

Multi-method monitoring for coastal cliff stability analysis: Integrating geotechnical surveys and terrestrial LiDAR at the Citadel of Bonifacio

STELLA COCCIA

`stella.coccia@ineris.fr`

Institut national de l'environnement industriel et des risques

Emmanuelle KLEIN

Institut national de l'environnement industriel et des risques

Morgane SALOMON

Institut national de l'environnement industriel et des risques

Christian FRANCK

Institut national de l'environnement industriel et des risques

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Abstract

On rocky coasts, the primary geohazards are associated with rockfalls and rapid, massive slope failures. The sporadic nature of these processes, compounded by climate change, renders their spatial and temporal prediction particularly challenging. Understanding the response of rocky coastlines to complex environmental forcing remains a critical scientific issue. This study investigates the soft limestone cliffs of the Bonifacio Citadel (Corsica, France), an iconic cultural heritage site supporting a dense urban area and experiencing high tourist traffic, where key structural discontinuities drive gravity-induced mass movements. The primary objective is to qualify and quantify the "massive collapse" hazard to support public safety risk assessment.

Since 2018, extensive site investigations have been implemented based on a dual-monitoring strategy: a continuous multi-parameter sensor network installed in 2019, combined with periodic, multi-temporal Terrestrial Laser Scanning (TLS) surveys. This paper synthesizes the findings of these complementary monitoring approaches. The integrated dataset provided high-resolution 3D structural mapping and successfully captured precursor micro-deformations prior to rockfall events. Multi-temporal TLS surveys enabled the quantification of volumetric changes (ranging from centimetric block failures to larger structural detachments), while the continuous sensor array resolved the short-term thermal and mechanical response of the cliff face to atmospheric and marine triggers. These results demonstrate that synergizing continuous high-frequency monitoring with periodic high-resolution spatial surveys is essential for robust cliff stability assessments, providing actionable decision-support data for local authorities in managing geohazards and coastal planning and management on vulnerable coastal heritage sites.

Keywords: Rocky coastal cliffs; Large-scale collapse hazard; Real-time multiparameter monitoring; Geotechnical time-series analysis; Terrestrial LiDAR; Diachronic point-cloud comparison

1. Introduction

Coastal cliffs are vital geomorphological assets of high scientific, ecological, and socio-economic value. However, as highlighted by Imam et al. (2023), these steep topographies are increasingly threatened by instability processes that compromise their structural integrity. While individual failures are often localized, processes such as rockfalls and toppling represent the most frequent geohazards along rocky coastlines. Although most events involve small, isolated blocks, large-scale cliff collapses pose catastrophic risks to human life, critical infrastructure, and coastal communities (Hampton et al. 2004).

Historically, research on coastal cliff evolution focused primarily on major mass movements visible in medium-resolution satellite imagery or aerial photographs. However, these catastrophic events represent only a fraction of the total material flux and ongoing coastal erosion dynamics (Letortu et al. 2022). Rockfalls are primary drivers of coastline retreat; they occur rapidly on steep slopes with minimal precursory warning signs. These dynamics are governed by the complex interplay between gravity, rock mass structure, and the spatial distribution of discontinuities, further exacerbated by marine and atmospheric forcing factors. Deciphering these failure mechanisms is imperative for developing proactive risk mitigation and heritage conservation strategies.

In rock mechanics and geomorphology, the drivers of slope failure are generally categorized into three main factors (Villarraga et al. 2018):

1. Predisposing factors: Inherent characteristics of the rock mass, such as lithology, geological structure, fracture density, and slope geometry, which remain static over human operational timescales.
2. Preparatory factors: Transient processes that induce a progressive decay in the mechanical resistance of the rock mass over medium- to long-term periods (e.g., progressive fatigue, weathering).
3. Triggering factors: Short-term environmental forcing events, such as heavy rainfall, rapid temperature fluctuations, or severe storm waves, that abruptly initiate failure.

A fundamental challenge in designing effective monitoring strategies lies in unraveling the coupled interactions between these factors. Identifying reliable physical precursors prior to collapse remains an ongoing problem in geotechnical engineering and coastal geohazard assessment. To date, no standardized, universally accepted monitoring protocols exist for coastal cliff stability, largely due to the site-specific complexity of environmental and geological conditions (Hung et al. 2013; Esposito et al. 2017). Consequently, monitoring frameworks must be meticulously tailored to local site conditions.

The advent of modern remote sensing techniques, particularly Terrestrial Laser Scanning (TLS) and digital photogrammetry, has transformed our ability to acquire ultra-high-resolution 3D spatial data. TLS allows rapid, non-contact mapping of complex topography, enabling precise assessment of structural discontinuities, surface deformation, and volumetric material losses. When coupled with continuous geotechnical instrumentation, these spatial techniques bridge a major knowledge gap regarding the specific role of high-frequency environmental triggers in initiating failure (Letortu et al. 2022). Recent developments in cloud-enabled IoT architectures further allow real-time data streaming, providing data redundancy and quantitative threshold alerts for proactive risk management.

This study investigates the active coastal limestone cliffs supporting the Citadel of Bonifacio, a World Heritage site at the southern tip of Corsica, France. The site represents a complex subaerial-marine boundary subject to intense natural forcing within a high-stakes urban environment. Since 2018, an integrated investigation program has been carried out to qualify the "massive collapse" hazard and evaluate public safety risks (Thoraval et al. 2021). The monitoring strategy combines periodic TLS surveys (2018–2023) to assess spatial failure patterns across the 330 m-long cliff face with an in-situ real-time multi-parameter monitoring array deployed in April 2019 (Coccia et al. 2024). This paper presents the synthesis of these multi-year spatial and temporal datasets, providing crucial interim stability insights while long-term vulnerability reduction and heritage preservation measures are formulated.

2. Geological and Environmental Setting

The soft rock cliffs of Bonifacio are situated at the southernmost extremity of Corsica Island, France. The study area experiences a typical Mediterranean climate (*Csa* according to the Köppen–Geiger classification), characterized by hot, dry summers and mild, rainy winters. The mean annual temperature ranges between 16 and 17 °C, with annual precipitation averaging 500–600 mm, predominantly occurring between October and April. Positioned along the Strait of Bonifacio, the site is exposed to persistent, high-velocity prevailing winds (mainly West/North-West *Libeccio* and *Mistral*), which induce high evapotranspiration rates and intense wave dynamics.

Geologically, the coastal cliff system consists of a Miocene carbonate plateau resting unconformably upon a fractured Hercynian granitic basement, with sedimentary thickness governed by the underlying bedrock paleotopography. The stratigraphic sequence exposed along the Citadel cliffs comprises variably lithified calcarenites and fine sub-horizontal sandstones, collectively designated as the Bonifacio Formation (André et al. 2011). Two major lithostratigraphic members form the cliff face (Fig. 1):

- The Pertusato Member: Forming the basal 30 m of the cliff, this unit consists of weakly consolidated fine sands deposited in ancient shoreface environments under strong hydrodynamic energy. Due to its low mechanical strength, this basal unit is highly vulnerable to marine erosion and notch formation, acting as a primary driver of upper-cliff destabilization.
- The Bonifacio Member: Overlying the Pertusato Member with a thickness of approximately 50 m, this unit exhibits alternating beds of sandstone and resistant calcarenites. Subaerial weathering (wind deflation and rain wash) drives differential erosion across these beds, leading to the formation of prominent, overhangs in the upper calcareous layers.

The structural architecture of the plateau is cross-cut by major syn-to-post-depositional tectonic faults and joint sets (Reynaud et al. 2012). The present-day morphology of the cliffs is heavily constrained by these structural discontinuities. Systematic structural mapping reveals four principal fracture sets oriented N20°E, N150°E, N110°E, and N190°E. Notably, sub-vertical, E–W striking fracture zones promote preferential groundwater flow and isolate sub-vertical block compartments.

The Citadel cliff section extends over 330 m in length, covering a vertical surface area of approximately 29,000 m², with heights ranging from 40 to 80 m. Its spatial orientation and internal compartmentalization are governed by two dominant joint families: N0°–20°E and N110°E. The prominent N110°E structural set, dipping 80° North, is prominently exposed beneath the Place du Marché within the upper Citadel sector (Figure 1). Furthermore, intersecting N20°E fractures crop out near the parapet of the same square (Thoraval et al. 2021).

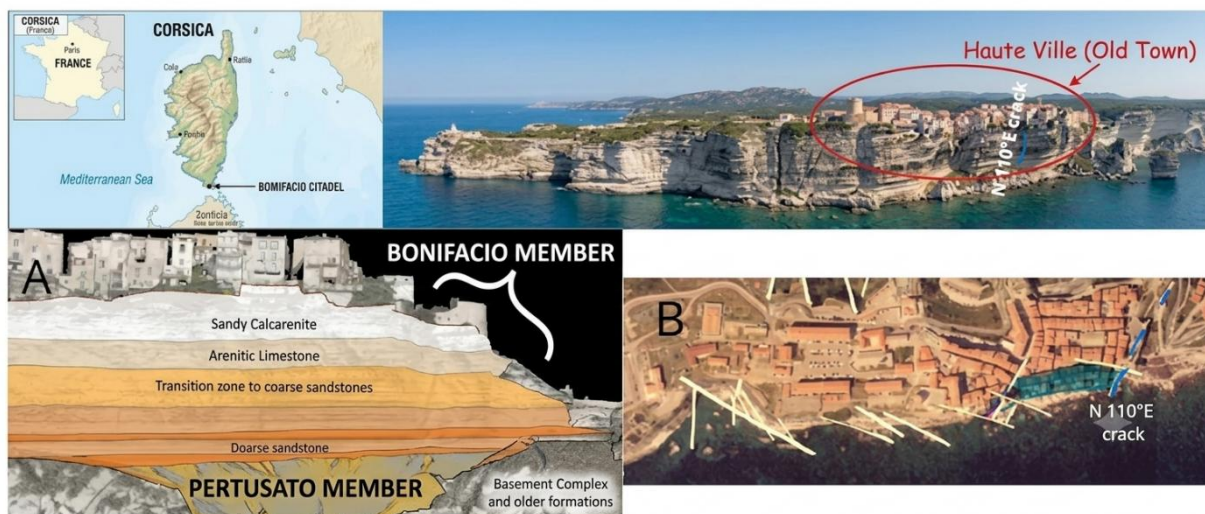


Fig. 1 Location and geological context of the study site at the southern tip of Corsica (France). **A** Geological map of the Citadel cliff area showing the Miocene carbonate succession over the granitic basement. **B** Structural map showing major fault lines and mapped fracture sets across the Citadel sector.

Slope stability analysis performed for the Citadel sector highlights the critical interaction between an extensive ~20 m deep basal overhang, which continuously expands under marine undercut, and the pervasive discontinuity network. The conceptual failure mechanism formulated in technical assessments (Cerema 2013) involves a progressive multi-stage process: (1) forward tilting of the overhanging block, (2) tensile fracture propagation along rear discontinuities, (3) shear sliding along structural planes, and (4) ultimate compressive crushing failure at the toe.

To evaluate the potential for "large-scale collapse", 3D geomechanical numerical models were constructed, incorporating spatial uncertainties regarding joint persistence and aperture. While isolated N110°E discontinuities show current static stability, their intersection with sub-vertical N20°E joints defines critical, unstable rock blocks. Three primary hazard scenarios were identified:

- Scenario 1: A $\sim 3,000 \text{ m}^3$ volume situated near the parapet. The center of gravity of this block extends beyond the pivot line of the basal overhang. Although isolated from direct wave action, failure is deemed probable within a 100-year horizon, representing a high hazard level.
- Scenario 2: A $\sim 12,600 \text{ m}^3$ mass beneath the Market Square. Continuous bounding fractures are not yet visually persistent on the cliff face, representing a moderate/developing hazard.
- Scenario 3: A massive $\sim 53,000 \text{ m}^3$ compartmentalized rock mass, which currently displays geometric stability but represents the maximum structural failure envelope.

Given the high socio-economic value, residential density, and heritage status of the Citadel, understanding the evolution of these risks is paramount. Historical records confirm ongoing cliff activity (Mercerat et al. 2020), with recent rockfalls occurring in November 2019, December 2021, and January 2022 following intense rainfall events. These occurrences emphasize the necessity of high-resolution monitoring to link transient environmental forcing to mechanical degradation (Gunzburger and Merrien-Soukatchoff 2011; Letortu et al. 2022).

3. Materials and Methods

The methodological framework combines multi-temporal Terrestrial Laser Scanning (TLS) surveys with continuous real-time geotechnical multi-parameter monitoring.

3.1. Terrestrial Laser Scanning (TLS) Campaigns and Strategy

Six TLS campaigns were conducted annually between September 2018 and June 2023 to generate high-density 3D point cloud time series, allowing precise quantification of surface change, block detachment, and volumetric coastal retreat relative to the baseline state.

