SEISMIC EXPLORATION FOR DEFINING SLOPE STABILITY IN THE *BANSKO* LATE ANTIQUE SPA IN THE REPUBLIC OF NORTH MACEDONIA

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ABSTRACT. The *Bansko* late antique thermal spa is located in the south-eastern part of the Republic of North Macedonia, ten kilometres southeast of the city of Strumitsa. The *Bansko* archaeological site covers an area of about 1500 m^2, and the immediate vicinity of the site, which was the subject of research in terms of defining slope stability on its southwest side, covers an area of about 2 ha.
Within the research of the exploration area, appropriate geological and geophysical researches were performed in order to define the slope stability.
Geophysical seismic surveys are planned and performed in accordance with the geological conditions of the location, as well as the methodology of the combined seismic surveys. Seismic refractive and reflective surveys have been applied to define geomechanical parameters based on the fact that fragmented rock structures tend to absorb seismic energy which ultimately results in a reduction in registered seismic velocities.
The seismic refraction method is applied in order to separate the surface earthen formations (based on the small values of the seismic propagation velocities) in the slope above the Roman bath which can be destabilised by further excavation and urbanisation of the area, while the method of reflection is applied for a more detailed limitation of the lime creations on the terrain, as well as for understanding the local tectonics that caused their occurrence.

Key words: spa, seismic, reflection, refraction, slope stability.

СЕИЗМИЧНИ ПРОУЧВАНИЯ ЗА ОПРЕДЕЛЯНЕ СТАБИЛНОСТТА НА СКАТА ПРИ КЪСНОАНТИЧНИЯ ТЕРМАЛЕН КОМПЛЕКС „БАНСКО” В РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЯ

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РЕЗЮМЕ. Късноантичният термален комплекс „Банско” се намира в югоизточната част на Република Северна Македония, на десет километра югоизточно от гр. Струмица. Археологическият обект „Банско” обхваща площ от около 1500 м^2, а непосредствената околност на обекта, която е била предмет на проучване по отношение на определяне на стабилността на ската от югозападната му страна, покрива площ от около 2 ха.
В рамките на проучването, за да се определи стабилността на ската в зоната на изследване, бяха извършени съответните геоложки и геофизични проучвания.
Геофизичните сеизмични картирания се планират и извършват в съответствие с геоложките условия на мястото, както и с методологията на съчетаните сеизмични проучвания. За определяне на геомеханичните параметри са приложени сеизмични рефракционни и отразяващи изследвания, основани на факта, че фрагментираните скални структури са склонни да абсорбират сеизмична енергия, което в крайна сметка води до намаляване на регистрираните сеизмични скорости.
Методът на сеизмична рефракция се прилага, за да се отделят повърхностните земни образувания (въз основа на малките стойности на скоростите на сеизмично разпространение) в склона над римските бани, който може да бъде дестабилизиран чрез по-нататъшни разкопки и урбанизация на района, докато методът на отразяване се прилага за по-подробно ограничаване на карбонатните образувания по терена, както и за разбиране на местната тектоника, причинила тяхното възникване.

Ключови думи: минерален комплекс, сеизмичен, отражение, рефракция, стабилност на ската.

Introduction

The refractive seismic method studies the propagation of elastic waves that are refracted at boundary surfaces. The refractive method is performed by placing geophones from the source of the elastic waves along the measuring profile line at a certain distance. Geophones are connected by cables to the seismic apparatus. At the moment when the seismic waves hit a boundary area that separates two different elastic media, they are refracted and, as such, the feedback signals are registered. The geophones placed on the surface of the ground convert the mechanical oscillations into electrical impulses that are transmitted to the seismic apparatus. The seismograms record the time of arrival of the elastic wave, as well as the moment of excitation of the ground. Based on the seismograms, diagrams are constructed that determine the dependence between the distance of the geophone from the point of excitation, as well as the time of arrival of the seismic oscillations to each geophone placed. Such diagrams are also called hodochrones.

The refractive seismic method successfully determines horizontal, vertical, and steep boundary surfaces, provided that the propagation velocity of the elastic waves in every deeper layer is higher than the velocity in the previous one. However, when this condition is not met, or in cases when the differences in the elastic properties of the media are not sufficiently pronounced and when the boundary surfaces are located at great depths, the application of the refractive method is ineffective. Due to the fact that the length of the refractive seismic profiles should be 3 to 5 times longer than the depth at which the boundary surface is located, seismic examinations are significantly more difficult for several reasons:

- When the length of the test profile is large, more explosives must be used to excite the ground;
- When using more explosives, the hole wherein they are placed should have a greater depth, which significantly complicates the operation procedure;
- Using more explosives significantly increases the possibility of damage to the surrounding buildings.

