МАКСИМАЛНИ СКОРОСТИ И ПОВЪРХНОСТНИ ДЕФОРМАЦИИ, СВЪРЗАНИ СЪС СИЛНИ ЗЕМЕТРЕСЕНИЯ НА ТЕРИТОРИЯТА НА ГР. ПЕРНИК

Иванка Паскалева

Резюме:

Земетресение с магнитуд 5.6Mw удари Юго-Западна България, на 22 май / 3:00 ч. местно време (00:00 UTC) / 2012 г., (25 км югозападно от българската столица, гр. София). Дълбочината е 9,4 km, а координатите на епицентъра са 42 ° 41'10 "N 23 ° 00'32" E; максимална интензивност MM VII –VIII. Районът в този ден бе въздействан и от серия афтършокове - 4.6Mw и 4.3Mw. Това сравнително плитко земетресение бе усетено и в региони на Гърция, Македония, Турция и Румъния. Не бяха регистрирани тежки наранявания, въпреки че в гр. Перник (най-близкият до епицентъра град) бе обявено извънредно положение заради наблюдавани значителни повърхностни щети.

Анализира се района на източника на разрушителното земетресение в гр.Перник от 22 май 2012 г. (5.6Mw). Обсъждат се структурата, дълбочината и геодинамиката на сеизмичния източник. Представено е разпределението на максималната скорост (PGV). Разпределението на деформациите е на базата на реални записи и анализи на затихването на PGV. Анализите са фокусирани единствено върху детерминистичната оценка на ефекта от земетресението 22, май 2012 г. и очаквани разпределения на щетите за дълги в план строителни системи.

Ключови думи:

Земетресение в Перник, максимална скорост, деформации, разрушения.

PEAK VELOCITIES AND SURFACE STRAINS ASSOCIATED WITH STRONG EARTHQUAKES ON THE TERRITORY OF PERNIK

Ivanka Paskaleva

Abstract:

An earthquake of magnitude 5.6Mw hit Western Bulgaria, on May 22-th/ 3:00 am local time (00:00 UTC)/, 2012, 25km South West of the Bulgarian capital, Sofia. The depth is 9.4 km, epicenter coordinates 42 ° 41'10 "N 23 ° 00'32" E; maximum intensity MM VII –VIII and aftershock series in this day - 4.6Mw and 4.3Mw. This shallow earthquake was largely felt in the region up to Greece, Macedonia, Turkey and Romania. No severe injuries have been reported so far, though a state of emergency was declared in Pernik (the closest city to the epicenter) and superficial damages were observed.

The source area of the Pernik destructive earthquake of 22, May 2012 (5.6Mw) is analysed. The depth structure and the geodynamics of the seismic source are discussed. The maximum ground velocity (PGV) distribution is presented. The strain distribution is carried out on the base of real records and analyses of attenuation of the PGV. The analyses are focused only on the deterministic assessment of the effect from the earthquake 22, May 2012 and the aftershocks series on the damage distribution in long in plan structural systems.

Key words:

Pernik earthquake, peak ground velocity, strain, damages.

1. INTRODUCTION

In the Bulgarian territory, earthquakes play a major role among geological hazards, as well as landslides, erosion processes, liquefaction and loess collapse. All the main Bulgarian cities are exposed to a significant earthquake hazard. Over the centuries, Bulgaria has experienced earthquakes with large epicentral intensities, I, e.g. the 1818, I=IX (MSK), and the 1858, I=IX (MSK), destructive events near Sofia. Some of the strongest earthquakes in Europe in the 20-th century, e.g. 4 April 1904, occurred in SW Bulgaria I=X (MSK). The seismic hazard of Bulgaria is controlled by seismic sources located in the country and in the territory of the neighboring countries (Romania, Greece, Turkey, Yugoslavia and Macedonia). Maximum intensity I=IX (MSK-64) is expected for the main Bulgarian city, Sofia.

An earthquake of magnitude 5.6Mw hit Western Bulgaria, on May 22-th/ 3:00 am local time (00:00 UTC)/, 2012, 25km South West of the Bulgarian capital, Sofia. The depth is 9.4 km; epicenter coordinates 42.66°N and 23.01°E. The maximum observed intensity Imax=VII-VIII (as spots). The main event within a few hours was followed by several major aftershocks. The aftershock series in this day are two events with magnitude 4.6Mw and 4.3Mw. This shallow earthquake was largely felt in the region.

