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LANDSLIDE TRIGGERING AS AN INDIRECT CONSEQUENCE OF AN EARTHQUAKE - CASE STUDY FROM NORTHERN CROATIA

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Abstract

A landslide is the movement of soil and rocks down a slope as a result of the loss of shear strength in the material that builds the hill. Although various human activities increase the risk of landslides, the most common causes for the loss of shear strength are geological and morphological. Thus, natural triggers for landslides can be the characteristics of the soil and rocks that build the slope, the slope angle, erosion, and water, but this paper will analyse the triggering of landslides as indirect consequences of earthquakes. In 2020, two significant earthquakes hit central Croatia. First, a moderate earthquake was triggered in the area of Zagreb, and towards the end of the year, a strong earthquake hit the regions of Petrinja, Sisak and Glina. In addition to the enormous damage to buildings, the mentioned earthquakes indirectly activated numerous landslides, including in the area of Northern Croatia. The landslide in Slatina Svedruška near Petrovsko was activated immediately after the Zagreb earthquake. This instability potentially threatened the D206 state road corridor. Engineering geological and recent geotechnical-geophysical investigations were applied to define the instability boundaries, the lithological composition of sediments in the subsurface, and the location of the sliding surface. The unfavourable geological structure was determined, as silty sands and clays predominate in the surface layers, and organic clays of low shear strength appear immediately before contact with marl. The mentioned location of the landslide was selected for microtremor measurements that will be carried out as part of the Croatian Science Foundation (HRZZ) project IP-2022-10-1296, SIGMATOPCRO.

Keywords: earthquake, landslide, geotechnical investigations, geological investigations, microtremor.

1. Introduction

Landslides are conditioned by several terrain and geo-environmental factors and can be triggered by different kinds of natural processes (rainfall, earthquakes, etc.) but also by man-made activities [1]. Understanding and mitigating the risks associated with earthquake-induced landslides requires a comprehensive approach tailored to specific geographical regions and local conditions. By recognizing the interactions between seismic events and slope stability, communities can better prepare for and respond to these natural hazards, ultimately reducing loss of life and property damage.

Earthquake-induced ground shaking can trigger landslides by applying horizontal and vertical accelerations to the soil or rock mass along a hillside slope. The critical or yield acceleration, denoted as ac, represents the peak ground acceleration within the sliding mass required to reduce the factor of safety to 1.0. Typically, this acceleration value is determined through pseudo-static slope stability analyses or empirical observations of slope behaviour during past earthquakes and does not depend on the earthquake hazard at the location. Simply, if the earthquake acceleration reached at a certain seismic event is higher than the critical acceleration of the potential sliding mass, landslide induced by earthquake will occur.

Several empirical models have been developed to predict the seismic displacements of sliding masses [2-4]. These models estimate downslope deformations when the induced peak ground acceleration

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within the sliding mass exceeds the critical acceleration. They are grounded on the assumption of a sliding rigid block, providing a measure of dynamic slope performance.

Site amplification related to topography can be also an important factor in coseismic triggering of landslides as an indirect consequence of an earthquake (it can be triggered at some time after mainshock). Furthermore, site response directivity can be relevant in enhancing susceptibility of slopes to earthquake induced failures considering that in most of the observed cases the direction of maximum shaking resulted close to that of the maximum slope [5-7]. Furthermore, site response directivity can be relevant in enhancing susceptibility of slopes to earthquake induced failures considering that in most of the observed cases the direction of maximum shaking resulted close to that of the maximum slope.

Slope response to seismic shaking can be influenced by directional variations of a factor of 2–3 or more prominent, with maxima oriented along local topography features (e.g. maximum slope direction, geotechnical and geological characteristics). This phenomenon appears influenced by slope material properties and has occasionally been detected on landslide-prone slopes, where a down-slope directed amplification could enhance susceptibility to seismically-induced landsliding [6,7].