For these reasons, since 1929, the reflective method has been used instead of the refractive one in certain seismic examinations.

Seismic exploration

The late antique thermal spa is located in the south-eastern part of the Republic of North Macedonia, ten kilometers south-east of the town of Strumitsa.

The area where the archeological site is located, orographically resembles the northern slopes of the Belasitsa Mountain which has a general extension east-west.

In a tectonic sense, the archeological site - the *Bansko* late antique thermal spa - belongs to the Serbian-Macedonian massif and is located near the western border with the Vardar zone. More specifically, this locality is situated on the southern edge of the Strumitsa ridge towards the Belasitsa horst. Namely, this part of the territory of Macedonia is a relatively depressed block (the Strumitsa graben), between the relatively raised blocks of Belasitsa Horst on the south side and Ograzhden batholite (Horst) on the north side.

The geological structure of the research area is represented by rocks from the Old Paleozoic, the Neogene, and the Quaternary. The Old Paleozoic rocks are represented by granite-gneiss; the Neogene, which gradually turns into a Quaternary, is represented by sands and clays and calcareous sediments, and the Quaternary is represented by proluvial deposits (Fig. 1).

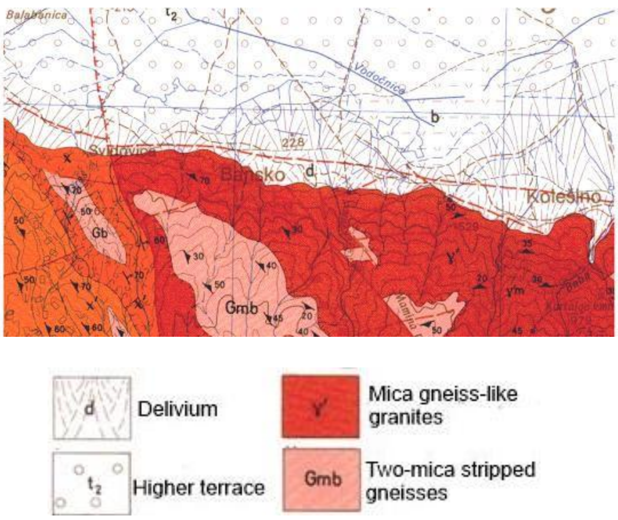

Fig. 1. Geological map of the investigated terrain

The method of seismic refraction is applied in order to separate the surface earthen formations (based on the small values of seismic propagation velocities) in the slope above the so called Roman bath which can be destabilised by further excavation and urbanisation of the space, while the method of shallow reflection is applied for more detailed limitation of calcareous deposits in the area, as well as understanding the local tectonics that caused their occurrence.

Refractive surveys were performed on four measuring profiles with a length of 180 m (RP - 1) and 100 m (RP - 2, RP - 3, RP - 4) with excitation of seismic waves every 25 m. The total seismic profile length is 480 m. These researches cover a depth of the terrain from 20 to 30 m below the surface, i.e. the thickness of the Quaternary sediments (which can form a landslide body) and the surface parts of the granite-gneiss bedrock are completely covered. The values of the seismic velocities of the elastic longitudinal P and transverse S waves (V_p and V_s) are measured with these explorations.

Refractive profiles are made longitudinally and transversely on the slope above the Roman bath. The same completely covers the slope - from the appearance of granite-gneiss at the top to the foot, i.e. the facilities of the Tsar Samoil hotel. The spatial layout and length of the reflective and refractive seismic profile lines are shown on the geological map of the survey area in Figure 2:

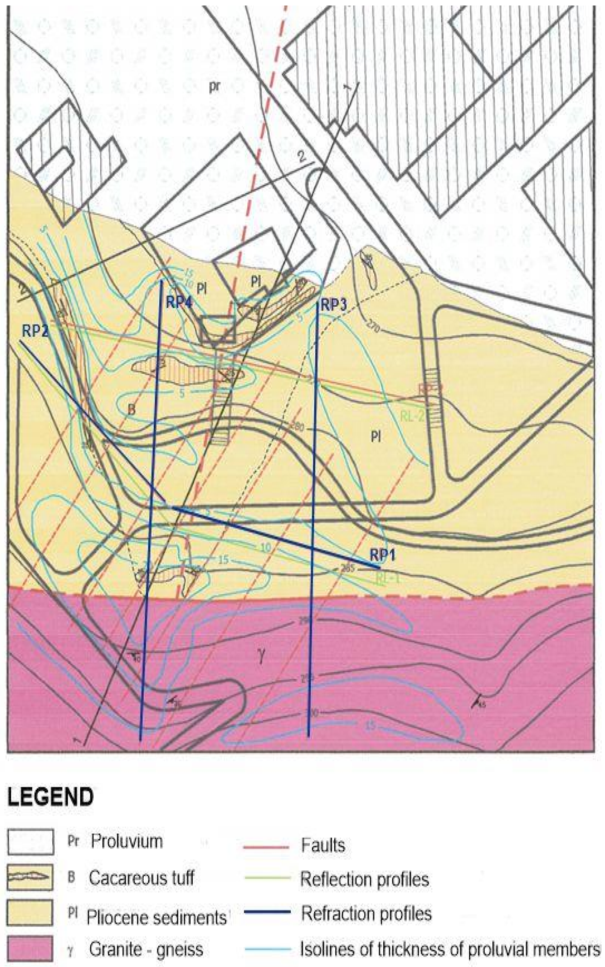

Fig. 2. Spatial map of the seismic explorations performed

The measurements were performed with a 12-channel Atlas Copco ABEM – Terraloc seismic system, a Swedish production, and the processing and interpretation of the measurement data was performed using the *Vesna* and *REFLEXW* computer programs.

Analytical processing and interpretation of refractive surveys obtained the values of seismic Vp and Vs velocities of the represented geological environments that are used for the following:

- Interpretation of reflective seismic surveys;
- Determination of the elastic boundaries between individual geological environments;
- Determination of the dynamic values of the elastic modules and coefficients of the members of the landslide body and the boundary geological environments, based on the relations from the theory of elasticity;
- Assessment of the values of the physico-mechanical characteristics of the materials of the geological environments on which the stability of the slope depends, based on the values of the seismic velocities and the dynamic modules and coefficients.

The following equations are used to determine the values of the elastic parameters through the propagation velocities of the elastic waves through them:

- Poisson’s coefficient - $\mu = (V_p^2 - V_s^2)/2(V_p^2 - V_s^2)$
- Elasticity module - $E = 2(1 + \mu)G$
- Shearing module - $G = V_s^2\rho$
- Volume module - $K = E/3(1 - 2\mu)$

To evaluate the values of the physico-mechanical characteristics, the following empirical correlation equations were used, obtained for similar materials for:

- Volume weight

  $\gamma = 7{,}15V_s^{0{,}168}$ - for Quaternary rocks

  $\gamma = 7{,}35V_s^{0{,}168}$ - for granite - gneiss
- Statical elasticity module

  $E_{st} = 8.25E^{1.26} * 10^{-3}$ - for Quaternary rocks

  $E_{st} = (170/340)V_p^{2.3}$ - for granite - gneiss (disintegrated / compact)
- Deformation module

  $E_d = (0.4/0.7)E_{st}$ - for Quarternary rocks

  $E_d = (50/95)V_p^{2.77}$ - for granite - gneiss (disintegrated / compact)
- Axial stiffness (strength) of pressure

  $\sigma_p = 0.1455(1 - 2\mu)V_s^2\gamma/(1 - \mu)$
- Strength parameters - angle of internal friction and cohesion

  $\varphi = (3{,}27/3{,}38)V_s^{0{,}4} and\ c = 0$ - for Quaternary rocks

  $\varphi = 23.5\sigma_p^{0.25} and\ c = (0.6/2.32)\varphi^4 * 10^{-7}$ - for granite - gneiss (disintegrated / compact)

In the above expressions, the values are presented in the following units of measure: Vs in m/s, Vp in km/s, γ in kN/m^3, and Est, Ed, σp, and c in MPa. It should be noted that the values estimated by the given correlation equations are mean and approximate and can be used for parametric analyzes.

Results of refractive investigations

By interpreting seismic data from refractive surveys, the following are determined:

- The values of the seismic Vp and Vs velocities of the surface Quaternary proluvial formations on the slope above the Roman bath and the basic granite-gneiss rocks;
- Elastic boundaries between Quaternary proluvial formations and calcareous tuffs with basic granite-gneiss rocks.