A preliminary field assessment was conducted prior to the baseline survey in September 2018 to establish scan station geometry and instrument parameters. A multi-station setup was mandatory to ensure full 3D coverage of the complex, highly indented topography, thereby minimizing data shadows (occlusions) caused by overhangs and optimizing laser beam incidence angles across the cliff face.

The spatial scope and scan network expanded over time. The baseline campaigns (2018–2019) utilized 11 fixed stations focused specifically on the high-risk Citadel sector and the underlying Sutta Rocca beach (Fig. 2). Following three unpredicted rockfall events between 2019 and 2022 in unmonitored sectors adjacent to the urban core, the network was expanded to 15 stations. Station locations were set at horizontal distances ranging from 5 m to 2,000 m from the cliff face and permanently referenced using brass survey markers sealed into bedrock where accessible.

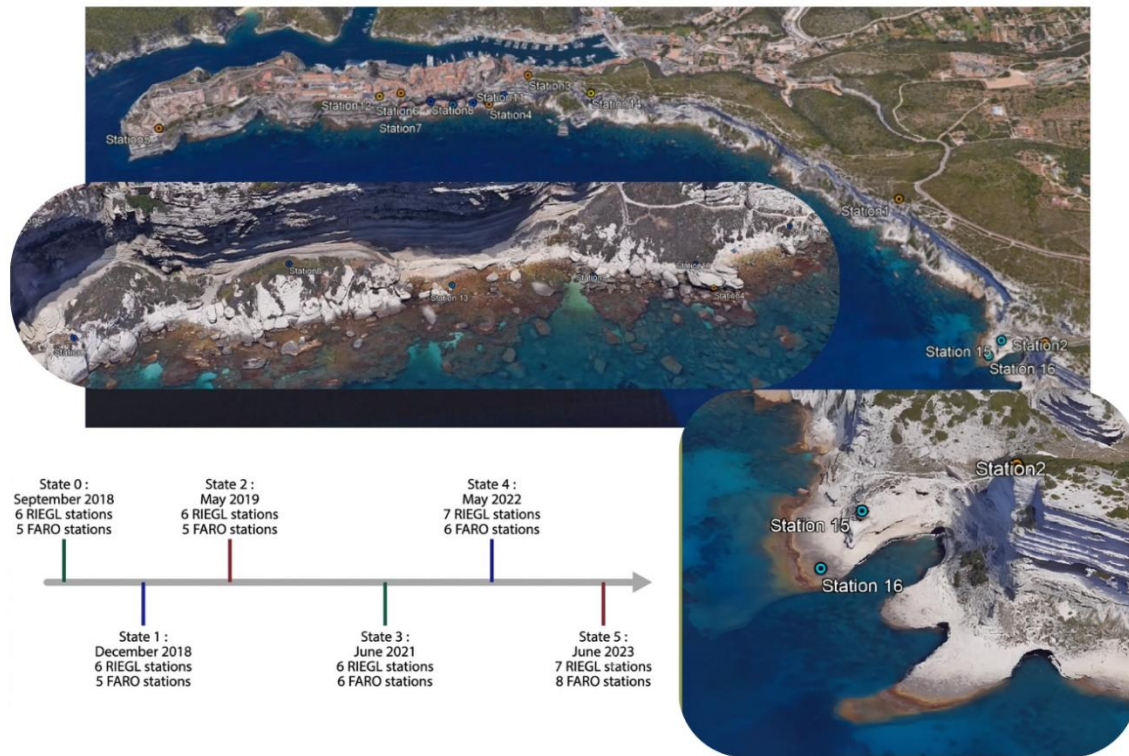


Fig. 2 Spatial distribution of Terrestrial Laser Scanning (TLS) acquisition stations around the Bonifacio Citadel. Blue circles highlight the 8 short-range FARO scanner positions (including Sutta Rocca beach and overhang zones), while distant stations denote long-range RIEGL positions. The survey timeline (2018–2023) is indicated below.

To address the dual requirements of long-range broad-scale coverage and close-range high-detail capture in complex geometries, two complementary TLS instruments were integrated (Hayakawa and Obanawa 2020):

1. Short-Range System (FARO Focus series): Deployed at near-field stations (e.g., Sutta Rocca beach and beneath narrow overhangs). Its wide field of view (360° horizontal, 300° vertical; -60° to +90° vertical aperture) allows line-of-sight acquisition beneath extreme overhangs without visual occlusion (Fig. 3).
2. Long-Range System (RIEGL VZ series, Fig. 3): Deployed at distant stations (up to 2,000 m). Designed for long-range targets (up to 4,000 m at 90% target reflectivity), the instrument operates reliably on Bonifacio's calcarenite (~40% reflectivity) at ranges exceeding 2,000 m. Its 360° horizontal and 60° vertical FOV provides complete vertical coverage of the ~100 m high cliff face from distance (e.g., a 500 m standoff yields a 577 m vertical span).

Acquisition parameters were refined over successive campaigns to optimize target point density, maximize signal-to-noise ratio, and account for atmospheric attenuation across long propagation paths:

- RIEGL Parameter Tuning: Pulse repetition rates (30 kHz, 50 kHz, 150 kHz, 300 kHz) were selected based on station distance (>1,000 m vs. <1,000 m) and atmospheric conditions. For long-distance stations (Stations 1, 2, 3, 5, 14; >1 km), lower pulse rates (30–50 kHz) were chosen to maximize maximum unambiguous range and mitigate atmospheric signal loss. For closer stations (Stations 4, 6, 12; <1 km), higher pulse rates (150–300 kHz) were selected to maximize spatial point density. Angular step sizes were calibrated via fast preliminary scans.
- FARO Parameter Tuning: Operating at a fixed vertical aperture and pulse rate (97 Hz), the FARO system utilized two distinct profiles: *"Outdoor 20 m"* (for high-density close-range scanning of overhang geometries) and *"Outdoor Long-Distance"* (employing noise-filtering algorithms to compensate for

beam divergence at mid-range targets). Quality settings were maintained at 4× hardware averaging per point to reduce range noise.



Fig. 3 : Terrestrial Laser Scanner (TLS) stations used for monitoring the cliff profile: Station 1 and Station 2 set up on the top of the cliff, Station 8 installed at the base of the cliff, and Station 7 positioned on the headland overlooking the study area.

3.2. 3D Point Cloud Processing and Diachronic Comparison

Raw 3D point cloud data underwent a rigorous multi-step processing workflow prior to spatial analysis, consisting of registration, spatial filtering, and diachronic distance computation.

Scans were registered independently for RIEGL and FARO datasets using instrument-proprietary software (RIEGL RISCAN PRO and FARO SCENE) using coarse feature matching followed by fine iterative alignment. The registered RIEGL datasets were exported in *.LAS format to Trimble® RealWorks for unified cloud-to-cloud global recalibration.

Unwanted spatial noise, predominantly sparse vegetation, birds, and marine spray, was removed. Manual filtering was favored over automated algorithms due to sparse vegetation cover, resulting in an average 25%-point reduction. Datasets were then spatially down sampled to optimize computational efficiency while preserving structural features (Table 1).

Table 1 Summary specifications of final, filtered TLS point clouds across the six monitoring campaigns (2018–2023).

Survey	Topographic state	Number of points in the final undersampled cloud	Average density of points per square meter (pts/m ²)	Number of stations
September 2018	0	761 880 040	64	11
December 2018	1	642 483 881	71	11
May 2019	2	866 196 879	64	11
June 2021	3	766 684 516	63	12
May 2022	4	982 883 151	64	13
June 2023	5	649 078 864	71	15

To evaluate surface morphology changes, diachronic distance comparisons were conducted using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague et al. 2013). Mesh-based distance algorithms or 2.5D Digital Elevation Model (DEM) differencing techniques were intentionally avoided; on vertical to overhanging cliff geometries, 2.5D raster projections cause severe projection distortions and fail to capture complex 3D overhang undercut structures (Esposito et al. 2017). The M3C2 algorithm operates directly on raw point clouds, calculating surface-normal distances along local orientation vectors, thereby providing robust, unbiased 3D distance metrics with defined confidence intervals (Limit of Detection, LoD) across the complex cliff surface.

3.3. Continuous Multi-Parameter Monitoring System

To evaluate environmental forcing and unravel the kinematics of fracture propagation within the rock mass, a continuous real-time multi-parameter monitoring array was deployed in April 2019. Covering a 220 m-long critical section of the Citadel cliff, the spatial layout of the network was strictly constrained by urban access, steep topography, and heritage conservation guidelines. All instrumentation streams data in real time to a centralized cloud-based web platform accessible via a secure interface.

The monitoring system comprises nine high-precision sensor units divided into two primary functional categories:

1. Kinematic and Mechanical Response Instrumentation: Designed to capture structural deformation, joint aperture variation, and slope inclination across different spatial scales.
2. Subaerial Environmental Forcing Sensors: Designed to measure meteorological triggers, featuring an automated weather station (monitoring air temperature, barometric pressure, relative humidity, wind speed/direction, and rainfall intensity) alongside thermistors integrated into each geotechnical instrument to track intra-rock thermal variations.

Based on preliminary structural assessments (Cerema 2013), the monitored cliff face was subdivided into two distinct monitoring zones corresponding to specific hazard domains (Fig. 4):

- The “Marché” Zone: Encompasses the high-risk sector directly threatening the Market Square, characterized by high vulnerability to massive failure scenarios.
- The “Torrione” Zone: Covers the adjacent sector categorized as a moderate-to-high hazard area.

The boundary between these two monitoring sectors coincides with the surface trace of the major N110°E sub-vertical fault zone. Given its structural dominance in defining potential unstable blocks, monitoring equipment was concentrated in its immediate vicinity.

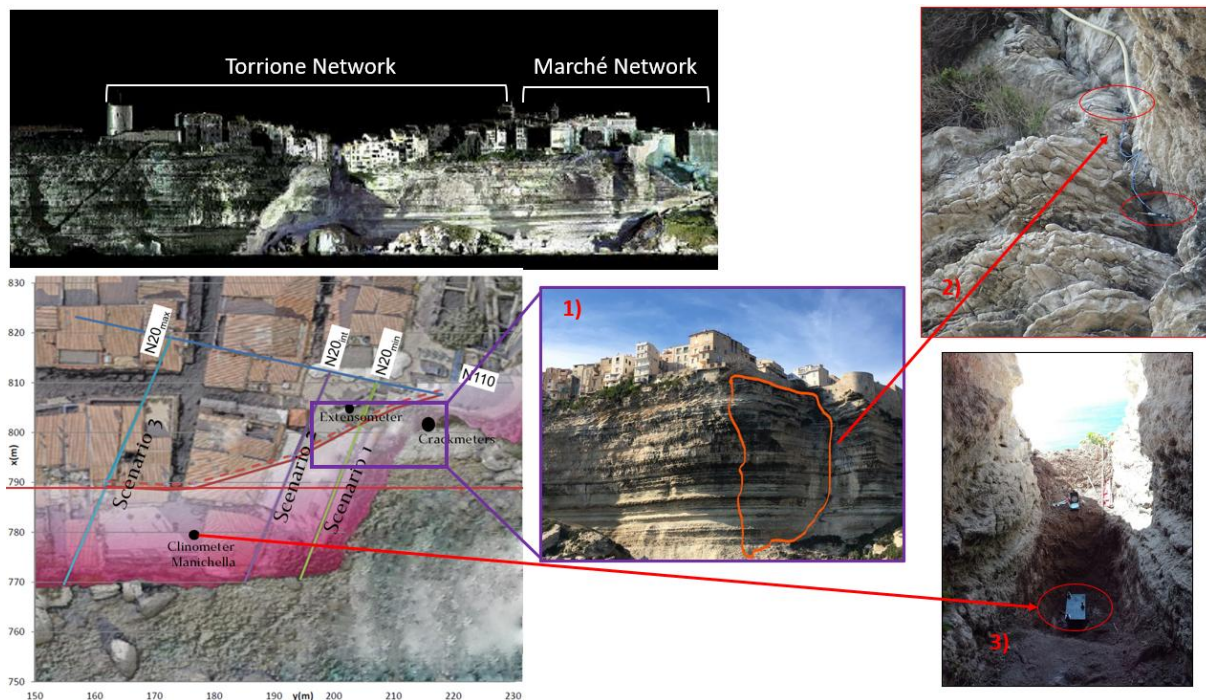


Fig. 4 Layout of the continuous multi-parameter monitoring network deployed across the Citadel cliff. 1) Spatial boundaries of the *Torriane* and *Marché* monitoring networks, indicating the surface traces of major structural fracture sets (N110°E and N20°E) and the spatial footprints of Hazard Scenarios 1, 2, and 3. 2) Photograph of the dual-oriented crackmeters anchored across the N110°E fracture. 3) Close-up view of the *Manichella* high-resolution biaxial clinometer.

