# EXPERT ASSESSMENT
# of the seismic hazard for Highway “Struma”, LOT 3.2, segment “Krupnik-Kresna”on the base of the seismotectonic characteristics

**<u>Grounds:</u>**
Request from the National Company Strategic Infrastructure Projects, Bulgaria


Expert:

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## Contents

## 1. Introduction

The expert assessment is elaborated on the request expressed in letter from National Company Strategic Infrastructure Projects, Bulgaria. It syntheses the studies on the seismotectonic conditions along the route of the variants for constructing the LOT 3.2 of Highway “Struma” – by 15 km tunnels (2 tubes) for the segment “Krupnik – Kresna” or by bridges and short tunnels for the same segment. Basic data have been used from previous studies for the design of the highway, the studies concerning the safety of the trans-border gas pipeline for Greece, as well as some other unpublished reports and published papers, listed in the References. Unpublished author’s information was also taken into account. Data for the earthquakes are representative and there are based on known national and international sources.

The general seismological background is discussed, as well as the normative documents for the anti-seismic design in the area. A special attention is paid on the local seismotectonic conditions – the position and the characteristics of these active faults that could impact directly the designed facilities. The nature of such one analysis could not be a base for separated characterization of every highway variant, because the expected strong impacts from the tectonic structures in the area are the same for the closely disposed route variants.

The variants of the highway for the segment “Krupnik – Kresna” are a part of the Third LOT of Struma Highway, starting from its crossing with the route from the city of Blagoevgrad to Stanke Lisichkovo (km 358+500) and ending near the railway station of Sandanski (km 419+000). The route of the highway LOT 3.2 (Fig. 1) is situated in one of the most seismically active area from this part of Balkan Peninsula. The earthquakes are of shallow type, and core genesis. The earth prone zones having the most important impact on the concerned segment of the highway will be presented here bellow.

Published data for the contemporary horizontal and vertical movements will be discussed, because they are an important element for characterization of the activity of the geological structures.

For the analysis of the seismotectonic conditions data from the area included inside the coordinates represented on Table 1 have been used. This area was chosen because it contains all known active faults that could impact directly or indirectly the future facilities of the highway. The direct impact is expressed as displacements from active fault crossed by the highway, and the corresponding damaging of the concerned route construction. The indirect impact could be expressed as strong seismic shaking from earthquake sources (active faults) that are not obligatory at the nearest vicinity to the concerned structures of the highway.

**Table 1.** Coordinates of the area of the seismotectonic characteristics

| **Projection** | **UTM [m]** | **Geographic** |
|---|---|---|
| **X** | From 645000 to 687000 | From 22.75470581$^0$ to 23.24740953$^0$ Eastern |
| **Y** | From 4619000 to 4667000 | From 41.70082064$^0$ to 42.14170690$^0$ Northern |

This information for the two projections coordinates is necessary, because the data for the earthquakes from the national and international catalogues is presented in geographic projection.

The Part “Other dangerous geophysical factors” will characterize in brief another source of unfavorable impacts, especially for the tunnels – the emissions of inert gas radon (Rn) from the active faults.

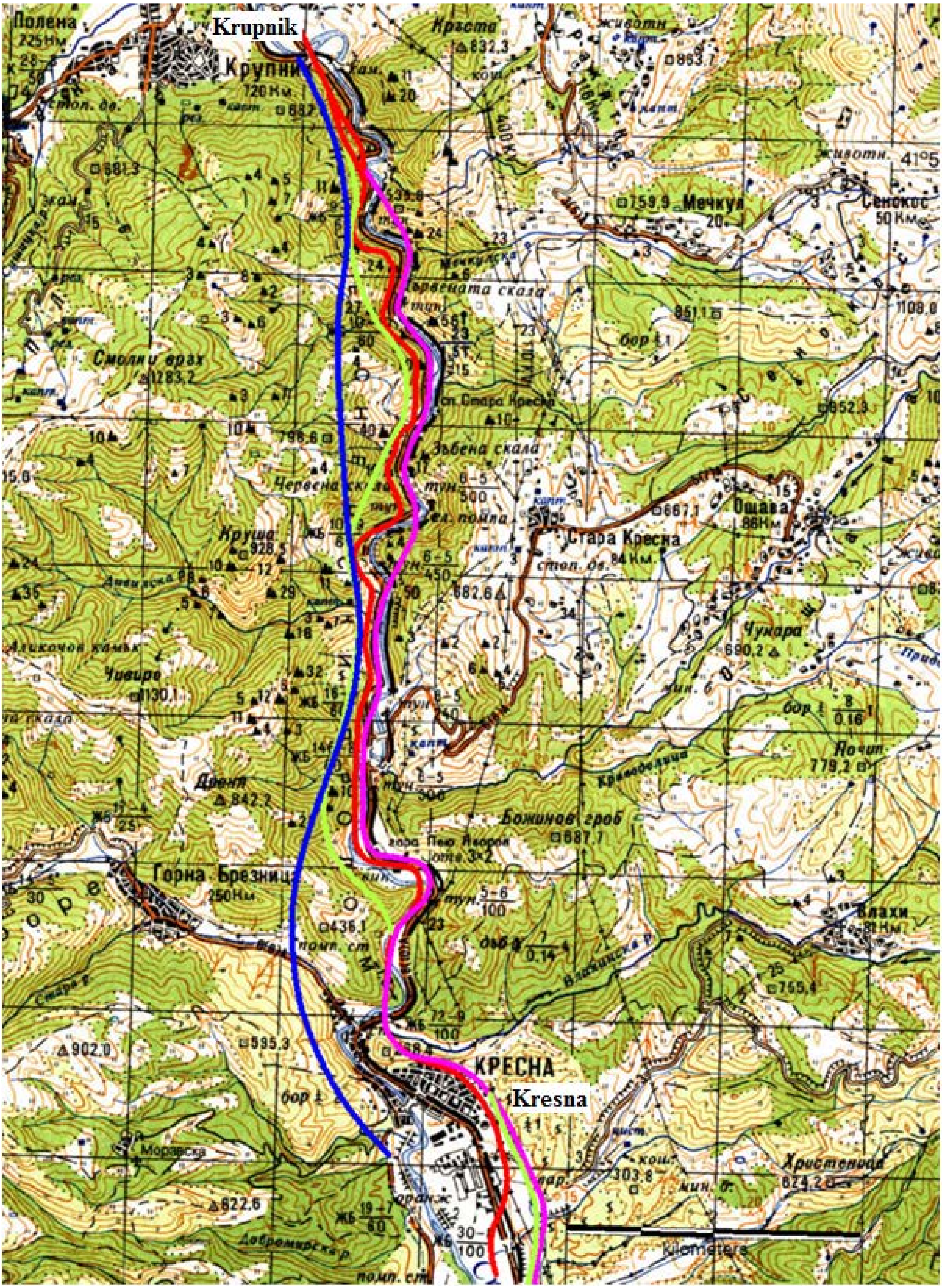



**Fig.1.** Variants of the routes of Struma Highway, LOT 3.2, segment "Krupnik – Kresna". The variant of 15 km tunnel is marked by blue line. Red, green and violet lines delineate the other variants.

## 2. Data and methods used for the study

### 2.1. Seismic information

***Earthquake Catalogue – sources of information and accuracy***

For the earthquakes before 1892 the information is not enough sure, it is based on personal communications, newspaper reports or chronics. The epicenters of these earthquakes have been evaluated with accuracy of about 0.3°. The accuracy of determination of earthquake epicenters increased to 0.1°-0.2° after the beginning of functioning of the first seismograph in Sofia City in 1905. Its installation was provoked by the catastrophic earthquake from 04.04.1904 with epicenter near the village of Krupnik. The strongest events affecting the studied area were recorded in the first half of the past century, data also exists for older events. The earthquakes from these periods were registered with low accuracy and only on the basis of macro-seismic effects they were related to some tectonic structures.

After 1977 the Bulgarian National Seismic Network started the creation of modern National operative telemetric system for seismological information (NOTSSI) and the accuracy of the epicenters determination raised, the magnitude level of the recorded events dropped bellow M=2.0. Between 2006 and 2007 the recording analog devices of the national network were replaced by digital recording equipment.

The data presented in the Catalogue of the earthquakes for the studied area are compiled from a number of accessible sources. They are:

- Catalogue of Earthquakes. 1974, UNESCO;
- CSEM European - Mediterranean hypocenters data file (1979 - 1985);
- ISC (1964 - 1981). 1982.
- Catalogue of International Sesmological Centre. Edinburg; Newbury, England, World's hypocentres data file (1939 - 1985) 1986.
- USGS - NOAA, USA, World's hypocentres data file (1885 - 1985) 1986. USGS - NOAA, USA
- The existing catalogues of the Laboratory of Seismotectonics (now Department of Seismotectonics) of the Geological Institute of BAS. These catalogues were compiled by some of above enumerated catalogues, but they are cleaned for duplicated events and they are supported and periodically upgraded since 1988.

For the last 30 years revised and more accurate data from the International Seismological Center (ISC) have been used (The Bulletin can be accessed via http://www.isc.ac.uk/doc/cite/index.html). This Bulletin presents information from the local national networks for the given area (for the concrete case these are the centers in Sofia, Thessaloniki, Skopje, Athens, Beograd and others).

Most of the historical earthquakes were evaluated with magnitude Ms. For homogenization of the data the requirements from two publications were applied (Shanov, Kurtev, 1994; Bayliss, Burton, 2007). In some cases the magnitude of the event is not shown. The zero for the magnitudes means that the earthquake is very weak, with magnitude bellow 2.0.

Principally, the less accurate parameter is the hypocentral depth. There is a tendency for giving more precise information, but especially for the weak earthquakes is prescribed the depth 0 (very near to the Earth's surface).

***Earthquake recurrence interval***

The movement along the faults generating earthquakes can be represented as an effect of repeated seismic displacements. The most ideal model represents number of periods when deformations have been accumulated, followed by release of energy trough earthquakes.

Hence, it is an effect of cyclic seismicity that could be well studied for a given seismic zone, and that could be applied for statistical prognosis of the earthquakes. One of the most important elements of the seismic regime, describing the relationship inside a multitude of earthquakes for given space and time is **the recurrence interval of the earthquakes**.

The law of the earthquake recurrence interval is described by the relationship:

$$\lg N_M = a - bM$$

where $N_M$ is the number of earthquakes of magnitude $M$. The linear relationship is deduced by statistics of the strongest earthquakes in the world. But it can be elaborated for every region of the Earth, for every seismic zone. Normally, the relationship is normalized for chosen time interval. For the present study a cumulative variant of the relationship is used - $N_M$ is the number of earthquakes stronger or equal to a given magnitude level $M$. All data is normalized for a period of 100 years

The coefficients of the regression are of importance for the analysis of the seismic regime and statistical forecasting. The slope of the recurrence relationship is the first important parameter (the coefficient $b$ of the linear regression). Bigger slope of the regression is due of the considerable quantity of weaker earthquakes and less often could be expected a strong earthquake. If the slope is smaller, strong earthquakes could be expected more frequently.

Because the coefficient $a$ is the cross-value with the ordinate axis (lgN), it is very impacted by the quantity of data used. The earthquake focus is normally related to some fault, and the potential capability of this fault to generate earthquakes with appropriated maximum magnitude borders the recurrence relationship in the part of high magnitudes. The next limitation is for the interval of lower magnitudes. The sensibility of the seismic recording has increased considerably for the last decades, the seismic networks have been improved and all this has lead to decreasing of the level of the recorded magnitudes. But nevertheless the statistical information for the weak earthquakes is not sufficient and that is why the graphs of the recurrence relationship are not assured for the magnitude level bellow 3.0.

***Earthquake fault plane solutions***

Normally it is difficult to get sufficient quantity of sure data for the surface displacements and to give solution for the strike of the faulting. This problem is partially solved when using the records of the seismic waves from stations disposed at different azimuths relatively to the epicenter. The theory of the earthquake mechanism has been created at the 60 years of the past century. The basic idea is to present the final dislocation in the focus as equivalent of double-couple strengths with or without moment. The double-couple strengths with moment describes well the appearance of dislocation of the medium, the displacement along this dislocation and the emission of waves of “contraction” and “dilatation” recorded as first breaks with different polarity on the seismograms.

The information from the fault-plane solutions is used for determining of the most probable fault activated during the earthquake. It is used also for evaluation of the basic traits of the regional tectonic stress field. This helps the decision about the most probable tectonic displacements along faults that have potential characteristics for activity, but without manifestation for the historical time.

The present study uses published fault-plane solutions from earthquakes. These solutions are presented that have epicenters at the nearest vicinity to the route variants of the highway. The number of the available solutions is 23, the first one being from 1978. All earthquakes with fault-plane solutions are relatively stronger than the other events from the catalogue of the studied area. The quality of the solutions is depending of the number and the space disposition of the recording stations. These solutions were done after the optimization of the regional seismic network. The data is applied also for determining of the position of the axes of pressure P and “tension” T. These axes could be accepted under conditions as reflecting the trend of the maximum $\sigma_1$ and the minimum $\sigma_3$ contemporary stress field for the region.

### *Seismotectonic prognosis*

The evaluation of the seismic potential ($M_{max}$) of well defined fault can be done using the empirical relationships between the maximum magnitude and the length of the rupturing (L). For the assessment of the maximum potential earthquake empirical relationships are used, deduced on data from the concrete region (if enough information is available), or from generalized relationships on the base of data from all over the world.

