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Addressing Rockfall Challenges in flysch environment - A case study from Greece

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Abstract Rockfalls pose a significant hazard in mountainous regions, affecting infrastructure, obstructing roads, and posing a risk to human life. This hazard is particularly high in flysch environments, marked by a heterogeneous composition of rock formations of varying strengths, prone to erosion that compromises the stability of slopes. This paper examines an engineering geological investigation addressing rockfall hazards on a mountainous provincial road in central Greece. Utilizing traditional in-situ geological studies and remote sensing technologies, primarily Structure-from-Motion (SfM) photogrammetry and also Light Detection and Ranging technology (LiDAR), the research team has identified the engineering geological factors influencing rockfall incidents, delineated hazardous zones, and predicted possible rockfall paths though physically-based modeling. SfM photogrammetry monitoring and change detection analysis revealed detachments, while trajectory analysis, updated by volumetric measurements, highlighted areas of significant danger. Our workflow contributes to understanding the instability mechanisms and directly support engineers in designing strategies to mitigate rockfall hazards, thereby increasing safety on this crucial transport route. This study demonstrates the power of combining geospatial technologies with engineering geological expertise to enhance public safety along transportation routes in mountainous regions prone to rockfalls.

Keywords flysch rock masses, SfM photogrammetry, TLS LiDAR mapping, rockfall monitoring, rockfall modeling.

Introduction

Rockfalls pose a critical hazard to transportation networks and public safety in mountainous regions, particularly where human development intersects with natural landscapes. These hazards are pronounced in flysch environments, where unique geomorphological conditions and the heterogeneity of flysch formations—comprising low-strength materials and structures affected by tectonic activity—increase the risk of slope failures (Marinos, 2019).

Building on the foundation of traditional engineering geological survey methods, the integration of remote sensing technologies, such as Structure-from-Motion (SfM) photogrammetry (Westoby et al., 2012) and TLS LiDAR, has revolutionized rockfall assessment and monitoring by providing high-resolution spatial data. This data enables the detailed analysis of complex topographies, deformation detection, and the precise estimation of rockfall events, including their precursors (Abellan et al., 2014; Kromer et al., 2019). The integration of these technologies with surface reconstruction algorithms allows for the automated addition of critical rockfall features to digital databases, enhancing our understanding of rockfall dynamics (DiFrancesco et al., 2021). Detailed 3D surface models generated from remote sensing technologies provide crucial inputs for numerical simulations. These simulations accurately depict rock face geometry, enabling physically-based modeling of the entire rockfall process – initiation, propagation, and deposition. Factors like trajectory energy, velocity, and potential reach are considered. However, identifying rockfall sources and obtaining accurate geotechnical parameters remains a challenge for creating realistic, high-resolution models. As demonstrated by Farmakis et al. (2023), data-driven models offer significant potential for improved rockfall susceptibility assessment, advancing our ability to predict and manage these hazards. Within this context, the presented case in the Valaora-Stavros village region in central Greece, demonstrates an integrated approach to addressing and mitigating rockfall hazards. This study, focused along a critical provincial mountainous route in a flysch environment, integrates SfM photogrammetry, Terrestrial Laser Scanning (TLS), and advanced digital tools for several key advancements.

High-resolution topographic data and engineering geological mapping are used to identify rockfall source areas, characterize failure mechanisms, and quantify rockfall volumes. Physically-based trajectory modeling, calibrated with monitoring data, pinpoints high-hazard zones and provides essential insights into rockfall dynamics. The integration of engineering geological and geomorphological analyses, alongside precise modeling, enables the development of targeted mitigation strategies specifically tailored to the constraints and failure modes of the Valaora flysch terrain. This multi-faceted approach enhances rockfall hazard analysis. It accounts for spatial limitations and complex failure mechanisms, typical in mountainous flysch environments, ensuring that mitigation measures are strategically designed for maximum effectiveness.