In 2008 Del Gaudio et al. [5] performed detection of directivity in seismic site response using microtremor (ambient noise) measurements compared with average H/V spectral ratios obtained for low-to-moderate earthquakes recorded by the accelerometric stations. Ambient noise vibrations allow rapid detection and seismic monitoring of dynamic response of topographic slope [8]. It is possible to distinguish unstable areas, slope eigenfrequencies and local amplification levels (due to weak excitation) [9]. Based on the above claims, microtremor measurements were conducted in the case of a landslide in Slatina Svedruška (Fig. 1).

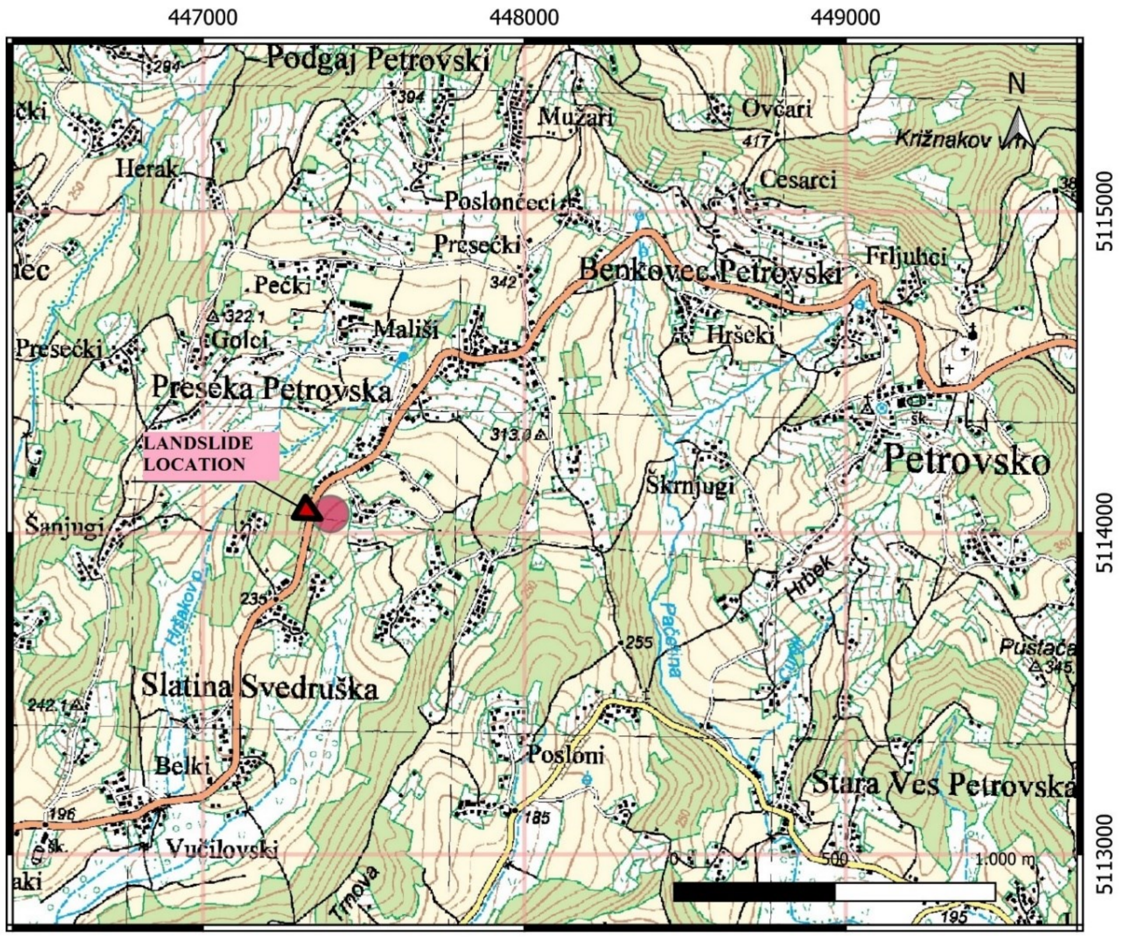

Figure 1. Map of landslide location in Slatina Svedruška near Petrovsko.