The empirical relationships between the maximum magnitude and the length of the rupturing L [M=M(L) and L=L(M)], elaborated on the base of selected worldwide data or available regional data are presented on Table 2. From the multitude of published relationships were selected only these ones that are based on data from the Balkan Peninsula and the surrounding territories.

Table 2. empirical relationships between the length of the active fault (L, km) and the magnitude M of the earthquakes that can be generated by it.

| N | Empirical relationship | Data | Magnitude interval | Source |
|---|---|---|---|---|
| 1 | M=5.13+1.14 log L | 150 (Eastern Mediterranean) | 5.0-8.0 | Ambraseys and Jackson, 1998 |
| 2 | Log L=-2.44+0.59M | 167(Worldwide data) | 4.8-8.1 | Wells and Coppersmith, 1994 |
| 3 | Log L=-4.09+0.82M | 150 (Eastern Mediterranean) | 5.0-8.0 | Ambraseys and Jackson, 1998 |
| 4 | Log L=-1.85+0.51M | 21(Balkan Peninsula and the adjacent territories) | 5.8-7.4 | B. and C. Papazachos, 1989 |
| 5 | Log L=-2.55+0.61 M | 11 (Balkan Peninsula and the adjacent territories) | 5.8-7.5 | Kiratzi et al., 1985 |
| 6 | Log L=-2.03+0.55 M | 18 (Balkan Peninsula and the adjacent territories) | 6.3-8.0 | Christoskov, Eneva, 1985 |
| 7 | M=0.90 log L + 5.48 | 36 (Eagean Region) | 5.2-7.9 | Pavlides, Caputo, 2004 |

The method for determination of the displacement along an active fault is based on the relation between the moment magnitude $M_w$ and the seismic moment $M_0$. The transition from magnitude $M_s$ to moment magnitude scale $M_w$ is an important element of the process. The studies of Bayliss and Burton (2007) for the territory of Bulgaria that the most acceptable relationship for the territory of Balkan Peninsula southern from the parallel N 43° is:

$$M_w = 0.56.M_s + 2.66$$

The definition of the Moment magnitude is:

$$M_w = (2/3) \log_{10} (M_0)-10.73$$

Here $M_0$ is the seismic moment [dyne-cm]. By definition:

$$M_0=\mu AD$$

Where $\mu$ is the Shear Modulus (often denoted by G in the engineering geology), A = the ruptured fault surface, D = the average displacement along the fault. For the earthquake foci conditions in the Earth’s crust the value $\mu$ = 3.3 x $10^{11}$ dyne/cm$^2$ is widely accepted. The surface of the fault is e:

$$A = LW$$

Where L is the length of the activated fault segment, and W is the width of the fault surface (practically the depth of the focus).

### 2.2. Active faults

Active faults are these faults along which surface or near surface rupturing could appear. The release of energy is cyclic and it is realized by faulting. Practically the sudden rupturing is the earthquake itself. The magnitude of the earthquake effecting surface rupturing, as a rule, is higher than 5.5. It is accepted that the impact of the earthquakes of magnitude lower than 5.5 is negligible (Vittori, Comerci, 2004) and every facility designed according to the corresponding seismic coefficient Kc, taking into account the coefficients of importance and the type of the construction, will not be damaged.

Two are the aspects of the hazard (following Shanov, Dobrev et al., 2008):

1. The first one is related to occurrence of earthquake of magnitude higher than 5.5 during the period of exploitation of the facility. Such one earthquake can provoke important co-seismic deformations on the Earth’s surface even remotely from the principal activated fault segments. Thus, the construction can be damaged even the fact that it was designed with high seismic coefficient Kc. The seismic coefficient is not taking into account the long-term co-seismic deformations of the Earth’s surface, the most important of them being the rupturing and the considerable level changes in the near fault vicinity.
2. The second one is related to the zone of inter-crossing of the facility with active fault. In this case, the occurrence of earthquake of magnitude 5.5 and higher along the given fault, rupturing can appear to the Earth’s surface that can impact directly the structure of the highway. More, along some of the active faults constant horizontal and vertical movements of the Earth’s blocks have been recorded without strong earthquakes. These movements can accumulate long-term deformations in the facilities in the zones of their crossing by active faults.

The cyclic realization of the surface rupturing of the given fault structure leads to important irreversible changes of the relief and differences of the surface structure of the two Earth’s blocks bordered by the fault. The traces of the previous rupturing are detectable using a set of specific geomorphological, geological and geophysical methods. The suggestions for studies of the active faults are very well presented in the documents of the International Atomic Energy Agency (IAEA) (Safety Guide, 2002).

The recognizing and the mapping of the active faults is done at two stages consequently. **The first stage** cover the medium scale studies for identification of the lineaments probably with relatively young tectonic genesis (about 7 millions of years) that are crossing the route or that are at its nearest vicinity. The purpose for realization of future rupturing is the condition that the kinematics of the fault has to correspond to the contemporary tectonic regime. The faults not responding to this condition are ignored. **The second stage** includes detailed on site studies and analyses of the collected data. The detailed studies have for aim to prove or to reject the existing of young rupturing (during the last 100 000 years) the exact localization of the rupturing at the nearest zone of the linear facility and preliminary assessment of the fault characteristics. The present study uses the results from the investigations for the safety of the gas pipeline Bulgaria – Greece, they respond exactly to the modern requirements for studies of linear facilities. The methodology and the results have been reported at international forum (Shanov et al., 2010).

***Medium scale studies (1:100 000)***

The lineaments of probable tectonic origin can be recognized by morphological analysis of thee digital model of the surface SRTM3 and the satellite images ASTER, LANDSAT ETM, and such as these from Google Earth when using the worldwide applied methodology. The fault scarp and the accumulation of fault coluvium are the primary fault indicators reflecting directly the traces from previous faulting. The changes of the width of the flood terraces, the change of the river bed direction, asymmetric and deep valleys and gullies cutting principal relief forms, high and escarped relief in the elevated blocks and quiet and slanting relief on the subsided blocks. The one-side developed Neogene and Quaternary basins are the secondary traits for recognizing the lineaments of tectonic origin.

The selected lineaments were compared with the faults and the structures from the Geological Map of Bulgaria in scale 1:100 000, with the existing generalization on the Neotectonic and the active tectonics in SW Bulgaria (ASPELEA, 2000; Zagorchev, 2006; Georgiev et al., 2006; Tranos et al., 2006), the gravity anomalies and the surface of Mohorovitchich (ASPELEA, 2000) and with the recorded seismicity. Today tectonic regime is evaluated on the base of the existing extension and the form of the young sediment bodies, the contemporary surface processes, the recent horizontal (Kotzev et al., 2006; Georgiev et al., 2007) and vertical movements (Georgiev et al., 2007), the today stress field using the focal fault-plane solutions (Shanov, unpublished data) and the tectonic stress fields reconstructions based on structural analysis (Tranos et al., 2008).

As a result from the medium-scale studies, the faults and the lineaments with the bigger probability to be capable for surface rupturing. Such type of studies for the concerned region have been done in 2009 (Shanov, Dobrev et al., 2009).

***Detailed studies (1:25 000)***

The field studies include visits of the sites with faults supposed to be active, determined during the first stage. The activity of the studied fault is approved by forms of the relief. Structures and sedimentary bodies created by the surface faulting. Applying geophysical methods as electrical profiling (electrical tomography) and vertical electrical sounding, as well as handy holing, information is collected for undoubtedly confirming or rejecting of the these for the presence and the activity of the fault, the structural peculiarities and the traces of cyclic surface rupturing. This type of studies was performed for the area from the town of Dupnitsa to the village of Mechkul in 2007. The area of Kresna was not included (Shanov, Dobrev et al., 2008).

### 2.3. Contemporary movements

The quantitative assessments of the movements of the Earth’s crust, together with the seismological and the geological information, are of critical importance for the evaluation of the seismic hazard and the behavior of the tectonic structures.

Data for the horizontal movements of the Earth’s crust in Bulgaria till the beginning of the years 90$^{th}$ of the past century were missing. Attempts for evaluation were done only for separated localities but the obtained results were unsatisfactory taking into account the accuracy of the measurements.

The data for the vertical movements of the Earth’s crust for the territory of the entire country were published by maps of the vertical movements (Hristov et al., 1973; Totomanov, Vrablianski,1980; Totomanov, Vrablianski - in Boncev et al.,1982, Map № 73). The velocity of the movements was obtained after processing 2 or 3 cycles leveling measurements of the National Leveling Network (Fig. 2). The different maps, taking into account different factors, show unconformity even contradictory information for the vertical movements. For the area of Kresna Gorge, after precise leveling measurements in 1970, analysis of the vertical block movements was done (Vrablianski, Milev, 1973), lately this information was re-interpreted (Milev et al., 1997).

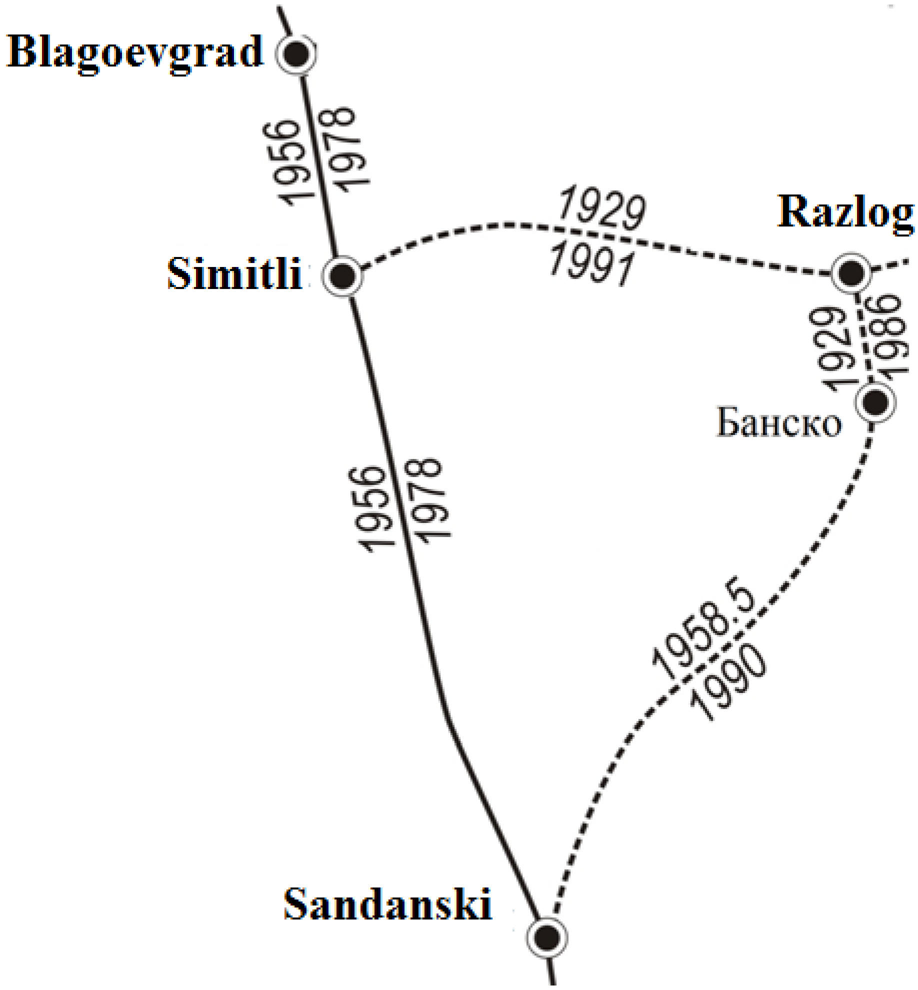



**Fig.2.** Scheme of the precise leveling lines for the studied segment of Highway “Struma”

***Contemporary state of the art***

The existing infrastructure (permanent GNSS stations) in the country, as well as the developed network of sites for periodic campaigns for GPS measurements, and especially for the area of Southwestern Bulgaria, permit to execute permanent monironing of the Earth’s crust movements on the base of the obtained velocities of the sites and the time series with the coordinates of the stations. This monitoring has been done by the ex-Central Laboratory of Geodesy of BAS that is now Department in the National Institute of Geophysics, Geodesy and Geography of BAS.

The recorded till now data from Bulgaria and Northern Greece prove the general tendency of the contemporary movement of the Earth’s crust to South. The velocities increase from 2 mm/y in the area of Central Western Bulgaria to 10 mm/y at Halkidiki Peninsula. It was created a profile with a length of 400 km oriented North-South along the valley of Struma River showing the increase of the velocities from Stara Planina Mountain to Halkidiki Peninsula. The increasing of the velocities from North to South confirm the extensional regime of this area (Georgiev, 2011; Georgiev et al., 2013).

The contemporary monitoring network permits to record more precisely the velocities of the vertical movements. Information concerning these records has been related to the of the concrete tectonic structures especially for the studied area of South Western Bulgaria (Georgiev et al., 2002; Georgiev et al.,2007).

Especially for the concerned area information exists from the geodetic measurements, but also from the installed and functioning 3 extensometric stations, measuring continuously the movements along active fault segments around Krupnik Fault (ex. Dobrev et al., 2005; Dobrev, Avramova-Tacheva, 2007). Beside the information for the velocity of the fault deformations, these data have prognostic character for the seismic processes in this part of the Balkan Peninsula (Shanov, 1993; Shanov, Dobrev, 1997).