Study Area Overview

The Valaora region, situated in the western part of the Evritania prefecture near Greece's artificially created Kremaston Lake, is characterized by its steep and precipitous slopes (**Fig. 1,2**). Recognized as one of the most susceptible areas to landslides in Greece, the mountainous terrain of Evritania necessitates a thorough engineering geotechnical analysis to secure infrastructure and public safety in this high-hazard zone (Marinos et al., 2015).

Predominantly composed of Gavrovos flysch, the geologic structure of the Valaora region features a sequence of sandstone, clay, siltstone layers, and an underlying limestone base. The complexity of this stratification plays a crucial role in defining the area's stability, influencing erosion patterns and the effectiveness of any mitigation strategies implemented.

Stability challenges in the area are significant, with rockfalls posing a severe threat to the adjacent provincial road. Medium to large boulders ranging from approximately 5 to 10 m³, often detach from the upper slopes, posing hazards due to the lack of protective infrastructure. Erosion and shallow slides, especially towards the area's northeastern parts, further contribute to the instability, undermining the surface layer and leading to potential road safety threats. Moreover, rockfalls occurring directly above the road (**Fig. 3**), amplify these dangers, compounded by the slope's steepness and the lack of catchment barriers.

The mechanisms behind rockfall failures, are intricately linked to their geological makeup, especially the presence of sandstone masses overlying weaker siltstones at various elevations. Erosion's role in undercutting the sandstone, along with the creation or expansion of tensile cracks within these layers, greatly accelerates the failure process. This issue becomes even more critical when water applies hydrostatic pressure within the rock's open discontinuities.

Figure 2 Aerial view of the Valaora region illustrating steep terrain where rockfalls threaten the road and public safety. Visible scars across the landscape mark recent rockfall events, underlining the need for continuous monitoring and mitigation. The potential trajectories of rockfalls from the upper sections of the slope, through thalwegs, to the road level are of particular concern.

Figure 3 Significant rockfalls involving sandstone at the slope NE edge, directly above the provincial road. This activity is intensified by the undercutting of sandstone caused by the differential erosion of siltstone beneath it.

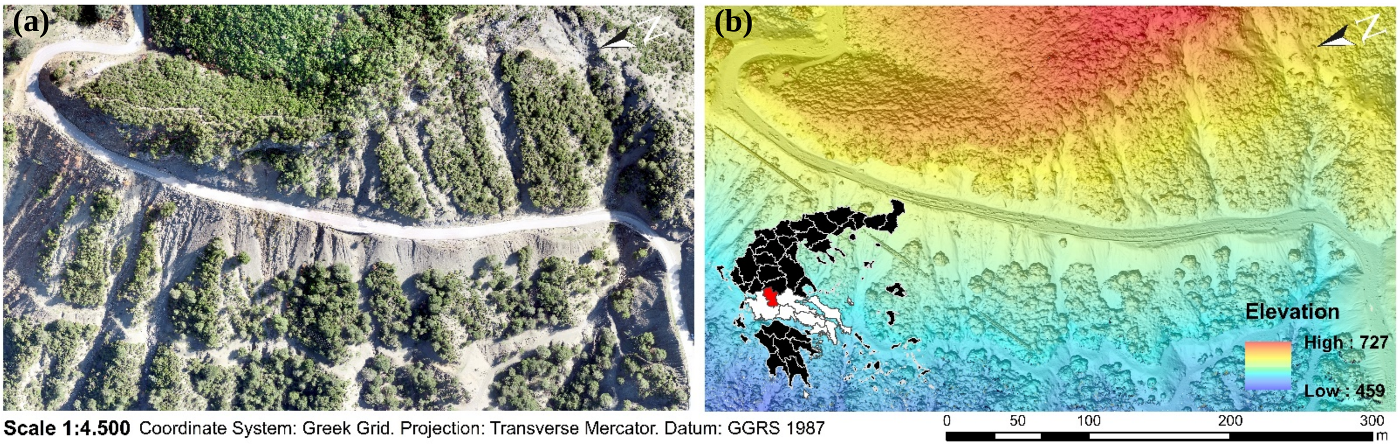

Figure 1 The Valaora study site in Evritania, Greece, featuring: (a) an orthomosaic and (b) a Digital Surface Model (DSM) (Surveyed on 15 September 2021) [For an interactive exploration and visual representation visit the latest digital twin (Chatzitheodosiou, 2023)].