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Detailed engineering geological and recent geotechnical-geophysical investigations on the landslide were carried out at the beginning of 2021, and detailed results are available in [10]. In 2024, additional geological and microseismic investigations through microtremor (ambient noise) measurements were carried out as part of the SIGMATOPCRO project.

2. Methods and results of previous investigations from 2021

According to information from residents of the village of Slatina Svedruška near Petrovsko (Fig. 1), a landslide occurred in early 2020, immediately after the earthquake in Zagreb. The D206 state road corridor may have been in danger due to this instability. At the beginning of 2021, detailed engineering geology and geotechnical-geophysical investigations were conducted on a 5000-square-meter landslide. The bounds of instability and the lithological composition of sediments in the subsurface and sliding surface were identified. The sliding surface's depth was assessed using a Dynamic Probe Light (DPL) and a Cone Penetration Test (CPTu). Geophysical investigations were conducted utilizing Electrical Resistivity Tomography (ERT), Seismic Refraction (SRF), and Multichannel Analysis of Surface Waves (MASW).

Sliding elements was evident in the landslide: material pushed into the foot, a forehead with a tensile crack, and a jump of up to h = 2.5 m (Fig. 2). The type of sliding indicates that the landslide is translational-rotational. The entire displacement is roughly 10 meters, and the displaced masses match a volume of about 2000 m^3. Over a distance of 150 meters, the tensile crack is visible. As the landslide is inched, the masses move 30 to 60 meters in courses.

Figure 2. Tensile crack with a jump in the northern part of the landslide.

The investigation's findings provided information on the structure of the soil stratigraphy, which in turn produced the comprehensive geotechnical landslide profile (Fig. 3). The lithological composition of the ground was ascertained by analysing the results of static and dynamic probing and geophysical surveys:

1. The surface soil up to a maximum depth of 6 m is built of siltstone sands and sand-siltstone clays. Klastites are in sedimentary exchange from silty sands (siSaP) to clayey silt, and fine gravel is also present within the sand series. At a depth of 6 m, the CPT probe identified clays with organic impurities, low shear strength. A sliding surface was identified at the same depth. Soil parameters at the 1st interval (0 – 6 m): c_u = 20 - 50 kN/m^2, γ = 14 - 16 kN/m^3, c = 0 - 5 kN/m^2, φ = 25°, V_P = 200 - 500 m/s, V_S = 180 - 300 m/s.
2. Solid marl deeper than 6 m. Soil parameters at the 2nd interval (> 6 m): c_u > 250 kN/m^2, γ = 19 kN/m^3, c = 50 kN/m^2, φ = 25°.

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An unfavourable fact is the geological structure, which is dominated by silty sands and clayey silts, and immediately before contact with marl appear organic clays of low shear strength, which are very sensitive to changes in humidity. The main cause of landslides is the drop in the strength of clay in contact with marl. The exact trigger is not entirely clear, and a possible scenario is a rise in groundwater levels and the effect on pore pressure and the effective pressure of deeper soil layers. Given that nearby Zagreb was hit by a strong earthquake in 2020, the impact of this event is associated with the triggering of a landslide.

