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THE ROLE OF SEISMIC GEOPHYSICAL METHODS IN NEAR-SURFACE CHARACTERIZATION

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Abstract

Near-surface characterization, i.e., determination of the physical-mechanical characteristics of the soil and rock masses that constitute the terrain structure is crucial in avoiding catastrophic consequences during seismic and geotechnical hazards. Geophysical techniques can provide a comprehensive understanding of subsurface conditions, including the presence of weak zones, local anomalies, groundwater levels, slope stability, and tectonic structures, offering valuable information for assessing potential risks and hazards. Surface seismic methods are non-invasive and widely accepted geophysical techniques for near-surface characterization and have been used in IZIIS for an extended period. This paper presents two case studies of geophysical surveys conducted for site characterization purposes. Combined seismic method surveys were performed in Strumica, N. Macedonia, at the site of the Orta Mosque. The primary motivation for this study was the appearance of cracks in the Orta Mosque building, which have progressively expanded over time. A similar procedure was applied at the location for tunnel construction in Aleksinac, Serbia. The main objective in both cases has been definition of the seismo-geological characteristics, potential anomalies, local tectonic deformations, and discontinuities in the terrain structure. The seismic models derived from the seismic refraction survey at the Orta Mosque site indicate layers of unconsolidated deposits, with a maximum recorded depth of over 20 meters. The seismic reflection sections, displayed in 3D to provide a more realistic view of the discontinuities and the slope of the bedrock, indicate deformations and local disturbances in the deeper layers. The variation in the thickness of the surface layers, as recorded in the seismic refraction profiles conducted at the tunnel site in Serbia, indicates anomalies, i.e., unstable zones, which are also identified in the deeper layers through reflection profiles. Interpreted discontinuities and deformations in the terrain structure in both case studies point to underlying dynamic processes.

Keywords: geophysical survey, seismic methods, site characterization, combined approach

1. Introduction

In this paper, the applied methodology and the results of two case studies of geophysical surveys conducted for site characterization purposes are presented.

The first location is situated in Serbia, near the town of Aleksinac, in the southern part of the country [1]. The main goal of the surveys was to perform seismo-geological modeling of the site proposed for tunnel construction. Geophysical surveys were conducted using a combined approach involving two different seismic methods: seismic refraction and seismic reflection [2]. Based on previously conducted geotechnical boreholes, the terrain structure comprises diluvial deposits in the surface layers, which overlay Miocene sediments. The seismic bedrock primarily consists of andesite gneisses and migmatites.

Considering the significant distances between the boreholes, the geophysical surveys conducted at this location were highly important. Combined with data from the drilled boreholes, they enabled advanced seismo-geological modeling and characterization. Seismic refraction surveys allowed the determination of the thickness of the unconsolidated deposits, as well as variations in their physical-mechanical characteristics both laterally and in depth, along with the detection of local anomalies. On the other hand, seismic reflection profiles provided valuable insights into discontinuities and deformations within the terrain structure.

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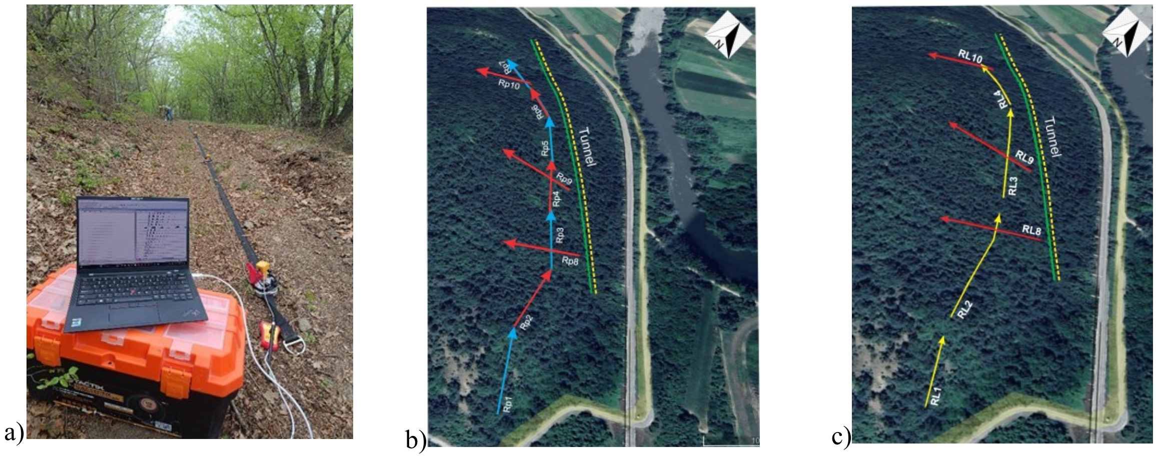

Figure 1. Geophysical surveys in Aleksinac. a) Photo of the survey location; b) Seismic refraction profiles layout; c) Seismic reflection profiles layout.