Materials and Methods

Engineering geological Investigation

This study commenced with detailed in-situ engineering geological mapping, including identification of tectonic structures to gain insights into the overall stability of the rock masses and identify potential sources of failure. Field investigations were followed by the classification of flysch formations into four distinct types based on sandstone-siltstone composition and tectonic disturbances, employing a modified Geological Strength Index (GSI) for heterogeneous rock masses like flysch (Marinos, 2019). Subsequent laboratory tests, including Point Load Tests (PLT), Brazilian tests, and direct shear tests on discontinuities, were conducted to determine key physical and mechanical properties of the intact rock, rock mass and joint strength.

While these initiatives significantly advanced comprehension of the geological context and mechanical properties of the study area, the complex nature of rockfall hazards demands a more in-depth analysis. Addressing these complexities requires an understanding of source areas, as well as estimations of potential volumes, magnitudes, and trajectories of rockfall events. This necessitated a shift towards the collection of high-resolution topographic data and the creation of advanced digital tools for a more detailed and accurate analysis of rockfall hazards.

High Resolution Topographic Data Acquisition

Following the groundwork established through initial engineering geological surveys, this investigation utilized Unmanned Aerial Vehicles (UAVs), notably a DJI Phantom 4 RTK and a DJI Mavic 3 Enterprise, to capture the dynamic landscape of the area under study. These UAVs, armed with high-definition cameras, undertook multiple flights to perform aerial photogrammetry. Coupled with an RTK base station, this approach ensured centimetre-level accuracy in the reconstruction of the terrain through SfM, facilitating the creation of detailed point clouds DSMs, and orthomosaics (**Fig.1**).

To enhance the detail on rock outcrops, especially in areas susceptible to structurally controlled failures, TLS LiDAR was implemented. The accuracy of LiDAR, which measures distances using light beams, yielded point cloud datasets with millimetre-level precision. This detailed topographic data offered a detailed perspective of the terrain's features and structures, crucial for identifying potential slope failure mechanisms.

Digital Tools Development

Utilizing the Leica ScanStation P40 TLS LiDAR system, precise orientation measurements and geometric characteristics (spacing, persistence) of discontinuity surfaces were captured for detailed kinematic analyses. This system's long-range capability (up to 270m), high-speed scanning (1 million points per second), and low noise ensured the acquisition of detailed 3D data essential for rock mass structural analysis. Joint surfaces were extracted by locally applying Principal Component Analysis (PCA) on the XYZ space of the 3D points and subsequently forming individual clusters through Density-Based Spatial Clustering (DBSCAN) (Farmakis et al., 2020) (**Fig.4**).

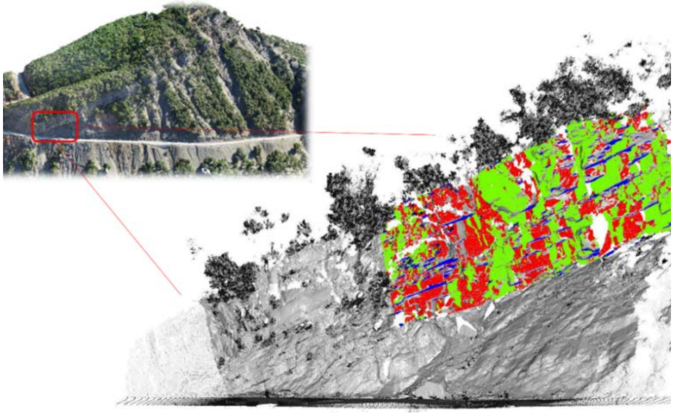

Figure 4 Digital Analysis of Discontinuity Sets in structurally controlled sandstone. Featured is a slope segment assessed using TLS LiDAR digital data for accurate orientation measurements of discontinuities. Geological compass data at the base of the slope, served for cross-verification of the digital analysis.

