Luisa Beltramone

Chapter 4

Discussion

The three case studies presented in this thesis—Vecchiano and Grotta Paglicci in Italy, plus the Sabereebi Monastic Complex in Georgia—demonstrate how integrated geomatic and engineering-geological approaches can be adapted to distinct geomorphological contexts and to varying monitoring and conservation objectives. Although these sites differ in lithology, environmental setting, accessibility, and cultural significance, the comparative analysis reveals a common framework in which multi-sensor and multitemporal datasets are necessary for understanding slope dynamics and designing effective risk mitigation strategies.

4.1 Geological and structural controls on instability

In all three sites, instability processes arise from the interaction between rock mass properties, discontinuity geometry, and external environmental drivers. Yet, the expression and progression of these processes differ substantially.

At Vecchiano, the high subvertical limestone escarpments of the "Calcare Massiccio" Formation are characterized by pervasive fracturing and karstification. Here, rockfall hazard is governed primarily by structurally controlled block releases along steeply dipping discontinuities. The concern is largely civil protection oriented, as detached blocks threaten infrastructure, transportation corridors, and inhabited areas at the slope foot. The geological setting therefore emphasizes the monitoring of discrete, localized failures, where small displacements can precede hazardous events.

In contrast, the Grotta Paglicci site presents a more confined environment, where stability is influenced by the geometry and persistence of bedding and joint surfaces intersecting the cave entrance. Although the potential failures are generally of smaller volume, even minor detachments pose a risk to archaeologically significant deposits and to research and visitation activities. The key challenge in this context is not only to assess stability but also to obtain reliable 3D documentation of a complex morphology affected by accessibility constraints and limited light conditions.

In both carbonate settings, structurally controlled instability mechanisms were primarily assessed through kinematic analyses.

From a methodological perspective, it is important to note that the kinematic analyses performed at both Grotta Paglicci and Vecchiano base on a friction angle representative of the rock mass rather than on residual joint friction values. The direct use of residual friction angles would represent fully mobilized post-peak conditions and would likely lead to an overestimation of kinematically admissible instability scenarios. Conversely, adopting a rock mass friction angle provides a more balanced approximation of the overall mechanical pre-failure response.

Sabereebi introduces an additional dimension of complexity, where soft sedimentary rocks (sandstone, siltstone, conglomerate and clay) have been anthropogenically carved to form monastic cells and architectural façades. Here, degradation is progressive, involving both granular disaggregation and episodic slab failures that cumulatively reshape the rock-cut surfaces. The semi-arid climate of the Gareja region, characterized by wide thermo-hygrometric oscillations and salt crystallization processes, plays a central role in accelerating façade retreat, particularly where carved surfaces and lithological interfaces are exposed.

In this context, the identified blocks that had fallen in the period between 2018 and 2025 underscore the need for non-invasive management of surface water runoff in such a way as to protect the cultural heritage.

Across the three sites, instability is therefore not attributable to a single controlling factor but rather emerges from the dynamic superposition of mechanical contrasts, geochemical conditions, structural arrangements, climate forcing and, at Sabereebi, anthropogenic shaping of the rock mass.

4.2 Role of multi-sensor surveying and monitoring

The methodological framework applied in this thesis confirms that no single survey or monitoring technique is totally sufficient to characterize instability in complex rocky environments. Instead, integrating complementary datasets enables the observation of deformation at different spatial resolutions and temporal scales, providing a more complete representation of slope behavior.

At the same time, the selection of topographic survey techniques is not neutral but is strongly influenced by the structural characteristics of the investigated rock mass. In discontinuous and structurally controlled carbonate rock masses, such as those of Vecchiano and Grotta Paglicci, topographic surveys (e.g., terrestrial laser scanning, UAV photogrammetry, and SLAM-based mapping) are primarily aimed at reconstructing high-resolution slope geometry and extracting discontinuity orientation, length and spacing, which are fundamental for kinematic and dynamic stability analyses. In these contexts, point-based measurements acquired through RTS or GNSS may support the control of selected targets and the georeferencing of multitemporal datasets.