2. GEOTECTONICS AND GEOLOGICAL DEVELOPMENT OF THE REGION

The geotectonics and the geological development of the region have been investigated by many researchers, and different interpretations are available (Ranguelov, 2011).

Almost all researchers mention faults and fault systems with NW-SE orientation and a complex block structure. Many of the faults are active, including some seismogenic. Past earthquakes in the region corroborate those hypotheses. The distribution of the aftershocks around the main shock is indicative of the volume of the seismic source and the faulting processes within. The specific behavior of the weaker aftershocks is indicative of the relaxation behavior of the source medium during the main event of 22, May 2012.

The joint analysis of present event and past earthquakes reveals some important relationships.

The location of the aftershock series supports the assumption on the regions of extension and compression, which coincide with the common trends established for the Balkans (incl. Bulgaria) and confirmed so far by all major earthquakes and the following aftershock series, e.g. Kresna 1904, Plovdiv 1928, Valandovo 1932 etc. (Григорова et al.,1964).

The common geodynamic model of the seismically active subduction zone situated in the Southernmost part of the Europe-Africa collision zone and the large seismogenic North Anatolia transform fault with its satellites in the Northern Aegean region, confirms the NNE – SSW trend of extension for the territory of Bulgaria. In the context of available observations, the development of the aftershock series and the spatial behavior of the source zone, the geodynamic model reveals the principle cause for the 22, May earthquake, namely tensile forces in the NNE – SSW direction which lead to a drop of a seismogenic block along the fault surface situated in the Southern part of the Pernik graben next to the border with the Golo Bardo massif, turning listric in depth and having surface manifestations in the NE part of the graben. (Radulov et al., 2014, Rangelov et al., 2013).

It can be concluded that practically the entire volume of the medium has undergone a quick, sharp subsidence of several centimeters, basin-shaped to depths 15-16 km. It is clear from the solutions of the mechanism of the main quake, published by the international seismological centers, that the fault movement was normal, with almost no horizontal component. The total size of the source zone may be established as block with dimensions 18x15x10 km.

A plan view of the city of Pernik together with the horizontal projection of the fault is shown in Figure 1. The southwestern parts of the country is subjected to most intensive contemporary uplift, its magnitude reaching 5—6 mm/a in the Sofia and Pernik region of (Figure 2) [redrawn from Brouchev et al. 2007].

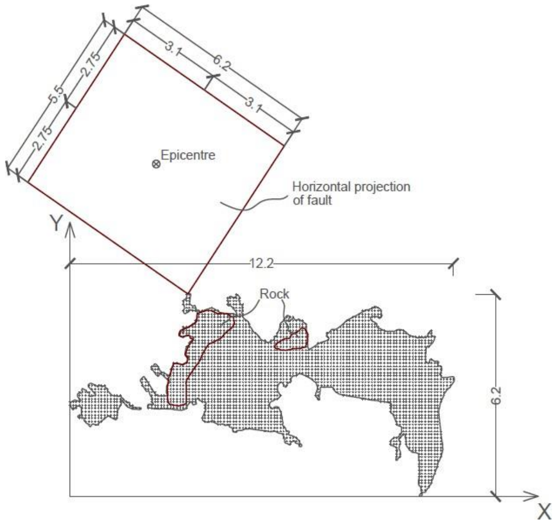

Figure 1. A plan view of the city of Pernik and the horizontal projection of the fault (dimensions in km)..