The results obtained from the refractive research are presented in Figures 3 - 6.

The refractive profiles RP - 1 and RP - 2 are performed in parallel approximately along the contour lines 282 - 283 and 274 - 276 on the slope above the Roman bath and with them are determined proluvial and calcareous structures with a thickness of 5 to 15 m. Or, these formations are found on the elevation between 268 and 273 and are cut with two faults (R1 and R2) at a distance of about 60-65 m. The second fault passes through the microlocation of the bath.

The refractive profiles RP - 3 and RP - 4 are made perpendicular to the slope, also parallel on the distance of about 35-40 m. With these profiles are ascertained the Quaternary proluvial and calcareous formations and the basic granite-gneisses. The maximum thickness of the proluvial creations (15-20 m) is found at about 50 to 60 m above the Roman bath. Also, with these profile lines, two parallel faults were ascertained at a mutual distance of about 55 m - the first near the bath (R - 3) and the second (R - 4) which follows the path above the bath. The R-4 fault is registered with a wider zone and it probably corresponds to the regional Belasitsa fault.

Based on the data interpreted from the refraction profiles, it can be concluded that the values of the seismic velocities of the Quaternary structures found in the slope structure and the basic granite - gneisses amount to:

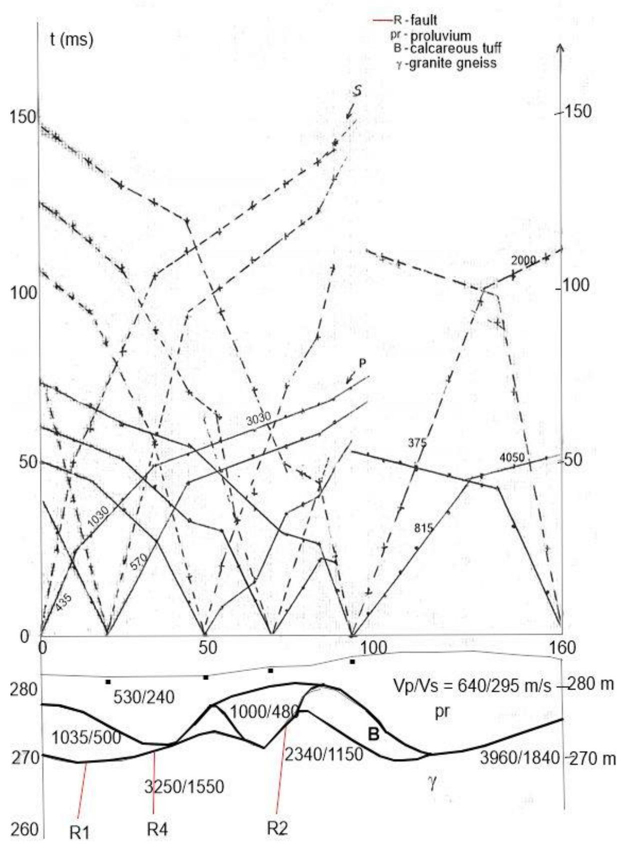

Fig. 3. Seismic refractive profile RP-1 with interpretation

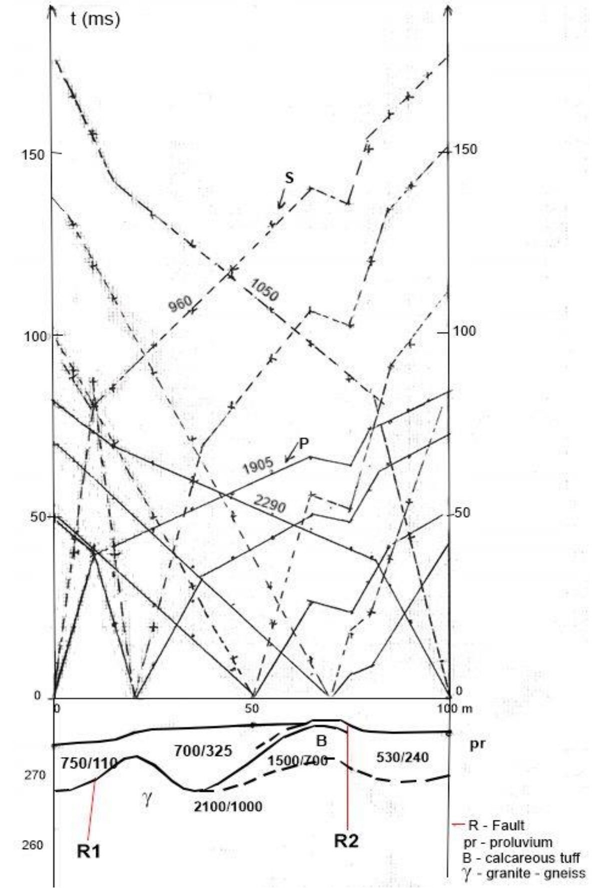

Fig. 4. Seismic refraction profile RP-2 with interpretation

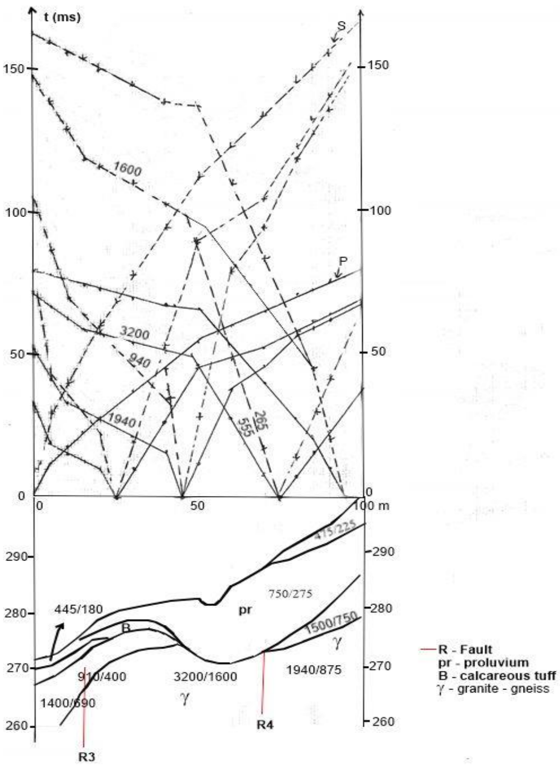

Fig. 5. Seismic refraction profile RP-3 with interpretation

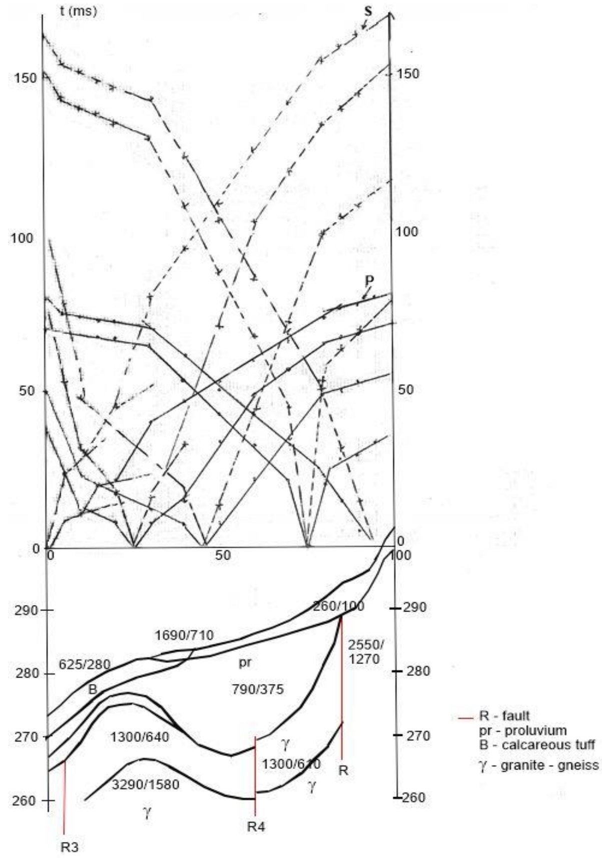

Fig. 6. Seismic reflective profile RP-4 with interpretation

- Old Paleozoic granite - gneisses:
- Mechanically crushed and cracked granite - gneisses, relatively compact (γ),

  $V_p = 3960\ m/s$

  $V_s = 1840\ m/s$
- Tectonically damaged and disintegrated blocks of granite - gneisses (γ) on depth > 20 m

  $V_p = 1950 - 3250\ m/s$

  $V_s = 880 - 1600\ m/s$
- Proluvial creations (pr), consisting of various granular sands, gravels and individual pieces with thin layers of sandy slope clays, with a thickness of 5-20 m and