Conversely, in weak rock environments such as Sabereebi, where instability processes are more diffuse and progressive, topographic surveys are mainly used to reconstruct the overall morphology and stratigraphy of the slope, to quantify volumetric changes, to document the evolution of rock-cut surfaces and, secondly to map rock discontinuities. In such cases, multitemporal laser scanning and UAV-based photogrammetry provide the geometric basis required for continuum-based numerical modeling and for the analysis of long-term degradation processes.

At Vecchiano, the combined use of RTS monitoring and PSI proved particularly effective. RTS offered high precision point measurements targeting specific unstable blocks, whereas PSI provided a broader view of deformation patterns at slope crests and in the surrounding alluvial plain. UAV photogrammetry served as the spatial reference framework, enabling discontinuity mapping and identifying sectors requiring monitoring. The integration of these methods demonstrated how coupling localized survey precision with regional-scale satellite observations produces a more robust interpretation of slope dynamics.

At the same time, comparing these techniques is not straightforward and requires careful consideration of their intrinsic differences. RTS measurements are typically expressed in a three-dimensional reference system, allowing the decomposition of displacement into its spatial components. Conversely, PSI provides average displacement values projected only along the satellite LOS, which represents a one-dimensional measurement. Therefore, a direct comparison requires separating the vertical and horizontal contributions from the LOS values. This difference reflects the complementary nature of point-based and distributed monitoring approaches.

The study at Grotta Paglicci has required a different strategy: here, spatial constraints necessitated flexible mobile scanning—achieved through SLAM-based LiDAR mapping—which enabled the acquisition of the cave's internal geometry even in narrow passages. UAV photogrammetry supplied the external 3D surface, enabling the linking of internal and external morphologies into a unified model. This integrated point cloud formed the basis for geomechanical characterization and stability assessment of the entrance sector and surroundings.

Sabereebi illustrates the value of multitemporal terrestrial laser scanning combined with UAV photogrammetry and surface change detection using the M3C2 algorithm. The extraction of volumetric differences between the 2018 and 2025 point clouds allowed the spatial localization and quantification of façade retreat, distinguishing between continuous background weathering and discrete collapse events. These results provided a dataset for both interpreting ongoing degradation and calibrating the boundary conditions of the numerical stability model.

4.3 Numerical modeling as interpretative support

Across the two case studies, Paglicci and Sabereebi, numerical modeling served not as an isolated predictive tool, but as a framework for testing hypotheses derived from field surveys, structural interpretation, and stability analysis. Its role was therefore primarily interpretative, aimed at constraining the range of possible failure mechanisms and supporting decision-making regarding monitoring and mitigation priorities.

At Grotta Paglicci, two-dimensional numerical simulations allowed the assessment of stress distribution and deformation tendencies in the cave entrance sector, where geometric conditions and the thickness of overburden material exert a strong influence on stability. The results highlighted areas where the interaction of bedding and joint sets could facilitate planar or flexural toppling, particularly when water pressure in discontinuities increases. This supports the interpretation derived from slope stability kinematic analysis and reinforces the need to monitor environmental conditions alongside geometric configurations.

The Sabereebi case study has required a more complex representation due to the rock mass's carved nature and the pronounced heterogeneity of the lithological units. A three-dimensional finite elements model allowed the simulation of internal stress redistribution associated with façade retreat and excavation morphology. The adoption of a hybrid constitutive approach, integrating the Generalized Hoek–Brown criterion (**Hoek et al., 2002**) for fractured sandstone and the Mohr-Coulomb criterion (**Coulomb, 1776**) for the other non-fractured horizons, was essential for capturing the contrast in stiffness and strength that governs the development of slab detachments and overhang collapse. The model provided a physically grounded interpretation of the observed detachment patterns and highlighted sectors where differential stress concentrations may promote future instability.