## 3. Analysis of the existing normative basis for the seismic characteristics of constructions in seismic prone areas

According to the **REGULATION № РД-02-20-2 from the 27th of January 2012 for designing of buildings and facilities in earthquake zones** (Published in State Gazette, nº 13 of 2012; corr., nº 17 and 23 from 2012), Al. 2 of Art. 15: " On the Map of the seismic zoning of Republic of Bulgaria for the period of 1000 years (Annex № 5) and on the List of the agglomerations with values of the seismic coefficient from the Map of the seismic zoning of Bulgaria (Annex № 6) the values of Кs are noted by Arabic numbers near the value of the corresponding seismic intensity, marked by Roman numbers. For building sites with executed or foreseen micro-seismic zoning the values of Ks have to be taken from the data of the micro-seismic zoning". I.e., for the designing of the future facility, **if micro-seismic zoning is performed, the design procedure has to use its results.**

Nevertheless, the prescribed by the Regulation maximum values of the seismic coefficient Ks and of the intensity (scale MSK-64) are the minimum possible values for the design of every type of facilities in the studied area – tunnels, bridges, routes. From Annex №5 of Art. 15, al. 2 and Art. 106 (Map of the seismic zoning of Republic of Bulgaria for the period of 1000 years and Annex № 6 to Art. 15, al. 2 (List of the agglomerations with values of the seismic coefficient from the Map of the seismic zoning of Bulgaria) for the area of segment "Krupnik – Kresna" the highest for the territory of the country values are prescribed – intensity of the impact **I = IX degrees and seismic coefficient Кs = 0.27.**

Practically the intensity of IX degrees can generate a larger scale of accelerations, the lower limit being 0.20 g, while the upper limit can rise to about 0.43 g (Okamoto, 1973). This is reflected in the documents for the national application of EUROCODE 8.

In the National normative document, Art. **136.** (1) prescribes: "When choosing of the tunnel route it is tectonic faults have to be avoid and soils of uniform seismic characteristics are preferred. According to al. (2) "In the areas of tectonic faults where they cross the tunnels and where movements of soil masses is possible, the necessary activities have to be performed for the safety of the facility". For the concrete case the avoiding of the faults is impossible for the tunnel variant, as well as for every type of linear facilities in the area. The designing has to take into account the concrete tectonic situation.

*Eurocode 8 –characteristics for the area*

In 2012 Bulgarian Institute for Standardization has elaborated the national application for **EUROCODE 8: CONSTRUCTIONS DESIGNING FOR SEISMIC IMPACTS.** This document is edited in Bulgarian to the National Application EN 1998-1:2004, that is a part of БДС EN 1998-1:2004. Here will be discussed the requirements for the construction in general, because the available documents have not specific demands especially for the route and tunnel constructions.

**Part 1: General rules, seismic impact and regulations for buildings**

Point 2.1(1) deals with the referent periods of earthquake recurrence $T_{NCR}$ for seismic impact responding to the requirement for no destruction (or the equivalent, referent probability for exidence for 50 years, $P_{NCR}$). This period is determined at 475 years, and the referent probability for over passing is 10 %. For the entire studied area the referent value of the maximum acceleration for a period of 475 years is 0.32 g.

According to Point 2.2(1) the referent period of earthquake recurrence $T_{DLR}$ of the seismic impact responding to the requirement for limitation of the damages (or the equivalent, referent probability for over passing for 10 years, $P_{DLR}$) is determined at 95 years (consequently, the referent probability for over passing is 10 %). For the area of part "Krupnik – Kresna" the referent value of the maximum acceleration for 95 years is 0.15 g at the Northern border and 0.11 g at the Southern border.

Besides, an additional map is presented in Annex D: Map of zoning of the territory of the country according to the referent maximum acceleration for recurrence interval of 1000 years. From this map it can be seen that the area of LOT 3.2 is totally inside the zone of value **higher than 0.40 g.**

**Part 5: Fundaments, timber constructions and geotechnical aspects**

Here is given an important clarification, related to the decrease of the seismic acceleration at depth from the Earth's surface. Practically, the tunnels will not be submitted to seismic impact at the level, calculated for free Earth's surface. The values will be reduced to given level depending of the depth. Tunnels are represented in all variants of the route of the highway.

According to **Annexe F – informative, NA.2.3 Point 5.2(2)P c) Reduction of the maximum seismic acceleration in depth from the Earth's surface:**

"If the presumption that the amplitude of the seismic movement (the maximum value) is diminishing with the increasing of the depth is accepted, it has to be approved from suitable study. The maximum value of the seismic acceleration at given depth could not be lower from the known ***p*** of the product ***αS*** (the maximum acceleration on the Earth's surface). It is accepted that:

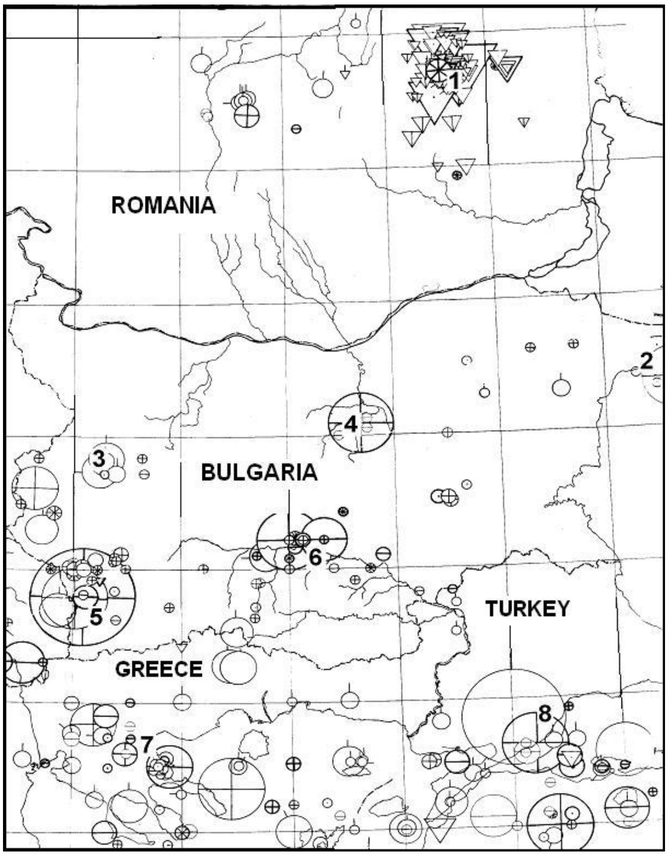
for $0 \leq z \leq 10$ m $p = 1 – 0{,}01z$;

for $z > 10$ m $p = 0{,}9$, where z is the depth from the Earth's surface in meters".

## 4. Seismotectonic analysis

The earthquake epicenter zones by definition are the projection on the Earth's surface of seismogenic volumes where the seismic events are occurring. They have well defined seismotectonic characteristics. The seismic zones of the territory of Bulgaria have been defined on the base of the space distribution of the seismicity and the possible earthquake foci zones (Boncev et al., 1982). The seismicity outside Bulgaria impacting the territory of the country is related to seismic zones as: Vrancha (Roumania), Northern Greece, Aegean See, Edirne (Turkey) and the North-Anatolian Fault. For the purposes of the seismic zoning different variants of the earthquake foci zones were elaborated (Fig. 3 and Fig. 4). The possible impacts from these zones are reflected in the final coefficients of the regulatory documents. But the impact of Kresna Seismic Zone is dominant for the studied area and this zone predestinates all seismic characteristics directly applicable to any type of construction in the region.

The variants of the route of Highway "Struma", LOT 3.2 are practically situated inside Kresna Seismic Zone, they cross the principal active structures that had generated strong earthquakes. The impact of the active faults on the facilities will be trough direct deformations or trough dynamic impact – seismic accelerations.



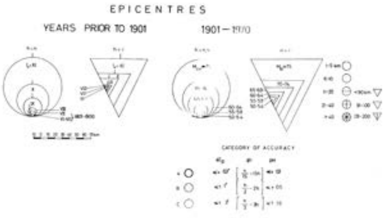




**Fig. 3.** Map of the known seismic zones in the Eastern Balkan Peninsula (according to the map from the Balkan Project of UNESCO - UNDP/UNESCO Survey on the seismicity of the Balkan Region, 1974).

1. Seismic zone Vrancha; 2. Shabla Seismic Zone; 3. Sofia Seismic Zone; 4. Gorna Oriahovitsa Seismic Zone; 5. Struma (Kresna) Seismic Zone; 6. Maritsa Seismic Zone; 7. Seismic zone Chalkidiki (Greece); 8. Marmara Sea Seismic Zone.

The earthquakes are historical (recorded before 1970) and the category of accuracy of their determination is showed on the Legend.

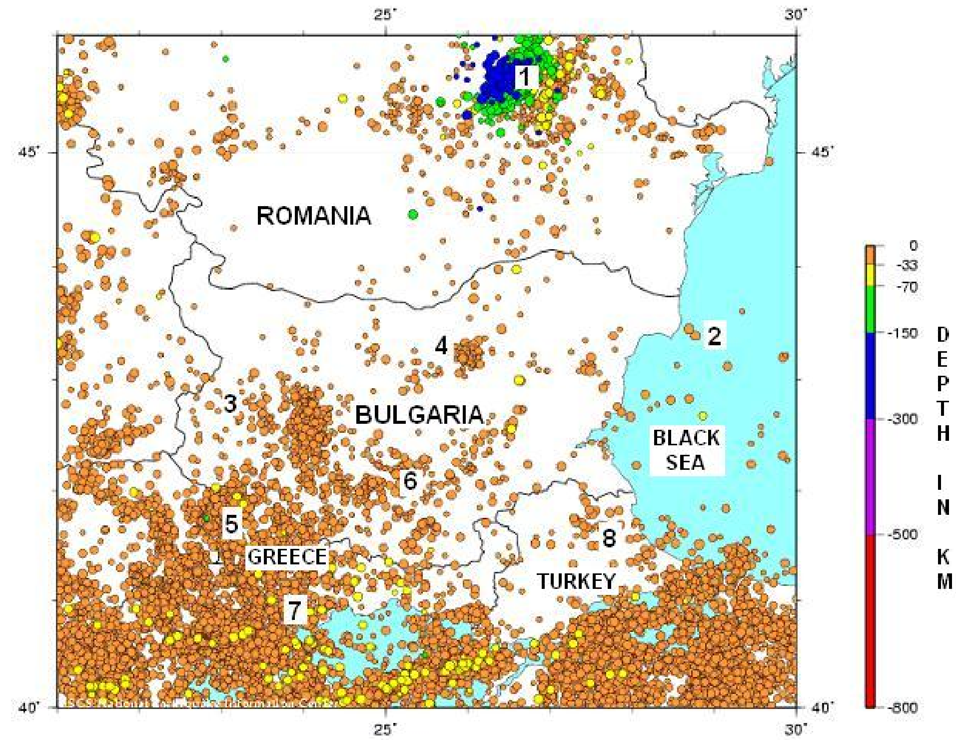



**Fig. 4.** Map of the earthquake epicenters fo the period from 1973 till today (from NEIC). The principal seismic zones are shown (the numbering of the zones is the same as on Fig. 3). Practically the same zones as the plotted on Fig. 3 are generating earthquakes, but the magnitudes are lower than these of the historical earthquakes.

### 4.1. Seismic characteristics

*Kresna Seismic Zone*

This zone is well known with the strongest earthquake in Europe for the last 200 years – from 04.04.1904. The coordinates of the epicenter have been determinate as 41° 48’E and 23° 07’N. The magnitude, according the evaluation from Pasadena (USA), was M=7.5, but data exists that they occurred two consecutive events of magnitudes 7.2 and 7.8. A number of revisions have been published, some of them have dropped the magnitude values even bellow 7.0 (Ganas et al., 2005). Most probably the hypocenters of the main shocks, as well as the aftershock series during the next two years were related to the regional and very active contemporary Kresna Fault.

The macro-seismic map of the earthquake from 04.04.1904 (Fig. 5) shows the impact of this earthquake (or pair of earthquakes) on the area of the studied segment of the highway with intensity between X and VIII degrees MSK-64. This is the strongest recorded impact for the area of the highway facilities. Krupnik Fault was and continues to be a generator of events of lower magnitudes.

A catalogue of the earthquakes (magnitude Ms) has been compiled for the studied region. It collects the complete available information for the seismicity, recorded from historical time till November, 2014 for the region framed by the coordinates reported on Table 1. The recorded seismic events are 697, the first one is dated from 896. The catalogue is disposable, if necessary, for the needs of other experts.

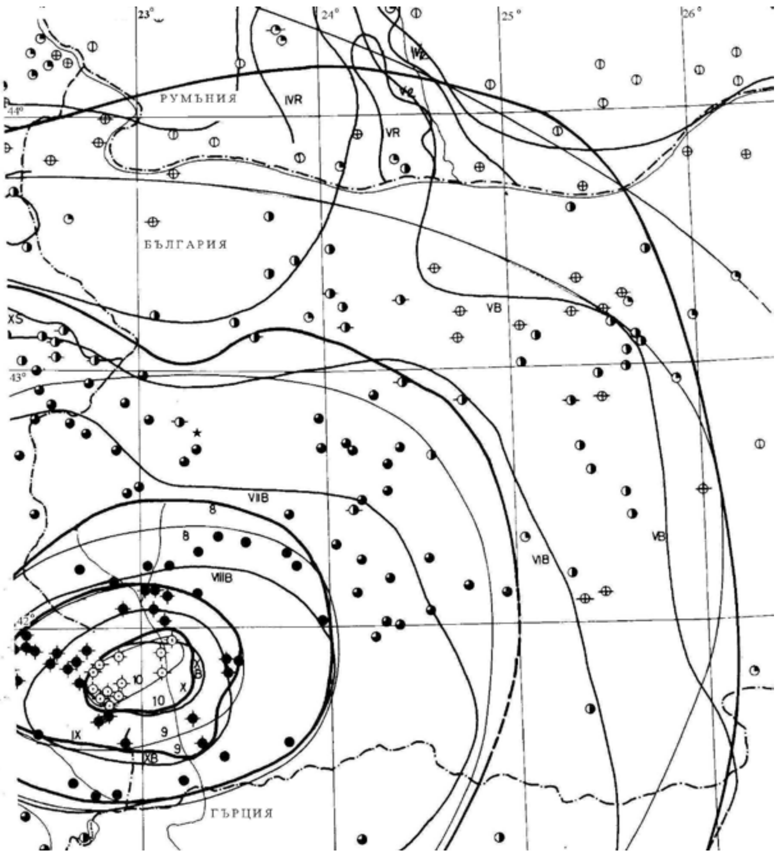



Fig. 5 Isoseist map of the earthquake from 04.04.1904, compiled by E.Grigorova (from Shebalin, 1976).

