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СЪДЪРЖАНИЕ

CONTENTS

СЕКЦИЯ ДОБИВ И ПРЕРАБОТКА НА МИНЕРАЛНИ СУРОВИНИ

SECTION MINING AND MINERAL PROCESSING

Асеновски, С., Д. Георгиев , Анализ на зависимостта на параметрите при математическо моделиране в открито разработване <i>Azenovski, S., D. Georgiev</i> , Analysis of parameter dependency in mathematical modelling of open-pit mining	9
Билев, Вл., Г. Мишев , Управление на взривосеизмичното влияние при извършване на взривни работи в близост до охраняеми обекти в условията на рудник „Елаците“ <i>Bilev, V., G. Mishev</i> , Managing seismic impact while blasting near safeguarded objects under the conditions of the <i>Ellatzite</i> open-pit mine	13
Василева, Е., Ц. Първанова-Манчева, В. Бешков , Влияние на постоянно електрично поле върху биоразграждането на халогенирани замърсители <i>Vasileva, E., Ts. Parvanova-Mancheva, V. Beschkov</i> , The effect of constant electric field on the biodegradation of halogenated pollutants	18
Величкова, К., Д. Крежова , Мониторинг на околната среда чрез хиперспектрални дистанционни изследвания: откриване на стрес в растителна екосистема <i>Velichkova, K., D. Krezhova</i> , Hyperspectral remote sensing in environmental monitoring: stress detection in a plant ecosystem	19
Дебеляшки, К., М. Николова , Избор на подход за изграждане на инфраструктура за управление на отпадъците в РСУО – Костинброд <i>Debelyashki, K., M. Nicolova</i> , Selection of an approach for the construction of waste management infrastructure in the Kostinbrod area	25
Димитров, Д., Д. Даков, С. Чавдарова , Използване на специализирана минна техника (багер) при оформяне на рудничните откоси <i>Dimitrov D., D. Dakov, S. Chavdarova</i> , Using specialised mining equipment (excavator) when forming the pit walls	29
Димитров, Л., Д. Кайков , Възможности за компостиране на органичен материал за нуждите на рекултивацията на минни обекти <i>Dimitrov L., D. Kaykov</i> , Possibilities for organic material composting for the needs of mining site reclamation	33
Иванов, И., И. Василев, Г. Петров, Д. Бенов , Развитие на системата АСМО Модул в рудник „Елаците“ <i>Ivanov, I., I. Vasilev, G. Petrov, D. Benov</i> , Developing the <i>АСМО Module</i> system in the <i>Ellatzite</i> open-pit mine	37
Кайков, Д., И. Копрев , Стохастичен подход за определяне на рационалните местоположения за поставяне на датчици, проследяващи отместването на скалата при взривяване <i>Kaykov, D., I. Koprev</i> , A stochastic approach for determining the rational places for installing blast movement monitoring sensors in the blasting area	43
Каназирски, И., К. Гиргинов, П. Недялкова , Електролитно оцветяване на порьозни анодни алуминиеви филми <i>Kanazirski, I., C. Girginov, P. Nedyalkova</i> , Electrolytic colouring of porous anodic aluminium films	49
Минкова, М. , Генетично инженерни бактерии за ремедиация на околната среда <i>Minkova, M.</i> , Genetically engineered bacteria for environmental remediation	53

