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Geological and Geotechnical Perspectives on Seismic Hazard Assessment of Landslides

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Abstract: The assessment of seismic hazard related to landslides is essential for understanding the complex interactions between seismic activity and slope instability, with direct implications for the protection of infrastructure and communities. This research investigates the role of geological and geotechnical conditions, seismic history, and slope dynamics in the triggering and evolution of earthquake-induced landslides. A multidisciplinary approach was applied, integrating detailed geological and geotechnical investigations with historical data on seismicity and past landslides. To improve the accuracy of the analysis, modern monitoring and modeling methods were employed: geophysical surveys for subsurface characterization, satellite remote sensing for deformation monitoring, and numerical simulations to reproduce slope behavior under seismic loading. The results indicate that areas with unfavorable geological structures, combined with moderate to high seismicity, present an increased probability of slope failure, generating significant risks for both the environment and society. These findings are highly relevant for disaster prevention policies, land-use planning, and the development of construction standards. The novelty of this research lies in applying natural hazard assessment methodologies to ground instability processes with unusual characteristics.

Keywords: Landslides, Instability, Seismic hazard assessment,

Introduction

The assessment of subsurface hazards in areas susceptible to ground instability is critical for ensuring the safety of infrastructure and local communities (Terzaghi et al., 1996; Angeli et al., 2000). In the Slănic, Prahova site, the main concern is a presumed sufoziune, which can compromise tunnel construction and road stability (Wang et al., 2007). A multidisciplinary methodology was applied to characterize the subsurface conditions and evaluate the potential hazard. This approach integrated geophysical investigations, specifically electrical resistivity tomography (ERT), with detailed geological mapping and geotechnical surveys (Loke et al., 2021;

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Adedibu et al., 2024). Modern monitoring techniques, including geophysical surveys for subsurface characterization and numerical modeling to simulate soil behavior under stress, were employed to increase the accuracy of the hazard assessment (Angeli et al., 2000). The results provided a clear image of the heterogeneous subsurface layers and highlighted zones potentially affected by sufoziune. This methodology offers a non-invasive, cost-effective tool for identifying areas of risk, supporting the design of preventive measures, and informing engineering decisions in Slănic (Stoian et al. 2024).

Characteristic Resistivity Ranges and Their Geological Interpretation

Based on literature sources (Table 1) and available data for similar geological structures (e.g., salt diapirs interacting with groundwater), typical ranges of electrical resistivity and their possible geological correspondences have been synthesized (Loke et al., 2021, Adedibu et al., 2024), providing a useful interpretative reference for geoelectric data analysis:

Table 1. Electrical resistivity ranges and geological significance

Resistivity Range (Ω·m)	Possible Geological Interpretation
< 5 Ω·m	Media with highly mineralized water (brine) or zones intensely saturated with brine, associated with very low resistivity anomalies and high electrical conductivity
5 – 10 Ω·m	Clays saturated with water or saline breccias impregnated with brine; characterized by high conductivity (Loke et al., 2021).
20 – 30 Ω·m	Aquifers with fresh water (low salinity) or coarse-grained wet sediments (sands, gravels)
> 100 Ω·m	Massive salt formations (dry halite, with high resistivity) or compact, very dry rocks (Milsom & Eriksen, 2011).

Intermediate ranges (approximately 30–100 Ω·m) may indicate the presence of partially saturated carbonate or marl formations, slightly wet slopes, or transition zones between the lithological units mentioned above. It is essential that the interpretation considers the local geological context. For instance, in the Slănic region, the salt massif generates very high resistivity anomalies, whereas salt breccias resulting from dissolution and collapse processes exhibit very low resistivity values (Stoian et al., 2024).

