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GEOPHYSICAL AND GEOTECHNICAL EXPLORATIONS ON THE FORTRESS ISAR – ŠTIP

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A b s t r a c t: The aim of this paper is to define the geotechnical and seismic-geological characteristics of the terrain of the investigated area, the local disorders and discontinuities that indicate the presence of weakened and disintegrated zones. The research is performed using the geotechnical investigations and seismic refractive method and consists of field measurements, processing and analysis of the obtained results. The object of the investigation is the Acropolis of the fortress Isar. Analyzing the obtained data, three lithological environments are distinguished which are characterized by different physical and mechanical characteristics. The following lithological environments are distinguished: surface layer made of deluvium and crushed material from a mother rock reaching an interval of 0–4 m; subsurface zone consisting of a fragmented degraded mother rock with a depth of 6 to 10 m, characterized by quite poor physical-mechanical characteristics and represents a critical zone; intensely cracked rocks at depths greater than 10 m where the physical-mechanical characteristics of the rock are improved.

Key words: exploration; geotechnics; seismic method; refraction; tomography; fortress Isar

INTRODUCTION

The seismic refractive method is widely used in modern engineering: engineering geology, geotechnics, soil mechanics, rock mechanics, hydrogeology, etc. With it is very successful to determine the horizontal, vertical and steep boundary surfaces. For successful application, the condition for a normal range of speeds is required. The velocity of propagation of the seismic waves should be greater in any deeper layer from the velocity in the upper layer. In the seismic refractive method, geophones are placed at a certain distance along the line of exploration, which are connected by cable to the seismic measuring equipment. Once the ground mass is induced (by the force of an external cause), elastic seismic waves spread out from the point of excitation in all directions. When the elastic wave hits a boundary between different elastic environments, the wave refracts and returns to the surface of the ground. On the surface, the set geophones (receivers) convert the mechanical oscillations into electrical impulses and transfer them to the seismic apparatus. In the apparatus impulses are amplified, filtered and recorded moment of thrust and time of arrival of the wave. Based on the seismographs, diagrams can be constructed which give the dependence between the distance of the geophones from the point of excitation and the time of receiving the waves in the receivers. Such diagrams are called hodochrons [7].

Geotechnics is the application of scientific methods and engineering principles to the acquisition, interpretation, and use of knowledge of materials of the Earth's crust and Earth materials for the solution of engineering problems and the design of engineering works. It is the applied science of predicting the behavior of the Earth, its various materials and processes towards making the Earth more suitable for human activities and development [15].

Geotechnics embraces the fields of soil mechanics and rock mechanics, and many of the aspects of geology, geophysics, hydrology and other related sciences.

GEOLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS OF THE INVESTIGATION AREA

The terrain of the location on the fortress Isar in Štip, generally, has very simple composition. It is composed of rock masses which, according their genesis, can be distinguished as [3]: Mesozoic Štip granitoide massiv which is divided in biotite adamelites (γ) which are present within the investigation area, biotite granites (γ) and applitoide granites (γ) which appear in the immediate vicinity, and Quaternary deluvial sediments (d) which partialy cover the exploration area (Figure 1).

Štip granite. – The entire investigative area, i.e. Isar fortress, is located within the Štip granite massif which has a general orientation northwest-southeast toward north-south. The creation of this massif is related to the first intrusive phase when granitoide magma intruded into highly metamorphic rocks (gneisses, amphibolites, etc.), with the separation of biotite adamelite wiith rare occurences of granodiorite rocks in the deeper and central parts, while biotite granites were gradually separated on the periphery. In the second phase were separated aplitoide granites which composed a relatively small part of the massif and penetrate the rocks created in the first phase.