Two cored boreholes, inclined at 30° from the vertical, were drilled to intersect the primary structural discontinuities:

- Borehole F1 ("Rue" Station): Drilled to a depth of 40.5 m to directly intersect the N110°E fault plane. The drill core confirmed the presence of the fault at a depth of 10.7 m, displaying a fracture aperture of approximately 5 cm. F1 was instrumented with a 4-anchor multipoint borehole extensometer. Anchor positions were strategically distributed to isolate displacement across the fault plane: anchors C1, C2, and C3 were installed at depths of 6 m, 11 m, and 18 m respectively within sandy calcarenites (straddling the 10.7 m fracture), while anchor C4 was anchored at a depth of 37 m within underlying arkosic sandstones.
- Borehole F2 ("Terrasse" Station): Drilled to a depth of 45.0 m to intercept potential secondary joint sets oriented N20°E and N160°E. Anchors C1, C2, C3, and C4 were set at depths of 5 m, 12 m, 30 m (alternating sandstone/calcarenite), and 44 m (arkosic sandstone), respectively.

All extensometer rods measure relative mechanical displacement between their respective anchor depth and the surface borehole head. Anchors were pre-tensioned to operate within an initial measurement range corresponding to 63–73% of their total stroke capacity. Internal thermistor chains were deployed downhole in both boreholes to record temperature profiles.

To track surface joint dynamics, two high-resolution crackmeters were installed across the surface trace of the N110°E fracture overlooking the Market Square. The sensors are anchored in competent calcarenite layers, vertically spaced by 2 m, and deployed in distinct orthogonal orientations (N60°E and N0°E). This dual-orientation setup isolates three-dimensional block movement and allows instantaneous detection of localized sensor anomalies or site-specific mechanical noise. The crackmeters were zeroed at 20% of their total stroke capacity and shielded beneath protective metallic covers against rockfall impacts. Integrated thermal probes record ambient surface rock temperatures to facilitate thermo-elastic strain correction.

In addition, a high-precision biaxial clinometer (*Manichella* station, Fig. 4) was anchored directly to the rock mass using stainless steel rods in the critical overhanging block identified in Hazard Scenario 1. This instrument records structural tilt variations along two orthogonal horizontal axes (X and Y) at high sampling frequency, complete with internal temperature logging.

3.4. Geotechnical Time-Series Processing and Decomposition

3.4.1. Analytical Framework and Data Preprocessing

Raw continuous geotechnical records constitute complex multivariate time series subject to subaerial environmental forcing, measurement noise, and sensor drift. To distinguish reversible thermo-elastic slope deformations from irreversible plastic precursors, a multi-step time-series analytical framework was established (Box et al. 2015; Ebrahim et al. 2024).

Prior to signal decomposition, automated raw data preprocessing was performed:

- **Handling Missing Data and Irregularities:** Short isolated data gaps were resolved via linear interpolation. Extended acquisition outages were managed by re-indexing the timestamp vector to the nominal hourly frequency (one hour for our dataset) and applying time-aware cubic splines or linear interpolation. All timestamps were recorded in Universal Time Coordinated (UTC) to eliminate artificial daylight-saving offsets.
- **Step-Offset and Jump Correction:** Sudden non-kinematic step jumps resulting from field maintenance, sensor recalibration, or telemetry resets were manually identified and offset-corrected to maintain signal continuity.
- **Outlier Detection:** Spurious measurement spikes were filtered using a rolling window robust Z-score approach based on the Median Absolute Deviation (MAD). Threshold limits were set to 3, corresponding to a 99.7% Gaussian confidence interval calculated over a rolling 30-day window. Identified outliers were removed and interpolated.

3.4.2. Exploratory Data Analysis and Non-Linear Regression

To characterize raw data distributions and evaluate environmental dependencies prior to signal decomposition, exploratory data analysis was conducted:

1. **Descriptive and Bivariate Analysis:** Kernel Density Estimation (KDE) plots and bivariate scatter diagrams were constructed to evaluate raw distributions and establish correlations between external forcing factors (air/rock temperature) and displacement or tilt response.
2. **Linear Correlation:** Pearson's correlation coefficient (r) was computed to quantify proportional linear relationships between thermal cycles and mechanical opening/closing of structural discontinuities.
3. **Generalized Additive Models (GAM):** Non-linear relationships were evaluated using GAMs to capture complex hysteresis loops induced by thermal inertia within the limestone mass (Shumway and Stoffer 2011).

3.4.3. Time-Series Decomposition Protocols

Observed displacement and tilt series $Y(t)$ were decomposed into three additive components:

$$Y(t) = T(t) + S(t) + \epsilon(t)$$

where $T(t)$ represents the secular deterministic trend (irreversible tectonic or gravity-driven deformation), $S(t)$ represents the cyclic seasonal/diurnal thermo-elastic response, and $\epsilon(t)$ represents the stationary residual component (random noise and high-frequency transient anomalies).

Two decomposition techniques were implemented and compared:

- Classical Seasonal Decomposition: Employs moving averages to isolate trend and seasonal patterns over automated windowing periods.
- Seasonal-Trend Decomposition using Loess (STL): Utilizes locally weighted regression (LOESS) in a nested dual-loop structure. The inner loop iteratively updates seasonal and trend components, while the outer loop assigns robustness weights to minimize outlier bias. STL was prioritized for its capability to handle non-linear trend evolutions and non-stationary seasonal amplitudes.

Additionally, polynomial trend fitting was conducted on detrended series to provide analytical expressions for multi-year creep velocity evaluation and operational threshold modeling.

3.4.4. Stationarity Validation of Residuals

To confirm complete isolation of environmental cyclic signals and secular trends, the residual component $\epsilon(t)$ was rigorously evaluated for stationarity.

Non-stationary raw time series exhibit strong long-range dependence, as demonstrated by the uncorrected autocorrelation function (ACF) of anchor C1 ("Rue" extensometer), which persists across multi-year lags (Figure 5). In contrast, a fully decomposed stationary residual displays rapid ACF decay toward zero within minimal time lags, confirming the removal of deterministic memory.

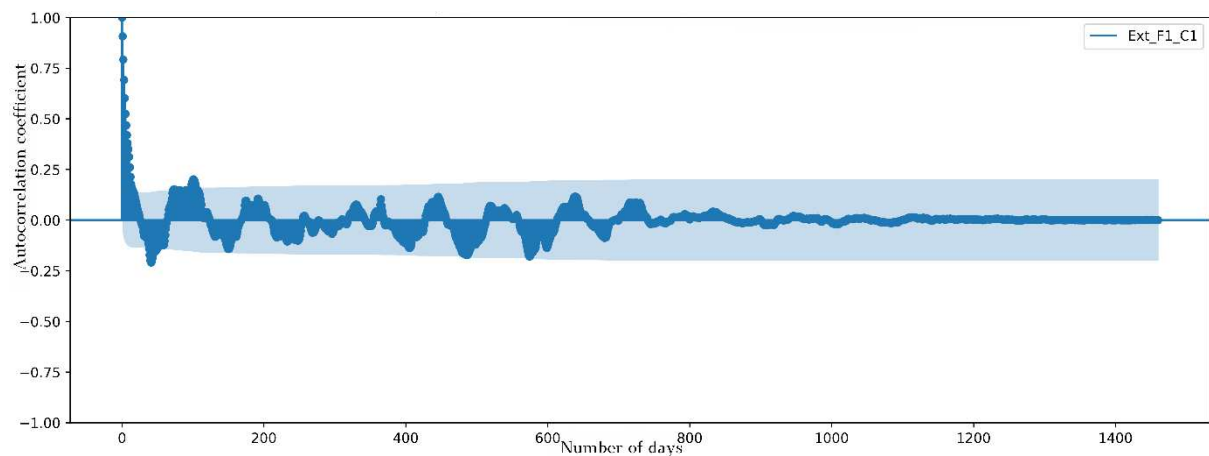


Fig. 5 Autocorrelation function (ACF) correlogram for the residual stationary component of the "Rue" extensometer anchor C1 (Borehole F1) over a 4-year monitoring period (2019–2023). Dashed lines represent the 95% confidence bounds.

Rolling statistical metrics (6-month moving average and rolling standard deviation) were computed to verify variance homogeneity over time (Fig. 6). Anchors C1, C2, and C3 demonstrate tight stationarity around zero, whereas anchor C4 exhibits higher residual dispersion, reflecting increased sensitivity to deep thermo-mechanical strain.

Stationarity was formally confirmed by applying complementary unit-root hypothesis tests:

1. Augmented Dickey–Fuller (ADF) Test: Evaluates the null hypothesis (H_0) of non-stationarity (presence of a unit root). Rejection of H_0 (p -value < 0.05) confirms stationarity.
2. Kwiatkowski–Phillips–Schmidt–Shin (KPSS) Test: Evaluates the null hypothesis (H_0) of stationarity. Non-rejection of H_0 ($p > 0.05$) confirms stationarity.

The simultaneous rejection of the ADF null hypothesis and acceptance of the KPSS null hypothesis systematically validated the stationarity of all processed residual time series across the Citadel dataset.

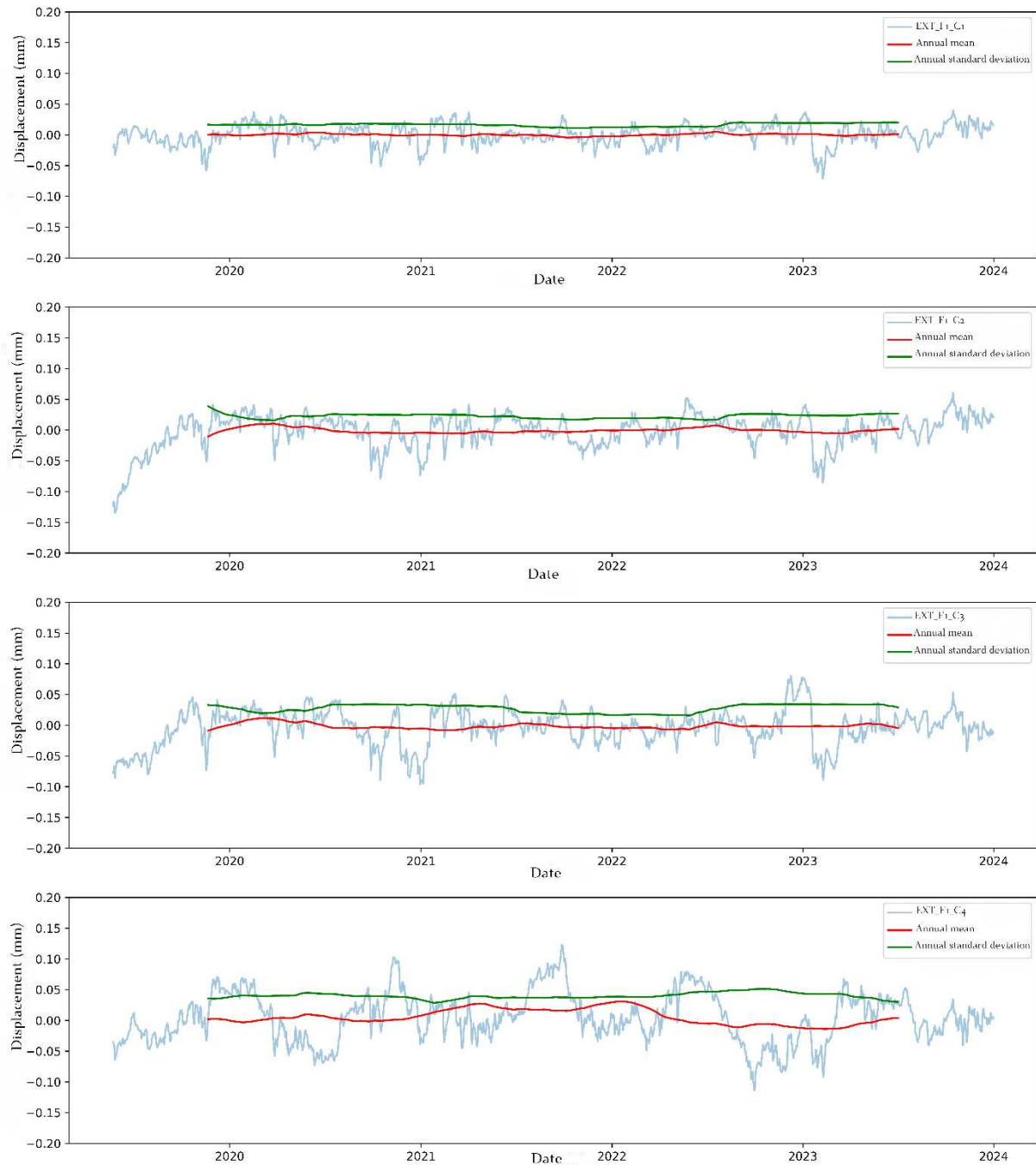


Fig. 6 Semi-annual rolling statistics (6-month moving mean and standard deviation) calculated for the decomposed stationary residual component across the four anchors (C1 to C4) of the "Rue" multipoint borehole extensometer (Borehole F1).