  $V_p = 250 - 900\ m/s$

  $V_s = 110 - 400\ m/s$
- Calcareous tuffs with thin layers of proluvial creations (B), with a depth of 5-20 m and

  $V_p = 1040 - 2340\ m/s$

  $V_s = 480 - 1150\ m/s.$

Based on the values of the seismic velocities, the the proluvial formations are conditionally unstable; they are characterised by reduced values of the seismic velocities $V_p < 800\ m/s$ and $V_s < 350\ m/s$. Their greater presence (with a thickness of 10-20 m) is determined in the zone of faults (along the length and above the existing path) above the Roman Bath and on the west side towards the Turkish Bath. Today's stability of the slope (above the Roman bath) is preserved due to the presence of the calcareous tuffs on the surface.

Based on the values of seismic velocities and with the help of the equations presented above, the values of the elastic and mechanical characteristics of the materials in the separated geological environments are estimated. The approximate values of the seismic velocities and the elastic mechanical properties are given in Table 1:

Table 1. *Border values for the seismic velocities of the elastic – mechanical characteristics of the geological environments*

Geomechanical characteristics	Proluvium (pr)	Calcareous tuff (B)	Granite-gneiss - disintegrated (Y')	Granite-gneiss – mechanically damaged (Y)
Depth H (m)	2 – 20	5 – 20	>20	>20
Seismic velocity Vp (m/s)	250 – 900	1040 – 2340	1950 – 3250	3960
Seismic velocity Vs (m/s)	110 – 400	480 – 1150	880 – 1600	1840
Volume weight γ (kN/m³)	15 – 20	20 – 23	23 – 26	27
Poisson coefficient. μdin	0.380 – 0.370	0.365 – 0.340	0.370 – 0.340	0.360
Elasticity module Edin (MPa)	50 – 870	1280 – 8300	5000 – 18000	25000
Shearing module Gdin (MPa)	20 – 320	470 – 3100	1800 – 6800	9300
Volume module Kdin (MPa)	60 – 870	1600 – 8650	6400 - 19000	30000
Static elasticity module Est (MPa)	1 – 40	60 – 1200	800 – 5000	8200
Deformation module Ed (MPa)	0.5 – 25	25 – 300	300 – 2500	4000
Pressure strength σp (MPa)	0.1 – 2	3 – 20	10 – 30	60
Angle of internal friction φ (°)	22 – 35	30 – 40	40 – 50	>50
Cohesion c (MPa)	0.0	0.0 – 0.5	0.6 – 2.0	>2.0

Conclusion

From the conducted research and obtained data from the seismic refraction measurements, the following can be concluded:

- In a tectonic sense, the archeological site of the *Bansko* late antique thermal spa belongs to the Serbian-Macedonian massif and is located near the western border with the Vardar zone;

- The method of seismic refraction is applied in order to separate the surface earthen formations in the slope above the so called Roman bath which can be destabilised by further excavation and urbanisation of the area;

- Refractive surveys have been performed on four measuring profiles with a length of 180 m (RP - 1) and 100 m (RP - 2, RP - 3, RP - 4) with excitation of seismic waves every 25 m;

- By interpreting seismic data from refractive surveys the following are determined:

- The values of the seismic Vp and Vs velocities of the surface Quaternary proluvial formations on the slope above the Roman bath and the basic granite-gneiss rocks;
- Elastic boundaries between Quaternary proluvial formations and calcareous tuffs with basic granite-gneiss rocks.

- Based on the data interpreted from the refraction profiles, it can be concluded that the values of the seismic velocities of amount to:

- Old Paleozoic granite-gneisses:

$V_p = 3960\ m/s$

$V_s = 1840\ m/s$

- Tectonically damaged and disintegrated blocks of granite-gneisses on a depth > 20 m

$V_p = 1950 - 3250\ m/s$

$V_s = 880 - 1600\ m/s$

- Proluvial creations (pr)

$V_p = 250 - 900\ m/s$

$V_s = 110 - 400\ m/s$

- Calcareous tuffs

$V_p = 1040 - 2340\ m/s$

$V_s = 480 - 1150\ m/s$

- Based on the values of the seismic velocities, the conditionally unstable formations are the proluvial formations which are characterised by reduced values of the seismic velocities $V_p < 800\ m/s$ and $V_s < 350\ m/s$.

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