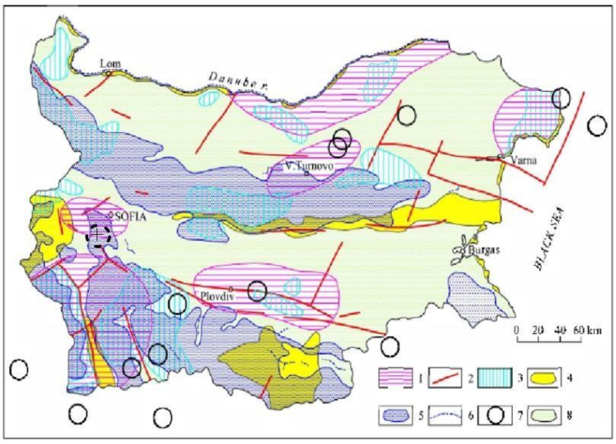

Figure 2. Endogenic and exogenic landslide factors of the country 1. Seismicity above VIII degree by MSK-64; 2. Active faults; 3. Regions with recent vertical movements > +2 mm/a; 4. Regions with river and sea erosion, slope destruction; 5. Regions with precipitation > 700 mm/a; 6. Levels fluctuation of rivers and reservoir more than 5 m; earthquake epicenters with magnitude M >5 (for period 1940 — 2000); 8. Regions with low degree of endogenic and exogenic landslide factors; + sign for Pernik region.

3. OBSERVED DAMAGES TO BUILDING STOCKS

The earthquake of May 22, 2012, and subsequent events caused damage to buildings in the town of Pernik (the closest city to the epicenter) and the surrounding villages (Paskaleva et al., 2013). The main quake significantly affected Sofia (the capital of Bulgaria) too.

The most widely observed damages, reiterated "old lessons" from other earthquakes. The damage results from the "new lesson" correlate well with the observed damages, and confirmed as main causes of the damages soft-stories, poor material quality, insufficient reinforcement, absence or insufficient structural design. The examples are taken from locations 7-10 km away from the epicenter. Most adobe houses and stone masonry structures with undressed stones, constructed in the first half of the century, suffered considerable damages. This included partial collapse of external walls, collapses of corners, separation of the two walls converging at a corner, and extensive cracking. On the other hand, brick masonry houses with reinforced concrete lintel bands or concrete roof slabs, built in recent years, survived with less damage. Significant damages were observed in the masonry structures, as most of the houses built in the late 50s of the twentieth century are without columns, and poorly executed masonry walls.

There have been observed cases with heavy damages (clearly visible cracks on all exterior walls and shift of superstructure above the floor slab by about 5-7 cm) at a base station of a mobile operator. The heavy antenna is anchored to the top slab of the house. The same problem has been detected in the large-panel buildings. Damage to buildings with a soft ground floor are observed Figure 3A. The considerably smaller rigidity of this floor, compared with the rest of the building, lead to large deformations of the soft floor. The absence of clear bearing system caused damages of masonry walls, Figure 3B.

Figure 3A. Typical 2-3 storey family house

Figure 3B. Close view from exterior wall

With heavy damages in the interior and exterior walls being a typical situation most of the damaged houses were designated as "yellow". A generally good response of the prefabricated 7-8 floor large-panel buildings built around 1982-1986 has been observed.

4. EARTHQUAKE RECORDINGS

The areal distribution of the records of the May 22, 2012 earthquake made on the territory of the capital and surrounding countries Macedonia, Turkey and Romania is shown in Figure 4. All registrations have been processed using the same procedure. A linear polynomial is used for baseline correction. A Butterworth filter is used for frequency filtering in this analysis. For the majority of applications, the use Butterworth filter type is advisable, as it features a maximally flat response in the pass band (i.e. practically no deviation from unity). The frequency range adopted was Freq1=0.10 Hz and Freq2=25 Hz. The appropriate processing and analysis were performed to define the broad range of useful engineering characteristics (Paskaleva et al., 2013).

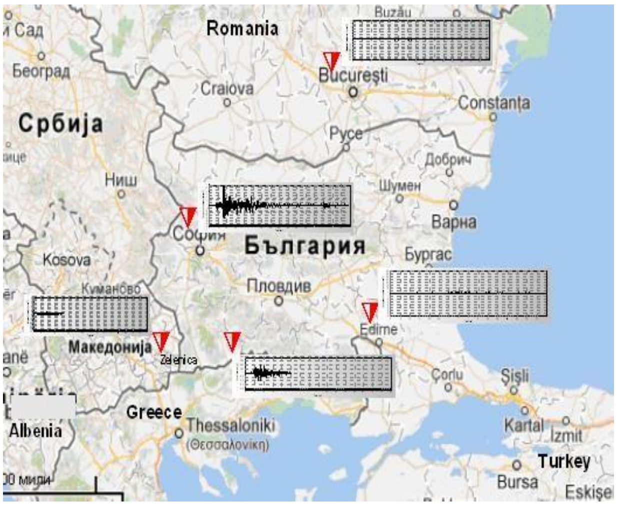

Figure 4. The distribution over the area of the corrected acceleration records (time not synchronized). The picture's scale is: acceleration max 40 cm/s^2, time 80 s (Paskaleva et al., 2013).