The second survey location is situated in the city of Strumica, which belongs to the southeastern part of North Macedonia. The motivation for this study stemmed from the appearance of cracks in the Orta Mosque building, which have progressively expanded over time. What is specific about this location is the lack of sufficient geological data, as well as the absence of geomechanical boreholes, which were not conducted due to the inaccessibility of the terrain for drilling machines. As a result, this case study relies only on the results of the geophysical surveys [3].

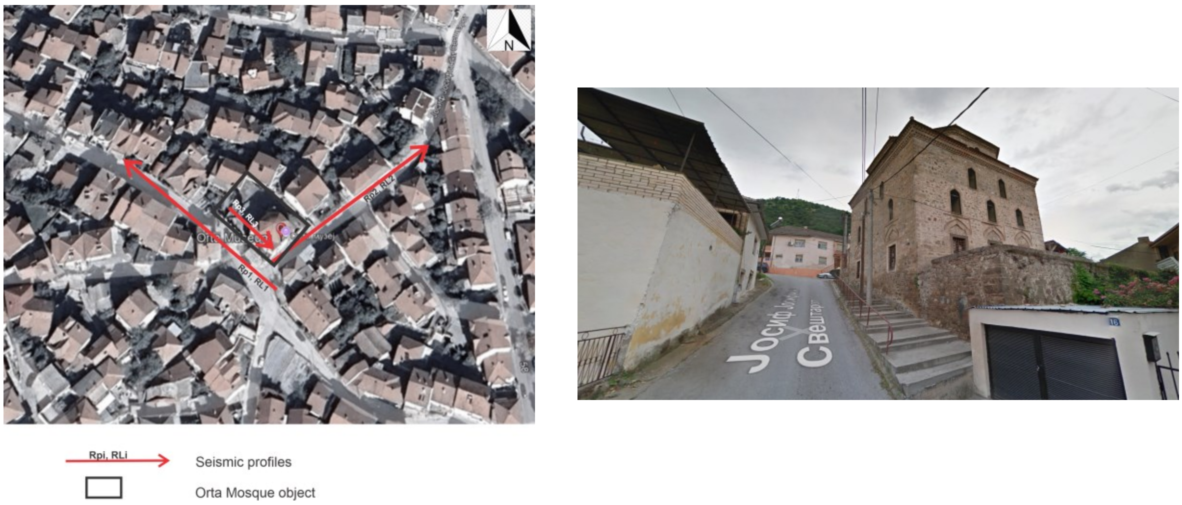

Figure 2. Geophysical surveys in Strumica – Orta Mosque. a) Seismic profiles layout; b) Photo of the survey location

In both case studies, the geophysical methods of seismic refraction and reflection were applied in a combined approach to achieve more detailed and higher-resolution seismo-geological modeling of the terrain structure [4, 5]. The results are presented primarily as 2D seismic models. A 3D display of the seismic reflection sections from the surveys conducted at the Orta Mosque location provided a more realistic view of the discontinuities and the slope of the bedrock [6].

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2. Research Methodology: Data Acquisition and Processing

In-situ measurements were performed using both seismic refraction and reflection methods with the SoilSpy Rosina multichannel digital seismograph (MoHo - Science & Technology, Italy). Additionally, a seismic landstreamer was employed for seismic reflection measurements, utilizing the roll-along method for data collection. The seismic energy was generated by vertical 10 kg sledgehammer blows on an aluminium plate and was recorded by 4.5 Hz vertical geophones.

The pre-processing of the data was performed using the SoilSpy Rosina software, MoHo - Science & Technology, Italy. The consecutive analyses and interpretation of seismic refraction and reflection data were carried out applying the ReflexW software - Dr. K-J. Sandmeier, Germany.