### 4.2. Earthquake recurrence relationship

The cumulative graph of the earthquake recurrence interval for the studied territory is elaborated on the base of the data in the catalogue of the earthquake (Fig. 6). The used data include all earthquakes, also these from the long aftershock sequence along the Krupnik Fault after the earthquake from 1904. The graph is normalized for a period of 100 years. The linear regression is:

$$\mathbf{Lg\ N = 4.569 - 0.709\ Ms}$$

From this relationship it could be calculated that from the active tectonic structures in the area can produce:

- One earthquake of magnitude Ms>7.0 for a period of 250 years;
- Two earthquakes of magnitude Ms ≥ 6.0 for a period of 100 years;
- Ten earthquakes of magnitude Ms ≥ 5.0 for a period of 100 years;
- 53 earthquakes of magnitude Ms ≥ 4.0 for the period of 100 years.

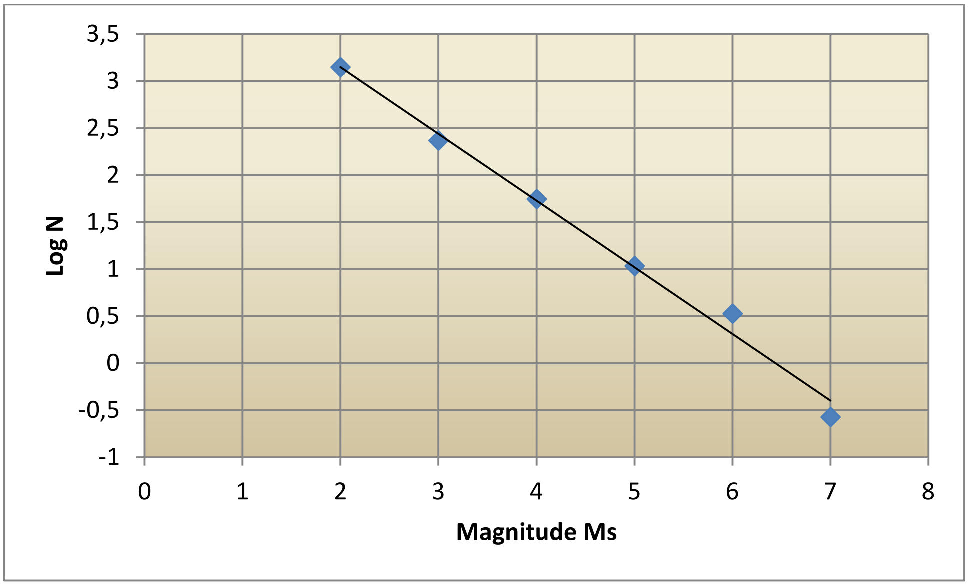



Fig. 6. Cumulative graph of the earthquake recurrence interval for the studied area. The graph is normalized for a period of 100 years. The coefficient of linear correlation is $K_{cor}$ = -0.995.

These prognoses are confirmed by the initial data, taking into account that the strong earthquakes are basically related to the main shocks from 1904 (long aftershock sequence):

- ✓ For the period of 1118 years they were recorded 3 earthquakes of magnitude higher than 7.0;
- ✓ For the period of 148 years is registered only 1 earthquake of magnitude higher than 6.0 and 2 earthquakes of magnitude higher than 7.0;
- ✓ For the period of 111 years 10 earthquakes of magnitude Ms≥5.0 have been recorded.

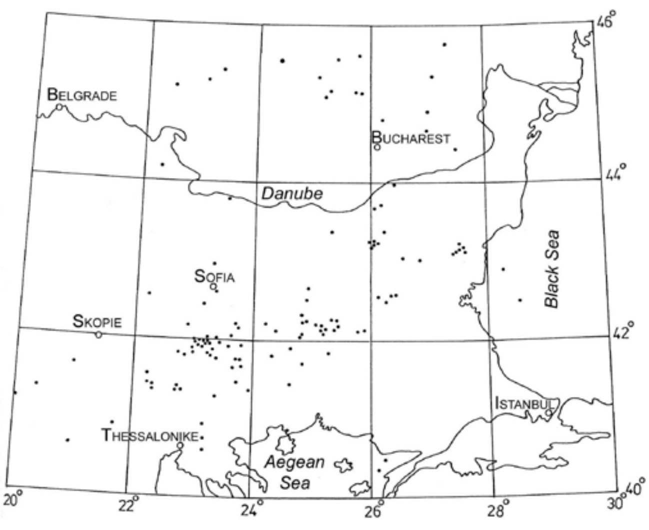
The result is logical, because the coefficient of linear regression is -0.995. Practically earthquakes of magnitude less than 5.0 will not especially damage the structure of the facilities, except in the case of shallow earthquake hypocenter or an activation of fault segment crossing the highway facility. Earthquakes of magnitude lower than 5.5 rarely create rupturing attending the Earth's surface.

#### 4.3. Contemporary tectonic stress field

All the available data till 1996 was used for reconstruction of the directions of the main axes of the tectonic stress field for the Central Balkan Peninsula (Shanov, Boykova, 1996). The published 155 fault-plane solutions from the Central Balkan Peninsula have permitted to draw the principal tendencies of the spatial position of the axis P (tectonic compression) and axis T (tectonic extension). On Fig.7 (from Shanov, Boykova, 1996) the concentration of T-axes around the direction N-S (the dispersion cone is 45°) is clearly seen, while the P-axes occupy large belt with orientation E-W with dominant concentration around the vertical axis.

Statistical analysis performed on 107 fault-plane solutions from earthquakes by a team from the Geophysical Institute (Simeonova et al., 1993), denoted the stable tendency of grouping of the nodal planes at direction E-W, the groups with direction NW-SE and NE-SW were less expressive. For the period from 1981 to 1990 on the territory of Bulgaria 55 % of the fault-plane solutions were of normal faulting type, 35 % were evaluated as reverse faulting type and only 10 % were of strike-slip type. The same authors only for the territory of Bulgaria deduced as dominant the horizontal extensional stress trending NNW-SSE. For the direction of tectonic compression they comment the bad expressed tendency of grouping but the general trend E-W was noted.

Another study for South Bulgaria was done on the base of 82 reconstructed mechanisms of earthquakes (Van Eck, Stoyanov, 1996). It has shown that for Struma Fault Zone the regime of extension is dominant, the axis of the maximum tectonic stress $\sigma_1$ being vertical while the minimum tectonic stress axis $\sigma_3$ is sub-horizontal directed N-S. These three publication discussing the contemporary tectonic stress field in the central part of Balkan Peninsula (Simeonova et al.,1993; Shanov, Boykova, 1996; Van Eck, Stoyanov, 1996) using different number of data for the mechanisms of the earthquakes, have achieved to the same general conclusions.



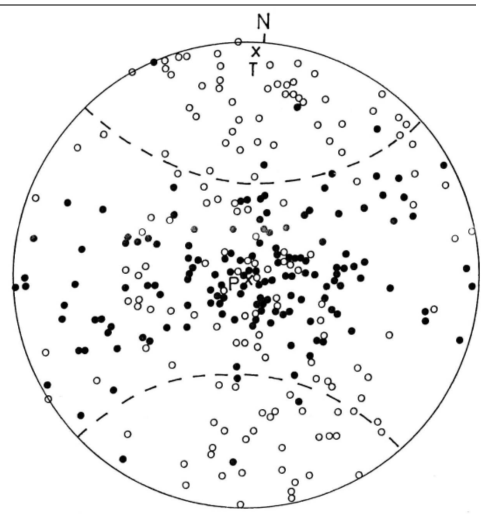




**Fig. 7, a.** Scheme of the earthquake epicenters in Central Balkan Peninsula with fault-plane solution in the focal zone.

**Fig. 7, b.** Stereographic projection in lower hemi-sphere of P-axes (black circles) and T-axes (empty circles) from the fault-plane solution in Central Balkan Peninsula (Shanov, Boykova, 1996).

The trends of the principal axes of the maximum $\sigma_1$ and the minimum $\sigma_3$ tectonic stress are deduced using information from larger territory than the studied one (Shanov, Dobrev et al., 2008). The general tendency of E-W trending of the maximum tectonic stress axis and N-S trending of the minimum tectonic stress axis is clearly seen (Fig.8).

**Table 3** Earthquake mechanisms from the studied area (territory framed by the coordinates: Northern: $41.7^0 – 42.4^0$ and Eastern: $22.8^0 – 23.3^0$)

| № | Date [year, month, day] | Time [Hour: min] | Coordinates | | Depth [km] | M | Nodal planes | | Main stress axes in the focal zone | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | North | East | | | Dip direction/Dip angle | | Direction/Plunge | | |
| | | | ºN | ºE | | | A | C | B | P | T |
| 1 | 1978/12/31 | 15:56 | 41.99 | 23.22 | 15 | 4.6 | 96/40 | 220/64 | 144/29 | 242/14 | 356/58 |
| 2 | 1978/12/31 | 16:26 | 41.97 | 23.17 | 10 | 4.4 | 118/50 | 214/40 | 136/48 | 274/20 | 354/33 |
| 3 | 1981/04/01 | 10:55 | 41.95 | 23.21 | 4 | 3.1 | 10/06 | 192/84 | 11/01 | 282/39 | 102/51 |
| 4 | 1981/04/02 | 12:30 | 41.93 | 22.99 | 8 | 32 | 261/23 | 156/86 | 323/22 | 89/47 | 228/35 |
| 5 | 1981/06/13 | 14:40 | 41.82 | 22.84 | 9 | 3.2 | 260/67 | 90/23 | 263/04 | 162/68 | 353/22 |
| 6 | 1981/07/17 | 19:17 | 41.92 | 23.00 | 8 | 3.0 | 214/55 | 49/36 | 220/07 | 92/78 | 310/09 |
| 7 | 1981/08/26 | 19:42 | 41.96 | 23.16 | 20 | 3.6 | 90/54 | 280/36 | 268/29 | 121/52 | 2/16 |
| 8 | 1981/09/05 | 00.08 | 41.85 | 23.24 | 16 | 3.0 | 159/50 | 351/41 | 164/06 | 225/05 | 21/82 |
| 9 | 1981/10/14 | 18:36 | 41.97 | 23.25 | 13 | 3.2 | 265/56 | 109/36 | 273/12 | 136/75 | 5/10 |
| 10 | 1983/03/11 | 23:06 | 41.92 | 23.07 | 18 | 3.1 | 14/59 | 178/36 | 99/09 | 220/74 | 8/13 |
| 11 | 1983/08/13 | 02.08 | 41.79 | 23.26 | 10 | 3.3 | 265/58 | 117/36 | 210/18 | 56/70 | 302/06 |
| 12 | 1985/09/17 | 06:53 | 41.90 | 23.00 | 13 | 3.4 | 110/15 | 309/75 | 128/04 | 35/30 | 226/59 |
| 13 | 1986/05/15 | 16:37 | 41.95 | 23.13 | 17 | 3.6 | 128/81 | 36/80 | 170/76 | 261/01 | 352/14 |
| 14 | 1986/05/15 | 16:45 | 41.94 | 23.15 | 19 | 4.2 | 47/47 | 263/49 | 65/19 | 241/71 | 335/01 |
| 15 | 1986/10/26 | 13:32 | 41.94 | 23.15 | 16 | 3.1 | 60/35 | 268/58 | 79/12 | 217/72 | 347/12 |
| 16 | 1987/02/04 | 06.07 | 41.97 | 23.18 | 13 | 3.0 | 51/44 | 557/49 | 64/12 | 232/78 | 334/03 |
| 17 | 1988/04/24 | 13:44 | 41.98 | 23.20 | 15 | 3.1 | 13/73 | 277/71 | 50/64 | 235/26 | 145/01 |
| 18 | 1988/09/23 | 06:26 | 41.91 | 23.04 | 9 | 3.2 | 140/07 | 352/34 | 140/03 | 79/39 | 266/41 |
| 19 | 1989/04/09 | 20:50 | 41.84 | 22.89 | 12 | 3.3 | 75/90 | 343/15 | 75/15 | 179/43 | 330/44 |
| 20 | 1989/06/03 | 16:37 | 41.96 | 23.27 | 12 | 3.4 | 200/89 | 109/36 | 201/36 | 79/36 | 321/34 |
| 21 | 1989/11/28 | 12:30 | 41.95 | 23.00 | 14 | 3.0 | 233/54 | 105/49 | 257/29 | 63/61 | 348/03 |
| 22 | 1990/03/22 | 07:15 | 41.95 | 23.07 | 15 | 3.2 | 22/67 | 286/75 | 75/62 | 243/27 | 335/05 |
| 23 | 1990/07/28 | 09:28 | 41.94 | 23.13 | 19 | 3.3 | 86/02 | 272/88 | 92/00 | 182/47 | 2/43 |

Only a part of the used earthquake fault-plane solutions for this reconstruction are situated near the route of the highway, generally they are grouped northward from the Krupnik Fault (Table 3). The averaged orthogonal to each other planes containing the axes of compression (P) and extension (T) from the fault-plane solutions show clear sub-horizontal conditional "tectonic extension" directed NW-SE and NE-SW direction of the tectonic pressure, but with larger variation from sub-horizontal to sub-vertical position.

