doi.org/10.62683/SINARG2025.065

Research paper

APPLICATION OF SEISMIC REFRACTION FOR DETERMINING GEOMECHANICAL PARAMETERS IN THE EXCAVATION ZONE OF THE VRANDUK TUNNEL ON THE CORRIDOR Vc ROUTE

Ekrem Bektašević[1], Ahmed Mušija[2], Kemal Gutić[3], Noris Sakić[4]

Abstract

The seismic refraction method belongs to the group of non-destructive testing techniques and represents an efficient geophysical approach for determining the propagation velocity of seismic waves through different geological environments. This allows for the assessment of key geomechanical parameters of the terrain. In this study, measurements were conducted along three profiles in the excavation zone of the Vranduk tunnel, located on the Corridor Vc route, with the aim of characterizing the rock mass and determining its condition before the commencement of construction work. Analysis of the obtained data defined the velocities of seismic waves, which were used to assess rock mass quality, classify materials, and identify potential discontinuities and weakened zones. The results indicated that in the upper zone, at a depth of 6–8 meters, the rock mass is weathered, whereas in deeper layers, the rock mass is more intact and only slightly fragmented. Since this method is entirely non-destructive, it enables rapid and reliable terrain investigation without disturbing its structure. The results were compared with in-situ geotechnical investigations, confirming the method's reliability in determining the mechanical properties of rocks. The obtained data served as a foundation for optimizing design solutions, adjusting excavation techniques, and improving the stability of the tunnel structure.

Keywords: *Seismic refraction, Geomechanical parameters, Vranduk tunnel, Corridor Vc route, Longitudinal wave velocity*

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1. INTRODUCTION

Geophysical methods play a key role in geotechnical investigations and the design of infrastructure projects [1]. When comparing the advantages of geophysical surveys to conventional underground or rock mass investigations, geophysics provides a larger volume of data over a greater area and depth while also offering significant savings in time and financial resources. This is because the instruments are relatively inexpensive, and the survey process is faster and simpler [2].

In addition to geophysics, conventional engineering investigations, such as borehole drilling, are also used. However, borehole investigations are costly. To develop an optimal investigation program, shallow seismic refraction was applied in the preliminary phase of research in the tunnel excavation zone of Vranduk. This method provided a general overview of the underground conditions and helped determine the optimal number and placement of boreholes based on the collected data.

The "Vranduk" tunnel is part of the motorway on Corridor Vc, specifically the section from the northern administrative border of the Municipality of Zenica (Nemila) to Zenica North (Donja Gračanica), within the Vranduk–Ponirak subsection [3].

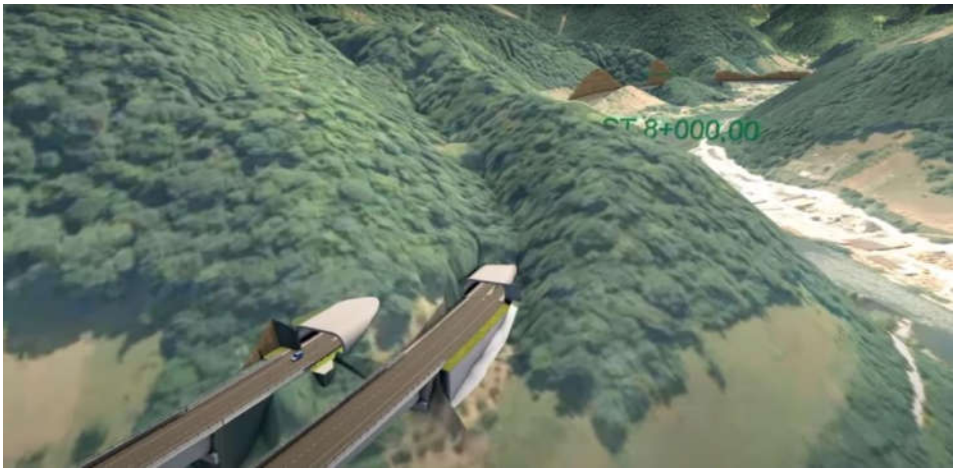

Figure 1. Satellite view of the Vranduk tunnel location

Shallow seismic refraction was developed more than 80 years ago [4,5,6]. The ASTM D5777-18 standard of the American Society for Testing and Materials (ASTM) outlines the methodological and equipment requirements for refraction measurements [7]. Seismic refraction is used to determine the velocities of longitudinal (P) and transverse (S) seismic waves, enabling the identification of the mechanical properties of rock and pressure formations [8,9,10,11].