The complex analyses of the available earthquake registrations recorded on the territory of the capital Sofia and surrounding countries Macedonia (Mac), Turkey (TU) and Romania (RO) show some specificities discussed in (Paskaleva et al., 2013), (Hadjiiski et al., 2012), (Paskaleva, 2014).

The maximal absolute values of peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) for the main event 22, May 2012 are given in Table 1. The analyses of the real recordings show a low attenuation of ground acceleration. The explanation of this conclusion is beyond the aim of this work.

5. LONG STRUCTURES UNDER STRAINS AT GROUND SURFACE

The standard approach of scaling earthquake ground motion for design applications and earthquake preparedness is based on PGA. This approach is reliable when the physics of the problem depend linearly only on the nature of the low period inertial part of the shaking. Referent design ground acceleration for a probability of 10% exceedance and an exposure time of 50 years over the part of West Bulgarian territory (recurrence period t = 475 years, BDS EN 1998-1:2005/NA:2012) for Pernik is $A_g = 0.15g$.

For long structure and for the nonlinear response analysis the representative strain ($\approx$ velocity) has to be considered too. Since we create a velocity "database" for Sofia, the peaks of horizontal strain components, associated with propagation earthquake waves are found. The approximation $\varepsilon \approx A\dot{x}/C$, where, $\dot{x}$ is the peak of particle velocity, C is 'propagation speed' of strong motion waves in the medium and A is some empirical scaling function (Newmark, 1971) is used to find critical span for single degree of freedom system

Table 1. Strong motion parameters; *(Hadjiiski et al., 2012), **(Paskaleva et al., 2013, 2018)

Station/ distance [km]	Component	PGA [cm/s^2]	PGV [cm/s]	PGD [cm]
*SBO/R=23.00	EW	81.99	8.02	1.52
	NS	98.55	12.01	3.43
	UD	46.97	3.21	0.81
*SGL1/R=26.00	EW	42.62	2.97	0.96
	NS	30.26	4.76	1.35
	UD	21.94	1.42	0.38
*SGFI/R=30.00	EW	38.33	4.88	1.08
	NS	29.91	4.73	1.43
	UD	17.81	1.55	0.52
**Shemus/25.00	EW	49.05	4.92	1.45
	NS	51.93	4.41	1.22
	UD	19.62	2.07	0.45
**SMac/88.00	EW	4.585	0.20	0.13
	NS	4.95	0.19	0.07
	UD	2.41	0.27	0.22
**STU/290.00	EW	5.37	0.70	0.87
	NS	4.18	0.56	0.62
	UD	2.72	0.32	1.71
**SRO/300.00	EW	1.37	0.13	0.04
	NS	1.436	0.128	0.03
	UD	0.613	0.087	0.02

The peaks of horizontal strain components, associated with propagating earthquake waves can be approximated by $\varepsilon \approx A.V_m/C$, where, V_m is the peak of particle velocity, C is 'propagation speed' of strong motion waves in the medium and A is some empirical scaling function (Newmark, 1968). This ‘speed’ depends on the type of the waves, on the properties of the local soil and the underlying rock, and on the direction of wave arrival. In general even for known velocity structure this 'propagation speed' will be different for every earthquake. In this respect **C** is unknown but for high frequencies is proportional to the shear wave velocity in the top layer.

Horizontal maximum velocity distribution (cm/s) around the Pernik region, obtained as a result of the deterministic zonation, for model - rock seismic sources in Bulgaria including the influence of Vrancea source is PGV = 39 ~ 49 см/с (Panza et al., 2001). This result is in a good agreement with the used attenuation relationship (Akkar et al., 2007).

The peak ground velocity (PGV) distribution for maximum possible earthquake scenario magnitude M=7 (Bonchev et all. 1982) in the vicinity of Pernik is demonstrated in Figure 5.

The peak ground velocity (PGV) distribution for earthquake scenario of 22, may 2012 earthquake in the vicinity of Pernik region is given in Figure 6.