Modeling of the stress using the method of Gephart and Forsyth (1984) based on earthquake fault-plane solutions is published for the area of Krupnik (Botev et al., 2006). Practically this is a reconstruction of directions of the stress axes $\sigma_1$, $\sigma_2$ and $\sigma_3$. The solution is fully confirming the tendencies shown on Fig. 8 – the maximum stress axis (tectonic compression) $\sigma_1$ is oriented N $92^0$ with a plunge of $43^0$, the intermediate stress axis $\sigma_2$ is oriented N $260^0$ with a plunge of $33^0$, and the minimum stress axis (tectonic extension) is oriented N $179^0$ with a plunge of $3^0$.

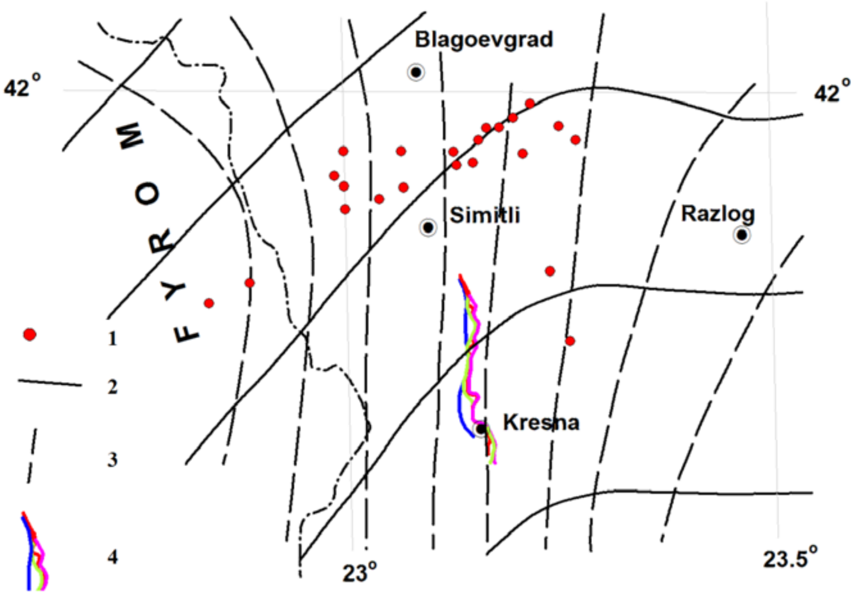



**Fig. 8** Reconstruction of the directions of the maximum contemporary tectonic compression and minimum contemporary tectonic compression (conditional tectonic extension) from the mechanisms of the earthquakes for the studied part of Highway "Struma"

1 – earthquake epicenter with reconstructed mechanism; 2 – direction of the maximum pressure; 3 – direction of the minimum pressure; 4 – variants of the highway routes.

This analysis shows that the area is under regime of tectonic extension with general trend N – S and the active fault structures of normal fault type are crossed almost orthogonally by the highway routes variants.

### 4.4. Contemporary movements

***Vertical movements***

The velocity of the contemporary vertical movements for the studied area, according to the published regional maps (Hristov et al., 1973; Totomanov, Vrablianski,1980; Totomanov, Vrablianski - in Boncev et al.,1982, Map № 73), is positive, about 1-2 mm/year, while the surrounding mountain structures of Pirin Mountain and Ograjden Mountain are uplifted with velocity of about 3 mm/year.

These maps are very schematic and they do not give enough possibility to study the character of the movements of smaller blocks of the Earth's crust.

Vrablianski and Milev (1973) have used the first category leveling of the country from 1930 along the line Dospat – Sofia, re-measured in 1956 and they performed third leveling in 1970. The analysis of the data has shown that the change of the sign of the exceeding differences between the consequently measured benchmarks in the area from Simitli to railway station Pirin coincides with the crossing of the principal tectonic structures determined by geological and geomorphological investigations. Three blocks were clearly determined (Fig. 9). For the first block, northern from Krupnik Fault the velocity of the contemporary vertical movements is in the frames from +0.8 mm/year at Simitli to 0 mm/year near Krupnik Fault. The second block, southern from the fault and westwards from the valley of Struma River shows tendency for subsidence – from 0 mm/year to -3.4 mm/year near the railway station Pirin. The third block, eastwards from the valley of Struma River shows highest velocity of uplifting - +1.4 mm/year at railway station of Kresna and +3.4 mm/year near railway station Yavorov.

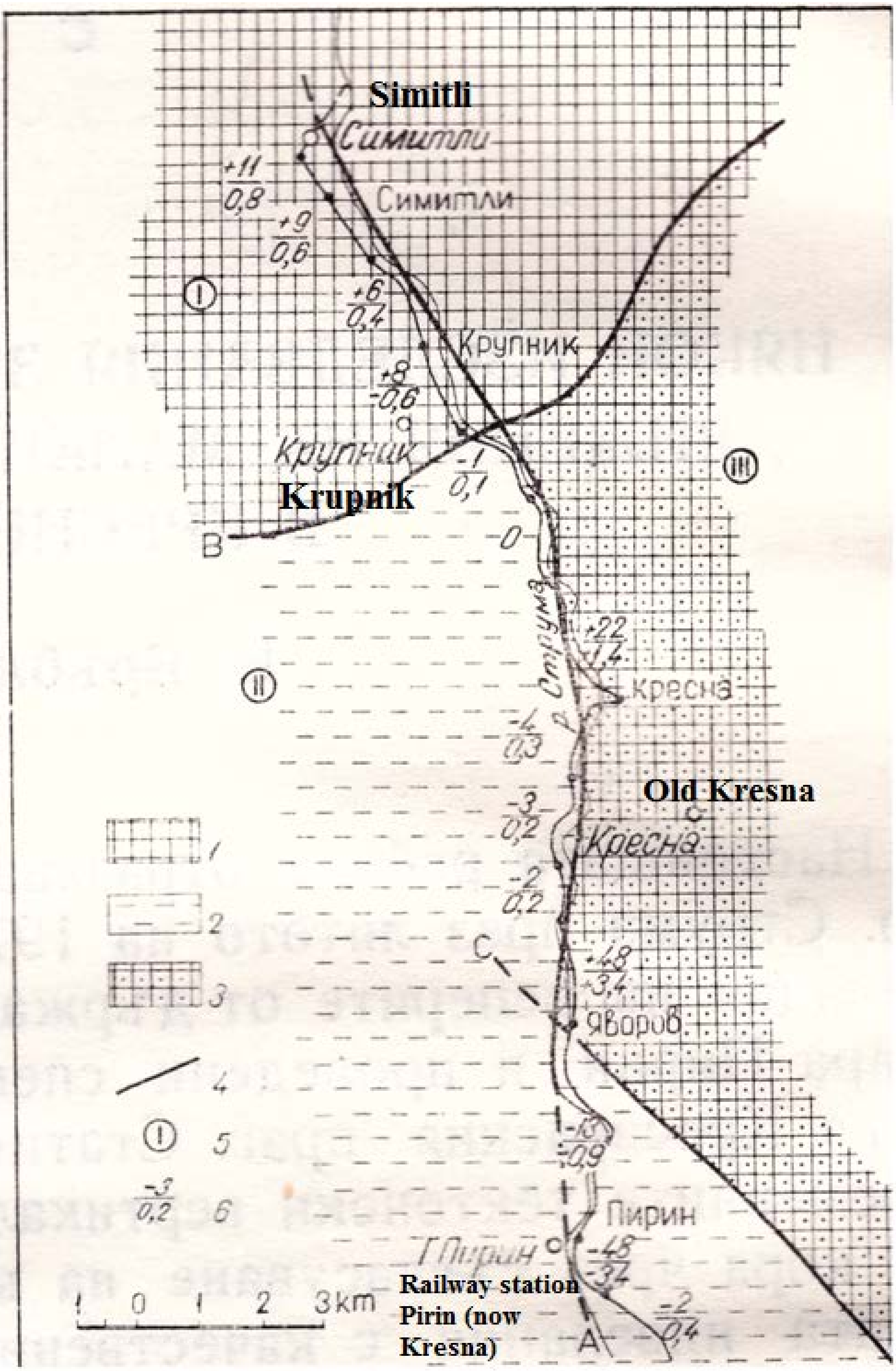



Fig. 9 Scheme of the disposition of the blocks in Kresna Gorge (original scheme without corrections from Vrablianski, Milev, 1973).

1 – Block I with medium values of the vertical movements; 2 – Block II with low values of the vertical movements; 3 – Blok III with high values of the vertical movements; 4 – Faults: A – Struma Fault; B – Krupnik Fault; C – Yavorov Fault; 5 - № of the block; 6 – numerator – the differences of the exceeding differences between the benchmarks, denominator – relative velocities in mm/year.

More recent publication re-interprets these data, the period of the repeated leveling being to 1991 (Georgiev et al., 2007). The last measuring of the first and second range leveling lines in SW Bulgaria were made in the periods 1978-1984 and 1983-1991. Especially for the part of the Highway "Struma" along the line Dupnitsa – Sandanski it is clearly evident the sharp changes of the velocities between the sites of Kocherinovo and Simitli, at Krupnik Fault and less expressive – near railway station Pirin (Fig.10).

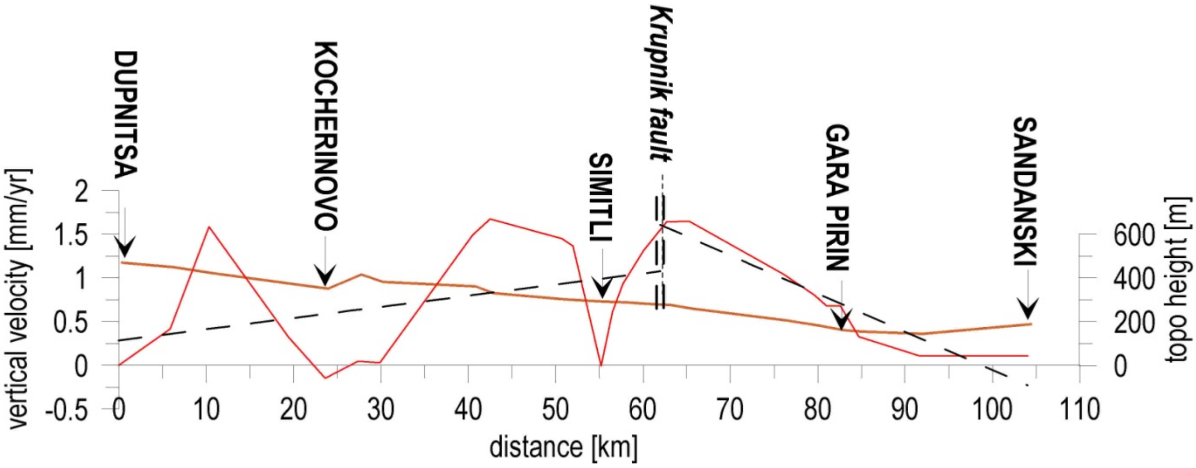



Fig. 10 Profile of the vertical movements velocity along the leveling line Dupnitsa - Sandanski (from Georgiev et al., 2007)

***Хоризонтални движения***

The horizontal velocities obtained from records of 38 GPS sites in SW Bulgaria show that the concerned territory south-southeastwards relatively Eurasia (Georgiev et al., 2007). The average velocity is 1.8 ± 0.7 mm/year (Fig. 11), the direction is N154$^0$. Especially for the studied area, Krupnik Fault is the most important structure. The movement of site KRUP (geodetic site from the local geodynamic network near Krupnik) is towards north with velocity of 3 mm/year. This displacement is conform to the slope towards north-northwest of the plane of Krupnik Fault (normal fault N60-70$^0$) and its strike - N50-60$^0$. It is in agreement also with the reconstructions of the contemporary tectonic stress field (see Fig. 8 above), as well as with the published data (Shanov, Dobrev, 2000). The calculated velocity of the total deformations along the fault on the base of the extensometric studies recorded on one of the fault segments is 3.4 mm/year, and in this way the geodetic measurements have been confirmed. According to the extensometric measurements the slip component along the fault is left lateral. This is an indication for the slower movement of the northern block towards northeast relatively to the southern one, ore this could be an effect of right rotation of the southern block. The nearest GPS site northern from Ktupnik is the site near Kresna, and its displacement to southeast is with velocity of 2-3 mm per year.

The tectonic units southwards from Krupnik Fault and eastwards from Ograjden Block are characterized by higher velocities of displacement southeastwards, and especially the northern part where are situated the sites KRES, GOST and VIHR. Similar trend of the movements, conforming to the principal trend for the all area, show the sites of Ograjden Horst. According to the paleomagnetic data on the territory of Macedonia (Pavlides, Kondopoulou, 1987), this part of Serbo-Macedonian Massif is 10$^0$ clockwise rotated from Oligocene time till Similar has been also the conclusion from the analysis of the Neotectonic and the contemporary stress field (Shanov, 1997). The sites CAPA, PETR and RUPI confirm completely the existing of such of rotation.