For the processing of seismic refraction data, the tomographic approach is used. This approach performs better in many situations where traditional refraction techniques fail, such as in modeling subsurface velocity structures with both lateral and vertical velocity gradients. The tomographic concept relies on a gridded initial model for an iterative process, determining the velocity of individual 2-dimensional grids within a profile, rather than modeling the subsurface structure as constant-velocity layers (commonly referred to as 'cake layers'). This method provides higher-resolution modeling of complex subsurface structures. [7, 8].

Processing of the seismic reflection data was performed using the Common Midpoint (CMP) technique, which involves stacking seismic records reflected from the same point at stratigraphic boundaries [9]. Pre-stacking static corrections and 1D and 2D filtering were applied to the raw data, followed by post-stacking depth migration. The complex processing of seismic reflection data enables the precise definition of layer boundaries, seismic bedrock, local deformations, and discontinuities with very high accuracy and resolution.

2.1. Case study: Aleksinac, Serbia – Data aquisition

Geophysical surveys along a total of 4 seismic profiles have been performed on the location planned for tunnel construction in Aleksinac, Serbia (Fig.1). Surveys with application of the seismic refraction method were performed along 1 longitudinal profile which consists of 7 segments (Rp1-Rp7) and 3 transversal profiles (Rp8, Rp9 and Rp10). Seismic reflection surveys were performed along 1 longitudinal profile which consist of 4 segments (RL1, RL2, RL3 and RL4) and 3 transversal profiles (RL8, RL9 and RL10).

Measurements using the seismic refraction method along the seismic profiles were conducted with a geophone spacing of 5.25 meters and a minimal offset (distance between the source and the first receiver) of 5.25 meters. Data acquisition was carried out with a sampling frequency of 512 Hz and a time length of 0.5 seconds.

For the seismic reflection method, the Common Depth Point (CDP) technique was applied with a fixed distribution for seismic profiles RL8, RL9, and RL10, using the same seismic spread as that used for the seismic refraction method. Measurements along seismic profiles RL1, RL2, RL3, and RL4 were performed using the roll-along technique, with a geophone spacing of 3 meters, an excitation step of 6 meters, and a minimum offset of 6 meters.

2.2. Case study: Strumica, N. Macedonia – Data aquisition

In-situ measurements using seismic methods were conducted at the survey locations in a practical and effective manner. The same seismic equipment and, in most cases, the same acquisition parameters were used, ensuring a time- and cost-effective survey for subsurface characterization, using the SoilSpy Rosina multichannel digital seismograph (MoHo - Science & Technology, Italy).

Certain site-specific details on the “in situ” measurements are as follows:

Seismic refraction measurements were conducted along a seismic spread of 17 channels (Rp1, Rp2) with a geophone spacing of 5 meters, a near offset (minimal source-to-receiver distance) of 5 meters,

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an excitation step of 20 meters at 5 points through the seismic spread. Measurements along Rp3 (seismic spread of 13 channels) were performed with a geophone spacing of 2 meters, a near offset of 2 meters.

Seismic reflection measurements were conducted along a fixed seismic spread of 17 channels (RL1, RL2) using the following acquisition parameters: a geophone spacing of 5 meters, an excitation step of 10 meters, a near offset of 6 meters. Measurements along seismic profile RL3 were conducted with a fixed seismic spread of 13 channels, a geophone spacing of 2 meters, an excitation step of 4 meters, a near offset of 3 meters.

In all cases, the seismic record duration was 0.5 seconds, with a sampling frequency of 1024 Hz.

3. Results: Findings and Interpretation

The results from the investigations using the seismic refraction method consist of 2D seismic models that map the lateral variations in Vp and Vs seismic velocities down to a depth of 20-30 meters. Based on these variations, different lithological media have been identified. The results from the seismic reflection survey consist of 2D seismic sections, which help identify local disturbances, deformations, and anomalies in the terrain structure, both in surface media and deeper layers, down to a depth of 150m.

3.1. Results from the Seismic Survey in Aleksinac, Serbia

According to 2D seismic models derived from data analyzed using the seismic refraction method, four lithological media have been identified. These media are characterized by distinct physical-mechanical properties.

