4.3.12. CONTEMPORARY VERTICAL MOVEMENTS OF THE EARTH'S CRUST ON THE TERRITORY OF BULGARIA

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4.3.12.1. General considerations

The study of the contemporary movements of the Earth's crust is an essential and important problem related with Geosciences – geodesy, geology, geomorphology, geophysics, oceanology, etc. Each of these sciences participates in the research on this phenomenon with its own specific methods but the contribution of geodetic methods is especially important in this respect. Using periodically repeated instrumental observations, geodetic science provides quantitative assessments for the magnitude of movements.

The contemporary movements of the Earth's crust have two components – horizontal and vertical one. The object of the present paper will be the vertical component of the movements, the so called contemporary vertical crustal movements. The character and magnitude of these movements are studied using the method of the highly precise geometric by periodic repeated measurement of single traverses forming independent profiles or of levelling networks covering the investigated region. The measurements of the State Levelling Network have been used in the study of the vertical movements in Bulgaria.

4.3.12.2. State of the Bulgarian levelling network. Measurements and investigations

The Bulgarian State Levelling Network consists of four classes, the I and II class being performed with accuracy allowing the use of these measurements for investigating the contemporary vertical movements of the Earth's crust. So far this network has been measured in three cycles and during each of them its configuration has been subjected to certain changes depending on different factors. The periods of the three cycles of network measurements are: 1920-1930, 1953-1967 and 1974-1984. Some technical characteristics of the levelling network from the last cycle are presented below (Fig. 4.3.12.1) (Belyashki, 2005).

Closed polygons	**23**
Levelling lines	**55**
Length of levelling lines	**5630 km**
Average perimeter of polygons	**360 km**
Average length of levelling lines	**102 km**
Node benchmarks (FLB)	**33**
Levelling benchmarks	**4630**
Period for measuring the polygons	
- minimal	**1 year**
- maximal	**9 years**

- average **5 years**
Average epoch of the levelling network **1979**

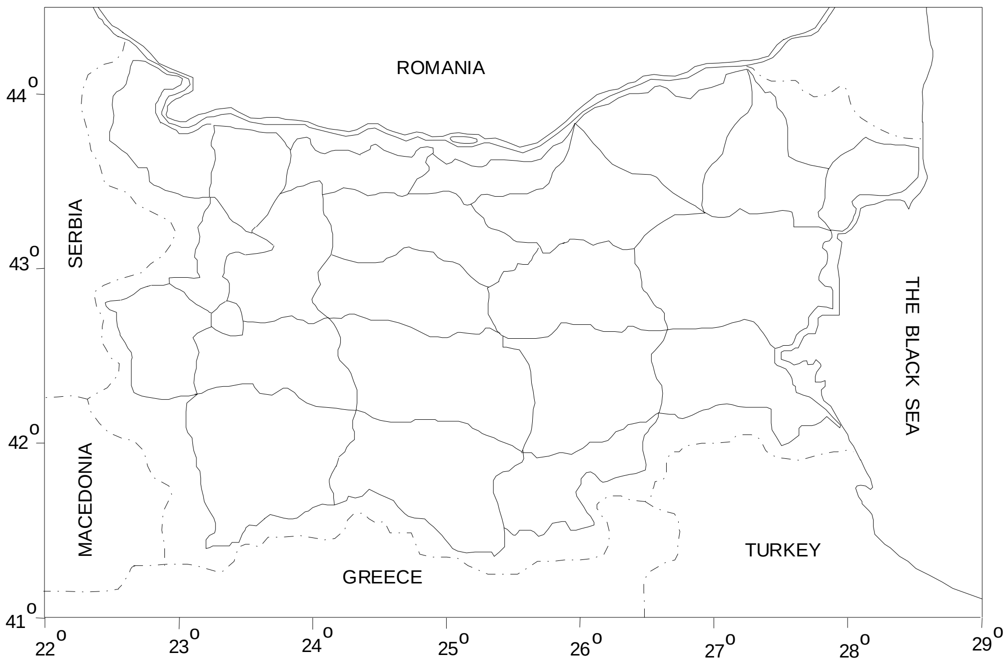

Fig. 4.3.12.1. network l order 1974-1984

The basis of the network is formed by the built in 1962-1963 about 300 underground fundamental levelling benchmarks (FLB) with special structure. The network measurement was realized using compensation levels Ni 002 ”Zeiss Jena” and three-meter long invar poles. The levelling measurements have to meet the following requirements according to (Instructions …, 1980).