Моллова, З. , Разработка на модел за оценка на въздействието на взрива върху сгради и съоръжения при използването на взривозащитни стени	56
<i>Mollova, Z.</i> , Development of a model for assessing the impact of an explosion on buildings and facilities when using blast walls	
Нейчева, Е., Д. Анастасов, З. Ефтимов , Анализ на иновативните решения при разработване на запасите в рудник „Джурково“ Лъки Инвест АД	60
<i>Neucheva, E., D. Anastasov, Z. Eftimov</i> , Analysis of the innovative solutions in the development of the reserves in the Dzhurkovo mine, Lucky Invest JSC	
Николов, И., Л. Свиленов , Методология за определяне на оптималната дълбочина при разработване на „Перспективен контур“ за рудник „Елаците“ чрез специализиран минен софтуер „HXGN-MINEPLAN™3D“	64
<i>Nikolov, I., L. Svilenov</i> , Methods for defining perspective pit shell optimal depth of the <i>Ellatzite</i> open-pit mine, by using the HXGN-MINEPLAN™3D mining software	
Николов, Ив., Р. Петрова , Опазване на околната среда – анализ на данните за антропогенно повлияните от минната дейност зелени пояси на град Перник	70
<i>Nikolov, I., R. Petrova</i> , Environmental protection – analysis of the data on the green belt sites of the town of Pernik, which are anthropogenically influenced by mining activities	
Първанова-Манчева, Ц., Е. Василева, В. Бешков , Толерантност на щамовете <i>Xanthobacter autotrophicus GJ10</i> и <i>Pseudomonas putida</i> към фенола	75
<i>Parvanova-Mancheva, Ts., E. Vasileva, V. Beschkov</i> , Tolerance of <i>Xanthobacter autotrophicus GJ10</i> and <i>Pseudomonas putida</i> strains to phenol	
Савов, П., В. Христов, С. Топалов , Изследване на качеството на въздуха в градски паркове с помощта на невронни мрежи	76
<i>Savov, P., V. Hristov, S. Topalov</i> , Air quality investigation in urban parks using neural networks	
Савов, П., Н. Колев, М. Вацкичева, К. Величкова, Д. Димитров, Б. Владкова , Влияние на градските паркове върху замърсяването на въздуха	81
<i>Savov, P., N. Kolev, M. Vatzkitcheva, K. Velichkova, D. Dimitrov, B. Vladkova</i> , Urban parks and their relation to air pollution	
Стойчева, Н., П. Шишков , Оптимизиране на недетониращи заряди в полимерни корпуси за прецизни взривни работи в кариери за скалнооблицовъчни материали	87
<i>Stoycheva, N., P. Shishkov</i> , Optimisation of non-detonating charges in polymer housings for cautious blasting activities in dimension stone quarries	
Терзийски, Д., Л. Димитров, Д. Кайков , Сравнителен анализ между работата на кофова трошачка и мобилна трошачка в кариери за варовик	92
<i>Terziyski, D., L. Dimitrov, D. Kaykov</i> , A comparison study between bucket crusher and mobile crusher performance for limestone quarries	
Янакиев, В., М. Бояджиев , Устройства в системи за дистанционно наблюдение и управление на средствата за търговско измерване на природен газ	98
<i>Yanakiyev, V., M. Boyadzhiev</i> , Devices in remote monitoring and control systems for commercial measurement of natural gas	
Янкова, Т., Т. Ангелов, И. Нишков , Изследвания върху веществения състав и физико-механичните свойства на меднопорфирна руда	103
<i>Yankova, T., T. Angelov, I. Nishkov</i> , Investigations on the composition and the physico-mechanical properties of porphyry-copper ore	

СЕКЦИЯ ГЕОЛОГИЯ И ПРОУЧВАНЕ НА МИНЕРАЛНИ И ЕНЕРГИЙНИ РЕСУРСИ
SECTION GEOLOGY AND EXPLORATION OF MINERAL AND ENERGY RESOURCES