To be realized an optimum design, the main is to understand and quantify all loads that act on the structures simultaneously. Earthquake resistant design provisions provide estimates of inertial forces that drive the structures during the earthquake. The contributions to response from pseudo-static deformation of foundations caused by passage of waves under long structures or under separate, but distant, foundations are usually not considered except in very special cases.

Observations from the near field moderate to large earthquakes showed that large differential motion, strains, and ground rocking accompany the large translational accelerations. Design practices have to include all these contributions to the structural response and have to consider all those simultaneously. To improve the earthquake resistance capabilities of structures, it is not sufficient just to increase the design levels because stronger columns, for example, will 'attract' larger moments, and may not result in better overall design. Increasing the ductility capabilities of structural elements will improve their survival probabilities during the first one or two cycles of response, but well-designed structural systems must last through the complete sequence of strong motion phases, which may involve long duration and many cycles of response. In this paper we calculated surface strains for the maximum scenario for Pernik [M=7 Bonchev et al. 1982]. A simple symmetrical shear-frame (which might be part of light pedestrian bridge) with mass M and height of columns ***h*** is consider as a "long" structure to illustrate the effects of an inelastic horizontal pseudo static displacement $\underline{\delta}$ at the boundary, caused by strain in the foundation medium (Paskaleva et al. 2003).

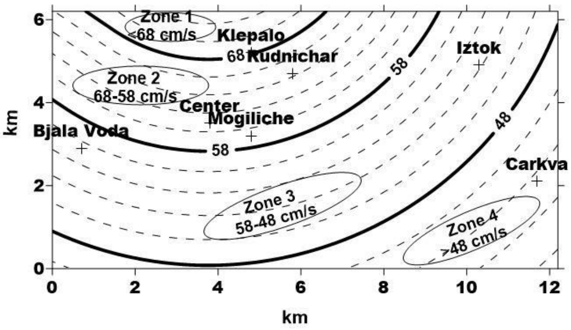

Figure 5. The strain factor $\log_{10}\varepsilon$ distribution supposing Vs=180 m/s and earthquake scenario for maximum possible magnitude M=7 in the vicinity of Pernik region.

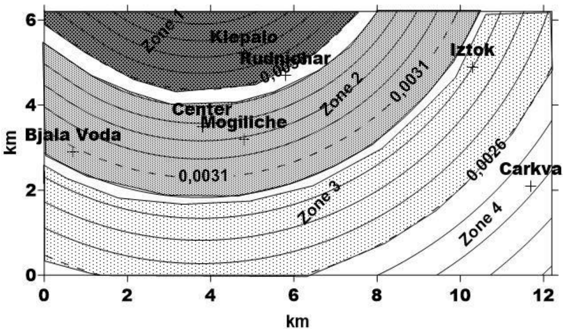

Figure 6. The strain factor $\log_{10}\varepsilon$ distribution supposing Vs=180 m/s and earthquake scenario of 22, May 2012 earthquake in the vicinity of Pernik region.

A comparison with a calculation on the basis of the equivalent static lateral seismic force $F = MS_a$ in terms of spectral pseudo-acceleration, is proposed. By varying the period, we deduce the stiffness in terms of flexural rigidity EJ of the columns trough the column stiffness $T \rightarrow K = (4\pi^2 M)/T^2 \rightarrow EJ = (Kh^3)/24 = (\pi^2 h^3 M)/6T^2$. The maximum moment due to the static equivalent seismic force independent on the distance between the supports, is $M_1 = 0.25MS_a h$. The maximum moment derived by the horizontal displacement of the support, $\delta = \varepsilon l$, $M_2 = \varepsilon l(3EJ)/h^2$, depends from the span l (distance between the supports). A critical span l_{cr} exists, at which the bending moments are the same and over it the ε verification will be more penalizing $l_{cr} = (0.5S_a T^2)/\varepsilon\pi^2$. In Figure 7 the variation of this critical span vs. natural period for the three main zones is shown. For many practical applications prediction of the peak surface strains will be sufficient to evaluate the pseudo-static part of the response directly from the strains.