4. Results

The results integrate long-term spatial deformation analysis derived from multi-temporal TLS point cloud comparisons with continuous, high-frequency temporal time-series (TS) processing of in-situ geotechnical sensors. The former provides spatial distribution and structural evidence of cliff morphology evolution, whereas the latter resolves thermo-mechanical strain mechanisms at localized structural interfaces.

4.1. Spatial Deformation Analysis via Diachronic TLS Comparisons

The initial survey acquired in September 2018 (T0) serves as the topographic baseline for multi-temporal change detection across the Citadel cliff face directly beneath the Market Square. In addition to change detection, this high-density baseline dataset provided the 3D surface mesh for geomechanical numerical modeling aimed at evaluating large-scale collapse hazard scenarios (Thoraval et al. 2026).

Cloud-to-cloud distance comparisons between the baseline (T0) and subsequent surveys (T1 to T5, 2018–2023) revealed no significant, widespread structural displacement across the main cliff face. Fig. 7 shows the diachronic comparison between September 2018 (T0) and June 2023 (T5), displaying surface-normal distance deviations bounded between 0.0 m (blue spectrum) and a maximum localized deviation of 0.50 m (red spectrum).

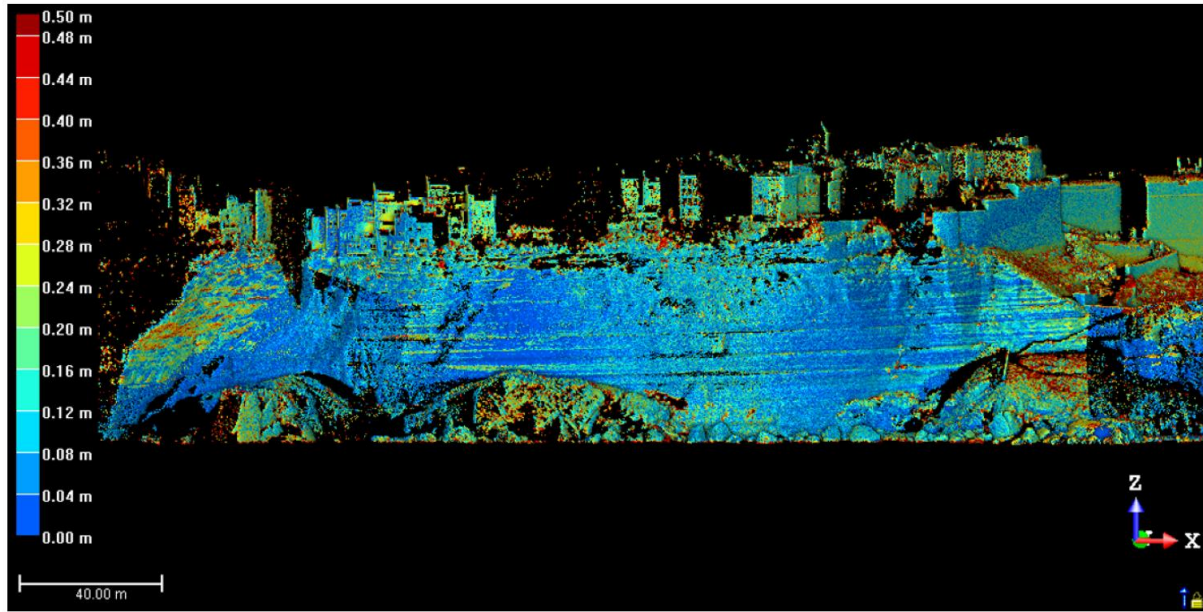


Fig. 7 Diachronic distance map between baseline state T0 (September 2018) and survey state T5 (June 2023) computed over the Citadel cliff section. Color ramp denotes surface-normal deviations ranging from 0.00 m (blue) to +0.50 m (red).

Detailed spatial inspection indicates that deviations exceeding 0.10 m do not represent structural mass movements of the limestone cliff, but stem from non-geological factors:

1. Vegetational variations: Seasonal growth and periodic trimming of sparse cliff vegetation.
2. Coastal dynamics: Sub-meter mobility of the basal sandy foreshore and intertidal block redistribution driven by wave run-up, micro-tides (~40 cm range), and localized marine currents.
3. Edge artifacts: Minor point cloud noise near the spatial boundaries where point density decays.

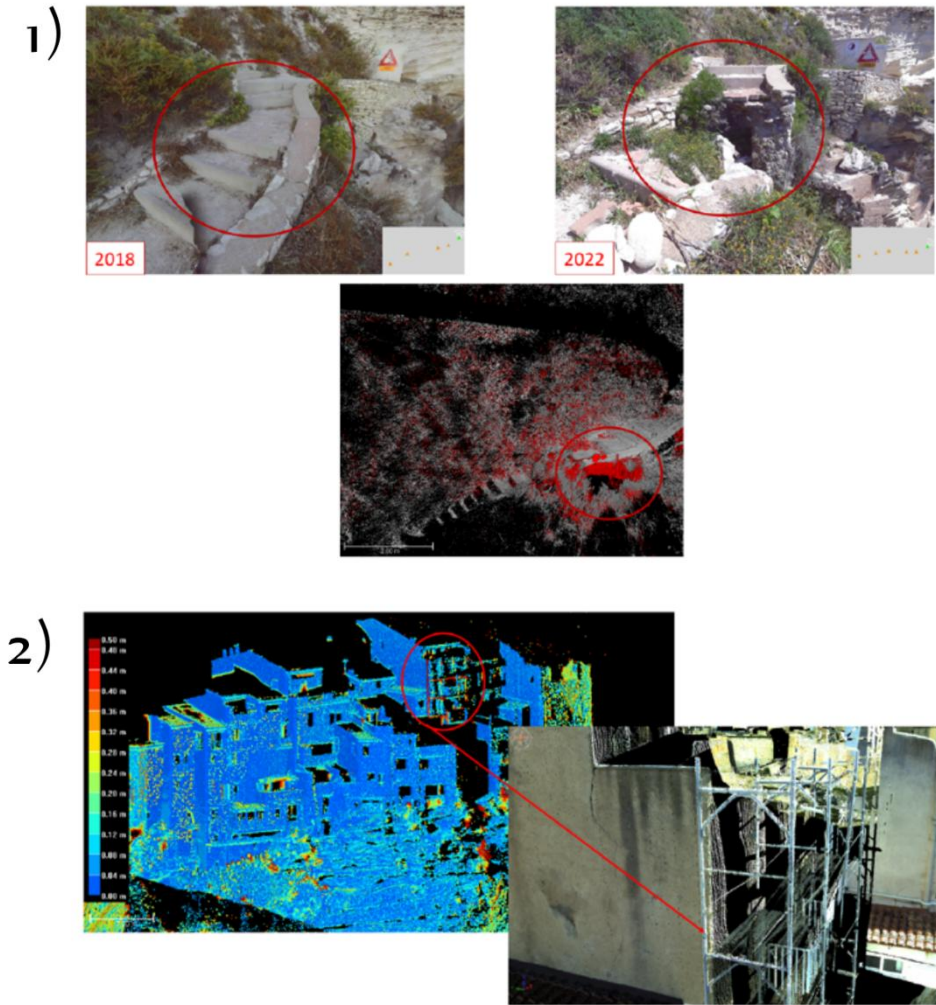


Fig. 8 High-resolution site photographic verification of transient spatial anomalies identified in TLS diachronic comparisons: 1) Structural collapse of the pedestrian access staircase at the cliff toe and localized sandbank erosion; 2) Temporary erection of metallic construction scaffolding on the cliff upper perimeter.

As illustrated in Fig. 8, contextual site photography confirmed that localized surface changes correspond to specific anthropogenic or transient geomorphic events, such as the localized collapse of a concrete beach access staircase, surface beach sand deflation exposing underlying bedrock, or the presence of temporary construction scaffolding. Furthermore, minor station placement shifts across campaigns; necessitated by tide and wave access constraints at the cliff base, introduced localized alignment noise in obstructed overhang zones.

The spatial measurement precision within the primary zone of interest (directly beneath the Market Square) is estimated at the centimetric level, multi-centimetric in adjacent zones, and decimetric at extreme long-range boundaries (>1 km standoff).

For the 2023 campaign (T5), direct georeferencing within the RGF93 / CC42 national coordinate system was applied to the RIEGL point clouds, allowing direct spatial alignment of the FARO scans without intermediate cloud-to-cloud registration steps. Eliminating secondary cloud registration reduced cumulative transformation errors. Direct GNSS-based georeferencing uncertainties are bounded between 5 and 10 cm. Consequently, the minimum Level of Detection (LoD) for structural cliff displacement between 2018 and 2023 is established at 5-10 cm (Fig. 9). Any spatial deviation below this threshold falls within instrumental and environmental noise.

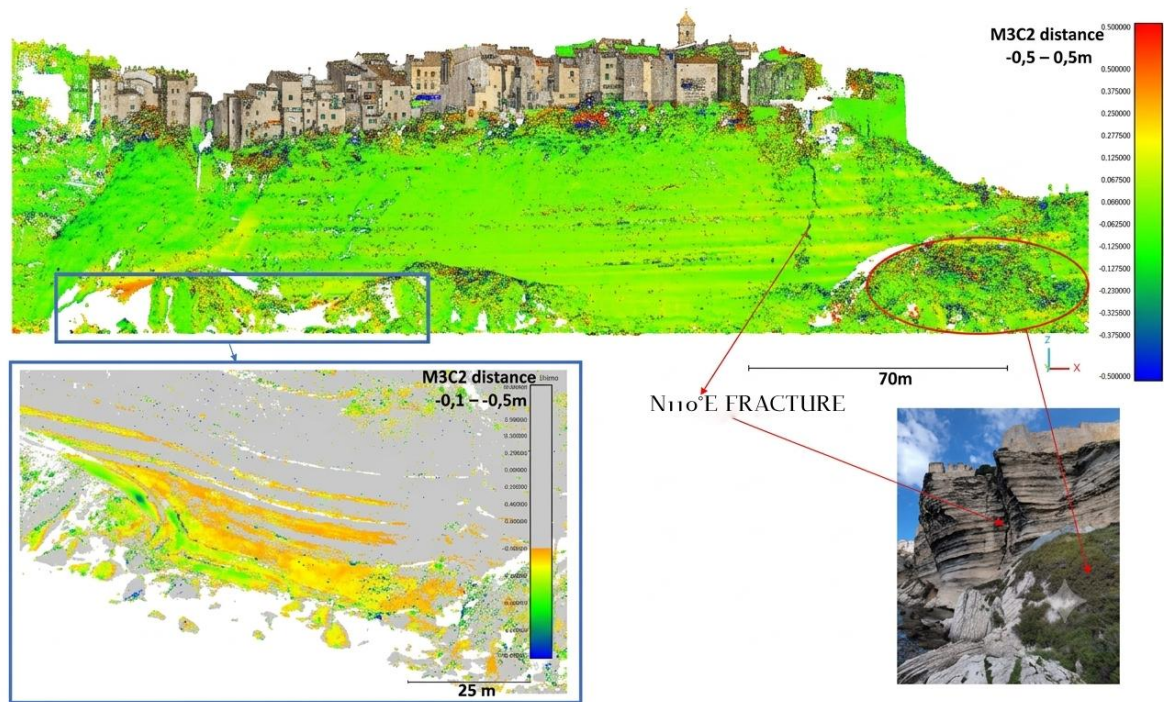


Fig. 9 M3C2 3D diachronic distance map between 2018 (T0) and 2023 (T5) point clouds calculated in CloudCompare. Insets show detailed close-ups of the primary N110°E fracture trace and basal wave-cut notch zone. Red oval denotes vegetation cover change; blue rectangle highlights localized basal spalling in friable calcarenite.

Cross-validation of 3D point cloud comparisons using the Multiscale Model-to-Model Cloud Comparison (M3C2) algorithm in CloudCompare (Lague et al. 2013) confirmed these findings (Fig. 9). M3C2 distance metrics calculated along local surface normals revealed no statistically significant mass movements along the main structural joints, including the critical N110°E fault zone. Isolating points within the distance window of -10 cm to -50 cm (blue rectangle in Figure 8) highlights minor, highly localized surface spalling at the cliff toe where weak calcarenite facies are exposed to wave impact and wind deflation.