- **Mean error for 1 km of levelling**

(1) $$m = \pm \frac{1}{2}\sqrt{\frac{1}{n}\sum \frac{d^2}{s}}, \quad m \leq \pm 0{,}40 \text{ mm}$$

where *d* is the height difference between the measurements in the two opposite directions of one levelling distance between two neighbouring benchmarks in mm,
***s* is the length of the levelling distance in km,**
***n* is the number of levelling distances in a levelling line.**

- **Mean random error for 1 km of levelling**

(2) $$\eta = \pm \frac{1}{2}\sqrt{\frac{\sum d^2}{L} - \frac{\sum s^2}{L^3}\left(\sum d\right)^2}, \quad \eta \leq \pm 0{,}40 \text{ mm},$$

where $L=\sum s$ **is the length of the levelling line.**

- **Mean systematic error for 1 km of levelling**

(3) $$\sigma = \frac{\sum d}{2L}, \ \sigma \leq \pm 0{,}10 \text{ mm}$$

- **Mean error after network adjustment**

(4) $$m_0 = \pm\sqrt{\frac{\sum pv^2}{q-r}}, \ m_0 \leq \pm 1 \text{ mm},$$

where *p* is the weight of the levelling line,

v **is the correction of the measured height differences obtained during the adjustment, in mm,**

q is the number of measured height differences,

r is the number of the unknown parameters.

The obtained accuracy of the levelling network is:

Mean error m = ±0,40 mm
Mean random error η = ±0,38 mm
Mean systematic error σ = 0,09 mm
Mean error of the network adjustment m_0 = ±1,21 mm.

The higher value of m_0 above the admissible one is due to the long periods of measurements on some polygons.

The levelling networks of the I and II cycle were measured using different instruments and for other instruction requirements and their mean errors *m* are about ± 0,65 ÷ ± 0,70 mm.

The levelling network of the I cycle was calculated in the Black Sea height system, epoch 1930, with an initial level determined by the mareograph in Varna. The networks of the II and III cycle, epochs 1958 and 1982, are in the Baltic height system with an initial level of the mareograph in Kronstadt. In 2003 the I class levelling network was connected with the Uniform European Levelling Network (UELN) and in this way it was included in the European Vertical Reference System (EVRS) with the initial level of the mareograph in Amsterdam (Sacher et al., 2004).

The II class levelling network is a densification of the I-st class levelling polygons. It was measured in two cycles, the last one being in the period 1982-1995. The obtained mean error according to formula (1) is ±0,57 mm, and for the first cycle it is about ±0,70 mm.

Using the results of the above described levelling network measurements, a number of studies were carried out on the contemporary vertical movements of the Earth's crust in Bulgaria. These investigations were performed both for the whole territory of the country (Kurtev et al., 1973; Totomanov, Vrablyanski, 1980; Mladenovski et al., 1987) and for single regions – the Black Sea coast (Belyashki, 1986), Northeast Bulgaria (Milev et al., 1983), the Sofia region (Totomanov et al., 1988). Special attention was paid to the investigations in the region of Krupnik (Southwest Bulgaria), where the maximum seismic activity for Bulgaria had been recorded (Milev, 1997; Milev, 2000; Dimitrov et al., 2001; Belyashki et al., 2006).

4.3.12.3. Maps of the vertical movement velocities and gradients

As a result of the research carried out on the contemporary vertical movements of the Earth's crust, several maps were composed for this geodynamic phenomenon on the territory of the country (Tsenev et al., 1961, Vrablyanski et al., 1971, Kanev, et al., 1973, Kurtev et al., 1973, Totomanov et al., 1973, Totomanov et al., 1979, Mladenovski et al., 1985). The obtained velocities differ to a various extent for the single maps. This is due to several factors – different information used for their composition, filtering of the measurements for some of them, various methods for the velocity adjustment. The accepted initial benchmark and its velocity exert the most substantial effect in this respect. For example, in (Kanev et al., 1973) this is the benchmark of the Naval barracks next to the mareograph in Varna with accepted velocity V = 0 mm/yr. In (Kurtev et al., 1973) the velocities are calculated in two variants. The initial benchmark for the first of them is the Harbor Administration building in Burgas with V = -1,3 mm/yr, calculated on the basis of mareographic data. The initial benchmark for the second one is FLB 16 in the town of Knezha, built in 1936, V = 0 mm/yr. In (Totomanov et al., 1973) and (Totomanov et al., 1979) the initial benchmark is the Burgas one with V = -1,3 mm/yr.