Regarding the choice of mechanical parameters, it is important to consider the simplifications introduced by the empirical formula based on the RMR and GSI classification systems. In particular, empirical classifications translate qualitative or semi-quantitative geological observations—such as joint condition, spacing, and weathering—into numerical indices that are subsequently used to derive mechanical parameters (e.g., cohesion, friction angle, and deformability). The latter, when used in numerical modeling, allow the derivation of results that should be interpreted pragmatically, as they represent idealized mechanical scenarios rather than fully constrained physical conditions, particularly in the absence of site-specific calibration data (e.g., stress and strain measurements).

The adoption of a continuum-based modeling approach (FEM) may represent an additional approximation when applied to rock masses characterized by discontinuity networks. However, its applicability depends strongly on the scale of analysis and the structural complexity of the investigated site. In the case of Grotta Paglicci, the relatively limited spatial extent of the study area and the reduced number of dominant discontinuities allow the rock mass behavior to be reasonably approximated through a continuum-equivalent approach. Under these conditions, FEM modeling can incorporate the overall geometry, the main structural features, and discontinuities, thereby providing a consistent representation of stress distributions and deformation patterns.

The numerical modeling was conducted within a deterministic framework, as required by the adopted software environment, which does not allow the direct implementation of parameter variability or statistical distributions. This constraint reinforces the need to interpret the results as indicative scenarios rather than precise predictions, highlighting general mechanical trends and potentially critical sectors.

Their integration with kinematic analysis and structural observations, therefore, remains essential for a consistent interpretation of slope behavior.

4.4 Implications for hazard mitigation and heritage conservation

The results obtained from the analyses have direct implications for both safety management and heritage conservation, though the specific interventions differ according to the site context.

At Vecchiano, the stability analysis supports the conclusion that the monitored rock walls are currently in a stable condition, with observed displacements largely attributable to ground movements in the alluvial plain rather than to active slope failures. Here, hazard mitigation focuses on maintaining long-term monitoring, improving reference stability, and periodically reassessing discontinuity conditions. The priority lies in civil protection, ensuring that any future change in rock mass behavior is detected before it poses a threat to infrastructure and the nearby community.

In Grotta Paglicci, the integration of 3D datasets serves a dual purpose. The digital models facilitate both geological interpretation and the long-term documentation of the cave morphology for cultural and scientific preservation. Although the main structural sectors appear stable under normal conditions, potential instabilities concentrated near the entrance warrant targeted preventive measures, such as localized reinforcement or access restrictions during periods of elevated humidity or after intense rainfall. The 3D survey workflow also provides a replicable method for conservation planning applicable to other cave systems with similar accessibility constraints.

For Sabereebi, conservation must address ongoing façade recession rather than isolated failures alone. The presence of temporary scaffolding demonstrates the recognition of local collapse risk, yet these structures do not mitigate the environmental drivers of degradation. The study underscores the need for non-invasive hydrological management, such as surface runoff diversion, micro-drainage channels, and protective buffering of key carved surfaces. These interventions, combined with multi-epoch 3D monitoring, allow the preservation of both the architectural integrity and the historical narrative embedded within the rock-cut structures. Importantly, mitigation at Sabereebi must balance structural stability, visual authenticity, and minimal disturbance to the cultural landscape.

4.5 Environmental stressors and climate change context

All three case studies reveal slope stability conditions that are strongly influenced by climate-sensitive processes.

At Vecchiano, the limestone walls are affected by karst phenomena, thermal expansion, rainfall-driven seepage, and seasonal variations in groundwater levels, which locally influence the stability of both the rock mass and the RTS installation area. Projections of increased precipitation intensity in Mediterranean regions may contribute to more frequent triggering of rockfalls in the long term.

In Paglicci, the cave microclimate exhibits relatively stable conditions, but the entrance sector remains exposed to external weathering. Increased variability in humidity and temperature could exacerbate stress cycling in joints, accelerating fatigue and promoting failure in sectors already identified as structurally susceptible. The cave therefore represents a system at equilibrium that could shift under modest climatic forcing.