Concurrently, the generation of Digital Depth Maps from UAV and LiDAR datasets provided a granular visualization of the terrain's surface variations, highlighting both potential rockfall sources and areas of instability indicated by undercuts (**Fig.5**).

Further advancing the project's capabilities, development efforts focused on creating computer vision solutions for the semantic segmentation of three-dimensional data. This approach aims to accurately categorize key terrain features such as vegetation, bedrock, and human infrastructure, within the point cloud data (**Fig. 6**).

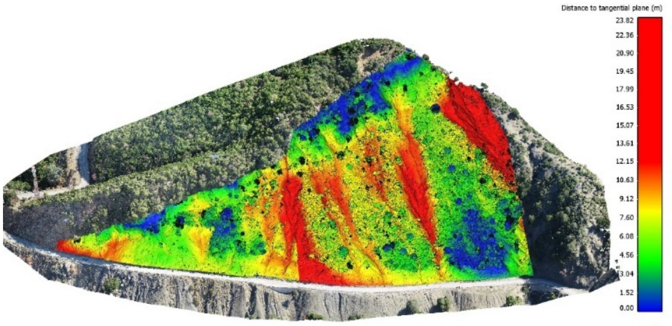

Figure 5 Depth map of the slope. This digital depth map renders the slope's surface against a reference plane, with a blue-to-red scale indicating distance from the reference. Overhangs and undercuts are clearly marked in blue and red, respectively.

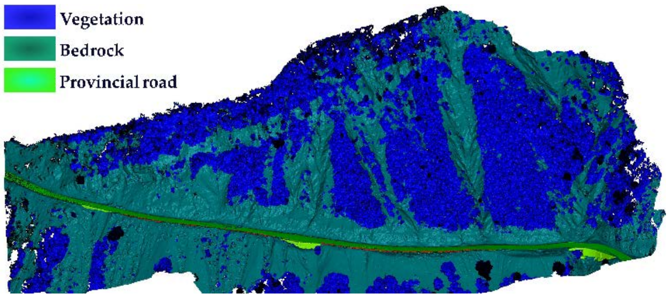

Figure 6 Point cloud after semantic segmentation, divided into three primary categories: ground, vegetation, provincial road.

Point cloud analyses were conducted primarily using Python programming mainly based on the Open3D library. Additionally, open-source software such as CloudCompare was employed for visualization and basic measurements.

Rockfall Monitoring – Rockfall Database

Throughout the study, SfM photogrammetry monitoring played a pivotal role, providing time-series data on terrain evolution in the Valaora region. Employing high-resolution UAV imagery to systematically generate precise point clouds, this approach facilitated the detection and analysis of geomorphological changes over time.

The deployment of the Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague et al., 2013) stood out by enabling accurate identification and quantification of alterations such as rockfalls and slope deformations (**Fig. 7**). By methodically comparing sequential point cloud datasets, the research team was able to detect instability zones and track the dynamic changes within the landscape.

This ongoing monitoring effort, essential for revising and refining assessments, continues to inform our understanding of landslide behaviour and hazards within the region. Further depth in analysis was facilitated by the adaptation of the DBSCAN algorithm (Ester et al., 1996) clustering spatial changes. Also, the Iterative Alpha Shape algorithm, as suggested by DiFrancesco et al. (2021), was used for volumetric calculations of these changes.

Volumetric measurements were also conducted on the blocks that had fallen onto the slope's face and the roadway, including overhanging blocks and grooves formed from detachments on the slope. A digital rockfall database was then developed, cataloguing attributes of each rockfall incident, including its location, volume, shape, and the timing of occurrence.

Physically-based Model - Trajectory Analysis

The final phase of this research involved the creation and application of a physically-based model to simulate rockfall trajectories. The 3D surface model created using UAV photogrammetry significantly benefited from implementing semantic segmentation. This technique enhanced the terrain representation by accurately removing vegetation and filling in data gaps across two distinct steps.