The variation in seismic Vp and Vs velocities, combined with existing geological data, indicates the following lithological media:

- Surface layer – deluvial deposits characterized by seismic velocities in the interval of: Vp=240-750 m/s; Vs=120-310 m/s
- Subsurface layer – decomposed sandstones, loose and crushed rock: Vp=750-1150 m/s; Vs=310-430 m/s;
- Intensively fractured rocks -with seismic velocities: Vp=1150-1700m/s; Vs=430 - 630 m/s;
- Intensively to moderately fractured rocks-with seismic velocities: Vp=1700-2000 m/s; Vs=630 - 780 m/s;

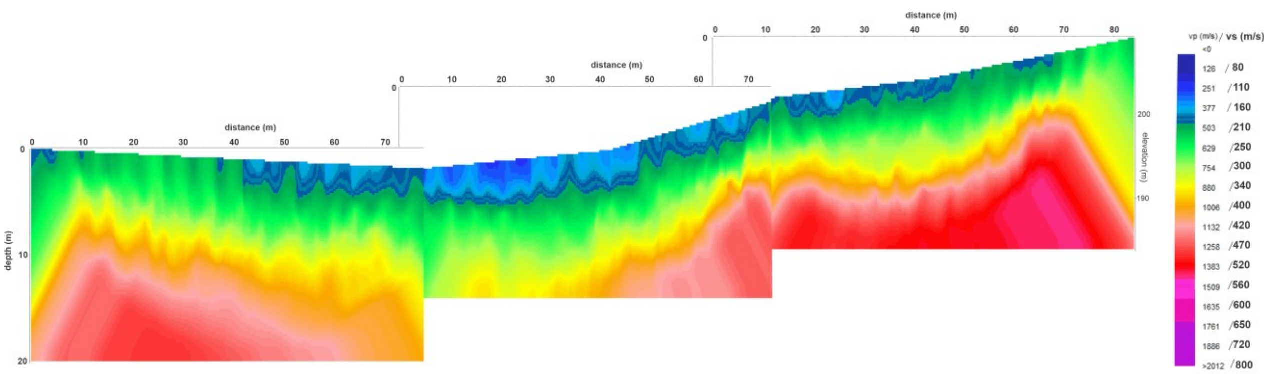

Figure 3. 2D Seismic refraction profiles Rp2, Rp3 and Rp4

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.123

By interpreting the final seismic refraction models, the following conclusions can be drawn:

- Surface layers with relatively weak physical-mechanical characteristics (Vs < 310 m/s) have been identified at depths ranging from a maximum of 3 meters along profile Rp1 to 7 meters along Rp2. At the positions of seismic profiles Rp3 and Rp8, as well as along profiles Rp4 and Rp9, the thickness of this layer varies between 7 and 10 meters. Seismic profiles Rp5, Rp6, and Rp7, indicate shallower deluvial deposits.
- Based on seismic wave propagation velocities (Vs = 310–430 m/s), the subsurface consists of decomposed, loose rocks. Between the end of profile Rp2 and the start of profile Rp3, located near the tunnel's exit, the layer is not detected down to a depth of 20 meters, as shown in Fig. 3, marking the most critical area. This anomaly is also observed along the first half of profile Rp8, which was conducted transversely to Rp3. In the central site, seismic profiles Rp3, Rp4, and Rp9 indicate the layer at depths of 10 to 15 meters. Along profiles Rp5, Rp6, and Rp7, extending from the central part toward the tunnel's entrance, the layer is recorded at a maximum depth of 7 to 10 meters.
- This interpretation is based on 2D seismic refraction profiles conducted along the longitudinal seismic profile, which consists of seven segments in total (Rp1–Rp7), as well as three transverse profiles (Rp8, Rp9, and Rp10) (Fig.1b). This paper presents three segments of the longitudinal profile—Rp2, Rp3, and Rp4—which represent the most critical zone of the survey site in terms of the thickness of the surface loose layers (Fig3).

The variation in the thickness of the surface layers recorded in the seismic refraction profiles indicates discontinuities in the terrain structure of the investigated site, as defined by the 2D reflection sections obtained from these investigations.