Sabereebi, located in the semi-arid Gareja region, is particularly vulnerable to projected intensification of wetting–drying cycles and enhanced salt crystallization processes. These mechanisms directly contribute to granular disaggregation of the sandstone matrix and the progressive retreat of carved surfaces. Under future climate scenarios, the pace of façade recession is likely to increase, reducing the timescale available for conservation intervention. As such, Sabereebi can be considered a climate-sensitive heritage system, where degradation processes are inherently coupled with environmental forcing. This highlights the need for adaptive, rather than static, mitigation strategies that evolve in response to climatic trends and monitoring data.

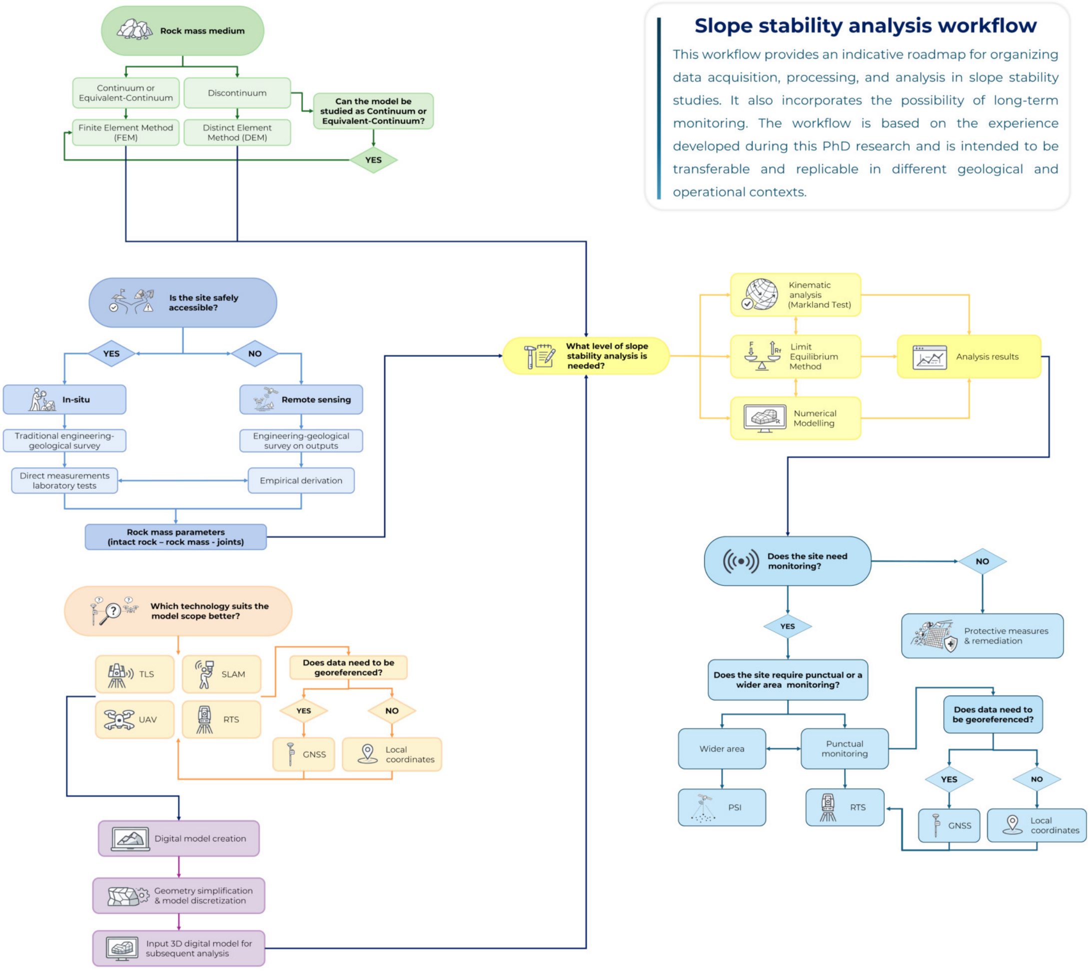
4.6 Synthesis

Taken together, the three case studies illustrate how integrated geomatic and geomechanical approaches can support both hazard management and cultural heritage conservation. The shift from static representations of rock masses to multi-temporal 3D and 4D models enables a dynamic understanding of slope behavior, improving decision-making capacity for both engineering interventions and preventive conservation planning.

To formalize the methodological approach developed throughout this research, a generalized workflow for slope stability analysis is proposed as shown in Figure 4.1. The workflow synthesizes the integration of geomatic and geomechanical methods into a structured and transferable scheme, highlighting the key decision points related to rock mass characterization, data acquisition strategies, model selection, and monitoring design.

In particular, the workflow emphasizes how the mechanical behavior of the rock mass, site accessibility, and the required level of analysis govern the selection of investigation techniques, ranging from in-situ surveys to remote sensing approaches, and from kinematic stability analyses to numerical modeling. It also incorporates the potential need for monitoring and the choice between punctual and distributed observation systems, such as RTS and PSI, as applied in this work.

This workflow is intended not as a rigid protocol, but as a flexible decision-support framework that can be adapted not only to different geological, environmental, and operational contexts, but can also be integrated with alternative analysis and monitoring techniques.



Slope stability analysis workflow

This workflow provides an indicative roadmap for organizing data acquisition, processing, and analysis in slope stability studies. It also incorporates the possibility of long-term monitoring. The workflow is based on the experience developed during this PhD research and is intended to be transferable and replicable in different geological and operational contexts.