The model's accuracy in predicting rockfall trajectories in the Valaora area was ensured through careful calibration using two years of monitoring data and change detection techniques. This calibration process utilized in-depth knowledge of the starting points, end zones, mechanisms of failure, and volume of rockfalls, which was gathered from both monitoring and geological engineering evaluations. This allowed for the precise adjustment of the model's restitution coefficients for both normal and tangential impacts on slope materials, vital for replicating actual conditions.

By integrating volumetric information into the simulations, the model could make detailed forecasts about the movement of rockfalls, including impact energy calculations, marking areas at high hazard.

Key Findings

An engineering-geological map was created, categorizing rock masses into four types (**Fig. 9**). The primary source of rockfalls was identified in moderately disturbed sandstones with thin layers of siltstones, classified based on GSI (Marinos, 2019) as **Type III**.

In the northern section of the study area, Flysch Type III is positioned at a modest elevation above the road, reaching a maximum of 25 m above a highly disturbed-folded rock mass (**Fig.8**). This underlying mass, not significantly deformed or sheared, consists of siltstone with layers of sandstone (**Type VIII**). Moving southward, the Type III Flysch formation is found at a higher altitude, above moderately disturbed siltstone with thin layers of sandstones (**Type VI**), and in the southern part, it reaches a maximum height of 90 m above a highly disturbed-folded rock mass (**Fig.2**). This mass retains its structure and is made up of alternating siltstones and sandstones (**Type VII**).

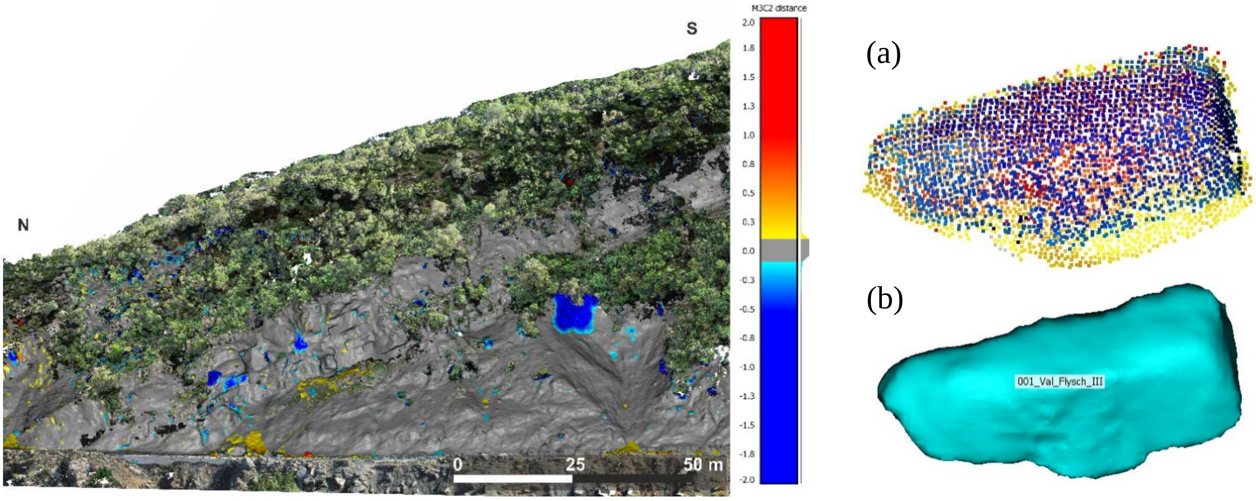

Figure 7 Left: M3C2 change detection output, depicting negative (loss) and positive (gain) changes presented by cooler and warmer colours, respectively. Right: An example of a rockfall detection presented: (a) as a point cloud and (b) as a 3D surface model.

The potential trajectories of rockfalls from the Flysch Type III either land directly on the roadway in the northern section or in the southern section travel through thalwegs from the higher parts to the road level.

Figure 8 The northern section of the slope clearly reveals the origin of rockfalls in Type III flysch above Type VIII. The failure mechanism is evident, characterized by the undercutting of the sandstone as a result of the differential erosion of the underlying siltstone. a) the main rockfall source with 13 m³ volume, measured by digital reconstruction of the detachment geometry, and b) a 6.5 m³ block from this detachment, located on the slope side.