The last map in chronological order is the one composed by Mladenovski et al. (1985) (Fig. 4.3.12.2.) within the framework of the international projects "Contemporary Vertical Movements of the Earth's Crust in the Carpathian-Balkan Region" and "Contemporary Vertical Movements of the Earth's Crust on the Territory of Bulgaria, Hungary, DDR, Poland, Romania, the USSR (European part) and Czechoslovakia".

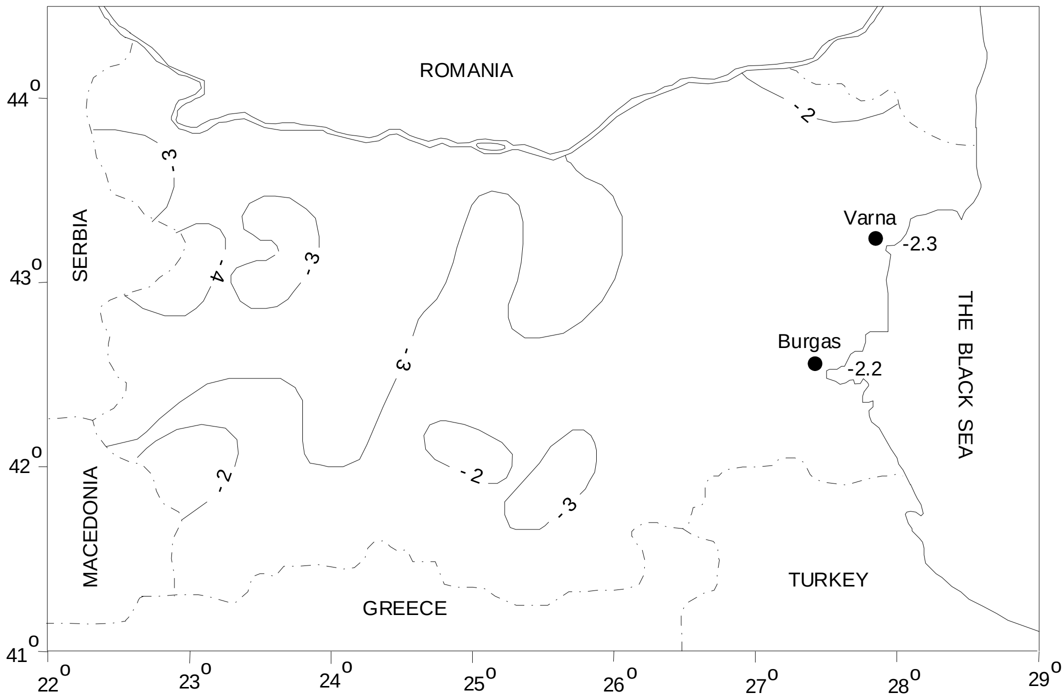

Fig. 4.3.12.2. Map of recent vertical crustal movements

- **2.3 reference point, velocity [*mm/yr*]**

– 3 velocity isolines [*mm/yr*]

The measurements of the I class levelling network (I and III cycle) were used for composing the map. The network consists of 52 levelling lines with length of 5740 km, which form 22 closed polygons. The number of the included identical benchmarks is 482 and the vertical movement velocities were calculated for them. The benchmarks belong to buildings, road facilities, and there are also 5 FLB. The minimum interval between the measurements of the I and III cycle is 19 years, the maximum one is 56 years, and the average one is 46 years. The mean errors *m* of the participating lines are ±0,71 mm for the I cycle and ±0,40 mm for the III cycle. The relative velocities were calculated for all benchmarks. These velocities were adjusted within the frame of the whole network and in this way the absolute velocities of the vertical movement were obtained. The absolute velocities of FLB 28 in Varna (V = -2,3 mm/yr) and FLB 63 in Burgas (V = -2,2 mm/yr) were used in the adjustment as initial velocities. These velocities were obtained from mareographic recordings of the Black Sea level in these two points for the period 1929-1979. The weights of the adjustment were calculated according to the formula

(5) $$p = \frac{100}{(m_I^2 + m_{III}^2)L}\left(\frac{t}{40}\right)^2,$$

where m_I and m_{III} are the mean errors of the measurements of the I and III cycle,
L is the length of the levelling line,
t is the interval between the measurements of the I and III cycle.

According to the programmes of the international projects "Map of the Velocity Gradients of the Contemporary Vertical Movements in the Carpathian-Balkan Region" and "Map of the Velocity Gradients of the Contemporary Vertical Movements on the Territory of Bulgaria, Hungary, DDR, Poland, Romania, the USSR (European part) and Czechoslovakia", maps of the velocity gradients were developed in conformity with the methodologies of the two projects (Belyashki, 1990). The initial information was the same as that in (Mladenovski et al., 1985). The velocity gradients complement the information about the vertical movements. Using the gradients it is possible to determine the active geological structures and the sizes of the blocks due to the change in the gradient sign at the places with disturbances in the Earth's crust (Belyashki, 1985; Totomanov et al., 1988).