Methodology

Geological and Geotechnical Investigations

Urban areas developed on geologically complex terrains are prone to instability phenomena that can compromise the structural integrity of buildings and the functionality of infrastructure (Terzaghi et al., 1996; Angeli et al., 2000). Long-term landslide monitoring requires the integration of complementary methods, combining field observations, geotechnical measurements, geophysical surveys, and remote sensing techniques, in order to capture both surface and subsurface deformation processes and to understand their temporal evolution (Angeli et al., 2000).The present study focuses on Slănic, Prahova County, along 23 August Street, where subsidence processes have caused structural damage to residential buildings, deterioration of public roads, and increased risk to underground utilities. To address these challenges, a multidisciplinary program of geological and geotechnical investigations was conducted to provide a robust scientific basis for stabilization measures and risk mitigation.

The investigation framework was designed in accordance with Romanian Norm NP074-2022 "Normativ privind documentațiile geotehnice pentru construcții" and Eurocode 7 (SR EN 1997-1 and SR EN 1997-2), ensuring that data collection, testing, and interpretation followed international geotechnical standards (CEN, 2004; Ministerul Dezvoltării, 2022). Preliminary assessments classified the site as Geotechnical Category 3, reflecting challenging soil conditions, significant groundwater influence, and a high seismic hazard (ag = 0.40g).

The investigation program integrated multiple complementary methods:

- **Geotechnical drilling** with mechanized equipment, providing disturbed and undisturbed samples for laboratory analysis. Recovery rates exceeded 70%, ensuring reliable material characterization.
- **In-situ penetration tests**, including dynamic, static, and CPTu tests, were performed to assess stratigraphy, soil compaction, and strength parameters.
- **Geophysical surveys** explored depths beyond 100 m, revealing lithological boundaries, tectonic discontinuities, underground cavities, salt layers, and potential collapse zones.
- **Hydrogeological studies** included the installation of monitoring wells, pumping tests, and water quality analyses to evaluate aquifer behavior and aggressiveness toward construction materials.
- **Laboratory testing** followed NP074-2022 (Annex L) and included grain size distribution, Atterberg limits, compressibility, shear strength, consolidation, and density analyses to derive reliable geotechnical parameters.

Integration of geological mapping, stratigraphic columns, and tectonic interpretation enabled the development of a detailed subsurface model, supporting the evaluation of bearing capacity, settlement behavior, and slope stability. This model also facilitates risk assessment by identifying vulnerable areas and prioritizing stabilization measures.

Historical Seismicity, Landslide Inventory, and Remote Sensing Monitoring

The methodology incorporated historical seismicity, landslide inventory, and satellite-based remote sensing to assess slope instability in Slănic. Regional earthquake catalogs and macroseismic records were reviewed, focusing on events with magnitudes greater than 5.0. A landslide inventory was compiled using aerial imagery, geological maps, and field verification, documenting past slope failures and their correlation with seismic events (Angeli et al., 2000). Satellite-based monitoring employed Sentinel-1 SAR and DInSAR techniques to detect subtle ground displacements (Necula & Niculiță, 2025), complemented by Sentinel-2 multispectral imagery for land cover and vegetation monitoring. The integration of these datasets enhanced the spatial and temporal coverage of slope activity and supported hazard assessment and monitoring.

Geophysical Surveys

Electrical Resistivity Tomography (ERT) was applied to obtain high-resolution, non-invasive images of the subsurface structures and identify zones affected by saturation and structural weakness (Loke et al., 2021). Data acquisition used an AGI SuperSting R8/IP system with up to 64 electrodes, configured in multiple arrays (Schlumberger, Wenner, Dipole–Dipole) to optimize lateral and vertical resolution. Electrode spacing ranged from 5 to 10 m, and profile lengths were 160–320 m, adjusted for site morphology. Data were inverted using EarthImager 2D with topographic corrections to identify resistivity contrasts associated with lithological boundaries, saturated zones, and structural weaknesses (Stoian et al., 2024).

Numerical Simulations

Slope stability was modeled under static and dynamic conditions using finite element methods. Geological and geophysical data were integrated to simulate potential failure mechanisms under seismic loading. These simulations allowed the quantification of safety factors and identification of threshold conditions for slope failure.

