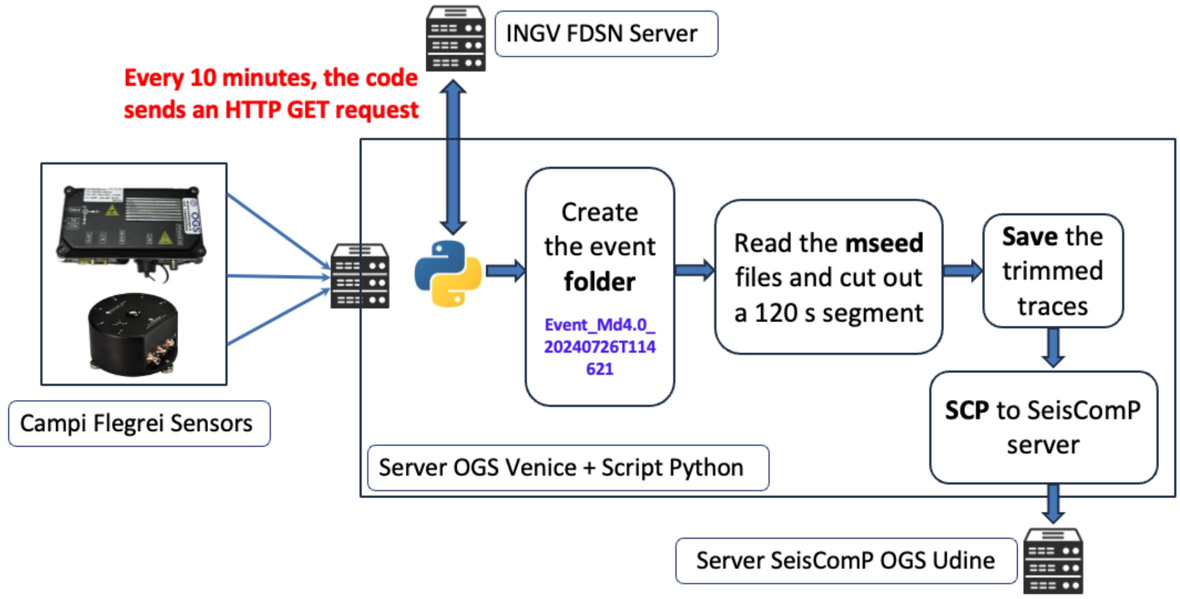


Figure 2 – *Automated workflow from event detection to waveform trimming and archiving*

4.5 Data Management and Event-Based Workflow

4.5.1. From continuous acquisition to structured event-based datasets

Monitoring systems operating in volcanic unrest environments produce continuous waveform recordings that, taken alone, are insufficient for engineering interpretation. In areas such as Campi Flegrei—where seismic activity consists of repeated low-to-moderate magnitude events distributed over extended time intervals—the analytical value of monitoring lies in the ability to construct homogeneous and comparable event-based datasets.

For this reason, data management must be conceived as an integral part of the monitoring architecture. In the Campi Flegrei implementation, continuous streams are systematically cross-referenced with regional seismic catalogues in order to identify events falling within predefined spatial and magnitude criteria. Each detected earthquake is automatically extracted using standardized time windows around the origin time. This ensures that all archived events share a consistent temporal structure, enabling meaningful comparison across the dataset.