- Аспарухов, Б.**, Златната металургия – цивилизационният принос на древните българи **111**
Asparuhov, B., Golden metallurgy – the civilisation contribution of ancient Bulgarians
- Банушев, Б., С. Димовски, Н. Стоянов**, Комплексен подход за картиране на **116**
приповърхностния разрез в карстови терени
Banushev, B., S. Dimovski, N. Stoyanov, An integrated approach for mapping the near-surface section in karst terrains
- Донева, Б., М. Делипетрев, Г. Димов**, Сеизмични проучвания за определяне стабилността **122**
на ската при късноантичния термален комплекс „Банско“ в република Северна Македония
Doneva B., M. Delipetrev, G. Dimov, Seismic exploration for defining slope stability in the *Bansko* late antique spa in the Republic of North Macedonia
- Мерачева, Г.**, Модели на палеореконструкция и геолошко развитие на СЗ част на Тракийския **127**
басейн
Meracheva G., Paleo-reconstruction models and geological evolution of the north-western part of the Thrace basin
- Тодоров, Т.**, Проблеми, свързани с наличието на археологически обекти по време на **135**
проучването и добива на полезни изкопаеми в България
Todorov T., Problems related to the presence of archaeological sites during the exploration and extraction of minerals in Bulgaria

СЕКЦИЯ МЕХАНИЗАЦИЯ, ЕЛЕКТРИФИКАЦИЯ И АВТОМАТИЗАЦИЯ НА МИНИТЕ
SECTION MECHANISATION, ELECTRIFICATION, AND AUTOMATION OF MINES

- Вучева, Р., В. Генова-Трифенова**, Определяне напреженията в нож на кофа за роторен **143**
багер SRS 4000
Vucheva, R., V. Trifonova-Genova, Determining the stresses in a bucket knife of the SRS 4000 bucket wheel excavator
- Горбунов, Я., Р. Александров, Х. Чен**, Оценка на мощността при безсензорно управление на **147**
превключваеми реактивни двигатели
Gorbounov, Y., R. Alexandrov, H. Chen, Power estimation in sensorless control of switched reluctance motors
- Димитров, А., Н. Иванова, Р. Нешева, Н. Янев**, Подготовка на индустриални данни с цел **151**
използването им в Big Data
Dimitrov, A., N. Ivanova, R. Nesheva, N. Yanev, Preparation of industrial data for implementation in Big Data
- Зъбчев, З.**, Разположение на сферични тела в коничен бункер **155**
Zabtchev, A., The arrangement of spherical bodies in a conical bin
- Минин, И., П. Недялков**, Компютърно симулационно изследване на манипулатор, носещ **159**
къртачен чук RB-2701
Minin, I., P. Nedyalkov, Computer-based simulative study of an *RB-2701* manipulator with a demolition hammer
- Тонкова, Г., С. Пулев**, Намаляване на натоварването при усукващи трептения на вал **165**
Тонкова, Г., S. Pulev, Reducing the elastic torsional moment of a vibrating shaft
- Тонкова, Г.**, Влияние на преходния участък на стъпален вал върху честотата на собствените **168**
трептения
Тонкова, Г., Influence of the transition section of a stepped shaft on the frequency of natural oscillations

СЕКЦИЯ УСТОЙЧИВО РАЗВИТИЕ НА МИНЕРАЛНО-СУРОВИННАТА ИНДУСТРИЯ
SECTION SUSTAINABLE DEVELOPMENT OF THE MINERAL RESOURCES INDUSTRY