This is the first assessment for maximum expected scenario done for Pernik town based on ground motion deterministic analyses, in terms of PGV over the central part of the town. The results of this study can readily be applied to site-specific design spectra based on average or maximum amplification and should be followed for site-specific design procedures especially for long structures and underground lifeline systems more sensitive to near surface stains than to maximum peak ground acceleration. This is a good starting point for the microzonation of Pernik. Many cross-geological sections will be required to cover the whole town for the purpose to be clarified and estimated the maximum expected risk.

The obtained results can be used to assess strain surface distribution, liquefaction susceptibility that will support many engineering and managing purposes like urban planning and earthquake preparedness.

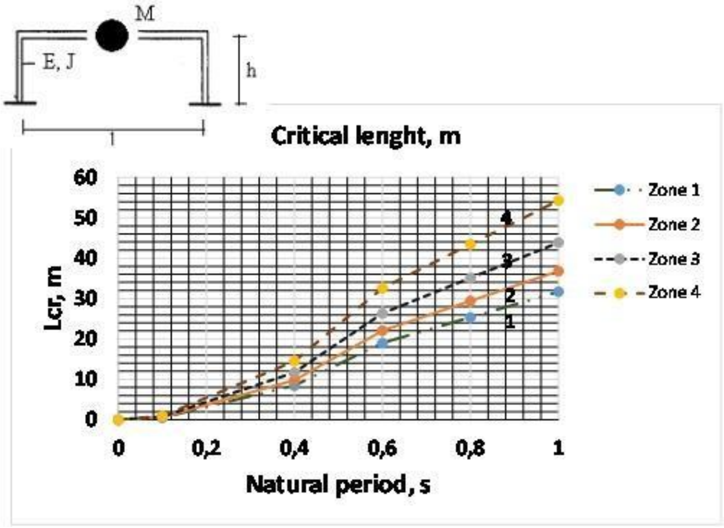

Figure 7. Critical length (m) vs. period (s) for four zones over Pernik town for simple frame model.

6. DISCUSSION AND CONCLUSIONS

The assessments of the complex geophysical and engineering investigations performed to study the area of the Pernik earthquake (M5.6):

- the listric faulting starting of about 70^0 - 80^0 (normal faulting) and resulting finally in depth of about 15-16 km to about 0^0 strike;
- the depth of the crust disintegration is strongly limited to 15-16 km;
- the extensional regime is confirmed;
- the detected damages and peculiarities of the registered strong motions are explained;
- the results obtained could be very useful for the future development of the monitoring and in the area of Pernik city;
- the simple approximate relationship between the strain and ground velocity, used here, (valid for linear ground response) gives the maximum strain factor for horizontal component $\varepsilon_H \approx 10^{-3.18}$ and for the vertical $\varepsilon_V \approx 10^{-3.65}$ at location of the records (Sofia city) for the main event 22, May 2012. The strain factor $\log_{10}\varepsilon$ distribution supposing Vs=180 m/s and earthquake scenario of 22, may 2012 earthquake in the vicinity of Pernik region range from -2,96 to -3,16.

The estimated predictions in this work will be useful to government officials for emergency planning, to the insurance industry for realistic assessment of insured losses, and to structural engineers for assessment of the overall performance of buildings. Therefore, it is not directly applicable to large amplitude non-linear soil response. However, it can be used to estimate the hazard that non-linear soil response will be initiated during the lifetime or the service time of structures vulnerable to large strains. The results of such microzonation studies can be used as guidelines in design of new and upgrade of existing long structures like pipelines.

ACKNOWLEDGEMENTS

This research work is supported by funds from National Science Foundation of Bulgaria contract № ДН 17/8 12.12.2017 and EPU scientific funds. The support is gratefully acknowledged.

REFERENCES

[1] Григорова Е., Григоров Б.(1964) Епицентрите и сеизмичните линии в България. Изд. БАН,81с.

[2] Boncev E., V.Bune, L.Christoskov, J.Karagjuleva, V.Kostadinov, G.Reisner, S.Rizhikova, N.Shebalin, V.Sholpo, D.Sokerova, 1982. A method for compilation of seismic zoning prognostic maps for the territory of Bulgaria. Geologica Balcanica, 12(2), 2-48.

[3] Duvall, W.I., Fogelson, D. E. (1962) Review of criteria for estimating damage to residence from blasting vibrations. Report 5968, U.S. Dept. of Interior, 1962.