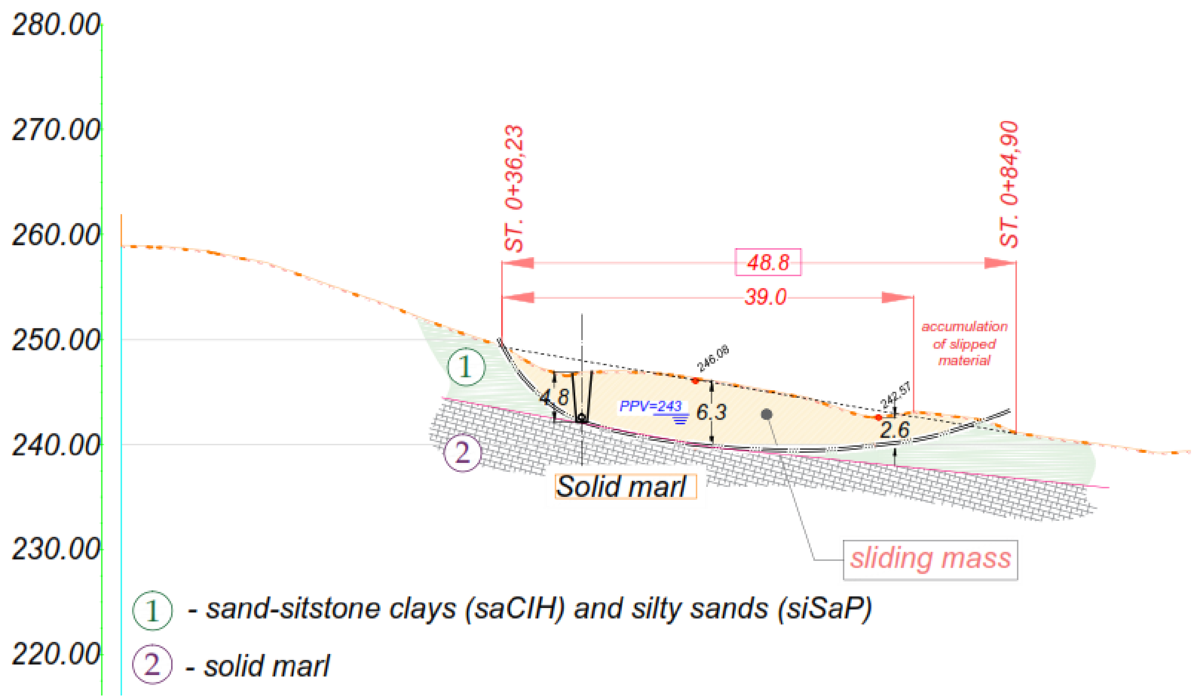

Figure 3. Characteristic geotechnical Slatina Svedruška landslide profile [10].

3. Methods and results of additional investigations from 2024

The landslide in Slatina Svedruška was selected for microseismic investigations through microtremor (ambient noise) measurements that were carried out as part of Croatian Science Foundation (HRZZ) project IP-2022-10-1296, SIGMATOPCRO. However, a detailed geological reconnaissance of the materials that make up the slope was carried out before the microseismic measurements.

3.1. Geological reconnaissance results

On the northern scarp, it is evident that under the humus layer, there is weakly bound to loose sediment (Fig. 4a). It is a poorly sorted clastic sediment whose composition is dominated by particles of pelitic dimensions (silt and clay), but also contains pebbles up to two centimetres in size (Fig. 4b). Sediment can be defined as gravelly clayey silt.

On the southern scarp, massive-looking sand emerges to the surface. The sand is completely loose, well-sorted, fine to medium-grained. Its composition is dominated by quartz, and macroscopically large-foliated micas are clearly visible.

Well-sorted micaceous sands are characteristic of the Upper Miocene deposits in the northern part of the Croatian Zagorje. They were formed as a result of the deposition of sandy detritus of Alpine provenance in the then Pannonian Lake, and their thickness in places exceeds a hundred meters. On the other hand, the poorly sorted gravelly-clayey silt discovered on the northern scarp probably represents a thin surface layer of younger sediments deposited perhaps during the Pliocene or Quaternary [11].

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Figure 4. a) Northern scarp of the landslide in Slatina Svedruška; b) Pebble-clayey silt of massive appearance on the northern scarp.

3.2. Microtremor results

To characterise properties of the topographic irregularity necessary to understand the dynamic behaviour of landslide in Slatina Svedruška, spectral frequency analysis of ambient seismic noise measurements was performed for the detection of possible changes in resonance frequencies at five microlocations (Fig. 5). The Nakamura technique or Horizontal-to-Vertical-Spectral-Ratio (HVSR) [12] is based on short-duration ambient noise measurements, and the spectral ratio is defined as a ratio of the horizontal and the vertical components using small portable seismographs.