Assessing this rockfalls, RocFall3 software of Rocscience Inc., was used to complement a trajectory analysis. Its methods for calculating runout distances (Runout Total – 3D, Runout XY – 2D, Runout Z – vertical) and algorithms for impact and sliding dynamics matched the physical principles of the developed model well.

The calibration of the model and the accurate calculation of restitution coefficients involved determining the initial positions of rockfall events using change detection data. Initial velocities for detachments were assumed, and a back trajectory analysis for deposit sources was conducted, utilizing change detection and reports from local authorities. After determining the restitution coefficients, simulations of trajectories were conducted. These simulations were followed by a statistical evaluation of the outcomes, focusing on the final impact spots and energy.

Results highlighted significant concerns regarding vertical trajectories towards road infrastructure in the northern sector dominated by Type III flysch (**Fig. 10,11**). Peak kinetic energies at the road level were estimated to be between 6200-6500 kJ, for rockfall volumes of approximately 13 m³, originating from a detachment height of around 20-30 m. However, the potential rock fragmentation during descent indicates that actual impact energies could be lower.

The southern sector appeared safer, with most trajectories ending in thalwegs and fewer reaching roads having lower bounce heights and speeds. The safety of this area was enhanced by the higher elevation of Type III flysch, requiring rockfalls to cover a larger distance before reaching the roadway, thus reducing their energy and hazard potential. Trajectory analyses for wedge-type slides in siltstone (Types VII and VIII) were excluded due to their tendency for immediate disintegration upon detachment.

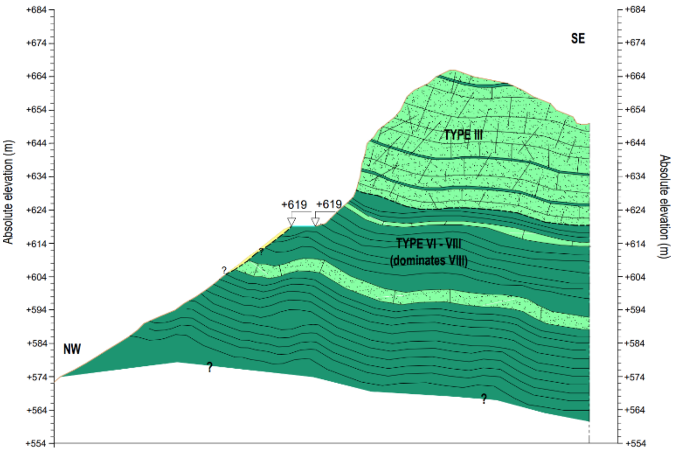

Figure 10 Engineering Geological Section: This section is illustrated in red on the engineering geological map (**Fig.9**).

Mitigation Strategies

Upon identifying failure mechanisms and rockfalls trajectories along the road's slopes, the study area was divided into two distinct regions (**Fig. 9**), spanning a total of 435 m. These sections necessitated different mitigation strategies due to limitations regarding the applicability of various technical solutions. The northern section faced significant large-scale rockfall issues (**Fig. 11**), with sandstone rock masses exhibiting a layered structure and minimal fragmentation.