[4] Hadjiiski K., Simeonov S., Botev E.: Seismic impact of the earthquake of 05/22/2012 for Sofia (2012), (in Bulgarian). pp. 28-34 , http://www.kiip.bg/eforum/07-2012/lquality/index.html#/27/zoomed

[5] Nenov D., Paskaleva I., Georgiev, G., Trifunac, M.: CATALOG of strong earthquake ground motion data in EQINFOS: Accelerograms recorded in Bulgaria between 1981 and 1987. (1990). Report No CE 90-02, Sofia and Los Angeles, published in Southern California University, 55 pp.

[6] Newmark NM. Problems in wave propagation in soil and rock (1968). Proceedings of the International Symposium on wave propagation and dynamic properties of earth materials. Albuquerque, NM: University of New Mexico Press, August 23-25, 1968 pp.7-26.

[7] Panza G. F., Romanelli F., Vaccari F.: Seismic wave propagation in laterally heterogene- ous anelastic media: theory and applications to the seismic zonation – Advances in Geophysics (2001). Academic press, 43, pp. 1-95.

[8] Paskaleva, I., G.F. Panza, F. Vaccari, S. Rajgelj, P. Ivanov (2003) Deterministic modeling for microzonation of Sofia: An expected earthquake scenario, Proc. of the International Conference in Earthquake Eng. SE 40EEE, 26-29 August, 2003, Skopje. CD-Rom paper 0049.

[9] Paskaleva I., Dojcinovski D., Ivanov R.: A note on the attenuation for peak ground acceleration and response spectra for the 22, May 2012 earthquake (Eastern Bulgaria) (2013). Proc. SE-50EEE International Conference on Earthquake Engineering - 29 to 31 May 2013 - Skopje paper with ID_578.

[10] Paskaleva I., Ivanov R., Dojcinovski D.: Analysis of the 22, May, 2012 Earthquake (Western Bulgaria) to Evaluate Regional Attenuation (2013). Proc., III-d Scientific Conference of EPU "Education, science and innovation", pp.123-133.

[11] Paskaleva, I.: Vulnerability Concept in Elaborating Earthquake Risk: Case study for West Bulgaria (2014). Proc., IV-th Scientific Conference of EPU "Education, science and innovation", 9-10, June, ISSN 1314-5711.

[12] Paskaleva I., Ivanov R., Kaneva A., Ivanchev I., Seismic effects in the Pernik area after the 22, May 2012 earthquake, Sixth International Conference “Earthquake Engineering and Engineering Seismology, 13-15 June, Kraljevo, Serbia, 2018, pp. 1-12.

[13] Radulov A., Yaneva M., Nikolov N., Kiselinov H., Donkova Y., Nikolov G.: Geological data on the source of the 2012 Mw5.6 Pernik earthquake SW Bulgaria (2014). Proceedings of XX CBGA Congress, Tirana, Albania, 24-26 September 2014 Special Session SS4 (available).

[14] https://www.researchgate.net/publication/271191058_Geological_data_on_the_source_of_the_2012_Mw_56_Pernik_earthquake_SW_Bulgaria

[15] Ranguelov B.: Natural Hazards – nonlinearities and assessment (2011). Acad. Publ. House (BAS), C. 327 p.

[16] Renguelov B., Paskaleva I.: The seismic source and seismic effects modeling in the pernik (2013). Proc. 13th International Scientific Conference VSU'2013, pp. VIII – 20-24.

[17] Sinan A., Bommer J. J.: Empirical Prediction Equations for Peak Ground Velocity Derived from Strong-Motion Records from Europe and the Middle East (2007). Bulletin of the Seismological Society of America, Vol. 97, No. 2, pp. 511–530.

[18] M. D. Trifunac Todorovska M. I.: (1997a) Northridge, California, earthquake of 1994: density of pipe breaks and surface strains Soil Dynamics and Earthquake Engineering,Vol. 16, pp.193-207.

[19] M. D. Trifunac & M. I. Todorovska (1997b) Northridge, California, earthquake of 1994: density of red-tagged buildings versus peak horizontal velocity and intensity of shaking Soil Dynamics and Earthquake Engineering, Elsevier, Vol. 16, pp 209-222.