This method provides a non-invasive approach to characterizing subsurface layers, which is particularly important for planning and optimizing engineering works [12,13,14]. The selection of a tunnel construction method for larger cross-sections is primarily based on the rock conditions through which the tunnel is being excavated [15,16].

Previous studies have shown that the application of seismic refraction allows for a reliable assessment of elasticity modulus, rock and soil resistance coefficients, and the identification of discontinuities in geological structures [17,18]. The method has been widely used in geotechnical analyses worldwide, including in complex geological environments where faults and zones of reduced strength have been documented [19,20].

2. RESEARCH METHODOLOGY

2.1. Seismic Refraction – General Overview

Seismic refraction is a geophysical exploration method based on measuring the first arrivals of a known signal source (artificially generated), while all later arrivals are disregarded due to complex reflection and interference processes. To generate mechanical force in shallow refraction surveys, a hammer weighing 5–10 kg, a dropped weight, or another impulsive source is used. For deeper investigations, reaching several hundred meters, explosives or heavy vibrators are typically employed [21].

When subjected to an external impulse, subsurface material particles temporarily shift from their initial positions, collide and transmit mechanical motion through the ground. This process enables the propagation of seismic waves from one point to another. If the waves are longitudinal (P-waves), the particles oscillate in the same direction as the wave propagation. In the case of transverse (S-waves), the particles move perpendicular to the direction of wave travel. During this motion, the particles do not permanently change their positions but merely oscillate around their equilibrium points, while elastic waves transmit mechanical energy through the subsurface medium [22]. The time elapsed from the emission to the reception of a seismic wave depends on the depth of the studied structures and the wave propagation velocities [23]. The fundamental principle of seismic refraction is illustrated in Figure 2**.**

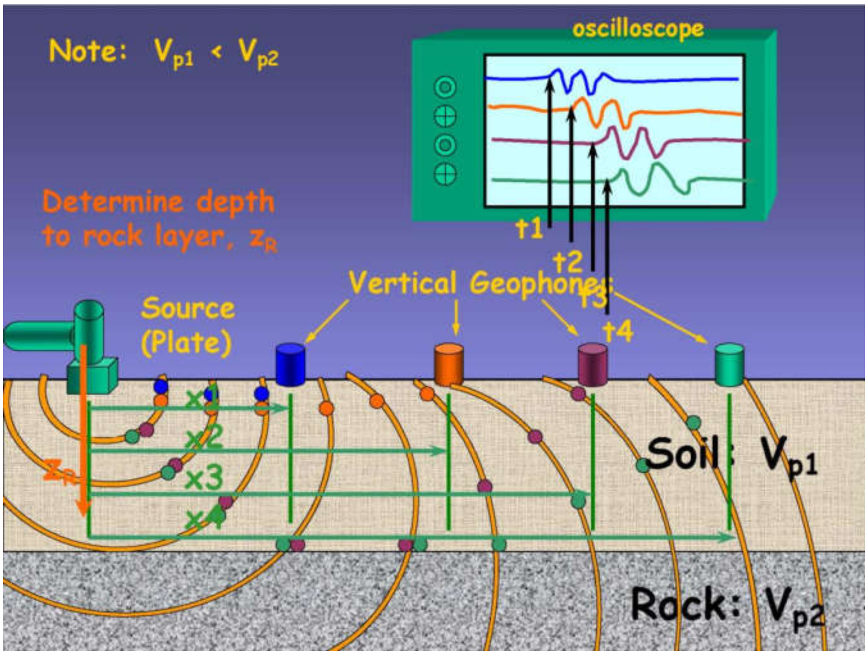

Figure 2. Principle of seismic refraction

The fundamental principle of this method is based on the fact that elastic waves, generated at the surface, begin to propagate at the velocity of the first medium (V1). The most important wave for this method is the one that reaches the boundary between two media at the critical angle or the angle of total refraction. This wave then propagates along the boundary at the velocity of the lower medium (V2) and returns to the surface, where it is detected by the placed geophones [24, 25].

Based on the arrangement of geophones and shot points, as well as the recorded first arrival times of the elastic wave, an x-t diagram (x-distance, t-time) is created, as illustrated in Figure 3.