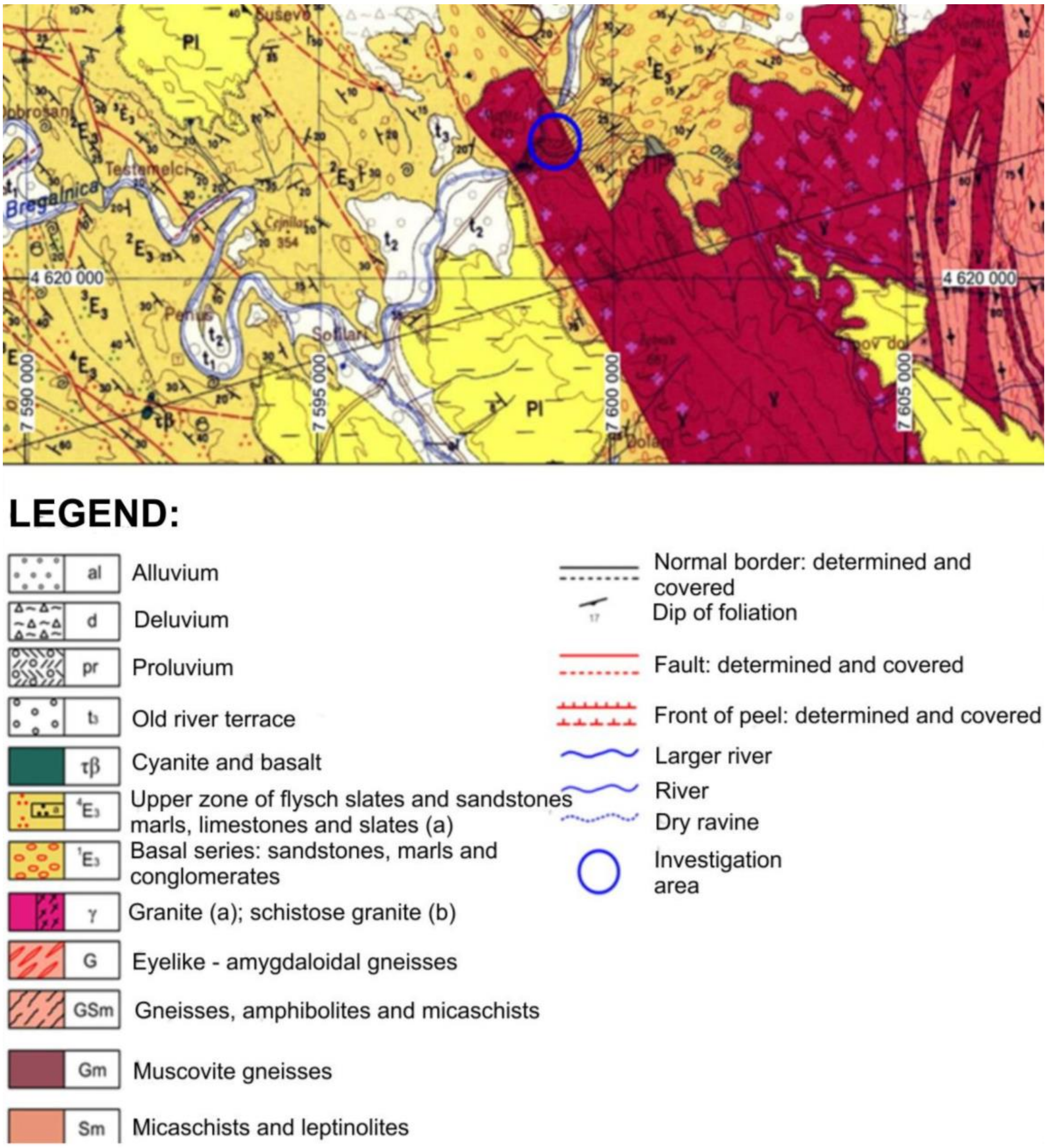

Fig. 1. Geology map of the vicinity of the investigated area [2]

Biotite adamellite. – Biotite adamelites occupy most of the Štip massif, including the Isar fortress. Toward the periphery they passed into biotite granites with a significant decrease in biotite and plagioclase content. Biotite granodiorites are frequently observed and appear in them. These rock masses are dark gray, medium-grained to coarse-grained, with a massive texture and hippidomorphic structure. They are composed, mainly, of K-feldspars, plagioclasses, quartz and biotite.

Biotite granite. – Biotite granites occur in the peripheral parts of the massif with a gradual transition. They are rock masses with gray and dark gray color, finely to medium-grained, with a massive texture and allotriomorphic granular to hippidomorphic granular structure. They have similar mineralogical composition with the adamelites, i.e. they are made of K-feldspars, plagioclasses, quartz and biotite. They differ in their modal composition

Aplitoide granite. – Aplitoide granites are found mainly in the eastern periphery of the Štip massif and sometimes in the inner parts where intruded in biotite granites and adamelites. They are characterized by very strong magmatization, and therefore gradually migrate to magmatites. Macroscopically, these rocks are very fine-grained with rare K-feldspar porphyroid grains, gray-white, gray-yellow or gray-pink in color with massive texture and allotriomorphic granular structure.

Deluvial sediments. – The deluvial sediments of the study area lie over the parent rock mass, biotite adamelites or granites. They are composed of dust sands with the presence of fragments of parent rock and singles $d_{\max}$ = 400 mm. Deluvium has insignificant thickness, which according to the investigated wells ranges between 0.80 and 1.20 m, while according to geophysical investigations, a deluvial cover with a thickness of 3.0–4.0 m may also occur locally.

In correlation with geological development and geological processes that took part on the explored area, appear geomorphological characteristics of the terrain and its vicinity.

The medieval Isar fortress, which is the subject of these investigations, is located in the western part of the town of Štip. The rocky hill rises above the city as the dominant elevation that lies between the Bregalnica (on the west side) and Otinja rivers (on the south side). From the riverbed of the Bregalnica river it rises with a height of about 100–150 m. It is surrounded by sharp and steep slopes in which foothills flow these two rivers. At the top of the hill there is an uneven plateau extending north-south in the length of 350 m on which the fortress itself lies. It is located at an altitude ranging between 385 and 395 m.

BASIC SEISMOTECTONIC CHARACTERISTICS OF THE TERRAIN

In correlation with the geological development of the terrain and the geological processes, the seismotectonic characteristics of the area are also found.