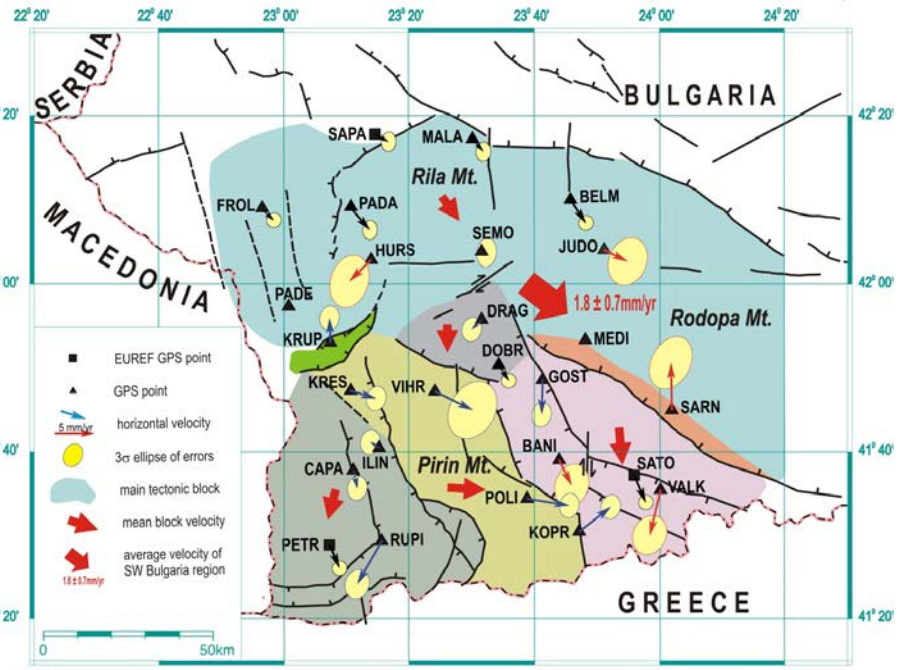



Fig. 11. Relative velocities to Eurasia from GPS records in SW Bulgaria. The ellipse of the confidence interval of 95% and the main tectonic blocks are shown (from Georgiev et al., 2007).

A special study for the region Krupnik - Kresna (Georgiev et al., 2006) has demonstrated the normal faulting north-northwest on Krupnik Fault (Fig. 12). GPS sites 5 and 11 from the local network show that Simitli Graben migrates towards north-northwest. The comparison with the velocities of the sites KRES, ILIN and VIHR confirms clearly the regime of extension in the region.

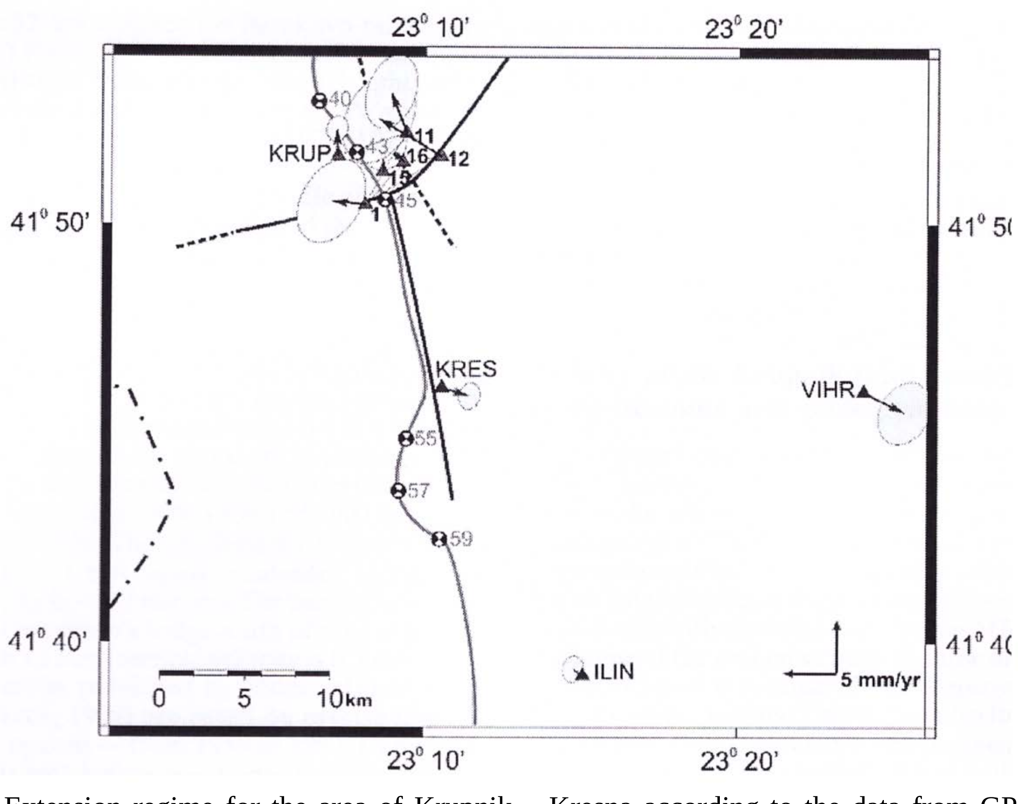



Fig. 12. Extension regime for the area of Krupnik – Kresna according to the data from GPS (after Georgiev et al., 2006).

### 4.5. Parameters of the active faults

On Fig. 13 the faults, recognized as active from the previous studies in the area, are plotted. The epicenters of the earthquakes are also given from the selected catalogue for the region. Active are the faults having general strike NE-SW, evidently related to the seismic events in the area. Four faults are defined as active ones. Their seismotectonic characteristics are given here bellows.

1. ***Stob (Rila) Fault***

Stob Fault, named also Rila Fault, is known as geomorphological structure limiting the SW flank of Kocherinovo Neogene Basin along the bed of Rilska River. The terrain investigations have detected surface rupturing from Holocene time in its NE part (Tranos et al., 2006). The same authors have reported that the rate of the vertical displacement of the adjacent to the fault blocks during the Holocene is 1.00 m, and the slip rate for the last 10 thousands years is 0.14 mm/y. The existing information from the investigations gives the length of the fault at 10.8 km and it is closely related to the evolution of Kocherinovo Basin. A lineament with the same strike is recognized on the remote photos, westwards from the bed of Struma River. The lineament can be followed as segmented structure striking N 47° between the valleys of Struma River and Bregalnitsa River, being of total length of 30 km. The lineament is determined by predominant flatter relief at NW, delimitation of the large valleys of Holocene sedimentation in the NW block by the deeply incised valleys with sharp scarps of the SE Block (Fig. 13). In the valley of Bregalnitsa River a typical basin on the hanging block, controlled from the fault activity. The lineament is reveled as a structure on the map of the local gravitational anomalies. Recent seismicity of the structure is recorded near the beds of the rivers Rilska and Bregalnitsa.

The morphology, the tectonic control on the Holocene sedimentation and the velocities of the contemporary vertical movements give reason to suppose the prolongation of Stob Fault south-westwards from the valley of Struma River. According to the empirical relationships of the slip rate and the length of the faulted segment, the reported by Tranos et al. (2006) Holocene faulting of amplitude of 1.00 m needs considerably longer fault segment then those of the SW flank of Kocherinovo Basin. Data is not existing about the possible prolongation of the structure towards NE.

Speculating with the known length of fault - 40.8 km (the two known segments are included) an assessment of the possible maximum magnitude that can be generated by it. The average value from the used relationships from Table 2, the maximum magnitude of an earthquake that can be expected from the fault is $M_s$ = **6.85±0.11**. Translated in moment magnitude this value is transformed at $\mathbf{M_w = 6.496}$.

The displacement in the epicentral zone of such one earthquake, following the relationships presented in Part 1, considering the length of the fault at 40.8 km and supposed depth of 25 km, is **20.5 cm**.

If the presumption that during the last 10 000 years the whole fault has been activated by earthquakes is acceptable, and adopting the hypothesis for more or less strictly periodical occurrence of the strong earthquakes, the reported rate of 1 m of displacement during the Holocene can be obtained from 5 earthquakes of magnitude $M_s$ = 6.85. The periodicity of the catastrophic events along the fault, for sleep rate 0.14 mm/y, is approximately **1 400 – 1 500 years**. There is no indications when the last event has occurred.

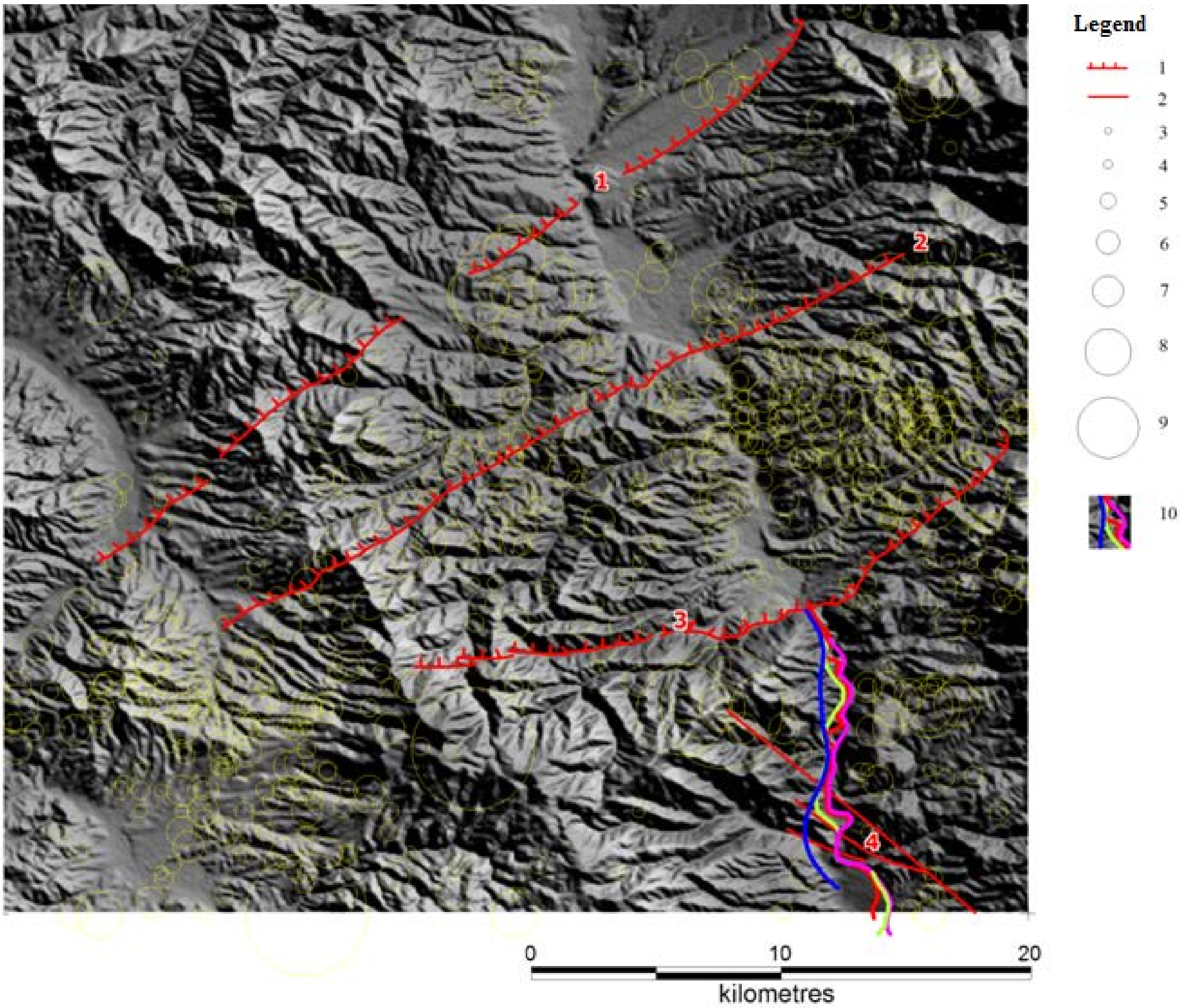



Fig. 13. Relief map of the studied area with the faults, recognized as active (base map: Digital model of the relief SRTM3) and epicenters of the recorded earthquakes till 05.11.2014.

**1** – normal fault; **2** – fault with unknown type of movement along it;
Faults: 1. Stob (Rila); 2. Padesh; 3. Krupnik; 4. Yavorov;

Earthquake epicenters of magnitude Ms:
**3** - 0÷1.9; **4** - 2÷2.9; **5** - 3÷3.9; **6** - 4÷4.9; **7** - 5÷5.9; **8** - 6÷6.9; **9** – more than 7;

**10** – variants of the routes of Highway "Struma", LOT 3.2.

## 2. ***Padesh Fault***

Padesh Fault forms a well expressed stepped fault scarp with amplitude till 270 m. Separated short segments are coupled and by overlaps and step backs of lengths less than 800 m have formed continuous linear structure. The geomorphological expression of the lineament was followed from the valley of Struma River to the valley of Bregalnitsa River and its total length is 23.8 km. The strake is N 50°. The fault dipping is NW. The subsided NW block is characterized by lower altitude (in average 100 m) and by flatter relief (the slope of the topographic surface is 2-4° lower) compared to the elevated SE block. The fault is clearly expressed structure on the gravity field. The recent seismicity is concentrated inside the block framed by Padesh Fault and Krupnik Fault. The space distribution of the seismic events gives reason to suppose the prolongation of this structure north-eastwards from the valley of Struma River as SE border of Blagoevgrad Basin south-westwards from the valley of Bregalnitsa River.