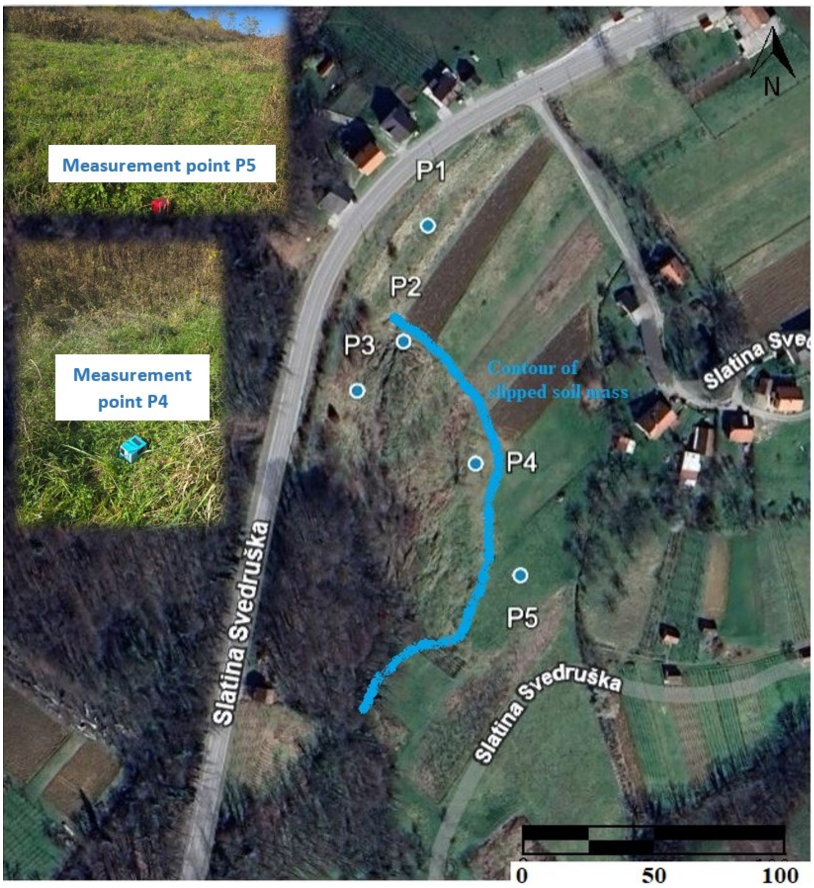

Figure 5. Map of microtremor measurement positions.

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The results of microtremor measurements (Fig. 6) show variable changes of frequencies along the landslide body ranging from 10 to 20 Hz, which is approximately 5 to 12 m of depth to bedrock [13] (solid marl in this case) that is well correlated with investigations results from 2021.