Figure 4.1: Proposed generalized workflow for slope stability analysis, illustrating the integration of geomatic and geomechanical methods and key decision-making steps.

Overall, the research demonstrates that effective slope stability management—whether in inhabited areas, archaeological sites, or remote cultural landscapes—requires interdisciplinary collaboration between geoscience, engineering, heritage conservation, and land management authorities.

This integrative perspective is particularly crucial under evolving climatic conditions, which are likely to intensify the processes driving rock mass degradation in the coming decades.

Chapter 5

Conclusions

The three case studies presented in this thesis demonstrate how slope stability and rockmass degradation can be analyzed effectively through the integration of advanced geomatic acquisitions, engineering–geological surveys, and analytical interpretation. Although the sites differ significantly in geological context, morphology, accessibility, and final objectives, the work shows that multi-sensor and multi-temporal data integration is a robust strategy for understanding instability processes and guiding risk mitigation decisions.

At Vecchiano, the objective was to assess rockfall hazard in a natural slope directly affecting infrastructure and the surrounding urban environment. Here, the coordinated use of UAV-based photogrammetry, engineering–geological surveys, and multitemporal monitoring through RTS surveying and PSI provided high-resolution spatial and temporal information on the stability state of the cliffs. The results confirmed the long-term structural stability of the monitored rock mass and revealed seasonal vertical fluctuations in the alluvial plain underlying the monitoring station. This case study demonstrates how combining point-based and satellite-based observations can support civil protection and local decision-making in areas with high rockfall exposure.

Grotta Paglicci required a different methodological approach due to its archaeological relevance and restricted accessibility. The integration of UAV photogrammetry for external environments and SLAM-based LiDAR for internal chambers enabled the generation of a unified 3D dataset that supported both geomechanical interpretation and morphological documentation. The resulting models provided essential insight into discontinuity persistence, entrance stability, and the spatial relationships between natural structures and prehistoric anthropogenic modifications. This case highlights how advanced spatial documentation not only contributes to hazard assessment but also serves as a tool for conservation planning, heritage monitoring, and long-term site management.