- Балев, В., Д. Кайков, Л. Димитров**, Изследване на структурните нарушения на скални откоси в близост до отделни участъци на републиканската пътна мрежа **175**
Balev, V., D. Kaykov, L. Dimitrov, A case study of the rock discontinuities in slopes situated near sections from the state road network
- Благоева, Е., Б. Кърков, М. Първанова**, Студенти-информатици от МГУ „Св. Иван Рилски“ по пътя на професионалната си реализация **181**
Blagoeva, E., B. Karkov, M. Purvanova, IT students at the University of Mining and Geology "St. Ivan Rilski" along the road of their occupational fulfilment
- Гълъбова, Б., Б. Трифонова, В. Петрова, Е. Димов**, Стратегии за адаптиране на политиките по управление на човешките ресурси в преприятията от минерално-суровинната индустрия в Ковид контекст: теоретични и приложни аспекти **187**
Galabova, B., B. Trifonova, V. Petrova, E. Dimov, Strategies for adapting human resource management policies in mineral resource enterprises in the covid-19 contex: theoretical and applied aspects
- Димов, П., Х. Добрева**, Изследване на системата за академична комуникация във Военна академия "Г. Раковски" **192**
Dimov, P. H. Dobreva, A Study of the System of academic communication in the Rakovski National Defence College
- Каминский, П., Й. Анастасова, Н. Янев**, Ролята на човешкия фактор при приложение на политиките за изграждане култура на сигурност при онлайн плащания с карти **197**
Kaminsky, P., Y. Anastasova, N. Yanev, The role of the human factor in implementing security culture policies in online card payments
- Кондев, Г., И. Михайлова**, Идентифициране на ключови възможности за подобряване на бизнес представянето при добив на инертни материали **201**
Kondev, G., I. Mihaylova, Identification of key opportunities for improving business performance in the extraction of aggregates
- Младенов, К., Б. Ценова**, Използване на модел за машинно обучение с дълготрайна памет (LSTM) за прогнозиране на отклонения в прогнозите **207**
Mladenov, K., B. Tsenova, Using a long short-term memory (LSTM) machine learning model to predict forecast bias
- Прокофьева, Л., Н. Кузовлева, З. Бамба**, Устойчиво развитие на нефтени компании в условия на нестабилна икономика **211**
Prokofieva L., N. Kuzovleva, Z. Bamba, Sustainable development of oil companies in an unstable economy
- Симеонова, Д., В. Христов**, Реализация на система, базирана на икономическата методика „Ползи–Разходи“ за повърхностни водни тела от Източно Беломорския регион **217**
Simeonova, D., V. Christov, Implementation of a system based on the "Benefits-Costs" economic methodology for surface water bodies from the East Aegean region
- Стратиев, Н.**, Банков риск – видове и управление **220**
Stratiev, N., Banking risk – aspects and management
- Съръстов, З., М. Димов**, Детерминанти на стойността в миннодобивните предприятия **225**
Sarastov, Z., M. Dimov, Determinants of corporate value in mining
- Тодоров, Д.**, Технопандемия **230**
Todorov, D., Techno pandemic
- Трифонова, Б.**, Приложение на компетентностния модел за управление на човешките ресурси в минно-добивната промишленост **236**
Trifonova, B., Application of the competency model for human resource management in mining industry

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 m², 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.

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

Б. Донева, М. Делипетрев, Г. Димов

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 м², 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 сейзмични картирания се планират и извършват в съответствие с геоложките условия на мястото, както и с методологията на съчетаните сейзмични проучвания. За определяне на геомеханичните параметри са приложени сейзмични рефракционни и отразяващи изследвания, основани на факта, че фрагментиранияте скални структури са склонни да абсорбират сейзмична енергия, което в крайна сметка води до намаляване на регистрираните сейзмични скорости.

Методът на сейзмична рефракция се прилага, за да се отделят повърхностните земни образувания (въз основа на малките стойности на скоростите на сейзмично 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, сейзмичен, 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).