In summary, diachronic TLS analyses spanning 2018–2023 demonstrate that no spatial deformation exceeded the defined (LoD) at 5–10 cm. The Bonifacio Citadel cliff remained structurally stable over the 5-year study period, with no detectable precursor displacement along major bounding discontinuities.

4.2. Exploratory Analysis of Continuous Time Series

To complement the spatial TLS observations, high-frequency continuous geotechnical monitoring was analyzed to evaluate micro-scale kinematics and thermo-mechanical drivers.

Exploratory processing is detailed using records from the 40.5 m deep "Rue" borehole extensometer (Borehole F1), which intersects the major N110°E fault at 10.7 m depth (Fig.10). Anchors C1 (6 m) and C2 (11 m) monitor shallow sandy calcarenites; anchor C3 (18 m) monitors intermediate calcarenites; and anchor C4 (37 m) is set in deep arkosic sandstones near the cliff face toe. Borehole temperature logging commenced in December 2019.

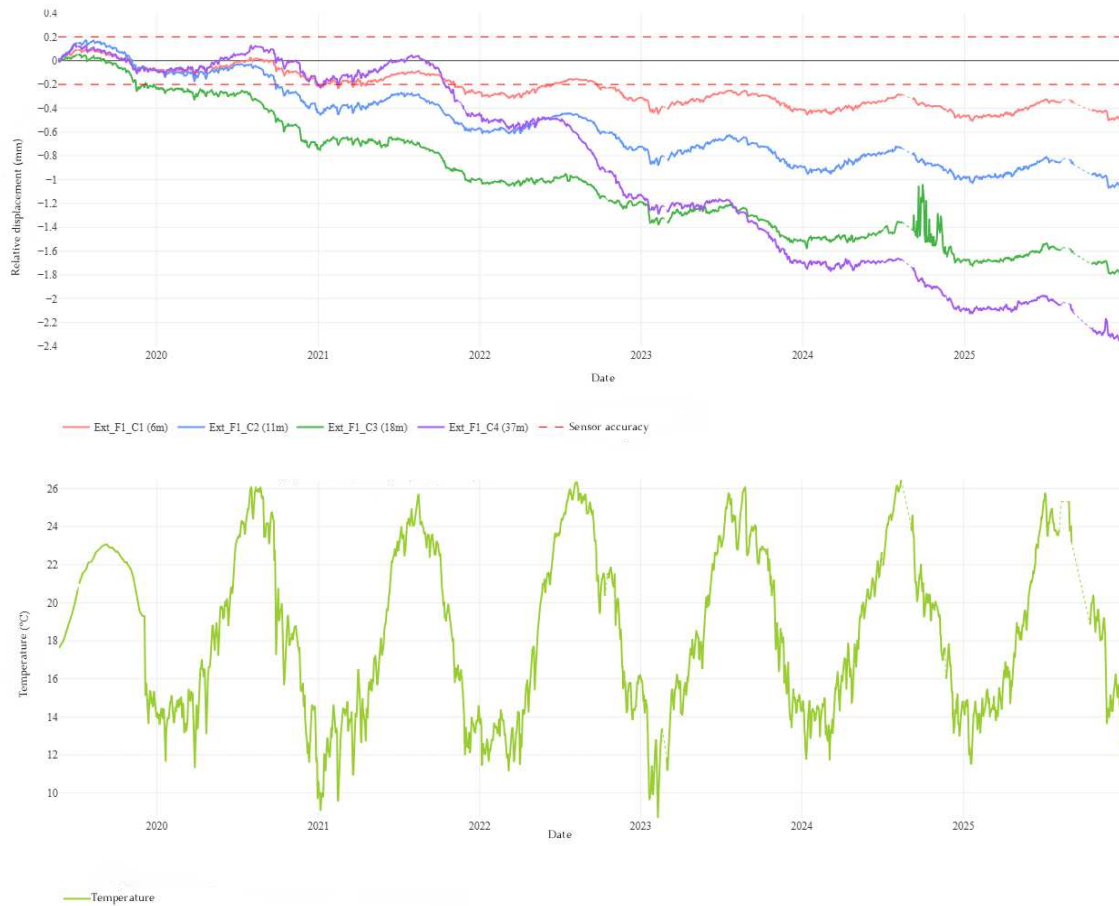


Fig. 10 Raw continuous time series recorded by the "Rue" multipoint borehole extensometer (F1 station) anchors C1 to C4, expressing displacement relative to borehole head) alongside downhole rock temperature records from late 2019 to 2023.

Descriptive analysis reveals pronounced annual cyclical oscillations synchronized with thermal variations. Peak relative shortening coincides with maximum summer temperatures. During late 2019, measurement gaps occurred and displacement trends displayed irregular settling behavior (Fig. 11); these initial months correspond to grout curing and mechanical anchor stabilization and were excluded from kinematic modeling.

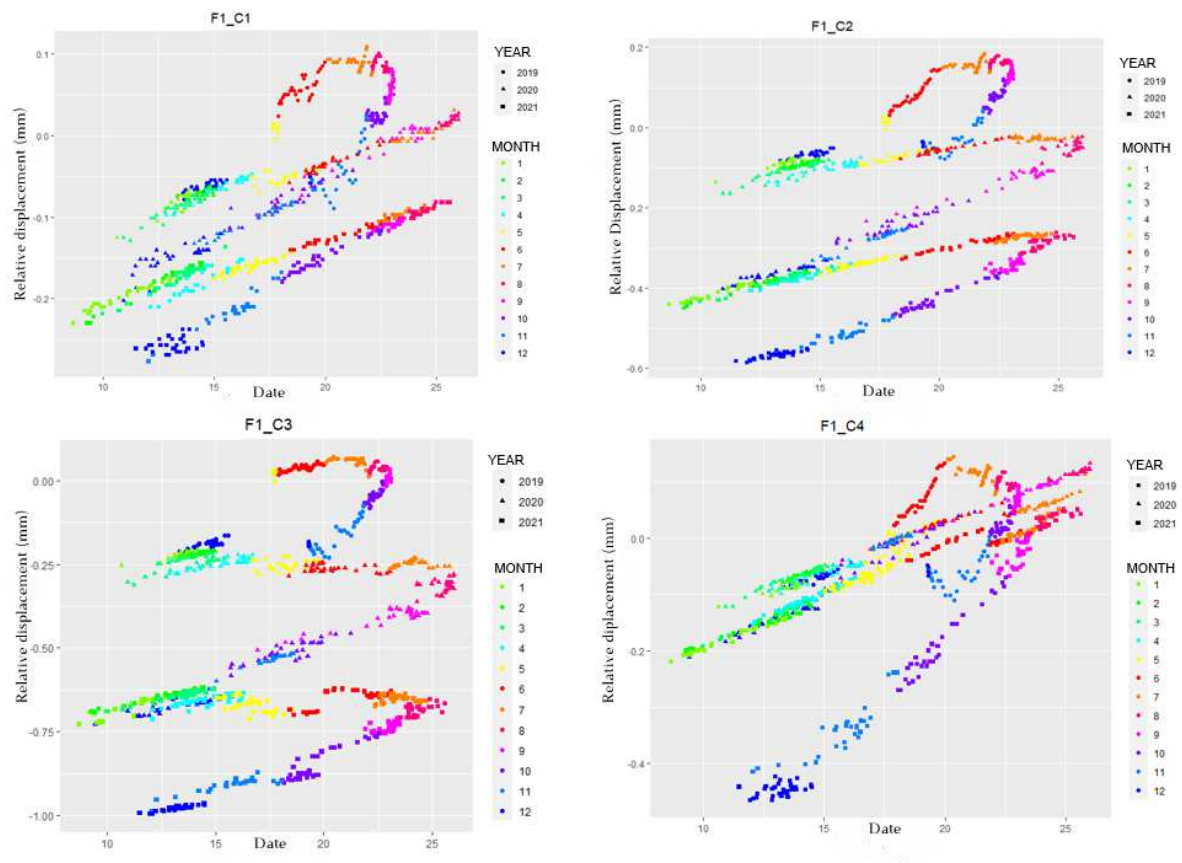


Fig. 11 Bivariate relationship between relative anchor displacement and downhole rock temperature across anchors C1–C4 of the "Rue" extensometer (F1 station).

From 2020 onward, the rock mass exhibits a highly repeatable, temperature-driven cyclic response. Anchors C1, C2, and C3 display sub-millimetric cyclic shortening during seasonal warming (January to July) and extension during cooling (August to December). In contrast, anchor C4 (37 m depth) exhibits distinct kinematic behavior: rather than following the monotonic amplitude-depth progression seen in C1–C3, C4 records higher oscillation amplitudes, attributable to its physical proximity to the exposed lower cliff face where diurnal and seasonal thermal gradients penetrate deeper into the rock.

Bivariate decomposition allows separation of:

- Reversible thermo-elastic strain: Cyclic annual thermal expansion/contraction (e.g., approximately ± 0.15 mm per year for anchor C1).
- Irreversible creep deformation: Cumulative multi-year displacement trends (+0.25 mm in 2020; +0.15 mm in 2021 for anchor C1), reflecting micro-plastic slip along intersected joint planes rather than matrix strain.

Linear correlation analysis (Figure 12) indicates strong linear dependence between adjacent shallow anchors ($r = 0.958$ between C1 and C2). However, linear regression models systematically fail to capture the non-linear curvature caused by thermal hysteresis and seasonal phase shifts across all anchors.

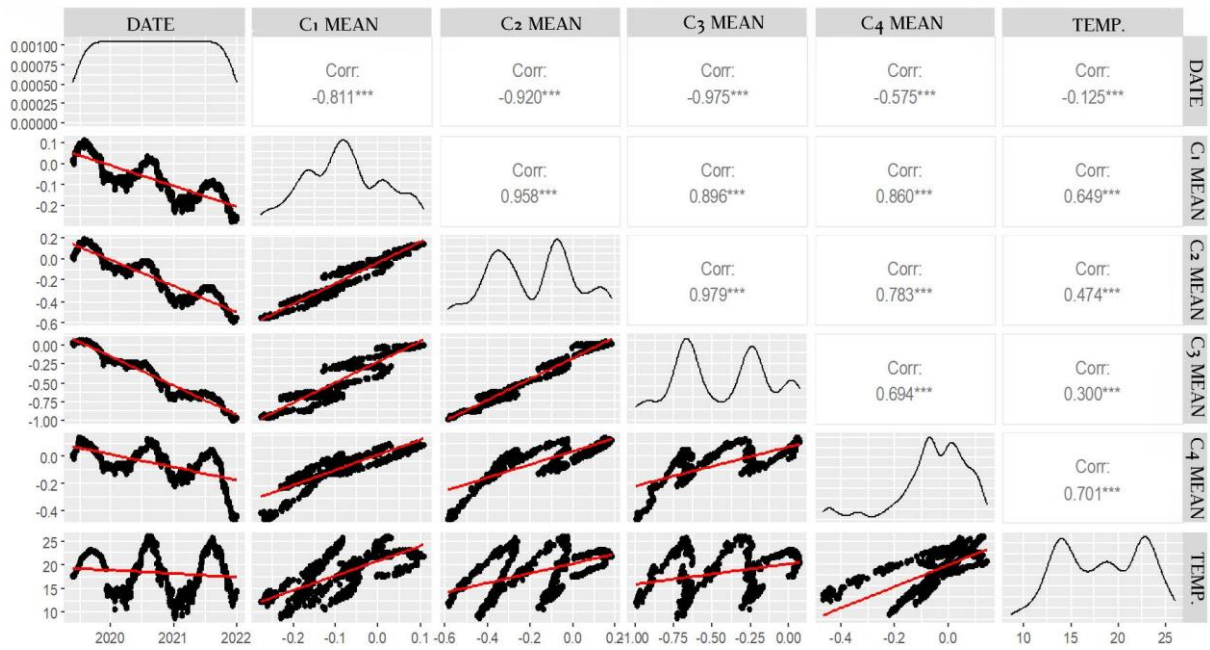


Fig. 12 Linear correlation matrix and Pearson correlation coefficients (r) between time (date), temperature, and relative anchor displacements for the "Rue" extensometer. Red lines denote simple linear regression fits.

To capture non-linear patterns, Generalized Additive Models (GAM) were applied (Fig. 13). Comparative GAM fitting demonstrates that the temporal predictor variable ("date") provides a superior explanation of total variance compared to temperature alone. Correlation coefficients for time-based GAM fits reach $r = 0.811$ (C1), $r = 0.920$ (C2), $r = 0.975$ (C3), and $r = 0.575$ (C4), whereas temperature-based GAM fits yield lower correlation values (0.649 for C1, 0.474 for C2, 0.300 for C3, and 0.701 for C4).