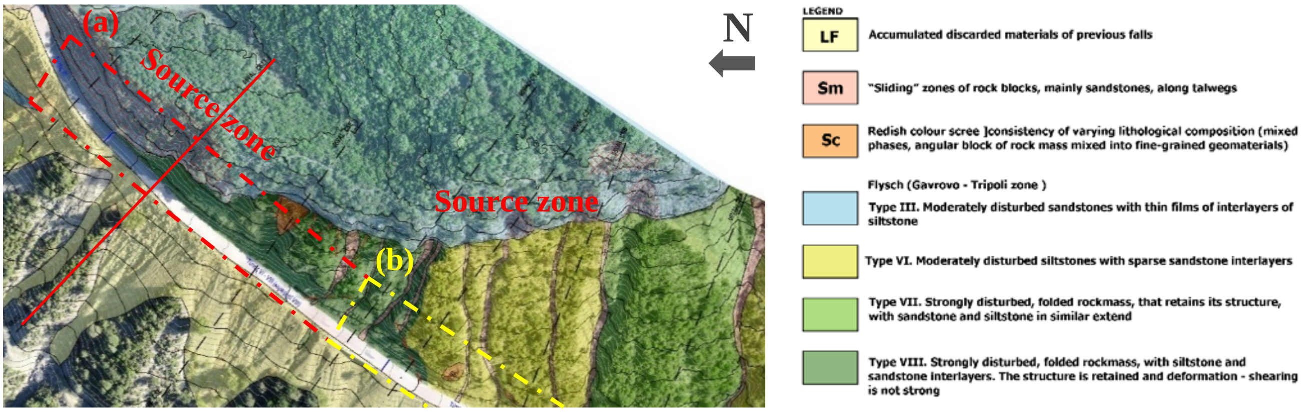

Figure 9 Engineering-geological map of the study area showing: (a) the high-risk northern area and (b) the safer southern area.

The southern section, characterized by rockfall sources at higher altitudes and increased slope height, exhibited a more favourable setting. In this section, most rockfalls end up in thalwegs, with a reduced probability of affecting the road and presenting lower impact energies.

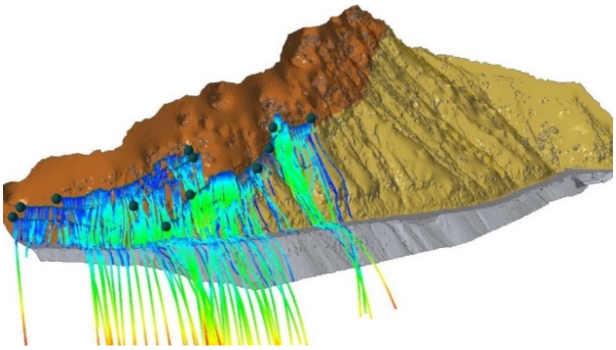

Figure 11 Trajectory analysis on the northern slope reveals high-hazard areas due to significant impact energies. Rockfalls originating from Type III flysch, marked in orange, display steep trajectories toward road infrastructure, with some impacts on Type VIII flysch, shown in yellow.

To address these hazards, a combination of active and passive stabilization methods was proposed. In the northern section, applying bolting techniques to sandstone benches in the upper sections of the slope above the road was limited due to accessibility challenges. Similarly, the implementation of passive measures, like barriers, was constrained by the lack of available space at the base of the slopes.

In light of these limitations, a reinforced concrete protective road shelter was the central proposed solution, featuring an internal width of 9m to accommodate traffic lanes, barriers, and sidewalks, adhering to road-cross-section standards. The shelter's design included a minimum free height of 5m which is supported by piles for stability (**Fig. 12**).

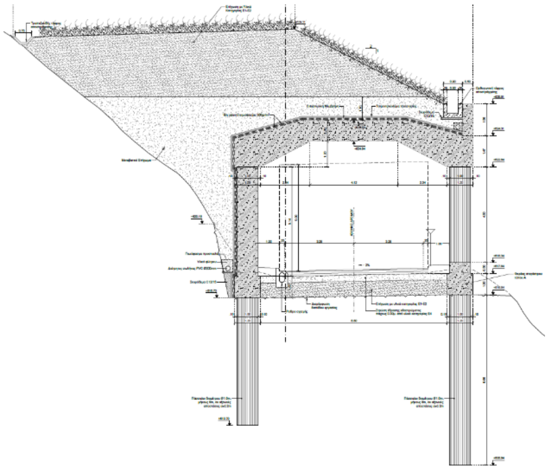

Figure 12 Typical cross-section of the proposed concrete road shelter in the northern part of the slope (**Fig.9 a**).