According to the geotectonic regionalization of the Republic of N. Macedonia, the researched area belongs to the Vardar zone. This zone is separated as a separate geotectonic unit between the Serbian-Macedonian unit and the Pelagonian massif.

The basic structures were formed during the Paleozoic within the Hercynian orogenesis, while during the Alpine orogenesis the development took place through phases of rest and vertical movements. Within the investigative area, as significant tectonic structures we will mention the Štip block. The central part of this block is made of adamelites, while the wings are mode of biotite and aplitoide granite. The crack system is particularly pronounced in the biotite granite in the northeast-southwest direction.

According to the existing map of intensities of the Republic of North Macedonia for a 500 years return period (Figure 2) (which is recommended for use according Eurocod 8 until a national seismic application document is adopted), it can be concluded that the site concerned is located in the border zone of intensity areas I = VIII°, MKS (by Mercali, Cancani and Zieberg scale).

HYDROGEOLOGICAL CHARACTERISTICS OF THE TERRAIN

Based of the performed hydrogeological exploration of the terrain, as well as other hydrogeological parameters that determine the water permeability of the rocks on the investigated location, a classification of the rock masses was made in terms of their hydrogeological characteristics and hydrogeological function. According the defined parameters, the following types of rock masses are separated:

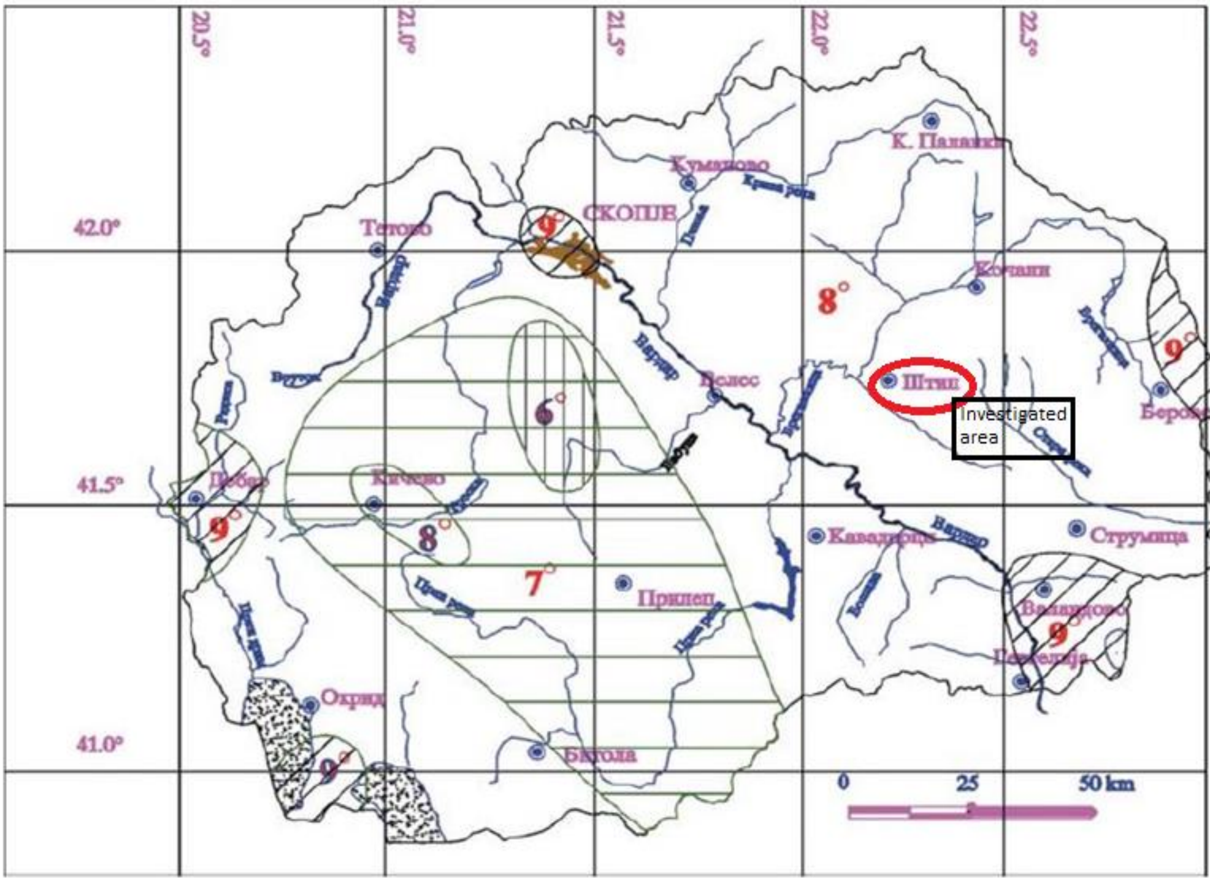

Fig. 2. Map of intensities in North Macedonia for return period of 500 years [8]

Hydrogeological collectors – include deluvial sediments that partially cover the investigated terrain. They are mainly made of dusty sands with the presence of fragments of parent rock and single pieces d_{max} = 400 mm, well granulated, well compacted with light brown color. These sediments are characterized by intergranular porosity and can form boundary type of aquifer with free groundwater level. They have low water permeability.