Results and Discussion

Historical Seismicity, Landslide Inventory, and Remote Sensing Monitoring

The assessment of slope instability in Slănic Prahova requires a comprehensive understanding of both natural and anthropogenic factors contributing to ground deformation. Historical seismicity represents a key element in this analysis, as the Carpathian and Subcarpathian region is moderately seismic. Archival records and catalogues of earthquakes in Romania indicate that even moderate seismic events can trigger slope failures in areas with unfavorable geological and geotechnical conditions. Knowledge of seismic history is therefore essential for identifying zones of increased susceptibility and for integrating seismic hazard into landslide risk assessment.

The landslide inventory forms the second fundamental component. Previous field studies, geological surveys, and remote sensing analyses have identified multiple instances of slope movement in Slănic Prahova, including slow-moving landslides, subsidence due to salt dissolution, and small-scale surficial failures. These records allow the development of detailed maps indicating both the spatial distribution of landslides and their morphological characteristics. The integration of historical data, field evidence, and geotechnical parameters supports robust hazard modeling and prioritization of high-risk zones.

Remote sensing monitoring, particularly using Sentinel satellite missions (Figure 1), provides a modern, non-invasive approach for continuous observation of ground deformation. Sentinel-1 Synthetic Aperture Radar (SAR) data enable interferometric analyses (InSAR and multi-temporal InSAR) to detect subtle movements with millimetric precision. Studies have shown differential subsidence and slope deformations in the Slănic Prahova region, with rates up to several tens of millimeters per year (Necula & Niculiță, 2025). Complementary Sentinel-2 multispectral imagery assists in identifying changes in land cover and vegetation health, which can act as early indicators of slope instability. The combination of these datasets allows researchers to detect precursory ground movements, validate field observations, and update landslide inventories in near real-time.

Integrating historical seismicity, landslide inventory data, and satellite-based monitoring provides a multidisciplinary framework for assessing slope hazard in Slănic Prahova. This approach supports risk assessment, urban and infrastructure planning, and the development of early-warning systems. Furthermore, the use of Sentinel-derived data ensures long-term monitoring capability, which is particularly relevant in areas influenced by both natural processes (e.g., earthquakes, karstification) and anthropogenic activities such as salt mining.