The Sabereebi Monastic Complex represents a further evolution toward multi-temporal change detection in rupestrian heritage environments. By combining TLS and UAV derived point clouds from different annual campaigns, volumetric change quantification revealed both progressive surface degradation and discrete collapse events along the walls of the rock-cut structures. The results illustrate how instability in soft sedimentary rock complexes is driven by the interaction between discontinuity networks, lithological contrasts, and climate-dependent thermo-hygrometric stress. The study also demonstrated the value of minimally invasive monitoring strategies in culturally sensitive contexts and underscored the need for preventive rather than reactive conservation approaches.

Across the three case studies, several broader conclusions can be drawn.

First, a single technique is insufficient to capture the spatial and temporal complexity of slope processes: if possible, hybrid monitoring frameworks are necessary to fully characterize rock-mass behavior.

Second, methodological choices must be tailored to site-specific conditions, including safety constraints, surface geometry, vegetation cover, and conservation priorities.

Third, 3D and 4D datasets serve a dual purpose, providing both analytical information for stability assessment and long-term digital documentation that can be shared across disciplines, including geology, conservation science, and cultural heritage management.

Finally, the results emphasize the increasing relevance of climate-driven stressors in the evolution of both natural slopes and rock-cut heritage sites. Variations in moisture regimes, temperature oscillations, and extreme weather events are likely to accelerate weathering and instability processes in the coming decades. Continuous, scalable, and non-invasive monitoring systems—such as those implemented in this work—represent a critical component for anticipating such changes and planning adaptive mitigation strategies.

Overall, the thesis demonstrates that integrating advanced geomatic techniques with classical engineering-geological analysis and numerical modelling yield a more complete understanding of slope stability conditions across diverse geological settings. By bridging natural hazard assessment and, where relevant, cultural heritage preservation, the methodologies adopted here contribute to more informed, sustainable, and site-responsive management practices.

5.1 Future research directions

The results obtained in this thesis provide a robust basis for understanding instability processes in natural slopes and rock-cut heritage sites, yet several research avenues merit further development.

First, the transition from periodic to continuous monitoring represents a crucial step forward. At Vecchiano, multitemporal RTS surveys were affected by repositioning uncertainties and interruptions in the observation timeline. Future work could therefore explore the use of fixed robotic stations, ground-based radar, distributed fiber-optic sensors, geotechnical sensors (e.g. crackmeters, extensometers), and long-term GNSS installations to ensure stable reference conditions and sub-millimetric precision. Integrating these systems with environmental sensors—such as temperature, humidity, and pore-pressure probes—would allow direct correlation between climatic forcing and mechanical response, improving the interpretation of precursory deformation signals.

Second, the potential of 4D geomatic approaches should be further exploited, particularly at Sabereebi, where multitemporal point-cloud comparison has already revealed patterns of façade recession and localized detachments. Future research should focus on automating multitemporal point-cloud registration, segmentation, and change detection using machine-learning techniques, with the aim of increasing reproducibility and reducing operator-dependent variability. The development of standardized 4D workflows for rock-cut heritage monitoring would enhance comparability across sites and support the definition of early-warning thresholds based on deformation rates rather than solely on episodic collapse events. Here, measures of support against the hydrogeological risk would benefit the protection of the cultural heritage.

Third, the reliability of numerical modelling could be substantially improved by integrating direct in-situ stress measurements. Previous applications of the CSIRO-HI cells overcoring technique (**Salvini et al., 2022**; **De Lucia et al., 2025**) have demonstrated the value of acquiring real stress–strain data to calibrate the models created for FEM and DEM simulations. These stress-measurements contribute to reducing the uncertainty associated with input parameters, enabling more realistic representations of stress redistribution around caves and rock-cut façades. At Grotta Paglicci, future research should also consider the development of a fully three-dimensional slope stability numerical model. Compared to the current two-dimensional approach, 3D analyses would better capture the complexity of the cave network and local stress concentrations generated by irregular geometries and joints. These models could be further constrained by geophysical surveys—such as elastic-wave tomography or microseismic monitoring—to derive site-specific mechanical properties and improve model reliability.