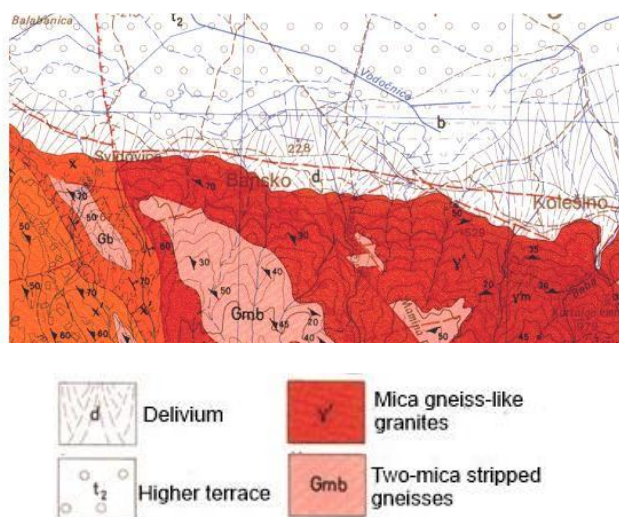
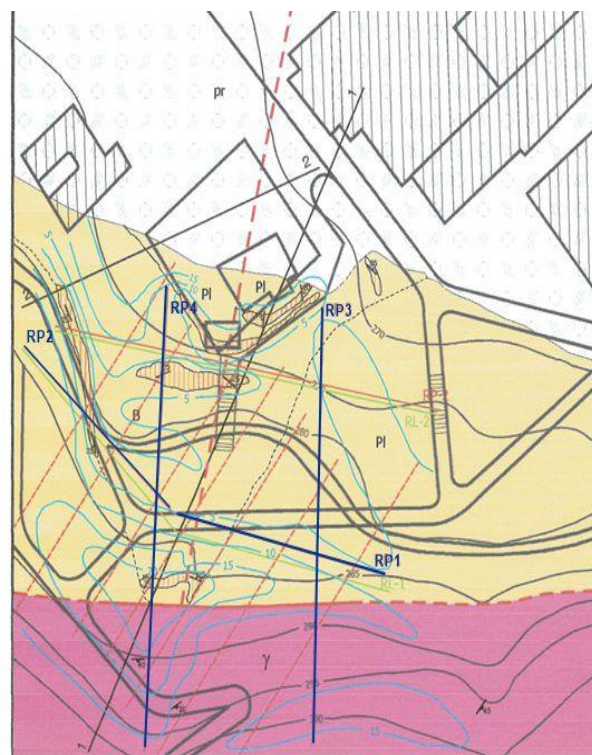


Fig. 1. Geological map of the investigated terrain

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:



LEGEND

- Pr** Proluvium
- B** Calcareous tuff
- Pl** Pliocene sediments
- γ** Granite - gneiss
- Faults**
- Reflection profiles**
- Refraction profiles**
- Isolines of thickness of proluvial members**

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 V_p and V_s 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 Quaternary 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: V_s in m/s, V_p in km/s, γ in kN/m³, and E_{st} , E_d , σ_p , 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 V_p and V_s 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:

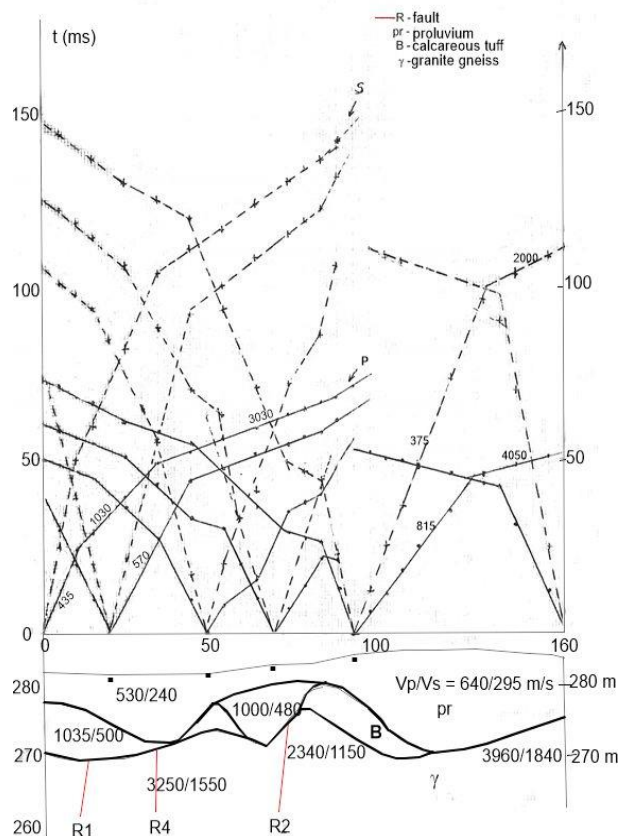


Fig. 3. Seismic refractive profile RP-1 with interpretation

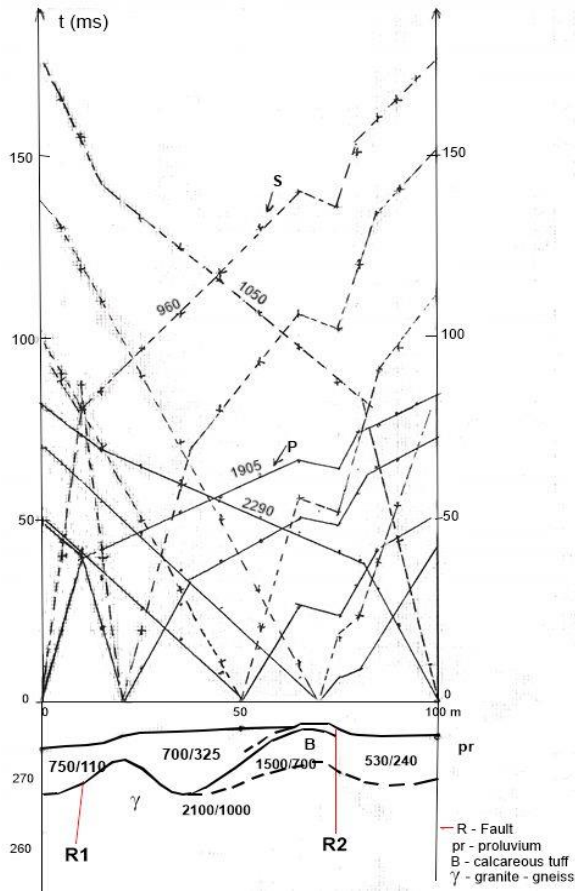


Fig. 4. Seismic refraction profile RP-2 with interpretation

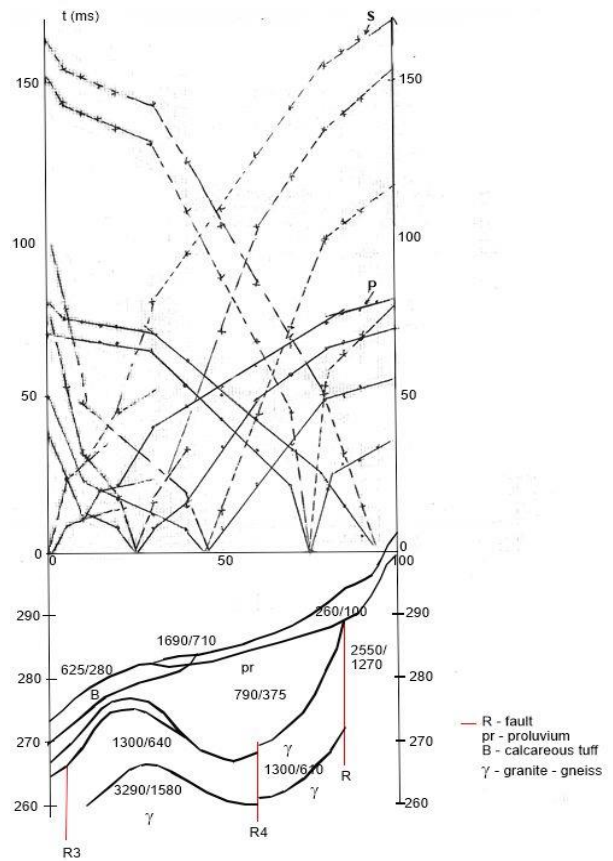


Fig. 6. Seismic reflective profile RP-4 with interpretation

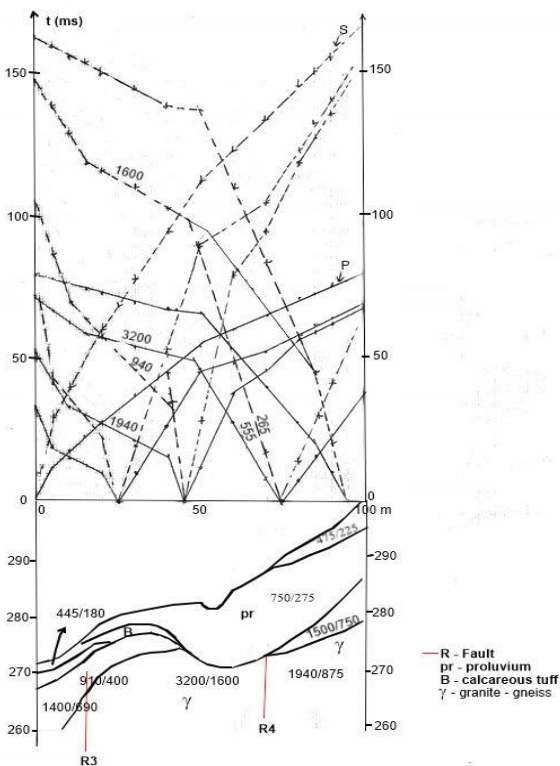


Fig. 5. Seismic refraction profile RP-3 with interpretation

- Old Paleozoic granite - gneisses:
 - Mechanically crushed and cracked granite - gneisses, relatively compact (γ),
 - $V_p = 3960 \text{ m/s}$
 - $V_s = 1840 \text{ m/s}$
 - Tectonically damaged and disintegrated blocks of granite - gneisses (γ) on depth $> 20 \text{ m}$
 - $V_p = 1950 - 3250 \text{ m/s}$
 - $V_s = 880 - 1600 \text{ m/s}$
- 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
 - $V_p = 250 - 900 \text{ m/s}$
 - $V_s = 110 - 400 \text{ m/s}$
- Calcareous tuffs with thin layers of proluvial creations (B), with a depth of 5-20 m and
 - $V_p = 1040 - 2340 \text{ m/s}$
 - $V_s = 480 - 1150 \text{ m/s}$.

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 $V_p < 800 \text{ m/s}$ and $V_s < 350 \text{ m/s}$. 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 (γ)	Granite-gneiss – mechanically damaged (γ)
Depth H (m)	2 – 20	5 – 20	>20	>20