Hydrogeological insulators. Within the hydrogeological insulators are included biotite adamelites that composed most of the exploration area. They are tightly bonded hard rock masses that are predominantly water impermeable. In the surface parts, due to fractures, locally, may occur poor water permeability along the cracks, which may form fissure type of aquifer with limited extension.

ENGINEERING-GEOLOGICAL CHARACTERISTICS OF THE TERRAIN

Within the research area there are several types of rock masses which, according to their engineering-geological characteristics, can be included in: unbound rock masses and tightly bound rock masses:

– ***Unbound rock masses*** include deluvial sediments that are composed mainly of dusty sands with a variety of granular crusts, i.e. rock fragments with d_{max} = 400 mm. According to the Construction Norms GN.200 [14] belong to Category III, where excavation can be done mechanically.

– ***Tightly bound rock masses*** include biotite adamelites. On the surface, they are very cracked, partially decomposed, while in depth they are more compact. According to the results of geophysical investigations these granites in the first 3 – 5 m are degraded, intensively cracked, on some places decomposed, whereas in the deeper parts they are mostly intermediate cracked. According to the Construction Norms G.N. 200 belong to Categories V and VI – where excavation can be done with rippering and blasting.

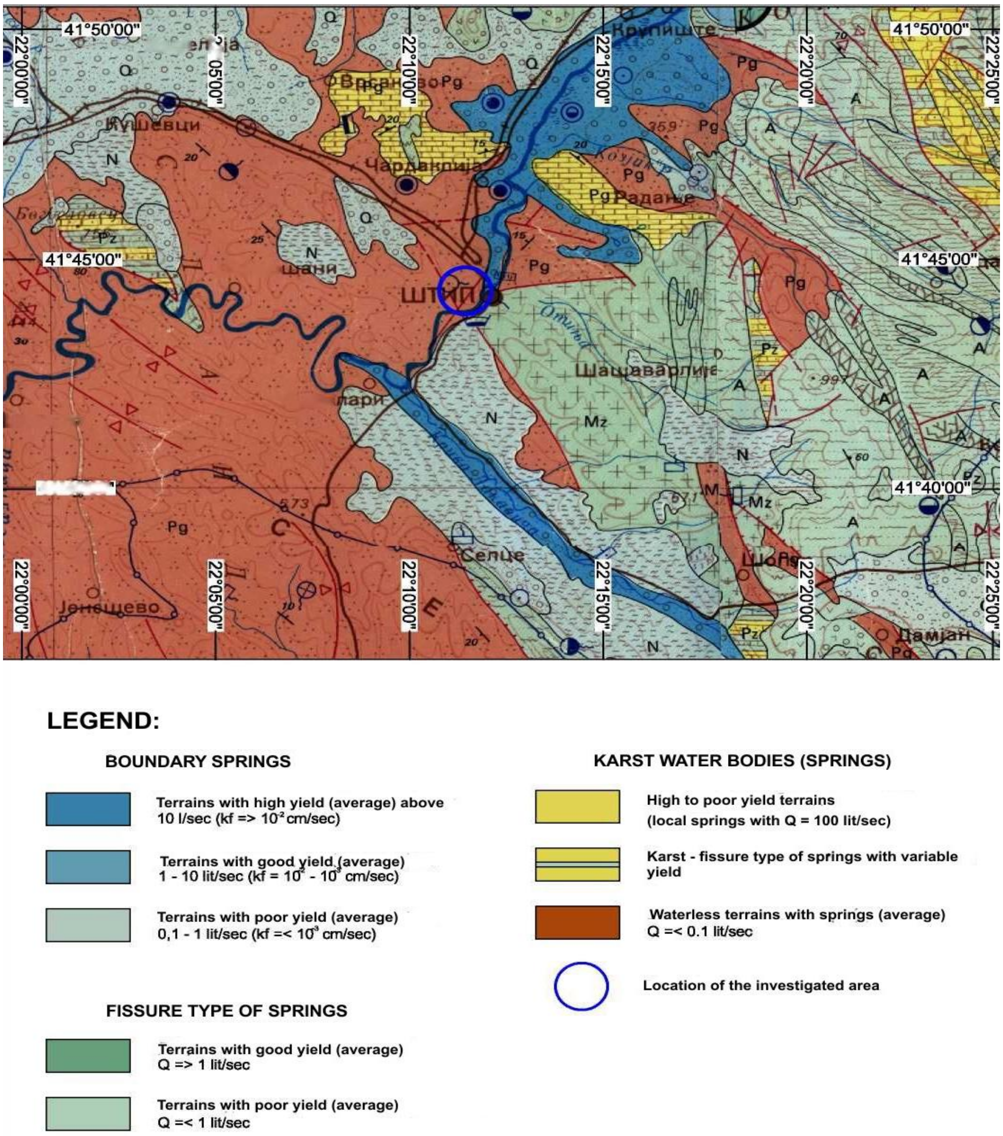

Fig. 3. Hydrogeological map of the terrain [6]

PHYSICAL-MECHANICAL CHARACTERISTICS OF THE MATERIALS AND THEIR CLASSIFICATION

Classification of soil materials

According to the classification made on the basis of field mapping it can be concluded that the following materials with physical-mechanical characteristics are represented at the investigated area as shown below [1].