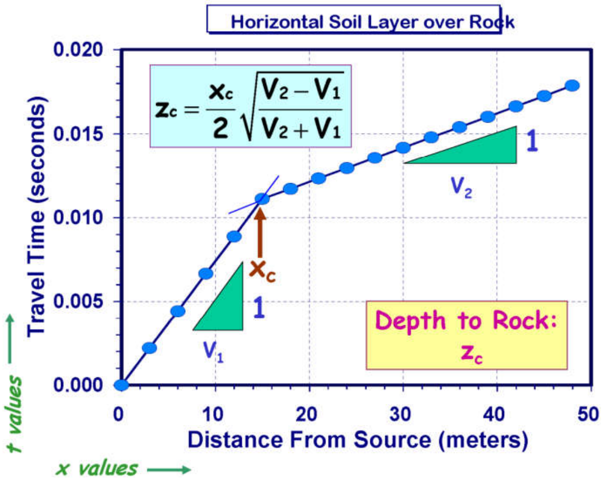

Figure 3. Representation of the x-t diagram

The coordinate system (x-t) in Figure 3 shows the first arrival times of waves [26] at individual geophones, starting from the moment the wave is generated. The points in the diagram are connected, ideally as shown in Figure 3, and represent two lines. The first line intersects the x-axis at the origin and has the equation [22]:

$$\mathrm{t} = \left(\frac{1}{\mathrm{V}_1}\right) \cdot \mathrm{x} \tag{1}$$

While the second line has the equation:

$$\mathrm{t} = \left(\frac{1}{\mathrm{V}_2}\right) \cdot \mathrm{x} + \mathrm{I}_0 \tag{2}$$

$\mathbf{I_0}$ is the intercept of the second branch of the dromochron on the ordinate through the shot point. From these equations, we determine the velocities $\mathbf{V_1}$ and $\mathbf{V_2}$ of the upper and lower seismic media, and calculate the depth to the first seismic discontinuity. The thickness of the upper layer can be calculated using the following equation [27]:

$$z_c = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \tag{3}$$

When excitation occurs in an elastic material, waves are immediately generated from the point of excitation and propagate with decreasing oscillation amplitude of the disturbance. Each of these waves behaves in a characteristic manner, and these characteristics depend on the elastic properties of the material. The obtained and processed velocities of the elastic waves, which depend on the elastic properties of the material through which the wave propagates, as shown in the equations for the velocity of P and S waves, are used to calculate the dynamic elastic constants [28]:

$$v_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \tag{4}$$

$$v_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}} \quad (5)$$

where:
$\mathbf{v_p}$ - velocity of primary (longitudinal) P – waves (m/s),
$\mathbf{v_s}$ - velocity of secondary (transverse) S – waves (m/s),
ρ - density (10^3 kg/m^3),
E - Young's modulus (GPa),
G - shear modulus (GPa),
K - bulk modulus (GPa).

By knowing the propagation velocities of elastic waves through the rock mass and the density, it is possible to solve two equations with two unknowns to calculate two dynamic constants, which can then be used to determine and calculate the other constants [29].

$$a = \frac{v_p}{v_s} = \sqrt{\frac{2-2v}{1-2v}} \quad (6)$$

$$v = \frac{\left(\frac{v_p}{v_s}\right)^2 - 2}{2\left\{\left(\frac{v_p}{v_s}\right)^2 - 1\right\}} = \frac{a^2-2}{2(a^2-1)} \quad (7)$$

$$E = \rho v_p^2 \left(\frac{(1+v)(1-2v)}{1-v}\right) \quad (8)$$

$$G = \rho v_s^2 \qquad K = \rho v_p^2 \frac{1+v}{3(1-v)} \quad (9)$$

where:
v - Poisson's ratio,
ρ - density of the rock (kg/m^3).

Using the above formulas, it is possible to calculate the dynamic elastic constants for each measurement position, and the density is calculated from the longitudinal wave velocity (v_p) using the known Anstey relation, as shown in the equation [30].

$$\rho = 0{,}31\sqrt[4]{v_p} \quad (10)$$

Based on the known velocities of longitudinal (V_p) and transverse (V_s) seismic waves according to the classification by Novosel and colleagues [31], it is possible to determine the engineering geological characteristics of soils and rocks, including the assessment of their seismic classification and deformability (Table 1). By analyzing these parameters, key shear strength parameters, such as cohesion and the angle of internal friction, can also be derived, allowing for a more accurate characterization of the mechanical behavior of geological materials. These data are essential for geotechnical calculations, assessing the stability of structures, and optimizing design solutions in engineering practice [32].