Seismic velocity V_p (m/s)	250 – 900	1040 – 2340	1950 – 3250	3960
Seismic velocity V_s (m/s)	110 – 400	480 – 1150	880 – 1600	1840
Volume weight γ (kN/m ³)	15 – 20	20 – 23	23 – 26	27
Poisson coefficient μ	0.380 – 0.370	0.365 – 0.340	0.370 – 0.340	0.360
Elasticity module E_{din} (MPa)	50 – 870	1280 – 8300	5000 – 18000	25000
Shearing module G_{din} (MPa)	20 – 320	470 – 3100	1800 – 6800	9300
Volume module K_{din} (MPa)	60 – 870	1600 – 8650	6400 – 19000	30000
Static elasticity module E_{st} (MPa)	1 – 40	60 – 1200	800 – 5000	8200
Deformation module E_d (MPa)	0.5 – 25	25 – 300	300 – 2500	4000
Pressure strength σ_p (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 V_p and V_s 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:

$$V_p = 3960 \text{ m/s}$$

$$V_s = 1840 \text{ m/s}$$

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

$$V_p = 1950 – 3250 \text{ m/s}$$

$$V_s = 880 – 1600 \text{ m/s}$$

- Proluvial creations (pr)

$$V_p = 250 – 900 \text{ m/s}$$

$$V_s = 110 – 400 \text{ m/s}$$

- Calcareous tuffs

$$V_p = 1040 – 2340 \text{ m/s}$$

$$V_s = 480 – 1150 \text{ m/s}$$

- 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 $V_p < 800 \text{ m/s}$ and $V_s < 350 \text{ m/s}$.

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