The velocity gradient represents the change in the Earth's surface inclination between two levelling benchmarks per unit of time. The gradient sign shows the relative vertical movement of one benchmark with respect to the other, and its magnitude - the intensity of the velocity changes.
The velocity gradients were calculated using the formula

(5) $$grad\ V = \frac{V_2 - V_1}{L}\rho'' \ ['' /yr],$$

where V_1 and V_2 are the velocities of the two benchmarks,
L is the distance between them.
The velocity gradient values are between -32.10^{-3} "/yr and $+35.10^{-3}$ "/yr. The mean value of $|grad\ V| = 5{,}7.10^{-3}$ "/yr, and 83 % of $|grad\ V|$ are within the interval from 0 to 10.10^{-3} "/yr.

4.3.12.4. Interpretation of the contemporary vertical movements

As already mentioned, due to some objective factors, the different maps do not reflect in the same way the geodynamic circumstances. In (Kanev et al., 1973) positive values within the range of 0 ÷ +2 mm/yr are predominant for the vertical movement velocity, the maximum values being -3 mm/yr in the region of the town of Burgas and +4 mm/yr in the region of the Rila, Pirin and West Rhodopes Mts. In the map (Kurtev et al., 1973) with an initial benchmark in Burgas, V = -1,3 mm/yr, negative velocity values between -1 mm/yr and -2 mm/yr prevail, the maximum values to +3 mm/yr being along the northern Black Sea coast. In (Totomanov et al., 1973) the values for almost the whole country are positive (0 ÷ +2 mm/yr) with maximum values of up to +5 mm/yr in the region of the West Rhodopes Mts. The region in Southeast Bulgaria is an exception (0 ÷ -1,3 mm/yr). This map is similar to (Totomanov et al., 1979), where the velocities are from -1 mm/yr to +2 mm/yr with maximum values of up to +5 mm/yr also in the region of the West Rhodopes Mts. The mean errors m_V of the calculated velocities are between ±0,2 mm/yr and ±0,8 mm/yr. With respect to the maximum positive values this map resembles the one in (Kanev et al., 1973).

In (Mladenovski et al., 1985) the obtained velocity values are between -1,8 mm/yr and -4,7 mm/yr. They are several times higher than their mean errors (m_V = ±0,3 ÷ ±0,6 mm/yr), which is a very good parameter for the reliability of the calculated movement velocities. It is worth noting that here the values for the whole territory are with negative signs, and for the predominant part (East and Southwest Bulgaria) the values are within the range between -2 mm/yr and -3 mm/yr. The negative character of the values in this map is in contradiction of the conclusion made in (Totomanov, Vrablyanski, 1980) that predominant rising is typical for the territory of Bulgaria. However, it has to be taken into account that for all the other maps the initial information was based on information from the I and II cycle of the levelling observations, while this is the first map using the measurements from the III cycle. The values for the initial benchmarks are also significantly different from these, used for all the other maps. If the hypothesis of zero velocity of FLB 28 is assumed (Belyashki et al., 2006), then the velocities will be about 0 ÷ -1 mm/yr. On the ground of these considerations it could be presumed that sinking had occurred between the II and III cycle, which is an indication for cyclic character of the movements.

The maps of the gradients show that the values above 10.10^{-3} "/yr are in the northwest 1/3 part of the territory of the country, which is agreement with the map of the vertical movements (Mladenovski et al., 1985), where the maximum velocity values are observed. To check the dependence between the velocity gradients and the fault disturbances, the correlation between the gradient sign changes and the fault lines location was analyzed. It was established that correlation exists for 70 % of all the 30 levelling lines, for which gradient sign changes are recorded.

4.3.12.5. Conclusions

The territory of Bulgaria is situated in a seismically active region, characterized by a complex tectonic picture. For this reason contemporary geodynamics has to be constantly in the focus of research from the viewpoint of all sciences concerned in this problem. The review on the studies of the contemporary vertical movements in Bulgaria using geodetic methods shoes that significant amount of work has been done and a considerable number of maps have been composed for these movements. However, the information reflected in them is not unambiguous due to the above mentioned reasons.

This shows that the approach to both the interpretation of this geodynamic phenomenon in the available maps and the development of new ones should be very careful.

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