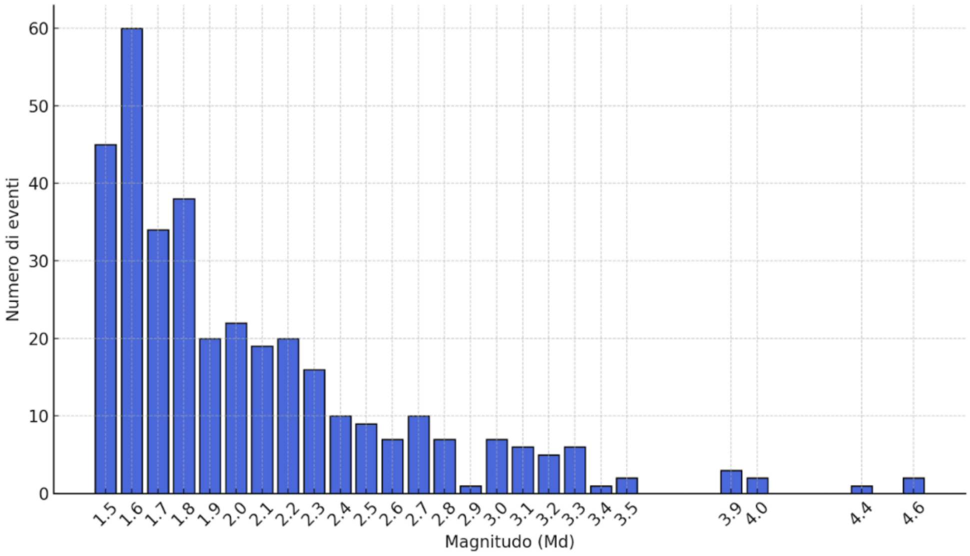


Figure 3– *Magnitude distribution of archived events during 2025 in Campi Flegrei*

The adoption of deterministic extraction rules guarantees that modal tracking, cross-event analysis, and longitudinal evaluation of structural response are based on internally coherent data rather than on ad hoc signal selection.

4.5.2. Calibration and engineering-ready data products

For monitoring to support structural assessment, waveform data must be expressed in physical units. Instrument response removal and metadata consistency are therefore essential components of the processing chain.

In the Campi Flegrei monitoring system, both raw and response-corrected waveform products are systematically archived. The corrected signals provide acceleration and velocity time histories directly usable for the computation of engineering demand parameters, such as peak ground acceleration, peak ground velocity, and spectral values. The preservation of raw data ensures traceability and reproducibility, while calibrated products enable immediate engineering interpretation.

By embedding calibration within the automated workflow, the Campi Flegrei system ensures that comparisons across stations and over time are not affected by instrumental inconsistencies. Data processing thus becomes a structural element of the monitoring architecture rather than a secondary technical step.

4.5.3. Deterministic archiving and interoperability

The long-term scientific and operational value of monitoring depends on structured and reproducible archiving. Event-based datasets must be organized according to deterministic naming conventions and metadata structures, ensuring that each waveform can be uniquely identified by origin time, magnitude, station code, and channel type.

In Campi Flegrei, each archived earthquake includes synchronized recordings from all operational stations, enabling complete cross-station comparison. This systematic packaging strengthens dataset integrity and facilitates automated analysis.

The formal registration of the Campi Flegrei monitoring network within the FDSN framework further enhances metadata standardization and interoperability. Alignment with international conventions supports integration with external datasets and improves the transferability of the monitoring architecture to other volcanic environments.

4.5.4. Operational accessibility and scientific continuity

In volcanic unrest contexts, rapid access to monitoring data is critical during intensified seismic phases. The Campi Flegrei system incorporates controlled web-based dissemination, allowing authorized users to retrieve event-based waveforms with limited latency. This capability supports timely engineering evaluation and inspection prioritization.

Beyond immediate operational use, the event-based archive constitutes a long-term scientific resource. Because event harvesting, windowing, calibration, and archiving follow deterministic and automated procedures, the dataset enables reproducible longitudinal analyses. Modal tracking under repeated excitation, evaluation of stiffness evolution, and comparison across homogeneous subsets of earthquakes become feasible precisely due to this internal consistency.

The Campi Flegrei experience demonstrates that, in volcanic environments, data management is not a peripheral activity but a structural component of monitoring architecture. Automation, calibration coherence, and standardized organization transform continuous recordings into an interpretable framework capable of supporting both engineering assessment and civil protection decision-making.

4.6 Interpretation of Monitoring Results for Engineering and Civil Protection

4.6.1. Trend-based evaluation under evolving unrest

In volcanic unrest contexts, structural interpretation must privilege temporal evolution over instantaneous exceedance. Unlike post-earthquake assessments triggered by a single identifiable event, precursor activity produces gradual and sometimes subtle modifications of structural behavior.

The central interpretative question is therefore not whether a monitored parameter exceeds a predefined absolute value at a given moment, but whether its evolution indicates a meaningful deviation from established baseline conditions.