Fourth, the dynamic stability analyses, as well as the numerical modelling, could be integrated with a probabilistic approaches, rather than relying solely on deterministic frameworks, given that engineering-geological parameters are derived from empirical formula and, therefore, affected by uncertainty not included in the present analyses. A probabilistic approach may allow the inclusion of the statistical variability of input data, hence enhancing the comprehensiveness of results. In parallel, another approach to improve model reliability is back-analysis, considering documented past events to feed the model calibration.

A further line of research that could be developed concerns rockfall hazard assessment. Although rockfall simulations were not carried out within this thesis, multitemporal point-cloud analyses at Sabereebi could allow for the identification of several detachment zones and block volumes that could serve as input for future modelling. Tools such as RocFall3 could be employed to simulate potential block trajectories, impact energies, and deposition areas. Coupling these simulations with observed change-detection results would support the construction of hybrid, data-driven hazard scenarios and contribute to more quantitative risk evaluations for this monastic complex and others sites across Georgia.

Another important direction of study could involve climate-driven degradation processes. Both Paglicci and Sabereebi case studies demonstrate the sensitivity of rock masses to moisture fluctuations, thermal cycling, and salt crystallization. Future studies should incorporate predictive climatic scenarios to estimate how instability rates may evolve under projected changes in temperature and precipitation. This would enable the development of adaptive conservation strategies in which mitigation measures evolve dynamically as environmental forcing intensifies.

A further relevant direction concerns the explicit integration of karst-related hydrogeological processes into slope stability analysis. Both Grotta Paglicci and Vecchiano are developed in carbonate settings affected by active karst processes, as confirmed through in-situ observation. Therefore, karst circulation should be considered an ongoing hydrogeological process rather than a relict feature. In this context, karst systems may significantly influence slope stability through multiple mechanisms. Water flow along joints and karst conduits may generate localized increases in hydraulic pressure, reduce effective stress, and promote progressive weakening of discontinuity surfaces through dissolution. Additionally, the presence of preferential flow paths and hidden voids may lead to heterogeneous stress redistribution and localized instability conditions.

Future research should therefore aim to couple geomatic and geomechanical datasets with hydrogeological modeling approaches specifically designed for karst systems. In this regard, the Conduit Flow Process (CFP) implemented in MODFLOW represents an example of suitable framework for simulating dual-flow systems, where both porous media flow and conduit flow are considered. This approach would enable the explicit modeling of water circulation within discontinuities and karst conduits, including rapid flow dynamics and transient pressure conditions. Such integration would allow the quantitative estimation of pore-pressure variations within discontinuities under different hydrological scenarios (e.g., intense rainfall events), improving the assessment of hydro-mechanical coupling and its role in slope instability. Incorporating these processes into geomatic-derived 3D models would contribute to the development of a more comprehensive hazard framework, accounting for both mechanical and hydrogeological controls in karstified environments.

Finally, the long-term protection of rock-cut heritage requires effective stakeholder integration. Collaboration among geoscientists, conservators, local authorities, and communities is essential for sustainable management. Future initiatives should explore the creation of shared monitoring platforms—potentially supported by WebGIS visualization dashboards—to enhance communication, facilitate decision-making, and promote transparent and socially sustainable conservation practices.

In summary, future research should prioritize: (i) continuous, sensor-integrated monitoring systems; (ii) automated and standardized 4D geomatic workflows; (iii) numerical models calibrated with site-specific in-situ stress data (e.g., CSIRO HI cell overcoring); (iv) the simulation of rockfall trajectories (e.g., RocFall3) to complement change-detection analyses; (v) climate- and hydrogeology-responsive mitigation planning; and (vi) inclusive, interdisciplinary collaboration frameworks. These developments will strengthen the protection of natural slopes and culturally significant rock-cut environments under evolving environmental conditions.

Chapter 6

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