The fault is controlling the Neogene, Pleistocene and Holocene sedimentation on the subsided NW block. Three typical basin have been formed on the hanging block: this one near the city of Blagoevgrad, the second is near the village of Padesh and the last one is in the valley of Bregalnitsa River. The stratigraphic interval of the basin sedimentation suggests Neotectonic and contemporary activity of the fault.

North-westwards from the fault, in the valley of Struma River relatively higher velocities of the recent vertical movements were reported. The velocities from the two sites of the fault are different.

Taking into account the fact that this fault was never described and recognized as an active fault till the studies performed in 2007, some additional detailed investigations have been done (Shanov, Dobrev at al., 2008). These investigations determined the presence of fault scarp and colluvium bodies near the fault – indicators for young, probably from Holocene time surface rupturing. They were discovered morphological forms of the relief than can be directly related to the contemporary activity of the fault. Geophysical profiling (Fig. 14) has shown clearly the geometric characteristics of the fault. The evident rate of displacement is about 25 m – a subsidence of the northern block. The fault dipping is near vertical north-northwestwards - the angle is about 80°.

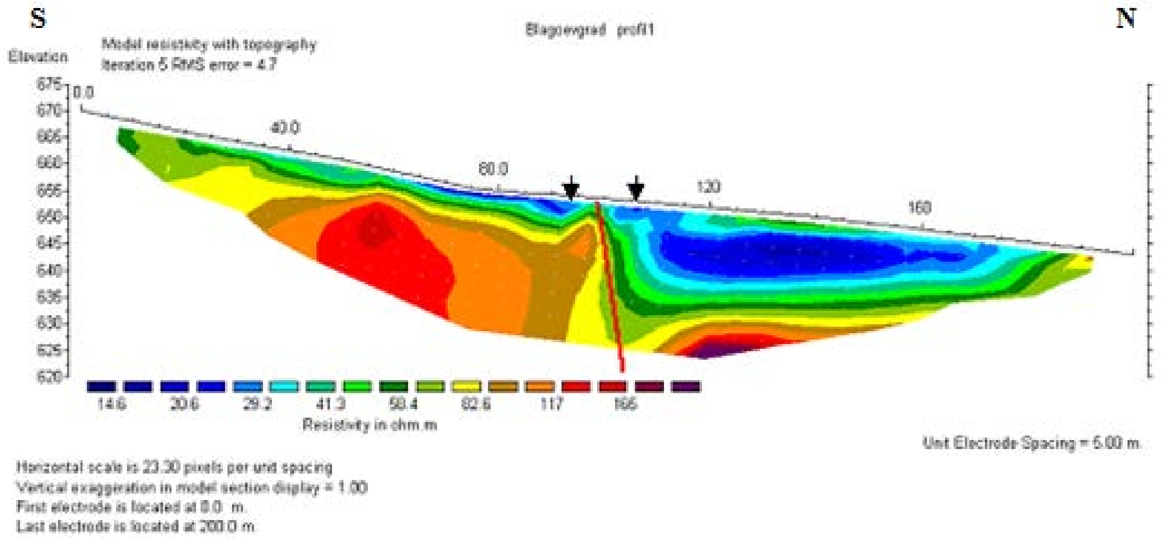



Fig. 14. Geo-electrical profile across Padesh Fault. Arrows indicate the sites of handy core holing.

The final prove for the recent activity of the fault was given by two handy holes executed in the foot wall and in the hanging wall. The hole in the foot wall attended weathered materials of the basic rocks at the depth of 2.5 m, while the hole in the hanging wall did not reach basic rocks to the depth of 4.20 m, but it crossed two levels of buried soils – at 2.6 m and at 3 m. This result has shown that at least two strong seismic events occurred during Holocene time, but there is no information for the time of the last one. Because the real length of the fault is not recognized it is not possible to evaluate the expected maximum magnitude generated by it. Indirectly this could be assessed by the relationships presented in Part 1. The displacement detected by the holes is **1 m,** as a minimum, for one seismic event. This amplitude is characteristic for earthquakes of magnitude **$M_s$ > 7.**

The fault is crossing the Highway route southern from the designed tunnel “Zheleznitsa”, but expected strong earthquake from this fault will affect a large area, including the infrastructural facilities of the segment “Krupnik – Kresna” of Highway “Struma”.

### 3. ***Krupnik Fault***

It crosses the route of Highway “Struma” at km 379+185, exactly at the northern entrance of the tunnels of one of the variants of the highway route.

Krupnik Fault is a system of fault segments of dominant strake NE-SW (N 50-60°) and dipping towards NW by angle of 50-62° (Vrablianski, 1974). On Bulgarian territory it is evaluated to be of length of 25 km. The displacements along the fault are normal with left lateral component. The fault is well studied, it is well expressed as geomorphology. High velocities of displacements have been evaluated for the Neotectonic stage, including during the Holocene time. Towards the border between Bulgaria and FYROM the fault is less expressed and it is difficult to be followed on the terrain.

A number of proves exists that during the earthquake from 1904 exactly Krupnik Fault was activated. Remains from this seismic event are clearly seen eastwards from the village of Krupnik (Fig. 15). The traces of the tectonic movements are kept on the fault surface (stria on slickensides). The analysis of these striations has shown their narrow relation to the ongoing faulting process during the last seismic events. On the base of these striations a reconstruction of the recent tectonic stress field has been done (Fig. 16). The solution from the total number of measured stria is, as follows: $\sigma_1$=>83°/32°, $\sigma_2$=>184°/9° и $\sigma_3$=>281°/37°. The solution is practically confirming the space position of the axes P and T from the earthquake fault-plane solutions of the region.

Fig. 15. Remains of the faulting along Krupnik Fault during the earthquake from the 4th of April, 1904

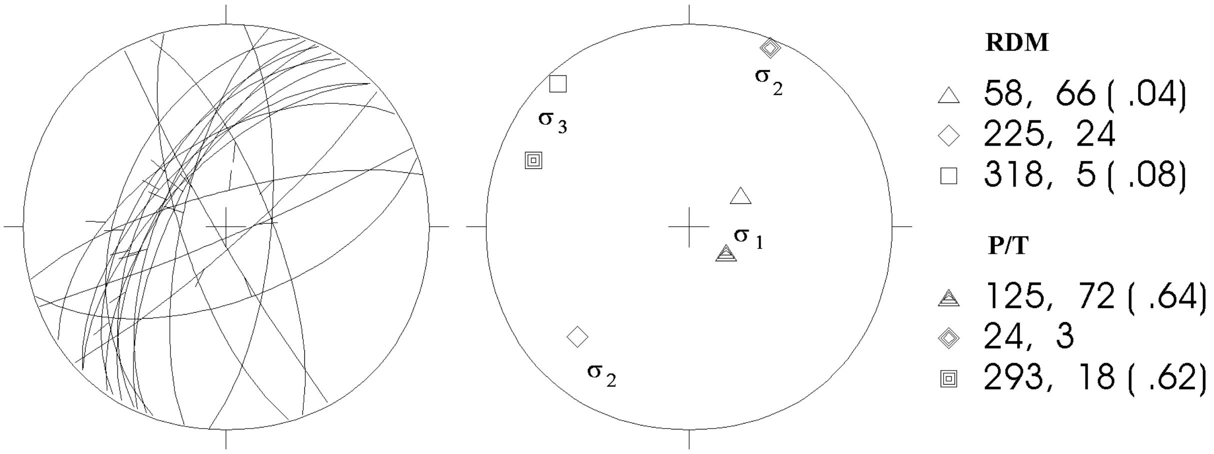



Fig. 16. Reconstruction of the principal axes of the tectonic stress field for the studied segment of Krupnik Fault at the nearest vicinity to Highway "Struma" (data from Shanov, Dobrev, 2000, lower hemisphere projection)

Additional information for the fault from the nearest site to the existing first category route has been obtained from geophysical profiles executed by the method of vertical electrical sounding (VES) in 1998 on the flood plain terrace of Struma River. 2D inversion along one of the profiles indicates the place of rupturing of the fault (Fig. 17).

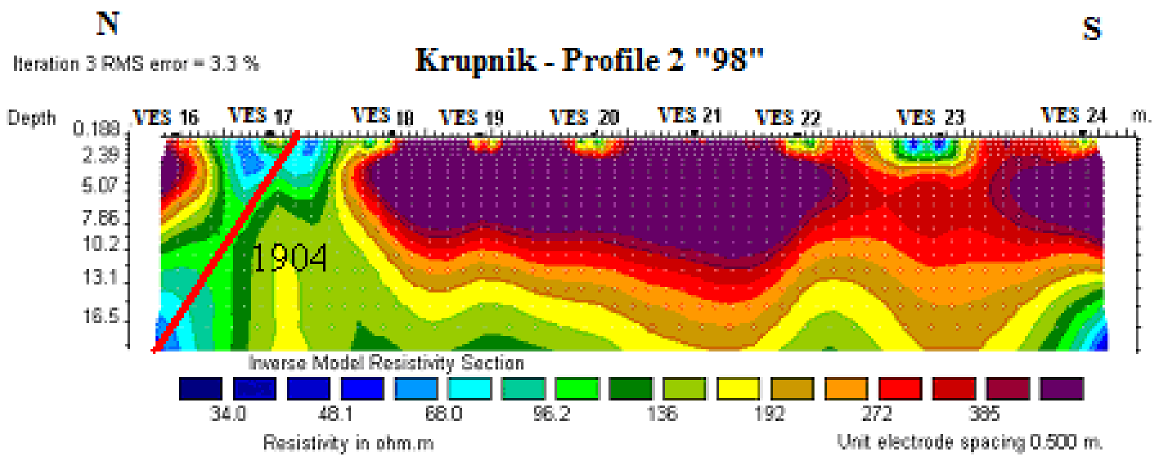



Fig. 17. Geo-electrical cross section along a profile on the flood plain terrace of Struma River, crossing Krupnik Fault. A step was formed during the earthquake in 1904, the stream of Struma River was barraged and a lake was formed for a number of hours.

The geodetic leveling has shown a difference of about 0.5 mm/year of the velocities of the vertical movements from the two sites of the fault in the zone of its crossing by the highway. The horizontal movements recorded during the last years (Georgiev et al.,2007) have demonstrated the clear differential displacements of the foot wall and of the hanging wall. The velocity of site KRUP (geodetic site from the local geodetic network, situated in the village of Krupnik) is 3 mm/year northwards. These data are well conformed to the results from the extensometric measurements since 1982 along one of the segments of Krupnik Fault – the velocity of the total deformations is 3.4 mm/year. The extensometric records confirm also the presence of left-lateral slip component along the fault. The southern block (foot wall) is moving south-westwards with velocity close to the above mentioned.

The studied segments of Krupnik Fault on Bulgarian territory have a total length of 26 km. Its length on the territory of FYROM is not known. On the hanging block Simitli Graben is situated. Since the Miocene time till now (Neotectonic stage) sediments of more than 1500 m thickness have been deposed.

The seismicity along the fault is well manifested, mainly by weak or moderate earthquakes (magnitudes lower than 5.0) since the earthquakes from 1904. The epicenters are situated north-westwards from the fault line – the direction of dipping of the fault surface.

The studied length of the fault do not give possibility to evaluate the potential maximum magnitudes of the generated earthquakes by Krupnik Fault. The displacements on it indicate clearly that magnitudes higher then 7.0 can be generated, what was the case in 1904. Paleoseismologic investigations performed by French-Bulgarian team (Mayer et al., 2007) have confirmed the rate of 1.5-2 m normal faulting during the earthquake from 1904. The same team evaluated that for the fault dipping angle of $45^0$, measured in the paleoseismological trench eastwards from the valley of Struma River, if the accepted thickness of the Earth's crust is about 15 km, the length of the fault is 20 km and the displacement is 2 m, the magnitude has to be Ms = 6.9. This assessment is one of the lowest in comparison to the previously done evaluations. One event was dated, occurring about 11000 years before the earthquake from 1904. The average slip rate has been evaluated at 0.15 mm/year.

### *4. __Yavorov Fault__*

The fault, or more correctly the group of fault segments striking NW-SE, situated north-eastwards from the town of Kresna, is drown on the geological maps in scale 1:100 000 and 1:50 000, but indicated as covered by younger, Quaternary sediments. Lately it was mentioned in the publications of I.Zagorchev under the name of Gradesh Fault (Zagorchev, 2006). It was not especially studied for contemporary activity. Vrablianski and Milev (1973) indicated it as a structure separating the Kresna Step (horst structure) from Sandanski Graben to the south. (see Fig. 9). It was recognized as potentially dangerous and an object for special studies in the Report for the risky areas for the National Gas Pipeline Network (Shanov, Dobrev et al., 2009). Around this fault a concentration of seismic events exists (Fig. 13). During the geological mapping along the route of the tunnels "Kresna", realized by the company "Geotechnika ABC" Ltd and the engineer-geological mapping on the other routes of the highway realized by the company "Bondis" Ltd, fault surfaces were also detected inside the zone where the route facilities cross this fault. Data for the geometry of the fault is not available. From geological reasons the fault has to dip SW, but probably antithetic segments also exist. The fault segments control the Neogene and the Quaternary sedimentation on the hanging wall (Fig. 18).

The different variants of the route of Highway "Struma" are crossed by the fault segments from kilometer 390 to kilometer 392.