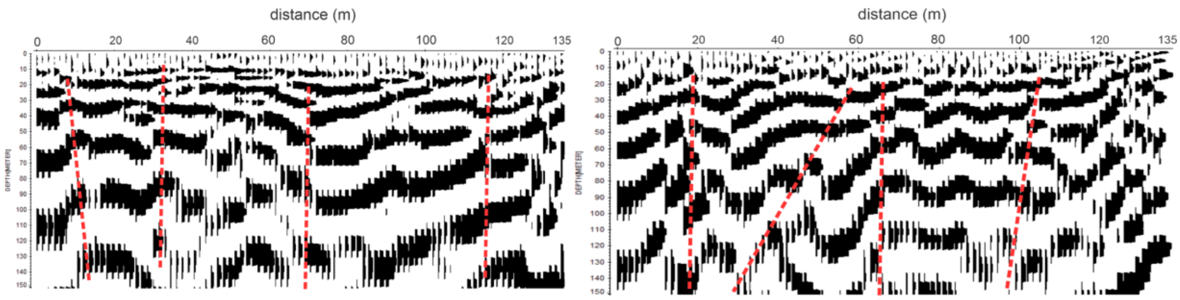

Figure 4. 2D Seismic reflection sections RL2 and RL3

- Very pronounced deformations have been recorded along the seismic reflection profiles conducted at the survey location. The interpreted discontinuities (marked by a red dashed line), observed along seismic reflection profiles RL2 and RL3—which were conducted along the same seismic line as the refraction profiles presented above—indicate anomalies, i.e., unstable zones, even in the deeper layers (depth > 20 m). These deformations, as identified in the seismic reflection profiles, have also been observed at the same positions within the surface layers, as determined from the seismic refraction profiles (Fig.4).

- The interpreted deformations and local disturbances in the terrain structure indicate the presence of internal dynamic processes of tectonic origin.

3.2. Results from the Seismic Survey in Strumica, N. Macedonia

The final results from the geophysical surveys at the Strumica site enabled successful seismo-geological modeling of the terrain structure, including the definition of the surface layer thickness composed of loose, degraded rock, as well as the identification of discontinuities and anomalies in both the surface and deeper layers, which was the main objective of the survey.

According to the final 2D seismic refraction models, the terrain structure at the Orta Mosque site consists of the following lithological media:

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• Surface layer with values of seismic velocities: Vp=200-750 m/s; Vs= 100-280 m/s;

• Subsurface zone consisting of degraded, decomposed, and intensely cracked rocks, with seismic velocity values: Vp=800-1500 m/s; Vs=350-580 m/s;

• Intensively cracked to more compact rocks with seismic velocity values: Vp>1600m/s; Vs>600 m/s