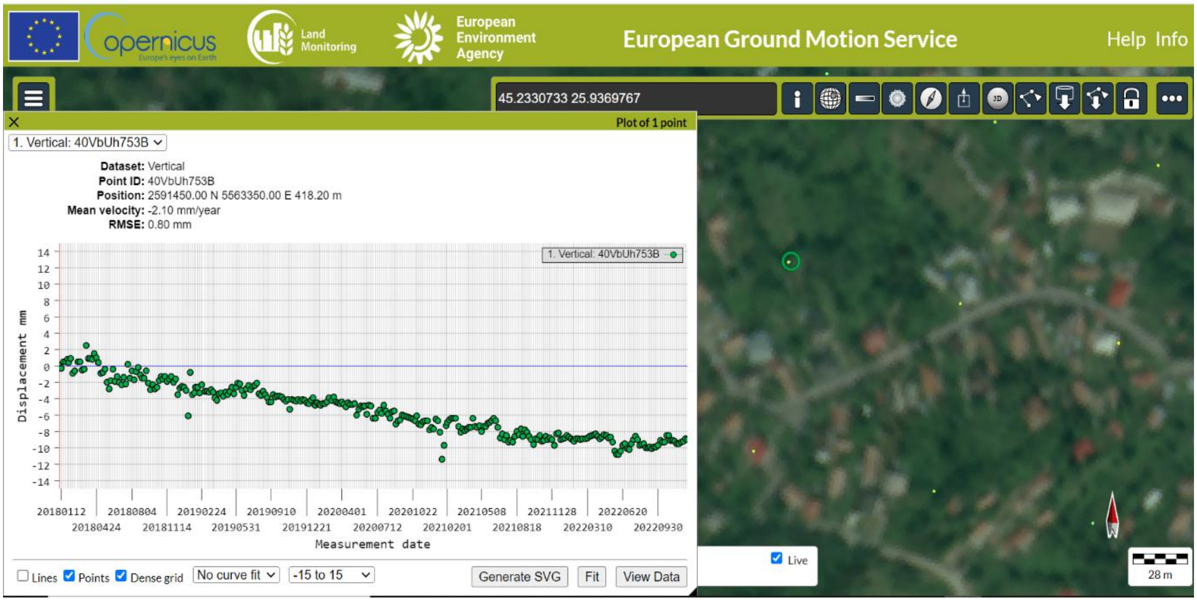

Figure 1. Sentinel-2 data regarding ground subsidence in the affected area

Geophysical Surveys

Geophysical monitoring of areas prone to instability plays a key role in the early identification of subsurface processes that may lead to collapse or suffosion phenomena. In the investigated area of Slănic Prahova, where geological and hydrogeological conditions favor water accumulation and the mobilization of fine fractions, successive geoelectrical surveys were carried out to capture the temporal evolution of subsurface structures. The first campaign focused on the preliminary characterization of the area prior to the occurrence of visible failures, while the second campaign, conducted one year later within the *Geomonitor* project, aimed to extend the depth of investigation and provide a more detailed image of the active processes. Comparing the two profiles offers insights into how the area evolved, from simple geoelectrical anomalies associated with water accumulation, to the development of unstable cavities subsequently filled with heterogeneous materials.

First Geoelectrical Profile

The first set of geoelectrical measurements(figure 2) was conducted prior to the collapse, using passive multielectrode cables with a length of and a maximum investigation depth of approximately 50 m. The chosen dipole–dipole configuration allowed for a large number of measurements and good resolution in the shallow subsurface. The results revealed an irregular relief, with depressional areas characterized by very low resistivity values (<10 Ohm·m), associated with water accumulations. These zones created instability conditions, favoring the onset of suffosion and gradual failure of the upper layers. In addition, GPS RTK data showed that the anomalies extend from 10 m to over 40 m depth, without directly intersecting the main collapse area, but highlighting the predisposition of the terrain to instability (Subsidence Raport,2024).

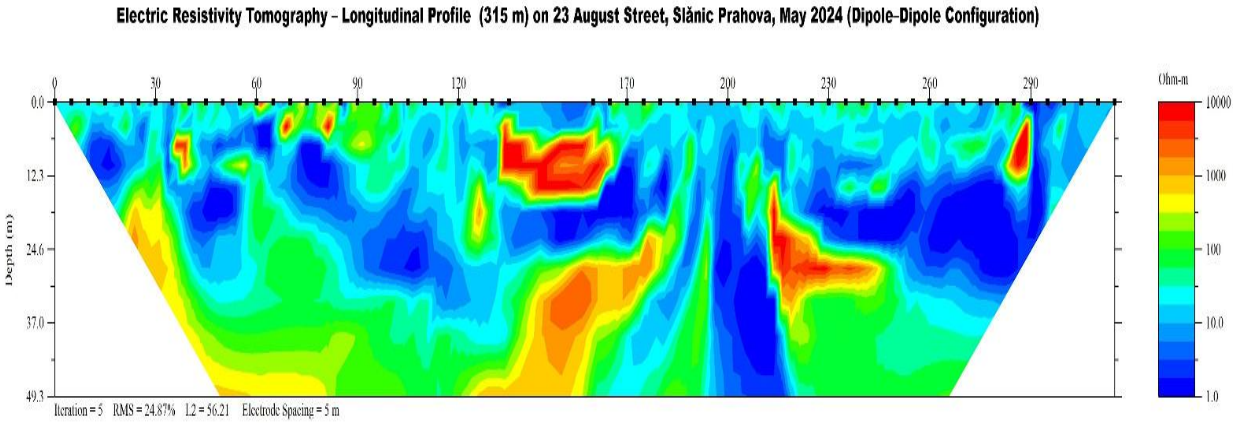

Figure 2. Electric resistivity tomography – Longitudinal profile (315 m) on 23 August Street, Slănic Prahova, May 2024 (Dipole–Dipole configuration)