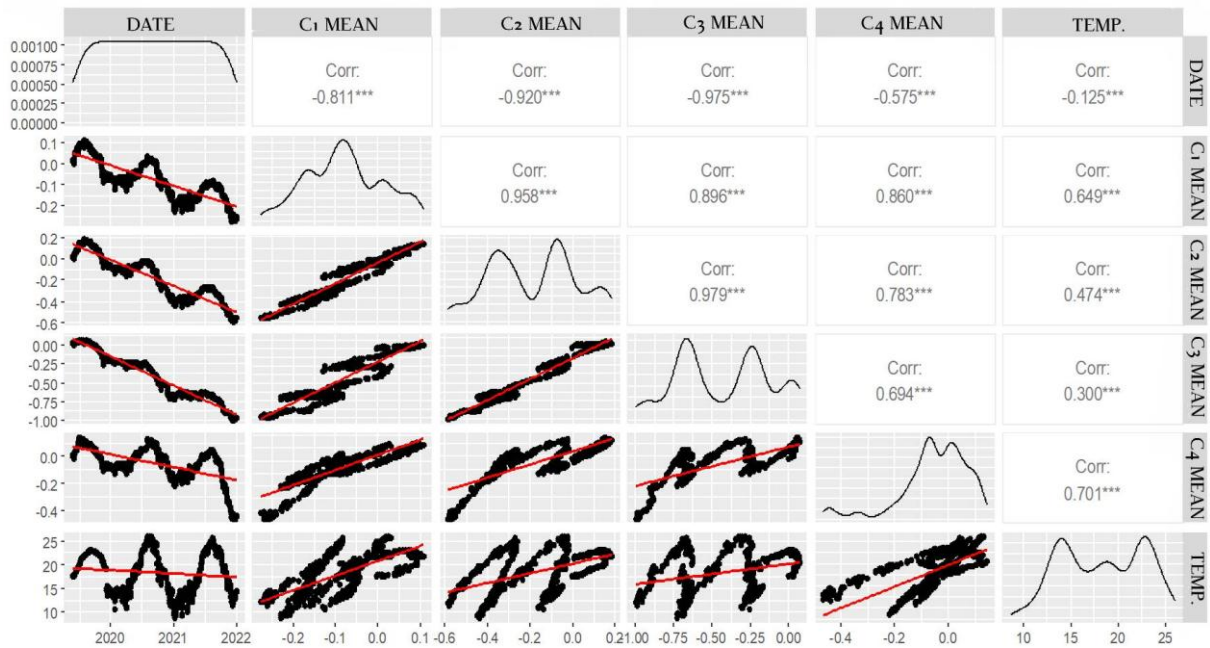


Fig. 13 Non-linear Generalized Additive Model (GAM) regression matrices for the "Rue" extensometer dataset. Red curves represent smooth non-linear GAM fits.

Identical exploratory protocols applied to the Market Square crackmeters (Fig. 14) and the *Manichella* biaxial clinometer (Fig. 15) confirm coupled thermo-mechanical dynamics:

- Crackmeters: The N110°E surface joint exhibits a persistent long-term opening trend (~ 0.20 mm cumulative irreversible widening over 4 years) superimposed on reversible annual thermal cycles approximately ± 0.05 mm). Joint opening accelerates during abrupt winter temperature drops due to thermal contraction of the bounding rock blocks.
- Clinometer: Following initial post-installation settling (December 2019 – June 2020), the Y-axis (WSW–ENE orientation) stabilized, while the X-axis (SSE orientation, facing the free cliff face) displays strong seasonal tilt oscillations driven by differential thermal expansion of the outer rock skin.

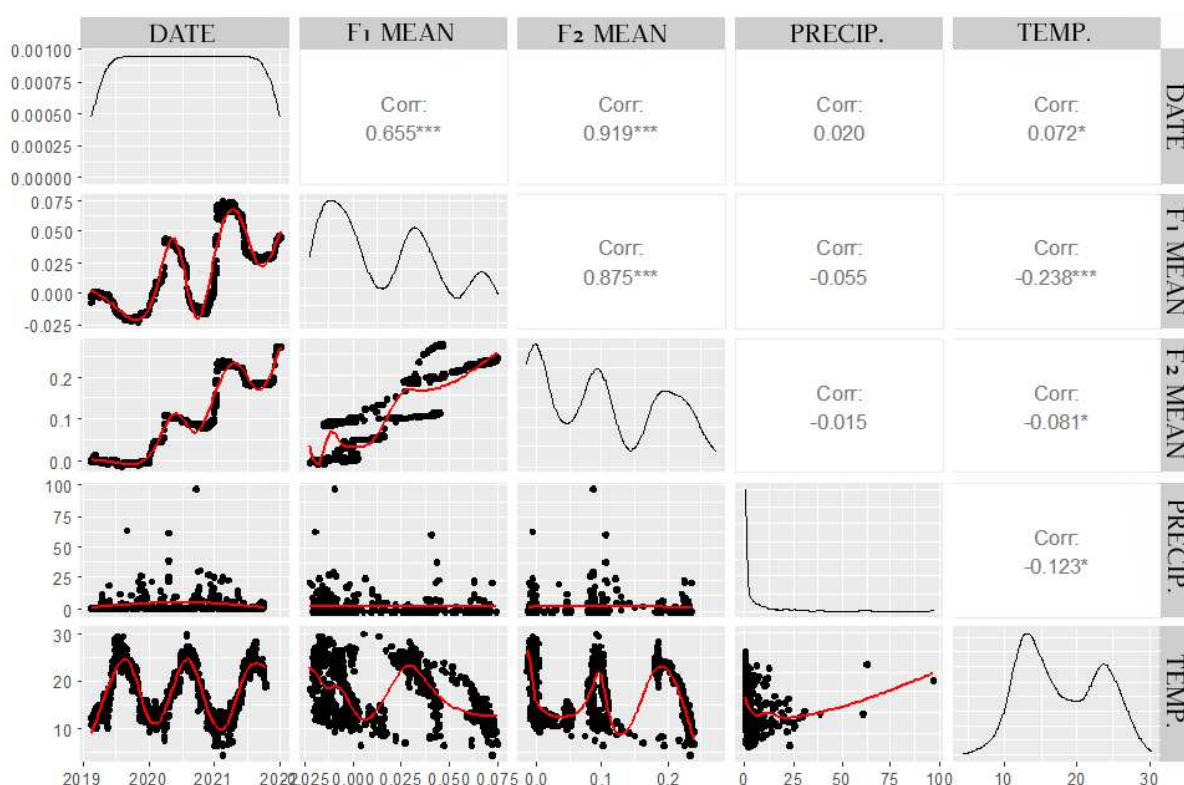


Fig. 14 Non-linear GAM regression matrix for the Market Square crackmeters showing relationships between joint opening, temperature, precipitation, and time.

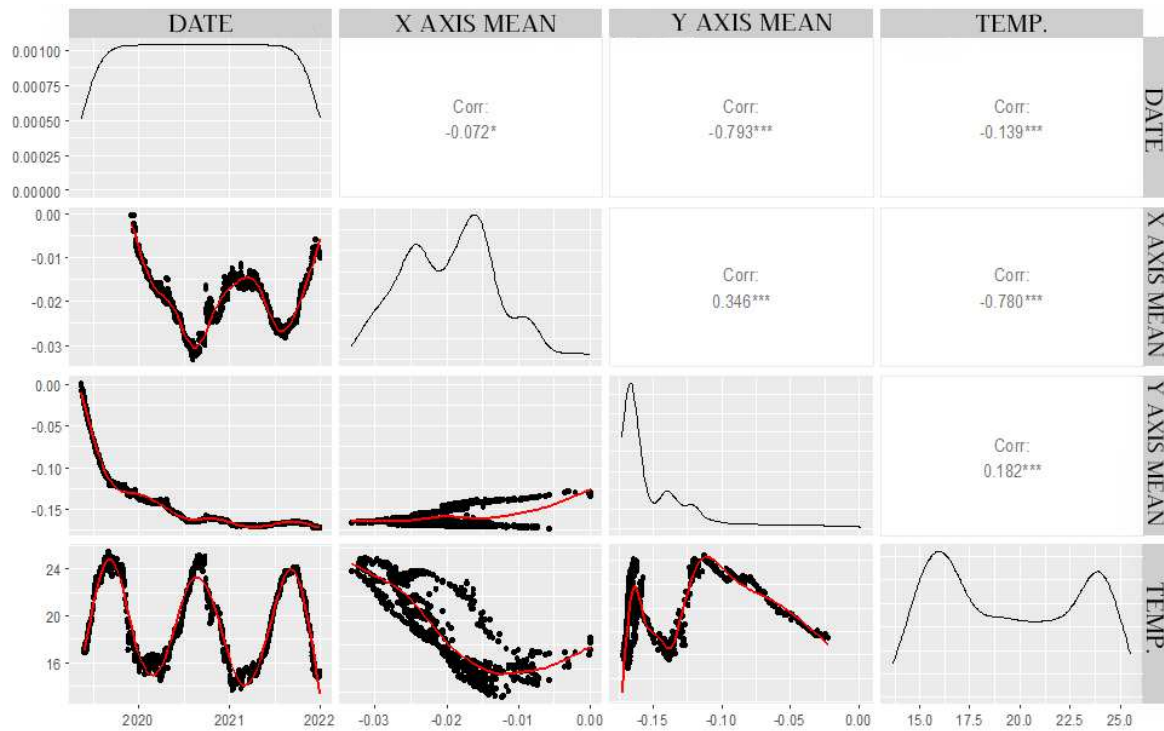


Fig. 15 Non-linear GAM regression matrix for the *Manichella* biaxial clinometer showing tilt response along X and Y axes against thermal and temporal predictors.

4.3. Time-Series Decomposition and Residual Analysis

4.3.1. Extensometer Signal Decomposition

Trend extraction via moving averages was performed on offset-corrected raw extensometer series (Fig 16).

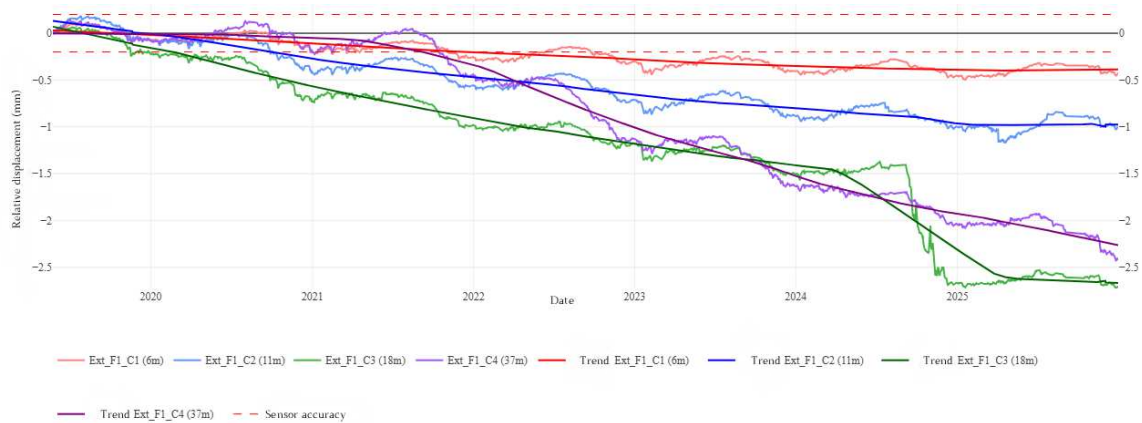


Fig. 16 Raw relative displacement time series and extracted deterministic trend curves $T(t)$ for anchors C1–C4 of the "Rue" extensometer (Borehole F1).

Subtracting the secular trend $T(t)$ yields detrended series dominated by seasonal thermo-elastic cycles $S(t)$ (Fig. 17). For anchors C1, C2, and C3, seasonal amplitudes remain close to the sensor accuracy threshold, whereas C4 exhibits larger thermal oscillations due to its proximity to the cliff face.