Parameters such as modal frequencies, displacement trends, or crack widths acquire diagnostic relevance when they exhibit persistent or accelerating variation. Relative frequency shifts, for example, provide indirect evidence of stiffness modification and are particularly informative when observed consistently across comparable seismic events.

In Campi Flegrei, the availability of repeated and standardized event recordings enables longitudinal comparison of structural response under similar excitation levels. This consistency strengthens trend-based interpretation and allows differentiation between variability driven by changes in seismic input and genuine structural modification.

Trend evaluation thus represents the primary interpretative framework for monitoring under prolonged unrest conditions.

4.6.2. Multi-parameter convergence and interpretative robustness

Because volcanic precursor processes generate coupled mechanical effects, interpretation should not rely on a single indicator. Deformation, repeated seismic excitation, and soil–structure interaction influence different measurable aspects of structural behavior.

Displacement and tilt measurements reflect quasi-static deformation; crack evolution captures material-level response; modal properties indicate global stiffness variation; ground-motion records quantify input demand. The reliability of interpretation increases significantly when independent indicators evolve coherently.

The multiparametric monitoring architecture implemented in Campi Flegrei demonstrates the practical value of this approach. The integration of accelerometric, velocimetric, and GNSS measurements allows cross-validation between structural response and ground processes, reducing ambiguity in diagnosis.

Isolated anomalies, particularly when transient, should be treated with caution. Measurement noise, environmental variability, or temporary boundary condition changes may produce apparent deviations that do not correspond to structural degradation. Multi-parameter convergence therefore serves as a safeguard against premature or disproportionate responses.

4.6.3. Operational thresholds and escalation logic

In conventional structural assessment, thresholds are often associated with deterministic limit states. In volcanic unrest environments, however, the gradual and uncertain character of precursor effects requires a more nuanced interpretation.

Operational thresholds should be understood as reference levels that trigger graduated actions rather than definitive indicators of failure. Relative changes in modal frequency, acceleration of displacement trends, or repeated moderate demand may serve as warning indicators, but their significance must be evaluated in relation to baseline variability and overall structural context.

In Campi Flegrei, the structured event-based archive enables comparison of modal properties across homogeneous subsets of earthquakes, providing a statistically coherent basis for defining variability ranges. Such consistency supports the definition of escalation levels that distinguish between normal variability, enhanced attention, targeted inspection, and potential usage restriction.

This graded logic avoids binary decision-making and aligns monitoring outputs with the needs of civil protection authorities.

4.6.4. Integration with inspections and emergency management

Monitoring does not replace engineering judgment; it supports it. Its primary operational roles include prioritizing inspections, informing updated safety evaluations, and reducing uncertainty in large-scale building assessment.

When persistent and coherent structural modifications are detected, monitoring results can guide targeted on-site verification. Conversely, stable trends and absence of multi-parameter convergence may justify maintaining current usage conditions, avoiding unnecessary disruption.

In densely urbanized volcanic areas such as Campi Flegrei, where unrest phases may involve numerous buildings, monitoring provides a scalable mechanism for risk-informed prioritization. It enables allocation of inspection and mitigation resources according to observed structural evolution rather than uniform precaution.

In emergency conditions—such as accelerated deformation or intensified seismic swarms—monitoring outputs may contribute to decisions regarding temporary restrictions or protective measures. Such decisions must always integrate structural assessment, volcanic monitoring data, and explicit consideration of uncertainty.

Clear communication is essential. Monitoring results should be expressed in terms of trends, relative changes, and associated confidence levels, fostering transparency and trust between engineers, authorities, and the public.

4.7 Implementation Example: The Campi Flegrei Multiparametric Monitoring System

4.7.1. Scientific context and rationale

The Campi Flegrei caldera (Naples, Italy) represents one of the most densely urbanized active volcanic areas in Europe. Recent unrest phases have been characterized by progressive bradyseismic uplift accompanied by recurrent seismic swarms, generating repeated low-to-moderate magnitude earthquakes and measurable ground deformation across urban sectors.