H – Humus

In the upper zone of the investigated location to a depth of 0.10 ÷ 0.30 m, measured from the surface of the terrain, humunized material was recorded.

Dusty sand with rock fragments PRP + dr [SFs]

This material is recorded under the humunized cover over the entire profile of the investigated site with a maximum layer thickness of up to 0.80 m. It is made of well-grained dust sands with the presence of rock fragments and singles d_{max} = 40 mm, well compacted with light brown color.

The adopted physical-mechanical characteristics are given as follows:

ρ mg/m³	φ °	c kPa	Mv kPa
2.100	30.00	6.00	18 000

Classification of rock materials

From the open profiles of the location where the Isar fortress is situated and is subject of these investigations, samples of rock material were taken and classified geotechnically. The basic physico-mechanical characteristics of the rocks have been investigated, i.e. volume weight and point strength index [17].

Adequate categorization was performed on the rock masses represented by Bieniawski's (1983) rock mass rating (RMR) system [10], taking into account the physico-mechanical characteristics and condition of the rocks. This system is simple to use and uses the following geological and geotechnical informations:

- one-axial compressive strength;
- rock quality designation (RQD) [9];
- distance between the cracks;
- condition of cracks;
- conditions of ground water.

The above parameters are obtained from the mapping of open profiles as well as from laboratory tests. The points adopted for the individual rock classification parameters, as well as the obtained RMR rating, are shown in Table 1.

Table 1

RMR classification of the present rock masses according Bieniawski (1993) [10]

Parameter	Rock type and points Biotite adamelites-granites (γ) subsurface layer 0.0÷0.5 m	Rock type and points Biotite adamelites-granites (γ) zone 0.5÷1.0 m
One-axial point load test	(25÷ 50 MPa) →4	(100÷ 250 MPa) →12
Rock quality designation (RQD)	(50% ÷ 75%) →13	(75% ÷ 90%) →17
Average distance between the cracks	0.2 ÷ 0.6 m →10	0.6 ÷ 2.0 m →15
Condition of cracks	10	20
Conditions of ground water	10	10
Correction points for cracks orientation	–5	–5
Rock mass raiting (RMR)	42	69
Geological strength index – (GSI)	37	64
Class of rock mass according RMR	Class III	Class II

From the classification of rocks according to the RMR parameter it can be concluded that biotite adamelites-granites (γ) depending on their condition in the investigative area can be distinguished as: biotite adamelites from the upper parts (0.0–0.5 m) which belong to III class of favorable rock mass, RMR = 42, with orientation strength parameters φ = 25 ÷ 35° and c = 200 ÷ 300 kPa, and biotite adamelites from deeper parts (0.5–1.0 m) belonging to II class of rocky mass, RMR = 69, with orientation strong parameters φ = 35–45° and c = 300–400 kPa.

Rock samples from the subsurface sections (0.0 ÷ 0.5 m) that are quite cracked and physically-mechanically modified, showed lower strength index, while rock samples taken from the deeper parts (0.5 ÷ 1.0 m), i.e. a fresh rock mass is taken, thus yielding a higher strength index.

Geological strength index (GSI) [18] is calculated with the following formula:

$$GSI = RMR - 5$$

Physical and mechanical characteristics of monolithic parts

Strength value of monolithic parts is obtained with the definition of strength index, examined with Franclin’s press for point loading.

The recommendations for calculating this parameter according to International Society for Rock Mechanics (ISRM) have been applied. It is calculated according to the following form [13]:

$$Js = p/D_2 \text{ (MPa)}$$

where:

Js – point strength index for monolithic parts;

p – force at the time of crussing of the sample;

D – distance between the points of crusshing.

Summarized parameters, as well as the strength of the pressure estimated by correlation, based on the point strength tests are shown below in Table 2.

Table 2

Overview of the parameters for the present rock materials (mean value)

Sample no.	Geological mark	γ ng/m^3	$Js_{(50)}$ MPa	$\sigma_p = 22 \cdot Js_{(50)}$ MPa
1	γ	2.57	6.25	137.5
2	γ	2.62	1.52	33.44
3	γ	2.65	4.67	102.74
4	γ	2.63	1.95	42.9

Physical and mechanical characteristics of rock massif

The characteristics of the monolithic parts of the rock massif are not essential for the mechanical behavior of the massif globally, in terms of stress-deformable state, permissible basement loads (when performing-engineering structures), expected deformation, and global and local stability.