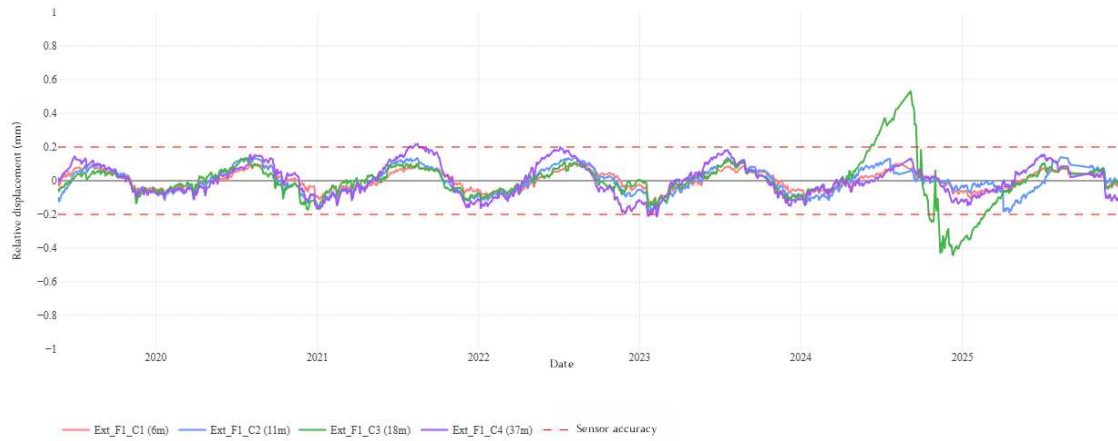


Fig. 17 Detrended time series $Y(t) - T(t)$ highlighting seasonal thermo-elastic components $S(t)$ for the "Rue" extensometer (F1 station) anchors relative to sensor measurement accuracy bounds (dashed red lines).

Isolating the stationary residual component by removing both trend and seasonal signals yields low-amplitude random noise centered around zero (Fig. 18).

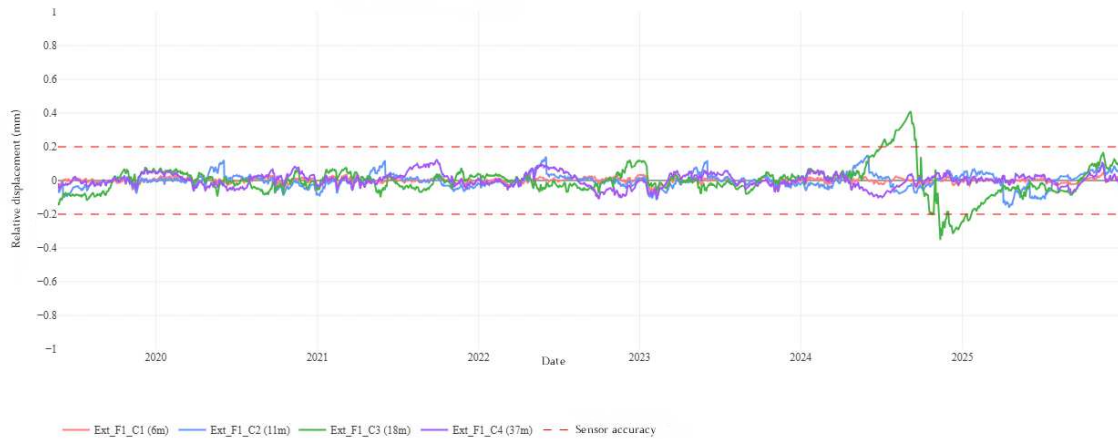


Fig. 18 Final stationary residual component for the "Rue" extensometer anchors across the 4-year monitoring period.

Calculating differential displacement between adjacent anchors (e.g., $C2 - C1$, $C3 - C1$, $C4 - C1$) confirms the absence of localized shearing or differential joint displacement within the rock mass (Fig. 19). Minor residual fluctuations correlate with transient extreme weather events recorded at Cap Pertusato station (Fig. 20), such as intense rainstorm infiltration or heatwave events.



Fig. 19 Relative inter-anchor differential displacement derived from stationary residual components for the "Rue" extensometer (Borehole F1).

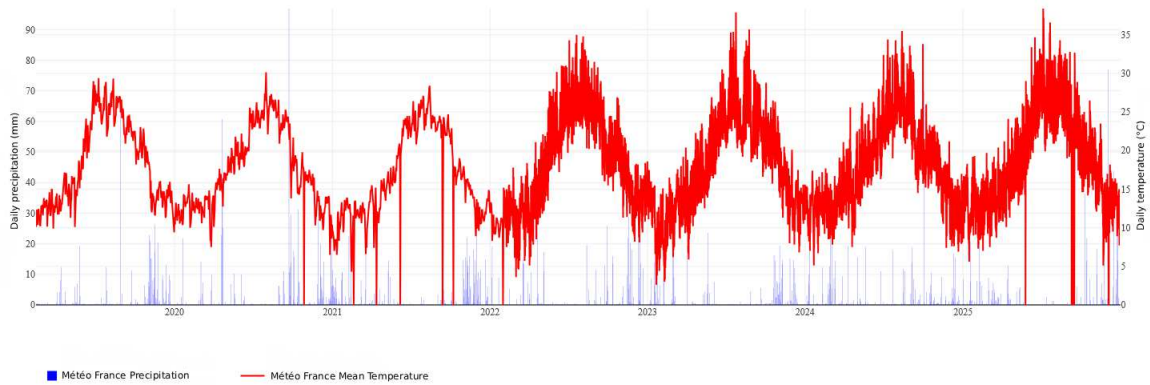


Fig. 20 Daily mean air temperature and cumulative precipitation records from Météo-France Cap Pertusato meteorological station over the monitoring duration.

4.3.2. Crackmeter Signal Decomposition

Polynomial trend fitting ($n = 2$) applied to crackmeter records confirms a slight long-term linear widening of the N110°E fracture (Fig. 21).

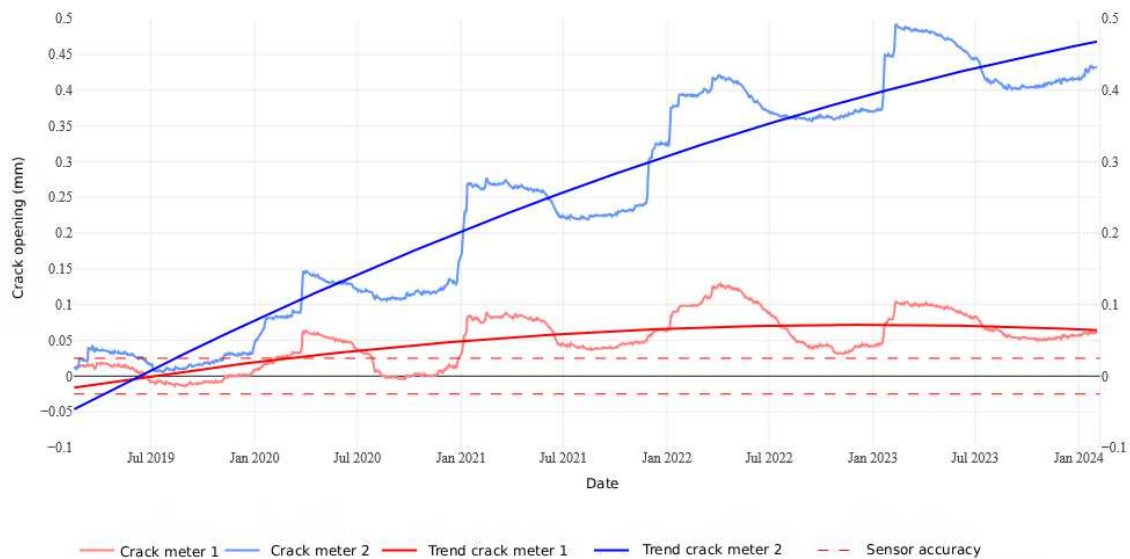


Fig. 21 Raw continuous displacement records from the dual Market Square crackmeters and fitted 2nd-degree polynomial trend curves.

Detrended crackmeter series (Fig. 22) exceed the nominal sensor precision limits, confirming that surface joint apertures are strongly governed by surface temperature fluctuations. Crackmeter 2 (installed perpendicular to the joint plane) records higher seasonal strain than Crackmeter 1 (installed at an oblique angle). The residual stationary series (Fig. 23) demonstrates that residual non-thermal fluctuations remain within instrumental background noise, confirming static fracture stability.

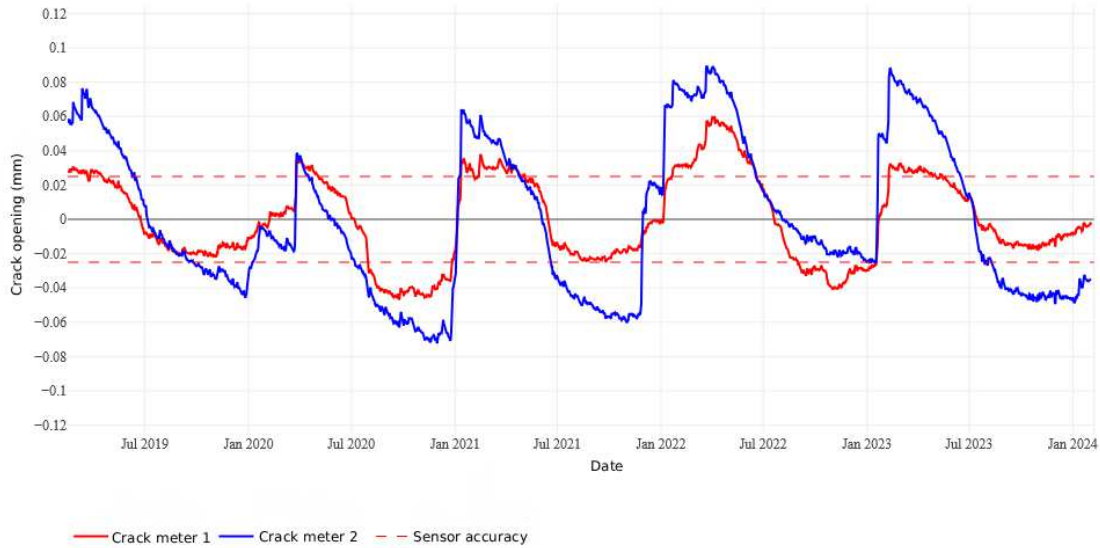


Fig. 22 Detrended crackmeter time series showing seasonal thermal expansion/contraction cycles relative to sensor accuracy bounds (dashed red lines).



Fig. 23 Isolated stationary residual components $\epsilon(t)$ for Crackmeter 1 and Crackmeter 2.

4.3.3. Clinometer Signal Decomposition and Polar Vector Tracking

Polynomial trend extraction ($n = 2$ for X-axis; $n = 3$ for Y-axis) was conducted on the *Manichella* clinometer time series (Fig. 24).

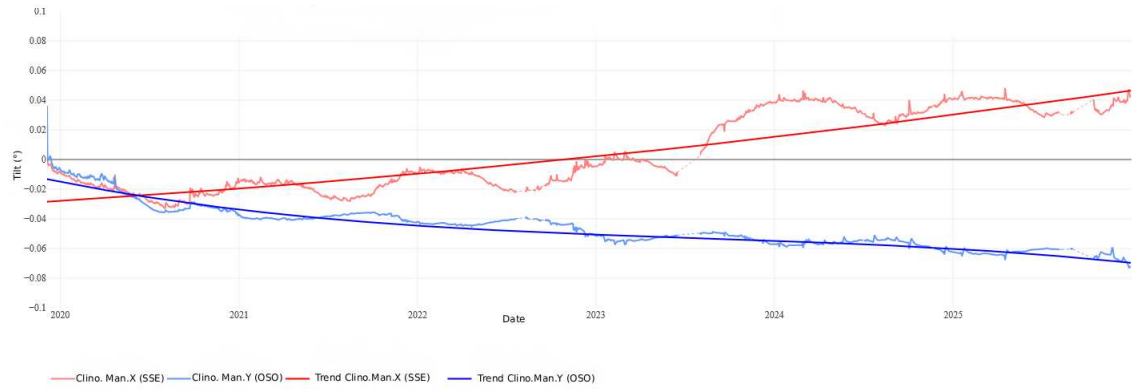


Fig. 24 Raw relative tilt records for X and Y horizontal axes of the *Manichella* clinometer with fitted polynomial trend lines.

Detrended tilt series (Fig. 25) reflect cyclic rotational tilting of the overhanging block toward the sea during warm periods. The stationary residual series (Fig. 26) remains stable near zero, except for a documented electronic telemetry interruption in July 2023.

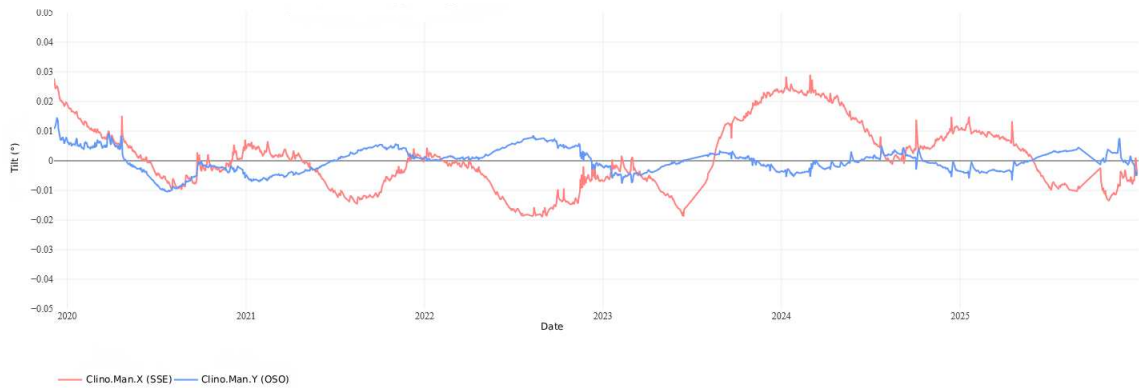


Fig. 25 Detrended biaxial tilt time series highlighting seasonal rotational oscillations.