In the area of the fault an abrupt change of the velocity of the vertical movements has been recorded. At railway station Kresna the measured velocity is +1.4 mm/year, and at the railway stop Yavorov - +3.4 mm/year (Vrablianski, Milev, 1973). The later performed analyses were not so affirmative (Georgiev et al., 2007). The velocity of the contemporary vertical movements is about +1.5 mm/year southwards from Krupnik Fault and gradually decreases to +0.75 mm/year near the railway station "Pirin".

The horizontal movements support the normal faulting with dip angle of the fault surface south-westwards. The recorded epicenters of the earthquake are at the same position – south-westwards from the fault.

The real active part of the fault is not known, but if the mapped length of the longer segment is about 15 km, the average value of the expected maximum earthquake magnitude is calculated using the relationships from Table 2. The assessment is Ms=6.2 or Mw=6.13. Similar earthquake can produce a displacement along the fault of about **26 cm** speculating with hypothetic depth of the focus at 15 km. At this stage of the knowledge it is not possible to give other characteristics for this fault.

**The right position of the fault segments accepted as active ones has to be determinate from special paleoseismological studies after the selection of variant of the route of the highway. These investigations will clarify the seismotectonic characteristics of the fault segments.**

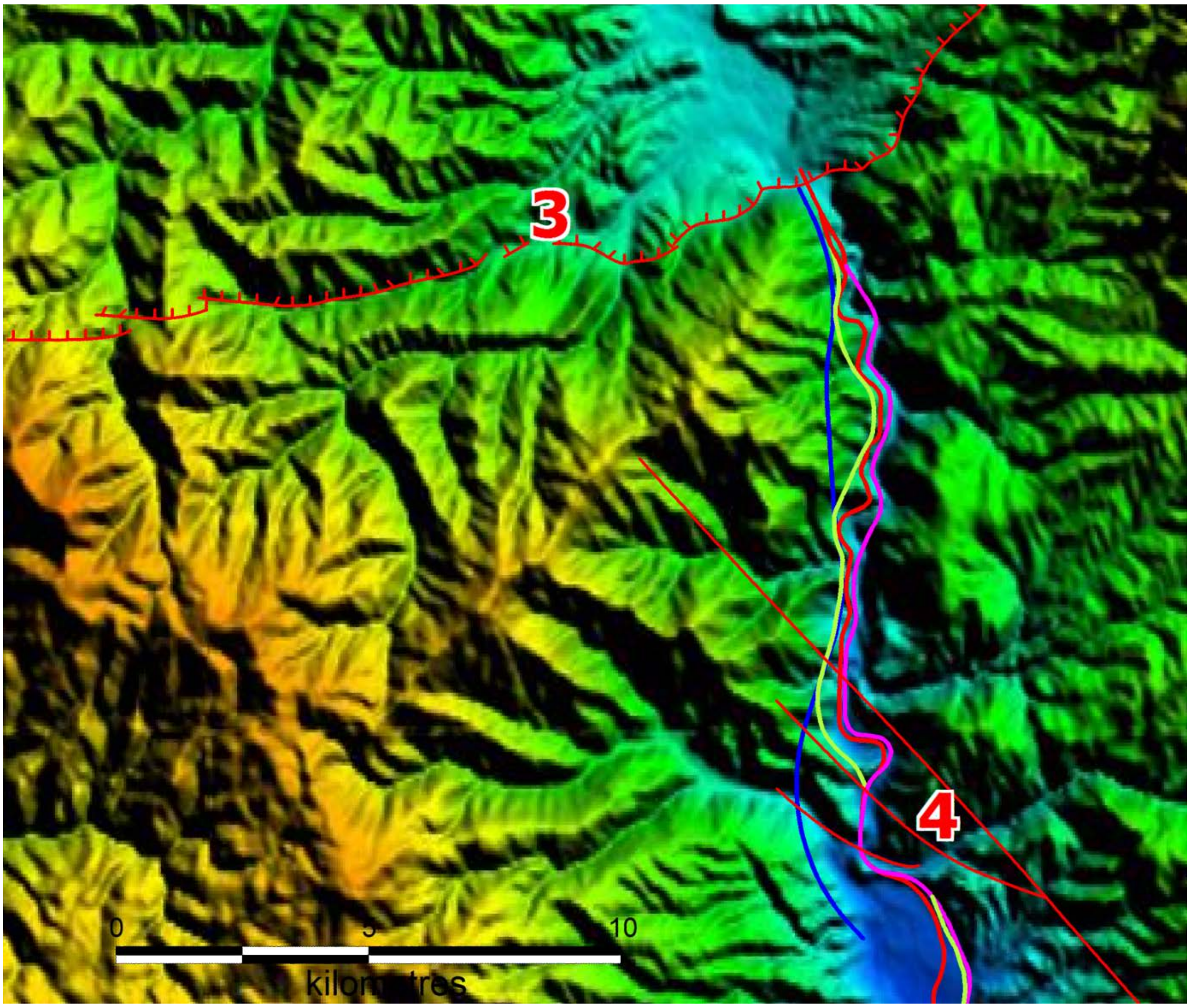



Fig. 18. Scheme of the fault segments of Yavorov Fault on the map of the relief of the studied area with the variants of the route of Highway “Struma” (base map: Digital model of the relief SRTM3). Faults:

3 – Krupnik; 4 – Yavorov.

## 5. Other dangerous geophysical factors

It is well known, that the active faults or their segments release at the surface the radioactive element radon (Rn). Radon could originate from the deep earth's interior. As an inert gas radon is very easily movable and in a fracture system can migrate and accumulate to high concentrations. A number of publications discuss this fact and even it is used for detection of covered by young sediments active faults (ex. Pavlides, 1997). Radon is a decay product of radium; it is the sole noble gas in the decay chain of uranium. Two short-lived decay products of radon are alpha emitters and, fixed on aerosols, are introduced to the respiratory tract. A high concentration of radon in the ambient air is supposed to be harmful, especially concerning lung cancer. There are recommendations for limiting radon concentrations in indoor air at homes and also in workplaces, 400 to 1000 Bq/m$^3$ for homes.

The studied area of the highway variants is geologically built by granitic rocks having relatively elevated background radioactivity. As example, the formation of the earth's component of the gamma-background at 1 m above the free surface is due mainly to the gamma emission by the natural radionuclides $^{40}$K; $^{238}$U and $^{232}$Th and the chain of isotopes of Ra, Th, Pa, Ac Pb, Bi and Tl. The concentration of these elements, as a rule, is higher in the volcanic rocks than in the sedimentary rocks. The Rn emission from the active faults could be additional negative factor for the safety of exploitation of the tunnel variant of the highway.

Especially for the concerned area continuous complex measurements were done in the basement of the Kroupnik seismic station and important results were reported lately (Ranguelov, Kies, 2001). The seismic station is built exactly on Krupnik Fault. The registered concentrations show high peaks in radon content, up to **50 000 Bq/m$^3$** in the air of the situated underground instrument room (Fig. 19).

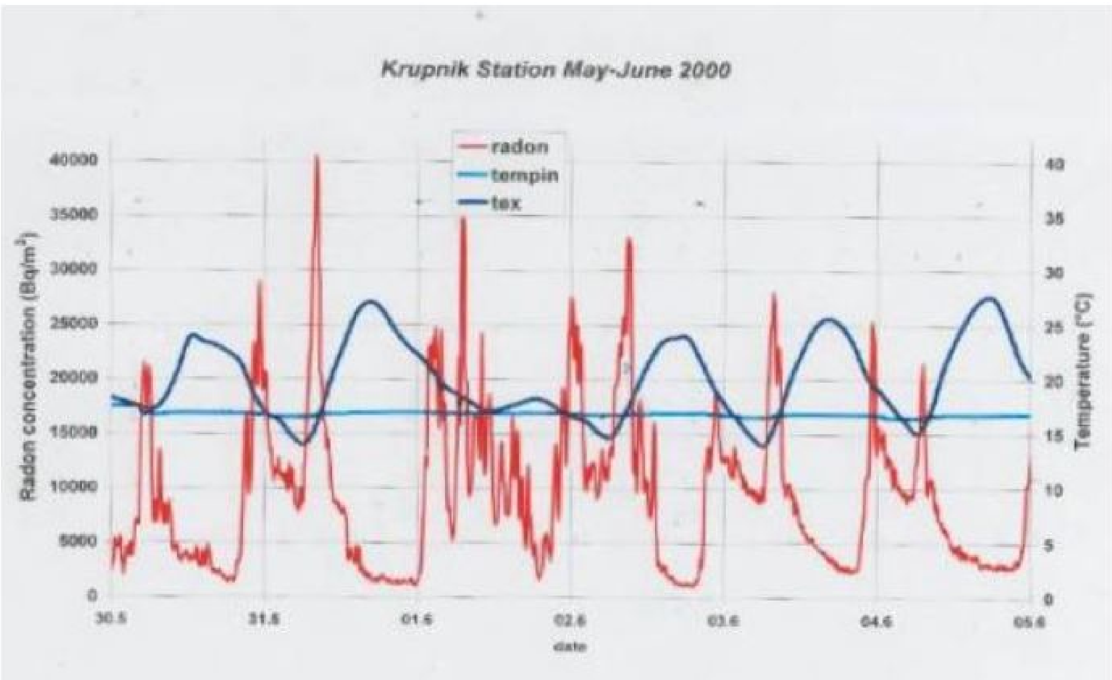



Fig. 19. Record of the concentrations of gas radon (Rn) inside the building of the Seismic Station "Krupnik" for the period from the 30$^{th}$ of May to the 5$^{th}$ of June, 2000 (from Ranguelov, Kies, 2001).

One explanation the sharp variation of the Rn records on the graphs is the very bad isolation of the measuring room and the periodical aeration of the room. So, the concentration of Rn inside closed spaces could reach dangerous levels for human health. Outside temperature changes induce an important air exchange at the measuring place and thus the radon concentrations are lowered. At night, when air exchange is minimal, radon exhalation from the ground can reach rather high concentrations in a very short time. A great underground radon potential for earthquake predictions is related to the expected sharp increasing of Rn emission by the faults and the fractures in the rocks before strong seismic events in the concerned area.

This information has to be taken into account when discussing the different variants of the future highway part of Lot 3.2. In any case, for the tunnels it will be important to control the radioactive background and to establish special rules for the underground service staff according the National and European normative documents.

## 6. Analysis of the variants for the highway segment (with 15 km tunnels or normal variant with bridges and short tunnels) from point of view of the seismotectonic conditions and other related geophysical characteristics

The seismotectonic conditions of the region of the designed route variants of Highway “Struma” LOT 3.2 are one of the most unfavorable for constructions on the territory of Bulgaria. The existence of 4 active faults that can have direct or indirect negative impact on every of the variants of the route imposes the realization of additional studies especially at the area of Yavorov Fault. This fault is crossed by the routes of the segment “Krupnik – Kresna” at km 390 – 392 and the existing data at present stage are not sufficient for its complete characterization as an active tectonic structure. If a strong earthquake occurs of magnitude higher than 6 on this fault, vertical displacements can be expected reaching the rate of about 26 cm. Similar displacement is unfavorable for every one of the variants, but for the tunnel variant this could be related to additional problems for the tunnel lighting and the ventilation systems.

The beginning of LOT 3.2 is in the zone of Krupnik Fault – active structure that is related to the destroying earthquake from 04.04.1904 with magnitude evaluated between from Ms = 7.8 to 6.9 and described displacements till 2 m, including the barraging of Struma River. The occurrence again of similar seismic event will have enormous consequences for the all existing infrastructure in the area. In any case, the damages on the variants without long tunnels will be easier repaired. The northern entrance of the tunnel variant is designed exactly on the fault and the possible approach is by bridge construction over Struma River. This construction is also vulnerable, grounded on two tectonic blocks having clear differential movements even without any seismic manifestations.

Stob Fault and Padesh Fault are not directly impacting the studied segment of the route variants, but the potential earthquakes that can be generated by them will be of magnitude higher than 6 and the seismic impacts cold lead to deformations on any of the facilities from the area of LOT 3.2.

The normative seismic coefficient for the whole region where are situated the route variants is Ks = 0.27, the highest one for the territory of the country. This is the minimal value that has to be included in the highway design. Priority, according to this coefficient, has to be assigned to the underground facilities. The seismic coefficient is reduced for the underground constructions and increased for important civil facilities on the Earth’s surface, as the bridge constructions are.

For the tunnel variant unfavorable factor will be also the increased radioactivity coming from the naturally high radioactive background of the rocks around the constructions and the continuous radon emissions from the active tectonic faults and their satellite faults. Conditions could be created for dangerous concentrations of this gas for the human health, especially for the underground facilities.

## 7. Conclusion

Having in mind the facts exposed above and their analysis, **more favorable will be any variant that avoids the long underground tunnels presently foreseen for the highway section of 3.2 "Krupnik – Kresna"**. The seismotectonic conditions and the related to the active faults increased emissions of the radioactive gas radon cannot be eliminated as unfavorable factors using technical solutions, but the minimization of their impact is in favor for the surface variants of the highway. If unfavorable events occur for the route facilities, the repairing of the damages will be the most difficult for the underground constructions.

On the base of the performed analyses on data from the existing reports and publications from previous studies it can be suggested to perform paleoseismological analyses of the active faults. Micro-seismic zoning for the most vulnerable facilities – bridges and tunnels, has to be done based on the results from them. This is the only objective approach for assessment of the seismic hazard and risk for the concerned facilities.

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