Table 1. Classification according to Novosel et al.

Category number	Description of Engineering-Geological Characteristics	The geophysical properties			Type of piozometric curve	RQD	Axial strenght	Shear strenght parameters	
		Seismic wave velocity		Magnitude of electrical resistance				Angle of friction	Choesion
		longitudinal	transverse						
		m/s	m/s	m		%	MPa		kPa
I	The rock is fresh the blocks are massive, and the frequency of fractures is very low. If fractures are present, they have very large surfaces, and the fracture width is very small. Fractures are either unfilled or filled with crystalline substances.	>4300	>2200	>1000	F	90-100	>100	>45	>500
II	The rock is weakly weathered, the blocks are large, and the frequency of fractures is low. Fractures are infrequent and large, with narrow widths. The fractures are rarely coated with a clay film on the fracture planes..	3000-4300	1600-2200	>1000	F	75-90	75-100	>45	>500
III	The rock is moderately weathered, the blocks are medium-sized, and the frequency of fractures is moderate. The fracture surfaces are of medium size, the fractures have a medium width, and the fractures are partially filled with clay.	2000-3000	1000-1600	300-1000	E	50-75	50-75	40-45	300-500
IV	The rock is highly weathered, the blocks are small, and the frequency of fractures is high. The fracture surfaces are mostly small, but the occurrence of medium-sized fractures is frequent. The fractures are filled with a mixture of rock fragments and clay or semi-consolidated breccias.	1400-2000	650-1000	300-1000	D	25-50	25-50	35-40	200-300
V	The rock is very highly weathered, with the frequent occurrence of very small blocks. The fracture surfaces are very small, and milonitized zones are observed. Large-width fractures filled with clay and rock fragments or semi-consolidated breccias are present.	900-1400	400-650	150-300	C	10-25	10-25	30-35	150-200
VI	The rock is extremely weathered, with the predominance of extremely small blocks and mylonitized zones. The fracture surfaces are extremely small, and the frequency of fractures is extremely high. Extremely wide fractures are observed, filled with clay, rock fragments, and semi-consolidated breccias.	600-900	250-400	150-300	B	0-10	3-10	<30	100-150
VII	Voids and depressions filled with clay or a mixture of clay and rock fragments.	300-600	150-250	35-200	A	0	0-1	<30	<100

2.2. Application of the Method in the Vranduk Tunnel Excavation Zone

The investigation was conducted on the section of Corridor Vc, where the excavation of the Vranduk Tunnel was carried out. The seismic refraction method was performed on three test profiles (17-17', 18-18', and 19-19'). Profiles 18-18' and 19-19' were positioned in the zone of the entrance profile excavation, while profile 17-17' was positioned in the zone of the exit profile excavation. This arrangement was chosen to cover the area with the smallest overburden thickness. The profile arrangement is shown in Figure 4.

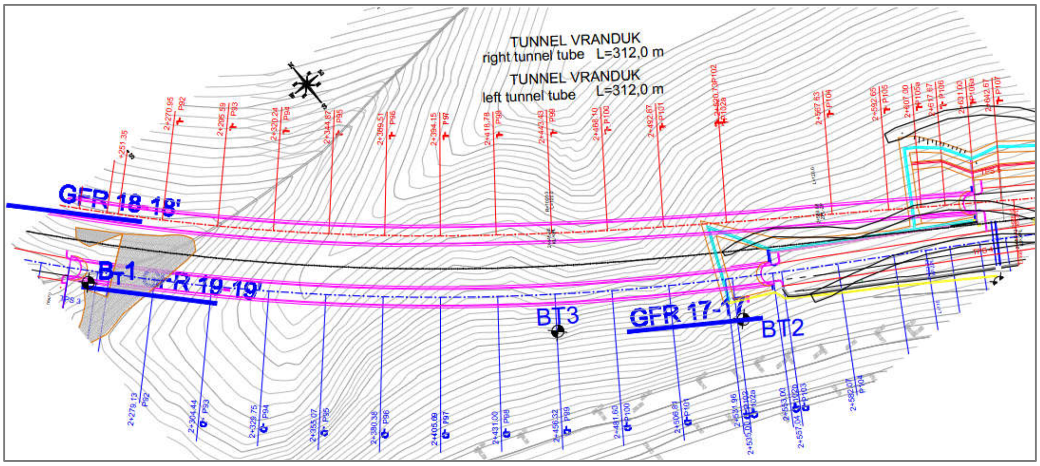

Figure 4. Arrangement of test profiles in the Vranduk Tunnel excavation zone

Seismic waves were generated using impulsive impact sources, and the data were recorded with a series of geophones placed at defined intervals. The recordings were made using a digital seismograph, which enabled precise registration of wave arrival times.