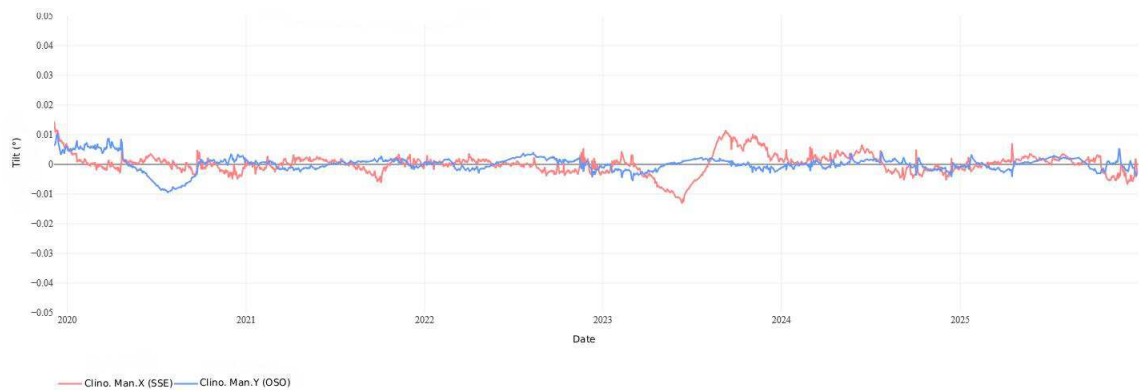


Fig. 26 Isolated stationary residual components for X and Y clinometer channels. Note the transient step in July 2023 associated with telemetry power loss.

Polar vector trajectories (Fig. 27) illustrate the directional stability of the overhanging block. The raw resultant vector (red curve) displays a slight, continuous migration toward the south-southeast (SSE), directly aligned with the unconfined cliff face of Scenario 1. Conversely, the stationary residual vector (blue curve) collapses into a tightly bounded cluster around the origin, demonstrating that short-term rotational fluctuations do not represent irreversible tilt instabilities.

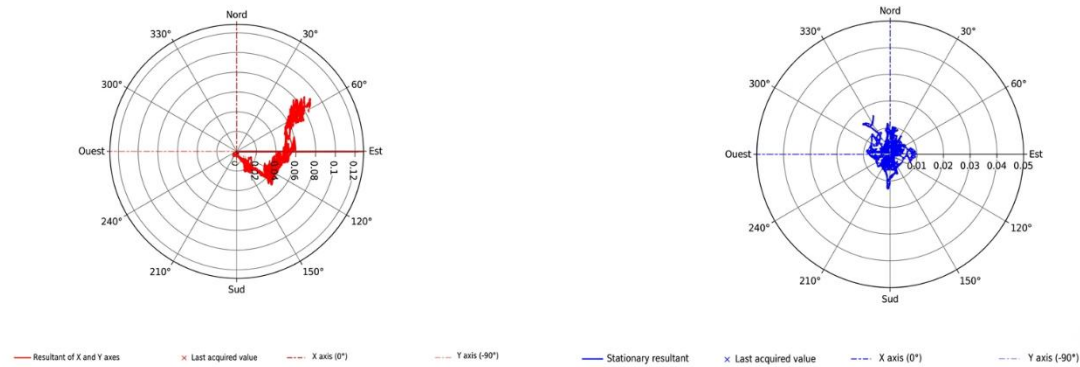


Fig. 27 Polar vector plot of resultant horizontal tilt direction relative to geographic North in upper-hemisphere projection. Red vector path denotes raw cumulative measurements; blue vector path denotes the isolated stationary component.

5. Discussion

5.1. Multi-Scale Strategy and Geomorphological Surveying Constraints

The results of this study demonstrate the operational value of coupling large-scale spatial remote sensing with continuous, high-frequency in-situ geotechnical monitoring to characterize the complex thermo-mechanical behavior of coastal heritage cliffs. The initial 2018 large-scale 3D LiDAR acquisition established a high-resolution topographic baseline of the Bonifacio Citadel cliff face, enabling both geomorphological mapping and the construction of precise 3D geometric meshes required for geomechanical collapse scenario simulations (Thoraval et al. 2026).

To resolve complex cliff geometries, severe overhangs, and spatial occlusions along the vertical rock face, a dual-scanner deployment strategy was implemented:

- A short-range terrestrial laser scanner (TLS) positioned at the cliff base for close-range overhang geometry.
- A long-range TLS deployed across the Bonifacio strait on opposing promontories to capture the upper cliff section and structural crown.

While emerging Unmanned Aerial Vehicle (UAV) LiDAR and photogrammetric systems offer flexible and cost-effective alternatives for inaccessible coastal environments, every surveying methodology exhibits operational limitations. TLS performance remains subject to distance-dependent spatial resolution decay (Kregar et al. 2025), line-of-sight occlusions beneath deep overhangs, and complex georeferencing constraints. In this study, establishing a network of 22 GNSS-measured control points anchored to permanent anthropogenic structures was critical to minimize registration drift. This spatial framework enabled the retrospective georeferencing of legacy datasets and ensured reliable diachronic point cloud comparisons within an absolute Level of Detection (LoD of 95%) bounded between pm 5 and pm 10 cm.

5.2. High-Resolution In-Situ Monitoring and Signal Decomposition

At the local structural scale, continuous high-frequency geotechnical monitoring (multipoint borehole extensometers, surface crackmeters, and biaxial clinometers) provided continuous kinematic insight into fracture dynamics preceding potential mass movement. However, raw geotechnical time series in coastal settings are

heavily corrupted by non-linear environmental noise and thermo-mechanical forcing (air/rock temperature, seasonal thermal gradients, rainfall infiltration, and wave action).

Autocorrelation function (ACF) analysis and moving-average decomposition of the stationary residual components demonstrate that a minimum continuous observation window of 2.5 years is strictly required to achieve statistically robust signal decomposition. This temporal threshold aligns with the findings of Gunzburger et al. (2005) at the Rochers de Valabres test site in the Southern Alps, highlighting a universal temporal requirement for sub-surface thermal cycle stabilization across differing lithological and climatic settings.

Key structural monitoring stations, including the 40.5 m deep "Rue" borehole extensometer, the N110°E fracture crackmeters, and the *Manichella* clinometer, exhibited stationary residual fluctuations bounded within nominal sensor precision limits. These findings confirm current structural stability across the monitored rock compartments beneath the Citadel.

5.3. Thermomechanical Drivers of Fracture Dynamics

Mediterranean coastal environments are characterized by high solar irradiance and significant seasonal thermal amplitudes exceeding tens of degrees Celsius. These conditions exert strong thermo-mechanical stresses on exposed calcarenite cliff faces, acting as primary preparatory agents for rock-mass degradation.

In the geotechnical records, joint aperture kinematics along the primary N110°E discontinuity correlate directly with thermal cycles:

- Abrupt joint opening during winter cooling due to matrix thermo-elastic contraction.
- Joint closure during summer warming driven by thermal expansion of the outer rock skin.

These recurrent cyclic thermal stresses induce microstructural fatigue along persistent discontinuities, driving localized mechanical weathering and potentially promoting irreversible plastic creep over multi-year cycles. Furthermore, these thermal variations are not confined to the superficial rock face; thermally induced stress waves propagate deeper into the rock mass, reaching crack tips situated beneath the active thermal boundary layer (Villarraga et al. 2018; Letortou et al. 2022). To further quantify these physical processes, integrating experimental cliff-scale thermal logging—combining Type-K thermocouple arrays and Infrared Thermography (IRT), with fully coupled thermo-hydro-mechanical (THM) numerical modeling represents an essential research avenue.

5.4. Implications for Risk Management and Early Warning Optimization

The integration of periodic multi-scale LiDAR surveys and real-time geotechnical monitoring establishes a robust decision-support framework for coastal risk management. The automated processing and streaming of detrended stationary components via the *e.cenaris* web-monitoring platform allow municipal stakeholders and geohazard managers to interactively monitor structural health indicators in near real-time.

To enhance the current monitoring network, specifically regarding Scenario 1 at the Market Square (*Place du Marché*), spatial redundancy must be optimized around critical structural boundaries:

1. Instrument Redundancy: Installing additional high-precision crackmeters and paired face-mounted clinometers across both sides of the N110°E fracture, systematically coupled with collocated temperature sensors.
2. Network Optimization: Optimizing sensor layout via preliminary geomechanical stress-strain modeling to target peak stress concentration zones.
3. UAV-LiDAR Integration: Implementing routine drone-based LiDAR acquisitions over high-risk, inaccessible cliff overhangs to enable rapid post-storm damage mapping and crisis verification.

5.5. Study Limitations

Despite the robust multi-scale workflow, several operational and statistical constraints were encountered:

- **Remote Sensing Limitations:** TLS and photogrammetric acquisitions were constrained by restricted site accessibility at the cliff toe, urban heritage spatial restrictions, high sensitivity to environmental conditions (wind, rough sea state, wave reflections, and dense vegetative cover masking structural joints), and distance-dependent beam divergence. Complex geometry created persistent shadow zones beneath major overhangs, complicating absolute GNSS control network expansion.
- **Sensor Longevity in Marine Environments:** Continuous geotechnical operations suffered from harsh coastal conditions, where aggressive salt spray induced sensor and cable corrosion, requiring frequent, high-risk maintenance interventions by specialized rope-access technicians.
- **Signal Resolution vs. Precision:** Extracting the stationary kinematic signal requires a minimum of 2.5 years of uninterrupted data. Observed deformation amplitudes often remained near or below the nominal precision thresholds of the instrumentation, requiring rigorous signal-to-noise filtering.
- **Spatial Coverage Gaps:** The current monitoring setup lacks spatial redundancy along secondary bounding joints and does not yet incorporate real-time multi-depth rock thermal profiling across the entire cliff height.

6. Conclusions

This study demonstrates that assessing the structural stability of complex coastal heritage sites, such as the Bonifacio Citadel, requires a tight synergy between high-resolution 3D spatial remote sensing and continuous, multi-parameter geotechnical monitoring:

1. **Spatial vs. Temporal Complementarity:** While periodic 3D TLS point cloud comparisons provide essential centimetric-scale geomorphological auditing, continuous in-situ geotechnical sensors deliver the sub-millimetric resolution required to detect real-time kinematic precursors to failure.
2. **Key Diagnostic Indicator:** Isolating the stationary residual component from raw geotechnical time series represents the most reliable indicator for geohazard assessment, as it eliminates the dominant, reversible influence of seasonal thermal expansion.
3. **Temporal Depth Requirement:** A minimum monitoring duration of 2.5 years is established as a critical requirement to ensure statistical stability during time-series signal decomposition, allowing long-term irreversible creep trends to be distinguished from short-term environmental forcing.
4. **Site Stability Confirmation:** Diachronic TLS comparisons between 2018 and 2023 (T0 to T5), cross-validated by stationary time-series analysis, confirm that no statistically significant structural deformation or precursor displacement occurred along major bounding discontinuities over the 5-year study period.
5. **Geohazard Context of Scenario 1:** The deployed instrumentation primarily addresses Scenario 1, identified as the most critical collapse hazard. In this scenario, structural fractures, though partially closed at the surface, trace a major potential failure volume at the top of the cliff directly beneath the Market Square (*Place du Marché*). The base of this overhanging block rests at an elevation of +30 m NGF, isolating it from direct marine wave action in the short to medium term. However, progressive thermomechanical weathering along bounding joints will gradually degrade its structural margin. Given the heavy tourist density on the Market Square esplanade and viewpoint, this zone presents a high societal risk despite the non-permanent nature of the exposed assets.

6. Coastal planning support & Climate Change Outlook: The integrated monitoring framework provides an operational decision-support tool through the *e.cenaris* web platform, serving both public safety and cultural heritage preservation. In the context of climate change, accelerating sea-level rise and heightened storm surge frequency will intensify basal wave-cut undercutting within the weak, poorly consolidated sands of the Pertusato Member (~30 m thick). The baseline established in this work provides a rigorous foundation to monitor whether changing coastal forcing will trigger a transition from reversible thermo-elastic behavior to irreversible structural creep preceding catastrophic failure.

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