Second Geoelectrical Profile

One year later, within the Geomonitor project, a new geoelectrical profile was acquired along a roughly similar alignment, extended over a length of 1 km, with electrodes spaced at 10 m intervals (Figure 3). This configuration allowed an investigation depth of approximately 200 m, providing a more detailed image of both lateral and vertical structures. The results revealed major resistivity contrasts: zones with high values (intense red, between 450–650 m, at depths of 50–150 m) interpreted as compact blocks or rock/gravel fillings, alternating with low-resistivity zones (green–blue), characteristic of clayey wet media or areas affected by infiltration. The profile clearly captured the interruption of a more impermeable layer beneath the shallow aquifer, favoring the accumulation and confinement of water in the suffosion zone. Elevated RMS values indicated significant heterogeneity, caused both by natural processes (infiltration, erosion, collapses) and anthropogenic interventions (successive fillings). During the survey, significant electrical anomalies were detected, likely caused by subsurface man-made sources such as deteriorated electrical cables, active grounding systems, damaged DC lines, or other underground current-carrying installations. These interferences necessitated careful differentiation from natural geological resistivity variations (GeoMonitor geophysics report, 2025).

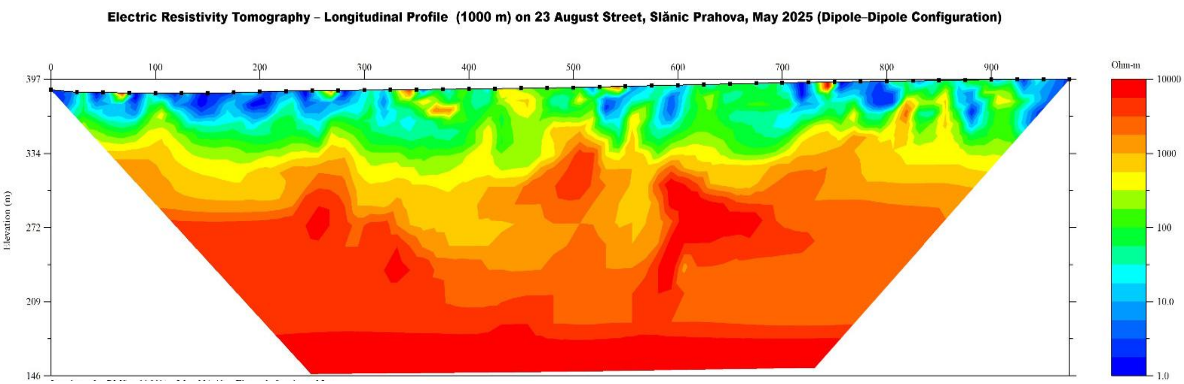

Figure 3. Electric resistivity tomography – Longitudinal profile on 23 (1km) August Street, Slănic Prahova, May 2025 (Dipole–Dipole configuration)

Comparison Between Profiles

A comparison of the two measurement sets shows a clear evolution (Figure 4) of instability processes. While the first profile only captured the presence of low-resistivity zones associated with a predisposition to suffosion, the second profile confirmed that the area continued to subside, developing an unstable cavity that was later filled, naturally and/or artificially, with heterogeneous materials (rock, gravel, clay). This sequence of collapses and fillings is reflected in the rapid alternation of resistivity values and the increased structural complexity revealed by the second survey.

Thus, the evolution from a localized anomaly of limited depth to an extended zone characterized by major resistivity contrasts and active suffosion processes demonstrates the accelerated dynamics of instability in the area. These observations highlight the importance of continuous monitoring and correlation with geological and hydrogeological data, in order to support appropriate risk mitigation measure.