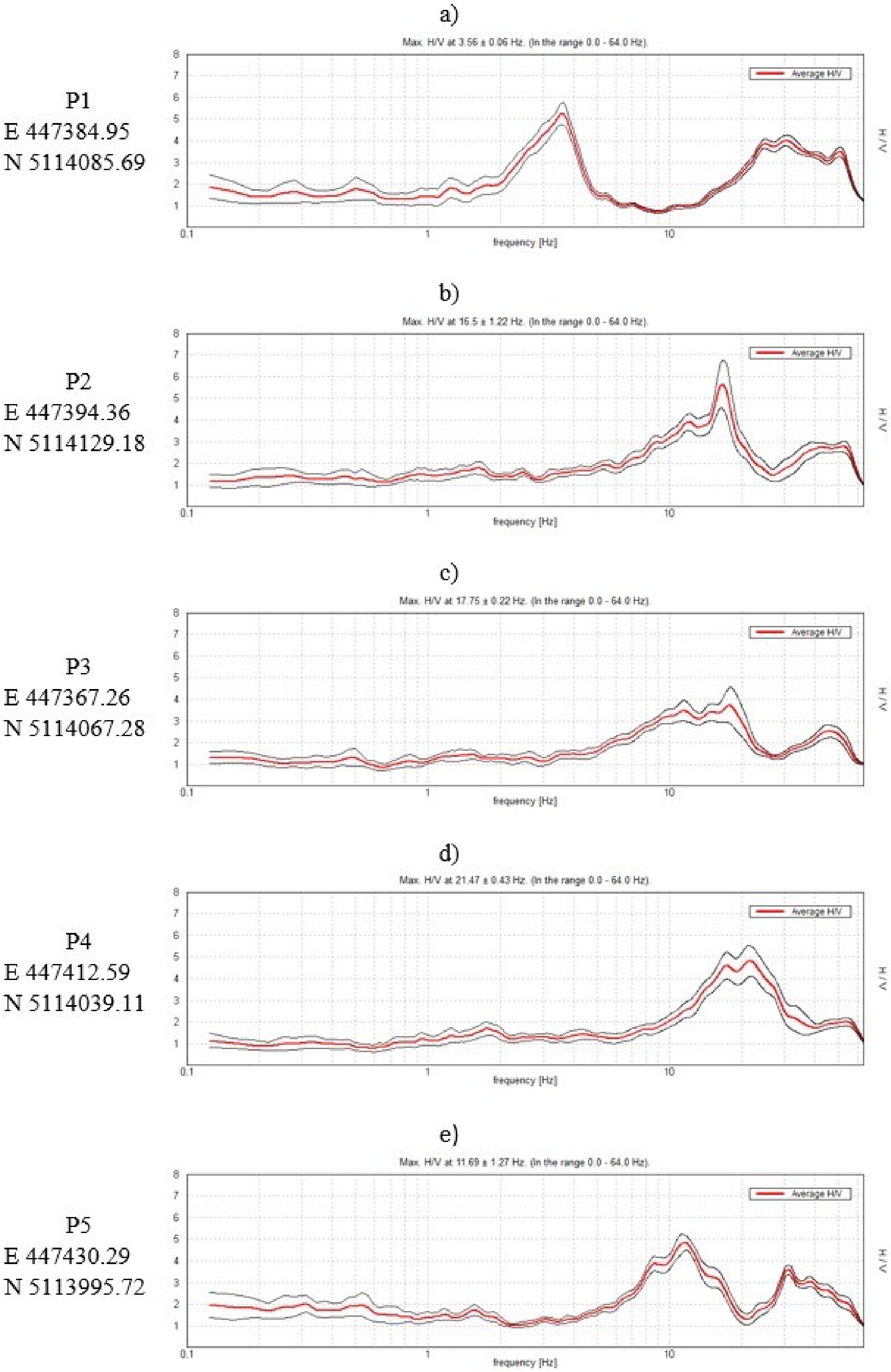

Figure 6. Results of microtremor measurements on the landslide in Slatina Svedruška: a) Measurement point P1; b) Measurement point P2; c) Measurement point P3; d) Measurement point P4; e) Measurement point P5.

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4. Conclusions

Natural causes (e.g., rain or earthquake), as well as anthropogenic ones, can decrease the shear strength of the material in the slope and ultimately cause the soil or rock to move. In Slatina Svedruška, in the municipality of Petrovsko, due to increased amounts of rainfall, there was an increase in the groundwater level and an impact on the pore pressure of deeper soil layers on the slope under the state road corridor D206. In 2020, Zagreb was hit by a strong earthquake, and the impact of that event triggered a landslide on the mentioned slope.

At that location, the majority of research was conducted in 2021, while additional geological and microseismic research was conducted later in 2024. The combination of geological, geophysical and geotechnical research methods provided information on the structure of the soil stratigraphy, which in turn produced the comprehensive geotechnical landslide profile. The lithological composition of the soil begins with the surface layer that has been built of siltstone sands and gravelly clayey silt, up to a maximum depth of 5-7 m. Deeper than that lies solid marl, which represents the bedrock. In this case, the contact zone between those mentioned above was relatively water-permeable surface materials and the marl, which was sensitive to increased humidity and became a sliding surface. In the area of Northern Croatia, there are numerous slopes of the same or similar geological structure, so it can be concluded that they are all potential landslides.

As part of the SIGMATOPCRO project, a spectral frequency analysis of ambient seismic noise measurements was subsequently performed in 2024 to detect possible changes in resonant frequencies. The results of microtremor measurements are well correlated with geotechnical and geophysical investigation results. However, it can be concluded that the use of ambient noise (microtremor) signals is attractive in studies on marginally stable slopes since other approaches require more time and money.

Acknowledgements

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