The decision for the selection of the shelter as the best technical solution, although costly for the category of the specific road, was based on certain particularities. These mainly concerned environmental restrictions for the excavation of high open cuts and the disposal of excavated materials in the nearby area. Additionally, technical solutions consisting of rock fall barriers were not preferable to the Client, due to its practical inability to properly maintain the barriers after a rockfall.

Conclusions

This engineering geological study of rockfall hazards along a provincial road in Valaora, Evritania, Greece, highlights the challenges of geotechnical characterization and mitigation in flysch terrains. The inherent heterogeneity and structural disturbances of flysch formations require advanced techniques to understand failure mechanisms and develop effective countermeasures.

The study combined traditional engineering geological mapping with remote sensing technologies (SfM photogrammetry, TLS LiDAR) along with innovative digital workflows, leading to significant advancements. High-resolution 3D models were instrumental in identifying rockfall sources and analysing structurally controlled failures. Insights from SfM monitoring and change detection algorithms enhanced the understanding of rockfall dynamics, enabling precise identification of detachment locations and a deeper comprehension of behaviour. Monitoring outputs and volumetric measurements supported the calibration of physically-based trajectory modeling, which accurately depicted potential rockfall paths and impact energies, identifying high-hazard zones.

The engineering geological and geomorphological insights, along with the modeling outputs, informed the development of targeted mitigation strategies for the complex flysch failure modes.

References

Abellan, A.; Oppikofer, T.; Jaboyedoff, M.; Rosser, N.J.; Lim, M.; Lato, M.J. (2014) Terrestrial laser scanning of rock slope instabilities. Earth Surf. Process. Landf. 39, 80–97.

Chatzitheodosiou, T. (2023). "One rock at a time" 3D Geology Mini Series. Available at: https://sketchfab.com/themisto123 [Last accessed: 02/2024].

DiFrancesco, P.M.; Bonneau, D.A.; Hutchinson, D.J. (2021) Computational geometry-based surface reconstruction for volume estimation: a case study on magnitude-frequency relations for a LiDAR-derived rockfall inventory. ISPRS Int. J. Geo-Inform. 10.

Ester, M.; Kriegel, H.P.; Sander, J.; Xu, X. (1996). A density-based algorithm for discovering clusters in large spatial databases with noise. In Proceedings of the KDD-96 Proceedings, Portland, Oregon, 2–4 August.

Farmakis, I.; Hutchinson, D.J.; Vlachopoulos, N.; Westoby, M.; Lim, M. (2023). Slope-scale rockfall susceptibility modeling as a 3D computer vision problem. Remote Sensing. 15(11): 2712.

Farmakis, I.; Marinos, V.; Papathanassiou, G.; Karantanellis, E. (2020). Automated 3D Jointed Rock Mass Structural Analysis and Characterization Using LiDAR Terrestrial Laser Scanner for Rockfall Susceptibility Assessment: Perissa Area Case (Santorini). Geotech. Geol. Eng. 38, 3007–3024.

Kromer, R.; Walton, G.; Gray, B.; Lato, M.; Group, R. (2019). Development and optimization of an automated fixed-location time lapse photogrammetric rock slope monitoring system. Remote Sens. 11.

Lague, D.; Brodu, N.; Leroux, J. (2013). Accurate 3D Comparison of Complex Topography with Terrestrial Laser Scanner: Application to the Rangitikei Canyon (N-Z). ISPRS J. Photogramm. Remote Sens. 82, 10–26.

Marinos, V.; Papathanassiou, G.; Vougiouka, E.; Karantanellis, E. (2015). Towards the Evaluation of Landslide Hazard in the Mountainous Area of Evritania, Central Greece. In: Engineering Geology for Society and Territory, Lollino et al. (eds.), Published by Springer – Volume 2, pp. 989-993,

Marinos, V. (2019). A revised, geotechnical classification GSI system for tectonically disturbed heterogeneous rock masses, such as flysch. Bulletin of Engineering Geology and the Environment, 78(2), 899–912.

Westoby, M.J.; Brasington, J.; Glasser, N.F.; Hambrey, M.J.; Reynolds, J.M. (2012). “Structure-from-Motion” Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications. Geomorphology 179, 300–314.