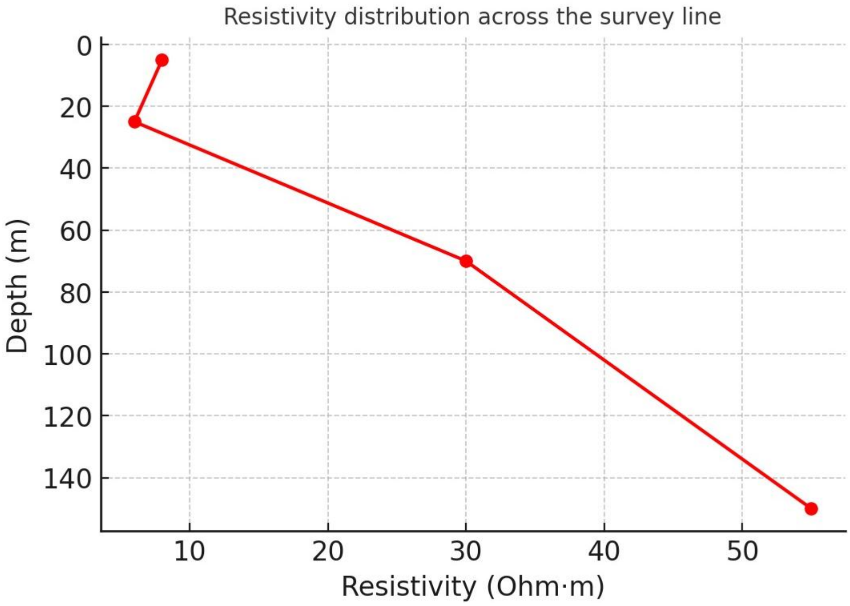

Figure 4. Resistivity distribution across the survey line

Seismic Response Analysis of the Ground in Slănic Prahova Using SHAKE 2000

The stability analysis of the ground in Slănic Prahova, an area prone to instability processes, was performed using the SHAKE 2000 program, which applies one-dimensional equivalent-linear analysis to simulate seismic wave propagation through layered media (Wang et al., 2007). The method accounts for changes in shear modulus and damping with strain level, enabling the assessment of local amplification effects. (Figure 5).

The modeling process included the determination of initial dynamic parameters for each layer (shear modulus and damping), the conversion of input seismic motion into the frequency domain, and the calculation of interactions between incident and reflected waves. The resulting transfer functions were used to evaluate seismic amplification, while the inverse Fourier transform allowed the reconstruction of displacements and strain distribution. Successive iterations led to the final calibration of parameters, with errors below 3%. Based on accelerometric data recorded by the National Institute for Earth Physics (INCDFP) during the Vrancea earthquake of August 30, 1986 (MGR = 7.5), the results for the geological profile at Slănic Prahova highlighted:

- a maximum spectral amplification factor (SAF) of **2.65**, corresponding to a severe Vrancea earthquake scenario (MGR = 7.5) (Figure 6);
- a peak ground acceleration at the surface of **0.254 g** (≈250 cm/s²)(Figure 7);
- a fundamental site period of **1.4 s**, associated with the stratified structure of deposits; (Figure 8)
- a maximum spectral acceleration amplitude of **0.812 g**. (Figure 9)

As a reference for the bedrock, the formation with a shear-wave velocity of 760 m/s was considered, representative of the more rigid structures at depth.

These results indicate that the ground in Slănic is highly sensitive to strong-magnitude seismic events, and the existing instabilities may be exacerbated by local seismic amplification effects. The integration of such evaluations contributes to a better understanding of hazard mechanisms and supports the development of risk reduction measures for infrastructure and communities.