All measurements were carried out using OYO equipment with twelve channels, with seismic wave initiation by hammer and electronic trigger. The profile length was 60 meters, with seismic Vp and Vs wave reception intervals of 5 meters. Data processing was done using the SeisREFA program [33]. The processed results are shown in Figures 5, 6, and 7.

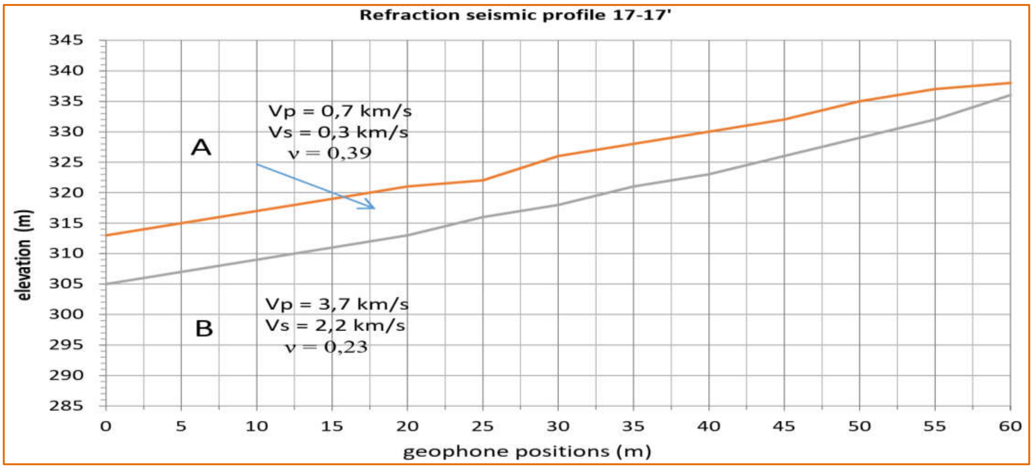

Figure 5. Distinct geomechanical environments on profile 17-17'

Two geomechanical environments with different seismic characteristics were identified, labeled as A and B.

A: This geomechanical unit is located at the surface and reaches a depth of approximately 8 meters, with a longitudinal seismic wave velocity of Vp = 0.7 km/s and ν = 0.39. It consists of a humus cover and clayey and granular material. According to the classification by Novosel et al., it has an axial strength of 3-10 MPa, φ < 30°, and cohesion of 100-150 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 0.7 km/s is calculated as E ~ 392.00 MN/m², the shear modulus G ~ 144.00 MN/m², and density ρ ~ 1,595.00 kg/m³.

B: The geomechanical unit at depths greater than 8 meters has a measured longitudinal seismic wave velocity of Vp = 3.7 km/s and a calculated Poisson's ratio of ν = 0.23. This is a weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD of 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 3.7 km/s is calculated as E ~ 28,552.00 MN/m², the shear modulus G ~ 1,171.00 MN/m², and density ρ ~ 2,418.00 kg/m³.