Within this context, building monitoring becomes an operational necessity rather than a purely scientific exercise. The interaction between slow deformation and repeated seismic excitation creates conditions under which structural modification may evolve progressively over time.

The multiparametric monitoring system implemented in Campi Flegrei was conceived precisely to address this condition. Its design reflects the principles outlined in previous sections: integration of deformation and dynamic measurements, automated event harvesting, standardized data management, and reproducible engineering interpretation.

Campi Flegrei therefore provides a real-world environment in which the proposed monitoring architecture has been deployed and tested under active unrest conditions.

4.7.2. Network deployment and sensor configuration

The Campi Flegrei monitoring system is installed within an urban building context in the Fuorigrotta district, near Piazzale Tecchio, in facilities of the University of Naples “Federico II”. The selected site combines structural relevance, accessibility, and proximity to active deformation zones within the caldera.

- The multiparametric configuration integrates:
- accelerometric sensors for structural dynamic response,
- short-period velocimetric sensors for ground-motion characterization,
- GNSS receivers for measurement of bradyseismic deformation.

Instrumentation is distributed across structural levels, including foundation and upper floors, enabling separation between input ground motion and structural amplification. This configuration supports modal tracking, stiffness evaluation, and comparison between ground demand and structural response.

4.7.3. Automated workflow and data infrastructure

A defining feature of the Campi Flegrei implementation is the automated event-based data workflow. Continuous waveform streams are systematically processed through a pipeline that identifies new seismic events from regional catalogues, extracts standardized time windows, applies calibration procedures, and archives synchronized recordings from all operational stations.

This deterministic workflow ensures internal consistency of the event-based archive and enables longitudinal comparison of structural response under comparable excitation levels. Both raw and response-corrected waveform products are preserved, allowing direct computation of engineering demand parameters while maintaining traceability.

4.7.4. Scientific and operational outcomes

The Campi Flegrei monitoring system demonstrates the feasibility of maintaining a resilient and scientifically robust infrastructure during active volcanic unrest.

From a scientific perspective, the structured event-based database enables modal tracking under repeated excitation, evaluation of stiffness evolution, and reproducible longitudinal analyses. The homogeneity of event selection and windowing supports statistically coherent comparisons across magnitude classes and temporal intervals.

From an operational perspective, automated harvesting and controlled data dissemination reduce latency between seismic occurrence and engineering evaluation. In a densely urbanized caldera environment, such capability supports prioritization of inspections and informed communication with civil protection authorities.

The Campi Flegrei case confirms that effective monitoring under volcanic unrest requires not only sensing technology, but also architectural coherence, automation, and data governance. While the geological and urban characteristics of Campi Flegrei are specific, the monitoring principles implemented there are transferable to other volcanic regions experiencing prolonged deformation and repeated moderate seismicity.

In this sense, Campi Flegrei does not merely illustrate the proposed Guidelines—it demonstrates their operational viability.

5. CONCLUSIONS

Building monitoring under volcanic precursor conditions operates within an inherent framework of uncertainty. Volcanic processes may evolve non-linearly, with spatial heterogeneity and temporal variability that complicate direct correlation between geophysical forcing and structural response.

In areas such as Campi Flegrei, deformation gradients and seismic activity may vary significantly across short urban distances. Structural behavior observed in one building cannot therefore be generalized automatically to adjacent structures without considering differences in soil conditions, foundation systems, and vulnerability profiles.

Additional uncertainty arises from pre-existing structural conditions. Buildings in long-inhabited volcanic regions may have experienced previous unrest cycles, historical earthquakes, or progressive material degradation. Distinguishing between long-term deterioration and unrest-induced modification requires cautious interpretation, particularly when baseline data are limited.

Monitoring systems themselves introduce further sources of variability, including sensor accuracy, environmental effects, and potential data discontinuities. Even within the resilient multiparametric architecture implemented in Campi Flegrei, interpretative prudence remains essential. Small variations in modal frequency or displacement trends do not automatically imply safety-critical conditions; their significance must be assessed within a broader structural and volcanic framework.

For these reasons, monitoring outputs should always be integrated with engineering judgment, field inspections, and volcanic monitoring data. No single indicator can replace comprehensive structural assessment.