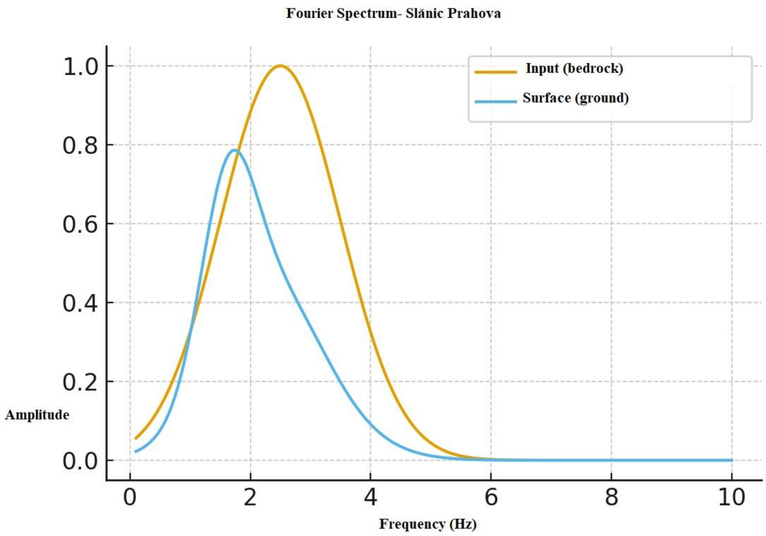

Figure 5. Fourier spectrum-Slănic Prahova

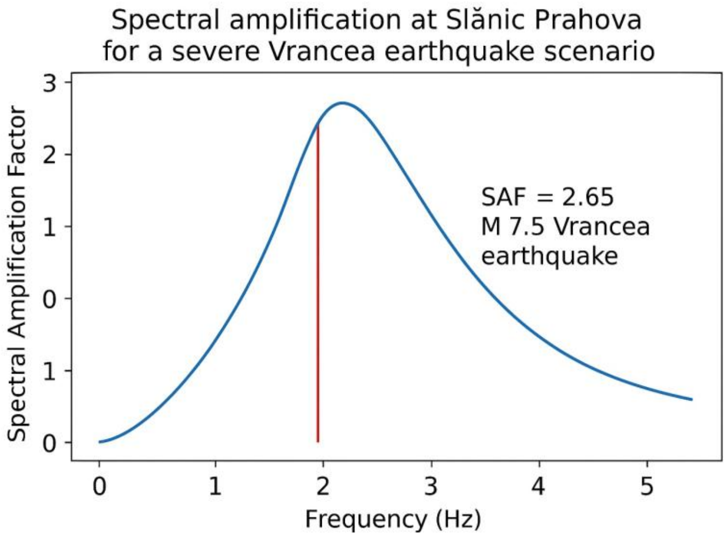

Figure 6. Spectral amplification factor (SAF)-Slănic Prahova

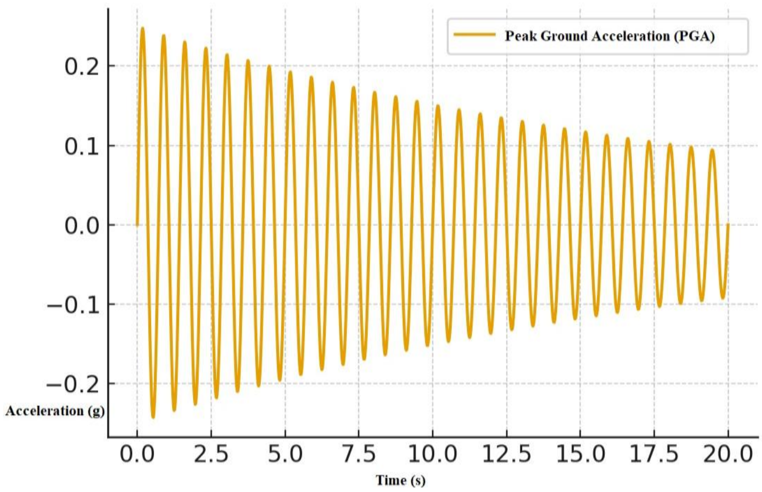

Figure 7. Peak ground acceleration (PGA)