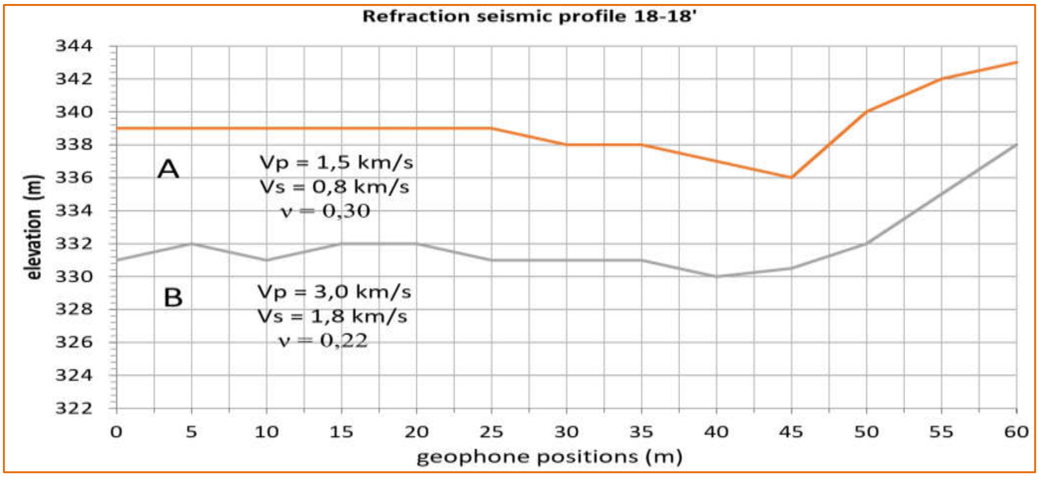

Figure 6. Distinct geomechanical environments on profile 18-18'

Two geomechanical environments with different seismic characteristics were identified, labeled as A and B.

A: This geomechanical unit is located at the surface and reaches depths from 5 to 8 meters, with a longitudinal seismic wave velocity of Vp = 1.5 km/s and ν = 0.30. It consists of a thinner humus cover and the remaining weathered surface part of solid rock mass. According to the classification by Novosel et al., it has an RQD of 25-50%, an axial strength of 25-50 MPa, φ = 35-40°, and cohesion of 200-300 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 1.5 km/s is calculated as E ~ 3,225.00 MN/m², the shear modulus G ~ 1,235.00 MN/m², and density ρ ~ 1,930.00 kg/m³.

B: The geomechanical unit at depths greater than 5-8 meters has a measured longitudinal seismic wave velocity of Vp = 3.0 km/s and a calculated Poisson's ratio of ν = 0.22. This is a weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD between 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 3.0 km/s is calculated as E ~ 18,086.00 MN/m², the shear modulus G ~ 7,434.00 MN/m², and density ρ ~ 2,295.00 kg/m³.

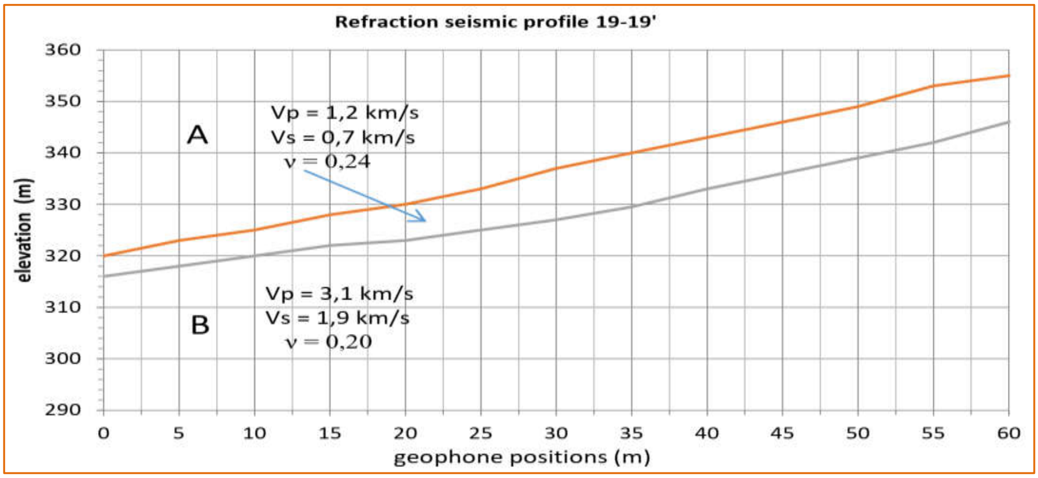

Figure 7. Distinct geomechanical environments on profile 19-19'

Distinct geomechanical environments A and B

A: This geomechanical unit is located at the surface of the terrain, extending to depths of 4 to 9 m, with a longitudinal seismic wave velocity of Vp = 1.2 km/s and ν = 0.24. It consists of a thin humus cover and a weathered surface layer of solid rock mass. According to Novosel et al.'s classification, it has an RQD of 10-25%, axial strength of 10-25 MPa, φ = 30-35°, and cohesion of 150-200 kPa. Using the formulas from section 2.1, the dynamic elastic modulus for Vp = 1.2 km/s is E ~ 2,230.00 MN/m², shear modulus G ~ 895.00 MN/m², and density ρ ~ 1,825.00 kg/m³.