The parameters of shearing strength φ_m and c_m were determined with the empirical criterion of fracture of rock masses after Hoek & Brown [11] and with laboratory testing of representative samples from the slope. These parameters more real defined the shearing strength of the massif related to those for monolithic parts, because the mechanical behavior is predetermined by the overall state of the massif, not by its healthier monolithic parts (due to the famous phenomenon of "scale effect").

$$\sigma_1 = \sigma_3 + \sigma_p \left(mb \frac{\sigma_3}{\sigma_p} + s \right)^a$$

$$mb = mi * \exp\left(\frac{\text{GSI} - 100}{28 - 14D}\right)$$

$$s = \exp\left(\frac{\text{GSI} - 100}{9 - 3D}\right)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\text{GSI}/15} - e^{-20/3}\right)$$

The values of angle of internal friction (φ_m), mass cohesion (c_m) and global rock mass strength (σ_{cm}) are obtained using the Hoek & Brown (1997) fracture criterion, while the mass deformation module (E_{rm}) is calculated with the empirical form of Hoek & Diederichs (2006) [12].

All input data for the geological strength index (GSI), pressure strength (σ_p), constant (m_i), mass disturbance factor (D), as well as the results of the performed analysis are given in Table 3.

Table 3

Overview of the physical-mechanical characteristics for the present rock materials

Sample	Geological mark	RQD	GSI	φ_m	c_m MPa	σ_{cm} MPa	E_{rm} MPa
1 and 3	γ	75–90	64	68.80	0.598	27.469	13312.97
2 and 4	γ	50–75	37	34.75	0.221	2.663	1458.35

GEOPHYSICAL SEISMIC EXPLORATIONS

With these investigations is covered the location of a part of the Isar fortress, which is the subject of investigations, or the Acropolis of the Isar fortress in order to obtain engineering-geological data for the terrain [16].

The investigations were performed using seismic refractive profiles with the following purpose [4]:

– Lithophysical distinction of the surface structure of the terrain at the specified locations according to the values of the seismic *Vp* and *Vs* velocities.

– Characterization of lithophysical members with values of dynamic parameters based on measured values of seismic velocities.

– Depth limit on rock masses.

Two seismic profiles are performed, one longitudinal with length of 80 m and a depth of 20 m, and one transverse profile with a length of 64 m and a depth of 20 m.

Geophysical investigations have been performed in order to define the seismologic characteristics of the terrain of the investigated locations, i.e. for:

- Defining the parameters of the lithological members of the investigated area, such as *Vp* and *Vs* – seismic velocities, and *d* – thickness of the layers;
- Dividing the terrain structure in lithophysical parts according the values of the velocities of the seismic waves *Vp* and *Vs*;
- Determining local disintegration and discontinuities in the structure of the terrain;
- Defining dynamic values of the geomechanical elastic parameters;
- Soil classification according the standards of Eurocod 8 (EC8).

Invetstigations were performed with the method of seismic refraction tomography – SIRT.

METHOD OF SEISMIC REFRACTION TOMOGRAPHY – SIRT

Measurements, using the method of seismic refraction, are performed along two seismic profiles (Figure 4) with lengths of 80 and 64 meters. There is a mutual distance between the geophones of 5 and 4 meters and a minimum offset (distance between the source and the receiver) of 5 and 4 meters, respectively. The acquisition is conducted with a sampling frequency of 1024 Hz and a time length of 0.5 seconds. To generate seismic energy was used knock with hammer (8 kg) on aluminium plate [5].

Fig. 4. Situation with arrangement of seismic refractive profiles

Processing of "raw" data was done with the software SoilSpy Rosina, MoHo – Science & Technology, Italy and ReflexW, by Dr. K-J. Sandmeier, Germany, while the lithological identification of the materials is based on the existing geological data.

The data processing consists of:

- Determining the first comings of the seismic waves.
- Entering topograph.
- Defining the hodochrones (distance – time).

- Marking the layers.
- 2D "wavefront" inversion.
- Comparation of calculated and measured data.
- Defining the finel model.
- Simulative technique of tomography:
  - The algoritm is based on iterative adaptation (SIRT – simultaneous iterative reconstruction technique).
  - Starting from the previously defined model, synthetic hodochrons are calculated.
  - Calculated hodochrons are compared with the measured ones.
  - Modifications of the model are automatically calculated from the residuals of hodochrons.
  - The procedure is repeated depending on the variation of the model.
  - The complete process stops when the maximum number of iterations is reached.

The final result of the researches is shown as a 2D seismic model that presents the variations of seismic waves velocities in depth and laterally to a maximum depth of 20–30 meters.

RESULTS FROM INVESTIGATIONS

2D seismic *Vs* and *Vp* models obtained as result of applied investigations in combination with the geological data define the seismo-geological characteristics of the investigated location. By applying this methodology, the separation of boundaries between different environments is with great accuracy.

The 2D model obtained by analyzing the data in this research singles out 5 lithological environments that are characterized by different physical and mechanical characteristics. The following lithological members are distinguished:

1. Surface layer – deluvium, crushed material of mother rock with values of seismic velocities: *Vp* = 400 – 750 m/s; *Vs* = 160 – 310 m/s;
2. Subsurface "weathered" zone – intensive cracked and desintegrated rocks, with values of seismic velocities: *Vp* = 800 – 1350 m/s; *Vs* = 350 – 600 m/s;
3. Intensive cracked rocks with values of seismic velocities: *Vp* = 1350 – 2000 m/s; *Vs* = 600 – 1000 m/s

The final 2D model is presented on Figures 5 and 6.