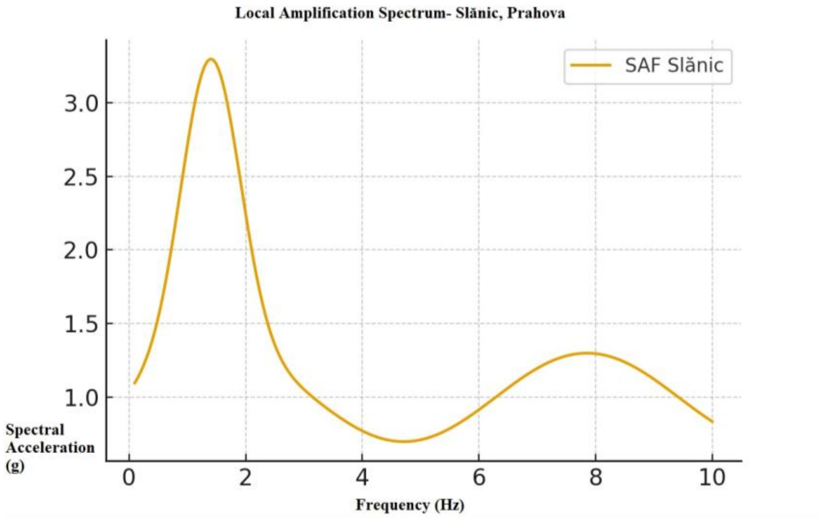

Figure 8. Acceleration time history-Slănic Prahova

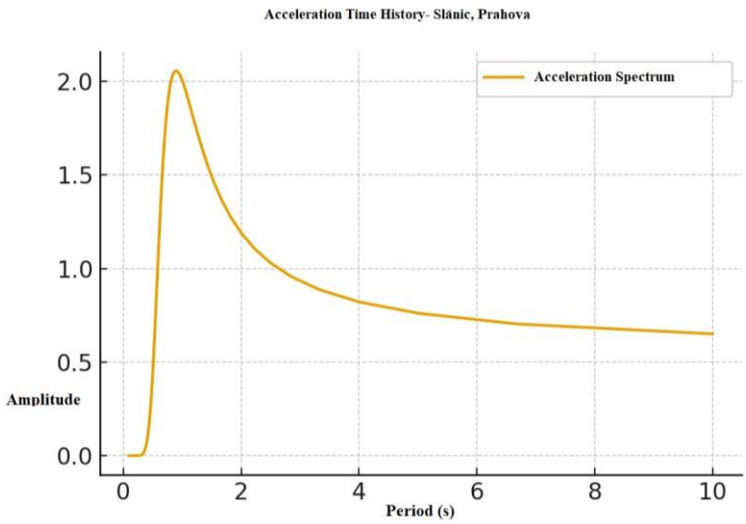

Figure 9. Response spectrum-Slănic Prahova

Conclusion

The geoelectric and hydrogeological analysis of the Slănic Prahova area highlights a complex interaction between the salt massif and groundwater, which influences both surface relief and terrain stability (Stoian et al., 2024). Zones of minimum resistivity directly indicate locations where the subsurface is weakened by water accumulation, representing potential collapse points. Detailed geophysical investigations indicate that the aquifer boundary and the compact clayey/marly formations supporting the main building foundations do not pose significant risks to their stability. However, the subsidence cone area on 23 August Street is not stabilized, and electrometry measurements indicate a continuous risk of collapse. This underscores the need for permanent monitoring and the implementation of proactive measures to prevent terrain instability phenomena (Angeli et al., 2000).

Recommendations

- *Expansion of the geophysical and hydrogeological monitoring program* through the installation of sensor networks for real-time measurement of water levels, ground displacements, and resistivity variations, enabling early detection of sufozional processes.
- *Execution of additional geological and hydrological boreholes* to investigate the depth of the salt massif, identify groundwater flow paths, and assess the structural stability of the soil in critical areas.

- *Development of an integrated geological and hydrogeological map* at a detailed scale (1:5,000), including geophysical, geochemical, and geomorphological parameters, highlighting zones with high risk of terrain instability.
- *Design and implementation of groundwater control measures*, including drainage, controlled diversions, or selective impermeabilizations, to limit salt dissolution processes and fine particle washout in high-risk areas.
- *Establishment of a rapid response protocol* in the event of instability phenomena, including automated alerts, evacuation plans, and coordination with local authorities to protect the population and built heritage.
- *Assessment and design of structural reinforcements* for existing buildings if significant subsurface changes or new unstable zones are detected, using methods adapted to the local soil characteristics and salt massif conditions.

Scientific Ethics Declaration

* The authors declares that the scientific, ethical, and legal responsibility for the content of this article, published in EPSTEM Journal, rests solely with the authors.

* No ethics committee approval was required for this study, as it did not involve human or animal subjects.

Conflict of Interest

*The authors declare that they have no financial, personal, or professional conflicts of interest that could have influenced the outcomes or interpretation of this research.

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