B: The geomechanical unit below the 4 to 9 m depth range has a measured longitudinal seismic wave velocity of Vp = 3.1 km/s and a calculated Poisson's ratio of ν = 0.20. It consists of weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD of 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from section 2.1, the dynamic elastic modulus for Vp = 3.1 km/s is E ~ 20,007.00 MN/m², shear modulus G ~ 8,351.00 MN/m², and density ρ ~ 2,314.00 kg/m³.

3. RESULTS AND DISCUSSION

The interpretation of seismic data enabled the differentiation of the rock mass based on the level of weathering. The data showed that zones with lower wave velocities (Vp < 1500 m/s) correspond to highly weathered rocks, characterized by the frequent occurrence of very small blocks, wide fractures filled with clay and rock fragments. On the other hand, zones with P-wave velocities above 3000 m/s represent rock masses with minimal damage, stable formations, as shown in Figure 8.

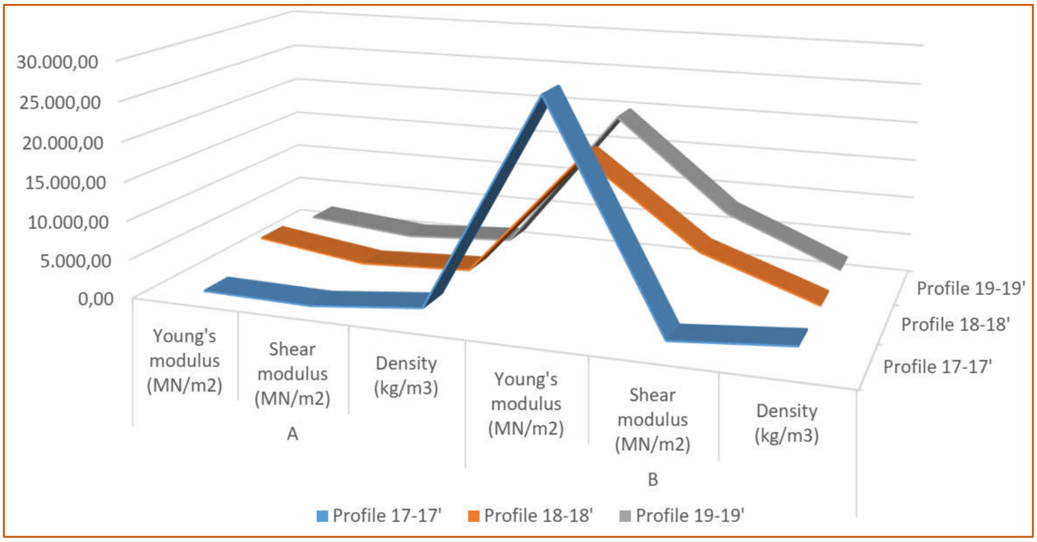

Figure 8. Elastic properties of the rock mass in the tunnel excavation area of Vranduk

Comparison with laboratory tests of rock samples revealed a good correlation between seismic velocities and mechanical parameters of the rock mass. These data were used to optimize excavation methods and the selection of the tunnel subgrade.

4. CONCLUSION

The application of seismic refraction in the tunnel excavation area of Vranduk on the Corridor Vc route proved to be an effective method for determining the geomechanical parameters of the rock mass. This technique enabled the differentiation of the rock mass based on its degree of weathering and provided key information about the underground conditions. The identification of zones with lower seismic velocities (V_p < 1500 m/s) indicated highly weathered rocks with fractures filled with clay and rock fragments, while areas with P-wave velocities above 3000 m/s represented more stable formations with less damage.

The obtained results showed a good correlation between seismic velocities and mechanical parameters of the rock mass, confirmed by laboratory testing. These data allowed the optimization of exploration works by defining the optimal number and location of exploration boreholes, thereby reducing costs and research time. Furthermore, the interpretation of seismic data was crucial for optimizing excavation methods and selecting the appropriate tunnel subgrade, contributing to the safety and efficiency of the works.

The results of this study confirm the importance of applying seismic refraction to determine the geomechanical parameters of the rock mass in the tunnel excavation zone. This method enables informed decision-making in the early stages of design, leading to improvements in the technical and economic aspects of tunnel construction and other underground facilities.

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