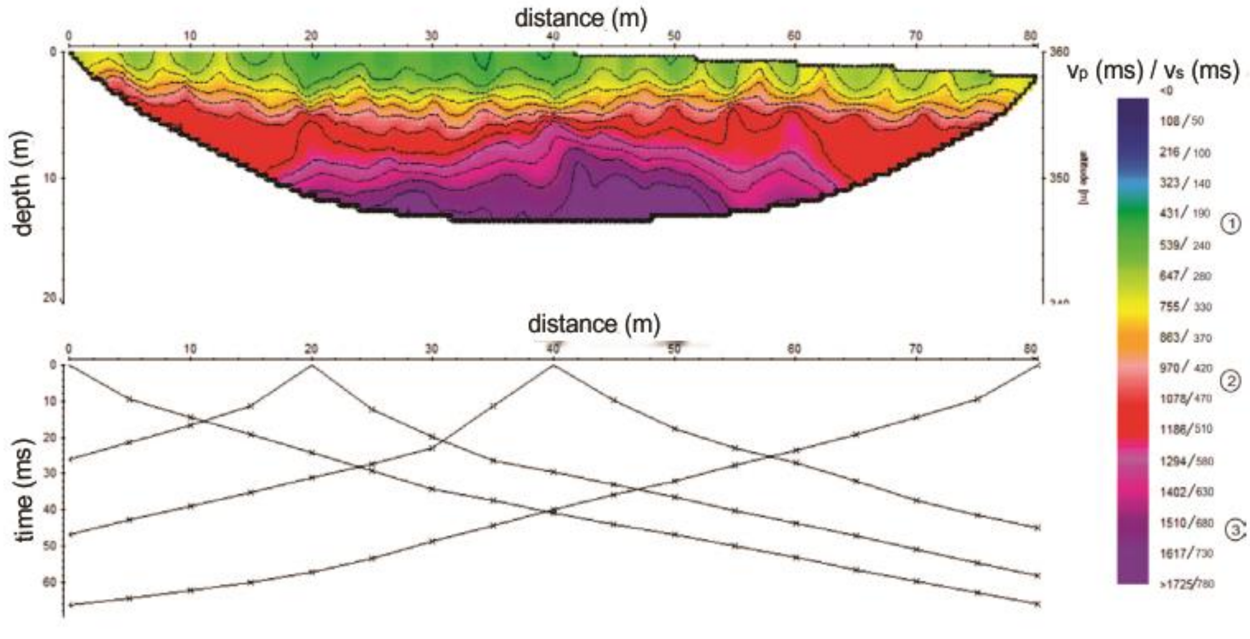

Fig. 5. Seismic refractive-tomographic profile *Rp*1
1) surface layer – deluvium, crushed material from mother rock, 2) subsurface "weathered" zone – disintegrated rocks, 3) intensely to medium cracked rocks

From the interpretation of the seismic model can be concluded that:

- The profiles Rp1 and Rp2 showed the thicknes of the surface layer in interval of 0 – 4 meters.
- On the investigation location, subsurface layer which is composed of crushed disintegrated mother rock reach the depth of about 6 – 10 meters.
- Subsurface layer, within the seismo-geological structure of the terrain is characterized with very weak physical-mechanical properties and represents critical zone, such as surface layer, on which should be paid attention.
- On depth larger than 10 m the physical and mechanical characteristics of the rock are improved and seismic speeds are registered: Vp > 1450 m/s; Vs > 650 m/s.