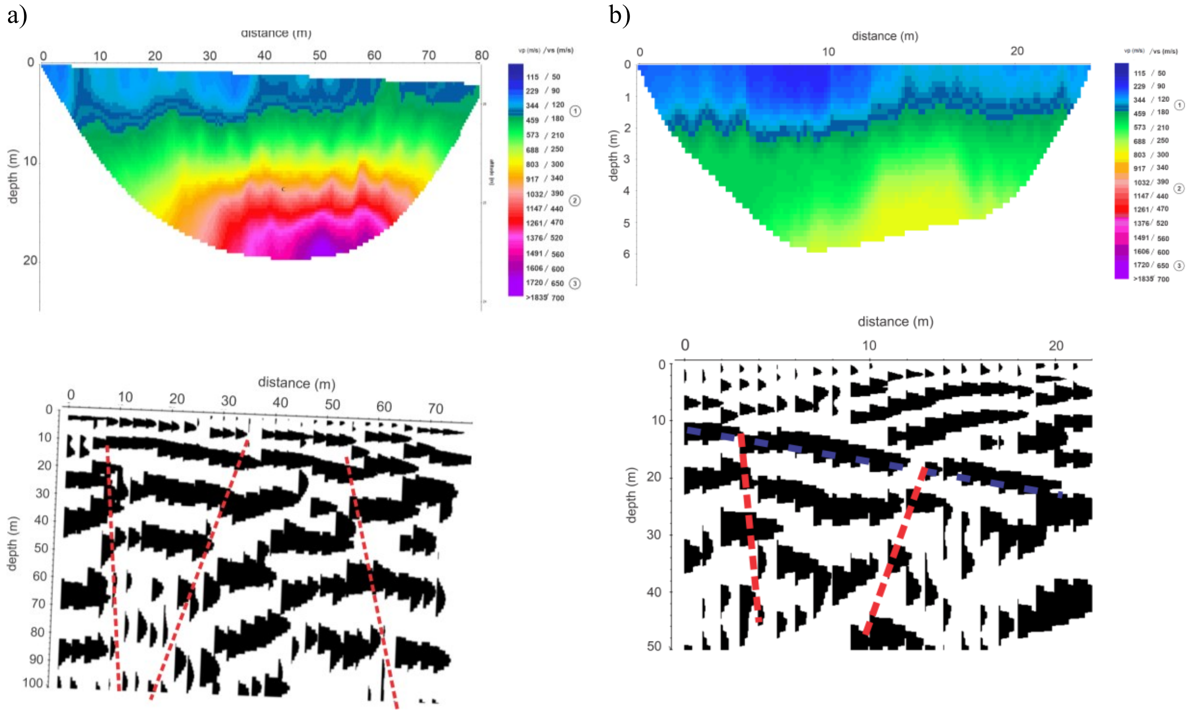

Figure 5. 2D seismic refraction and reflection models a) Rp2 and RL2 with defined discontinuities (red dashed lines). b) Rp3 and RL3 with defined discontinuities (red dashed lines)

Figure 6. 3D display of the seismic reflection sections. a) RL2 and RL3 with defined discontinuities (red dashed lines). b) RL1 and RL2 with defined discontinuities (red dashed lines)

Based on the interpretation of the final seismic refraction models, the following conclusions can be drawn:

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- Surface layers characterized by quite weak physical-mechanical characteristics (Vs<300m/s) have been recorded at maximum depth of 12 m at each of the performed refraction profiles.
- The subsurface zone, based on the defined seismic velocity values (Vs=350-580m/s), is composed of degraded, decomposed, and intensely cracked rocks, recorded at maximum depths exceeding 20m.

Although the refraction profiles do not indicate significant variations in the surface layers (d < 20 m), the seismic reflection profiles reveal discontinuities in the deeper layers (d > 10 m), suggesting deformations and local disturbances caused by internal dynamic processes. This can especially be concluded from the 2D models shown in Fig. 5, where in both cases, the refraction profiles indicate an improvement in the physical-mechanical characteristics of the rock with the depth, in contrast to the seismic reflection sections, which reveal deeper weak zones and deformations in the terrain structure.

In Fig.6, the seismic reflection sections are presented in 3D to provide a more realistic depiction of the local deformations, discontinuities, and the slope of the bedrock.

4. Conclusions

The results presented above emphasize the importance of applying geophysical methods for seismo-geological modeling of terrain structures and assessing potential risks and hazards.

The primary objective of the surveys conducted at the first location in Aleksinac, Serbia, was to identify critical loose zones that could pose hazards during tunnel construction. While geotechnical surveys offered preliminary insights into the terrain structure, they proved insufficient for detailed forward planning and analysis due to the large gaps between survey points and the lack of data on physical-mechanical characteristics. The application of seismic geophysical methods, using a combined approach, enabled a successful modeling of the terrain structure, determination of surface layer thicknesses, and characterization of seismo-tectonic structures.

In situ measurements using seismic methods at the Orta Mosque site were conducted in a practical and effective manner, using the same seismic equipment and, in most cases, the same acquisition parameters, ensuring a time- and cost-efficient survey for subsurface characterization. Seismic refraction models indicate the presence of unconsolidated deposits extending to a maximum depth of over 20 meters. Seismic reflection sections, presented in a 3D display, provide a more realistic visualization of local deformations, discontinuities, and the slope of the bedrock. These sections point to deformations and disturbances not only in the surface layers but also in the deeper layers. Such anomalies in the terrain structure indicate internal dynamic processes that are considered responsible for the cracks observed in the building.

From the findings presented above, it can be concluded that the most widely used seismic methods—seismic refraction and reflection—have once again demonstrated exceptional effectiveness for near-surface characterization. The methodology is particularly valuable for sites where access to conventional subsurface investigations, including drilling boreholes, is challenging or limited. This carries significant implications for future surveys focused on near-surface characterization, not only in urban environments where traditional invasive methods may be limited or unfeasible due to space constraints, infrastructure disruptions, and high costs, but also in rural or remote settings, such as mountainous regions, where the challenges, though different, are equally significant.

While conventional borehole drilling provides direct measurements of subsurface conditions and is essential for site characterization, surface seismic methods, with their ability to model subsurface structures in detail over larger areas, offer a broad view of subsurface conditions. This makes them invaluable for complementing localized borehole data and enabling more comprehensive assessments. In cases where geotechnical and geological data are insufficient, the combined use of these seismic methods has proven to be the most cost- and time-efficient approach, enabling complex modeling of terrain structures in both case studies presented in this paper.

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