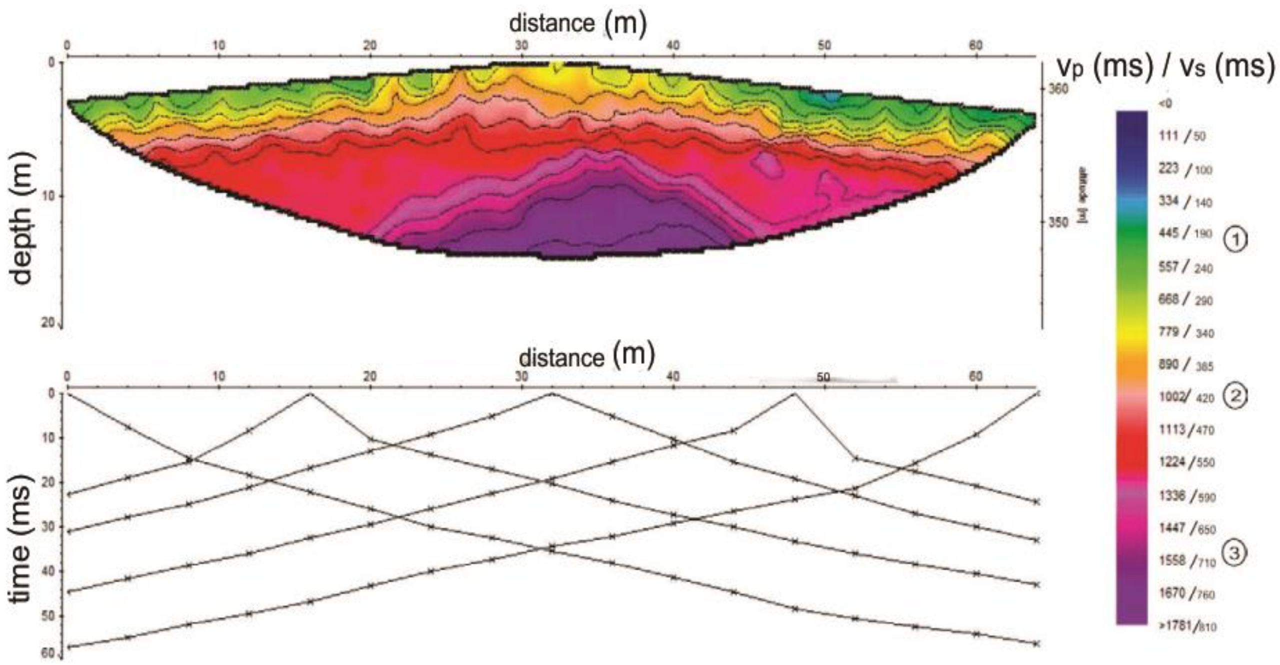

Fig. 6. Seismic refractive-tomographic profile *Rp*2
1) surface layer – deluvium, crushed material from mother rock, 2) subsurface "weathered" zone – disintegrated rocks, 3) intensely to medium cracked rocks

CONCLUSION

According the obtained results from the geotechnical and geophysical investigations and laboratory examinations, can be presented the following conclusions:

– The scope of the carried out investigations, 4 (four) investigated wells with an individual depth of 1.00 ÷ 1.30 m', 4 (four) open profiles, as well as geophysical investigations carried out at the investigation area, sufficiently define the lithological structure of the terrain and its physical mechanical properties.

– Laboratory tests are performed in accordance with Macedonian standards MKTS CEN ISO / TS [19]. The results are within the expected range.

– No ground water has been recorded during the field investigations.

– From the geological point of view, investigated location is composed of tightly bound petrified rock masses, biotite adamelite-granites that in the surface parts are covered with a deluvial cover represented with dusty sands with the presence of fragments of the parent rock.

– From the hydrogeological point of view, the investigated field belongs to the group of predominantly water impermeable terrains, within which a boundary type of aquifer can be formed in the deluvial sediments with low permeability. Locally, a shallow below the surface may form a fissure type of aquifer in biotite adamelites with limited extension. By hydrogeological function, deluvial sediments belong to the group of hydrogeological collectors, while biotite adamelites belong to hydrogeological insulators.

– According to the existing map of intensities of the Republic of North Macedonia, it can be concluded that the site concerned is located in the border zone of intensity areas I = VIII°, MKS (by Mercali, Cancani and Zieberg scale).

– The location is relatively homogeneous in terms of the origin of the present materials. The surface layer is made of dust sands covered with humus. The maximum depth of layer spreading according to the performed investigations is 1.20 m, while according to the geophysical investigations the local deluvial cover has a thickness of 3.0–4.0 m. Below this layer to the ultimate investigated depth are biotite adamelite-granites.

– For the research of the Acropolis of the Isar fortress located in Štip, geophysical investidations have been applied where a method of seismic refraction is used which allows to define the lithological structure on the terrain and its physical and mechanical characteristics.

– By analyzing the obtained results, we can distinguish three lithological environments that are characterized b y a relatively homogeneous composition and different physical and mechanical characteristics.

– The surface layer is composed of dusty sands covered with humus and represents the composition of the diluvial cover which is with thickness of 3.00 – 4.00 m.

– The subsurface zone is composed of biotite adamelite-granites which are crushed and disintegrated and are at a depth of 6.00 to 10.00 m.

– At a depth greater than 10.00 m, the biotite adamellite-granites are more compact and their physical and mechanical characteristics are improved.

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Р е з и м е

СЕИЗМИЧКИ ИСТРАЖУВАЊА НА ТВРДИНАТА ИСАР – ШТИП

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Целта на овој труд е да се дефинираат геотехничките и сеизмо-геолошките карактеристики на теренот на истражуваната локација, локалните нарушувања и дисконтинуитетите кои укажуваат на појава на ослабени и раздробени зони. Истражувањето е изведено со примена на геотехнички истражувања и сеизмички рефракциски метод и е составено од теренски мерења, процесирање и анализа на добиените резултати. Предмет на истражувањето е Акрополот на тврдината Исар. Со анализа на добиените податоци се издвојуваат 3 литолошки средини кои се одликуваат со различни физичко-механички карактеристики. Издвоени се следниве литолошки средини: површински слој составен од делувијум и здробен материјал од матична карпа кој достига длабочина во интервал од 0 до 4 метри; потповршинска зона составена од раздробена деградирана матична карпа со длабочина од 6 до 10 m, која се одликува со доста слаби физичко-механички карактеристики и претставува критична зона; интензивно испукани карпи на длабочина поголема од 10 m каде се подобруваат физичко-механичките карактеристики на карпата.