4.8.4. RECENT VERTICAL CRUSTAL MOVEMENTS IN REPUBLIC OF SERBIA FROM LEVELLING DATA

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4.8.4.1. Introduction

The object of this paper is to present vertical velocity field for the territory of Republic of Serbia (Fig. 4.8.4.1.). So far, there were only two local investigations concerning this area. The first was based on historical levelling data from epochs 1905-1932 and 1950-1960, covering the whole territory of former Yugoslavia, but the interpolation of vertical velocities was significantly influenced by geological and morphological information (Jovanovic, 1971). The second had used an incomplete levelling data from epoch 1970-1973, with vertical velocities derived only for the part of Republic of Serbia, Republic of Monte Negro and Republic of Macedonia (Blagojevic, 1993).

Fig. 4.8.4.1. Area under investigation

The current investigation became feasible because levelling data from epoch 1950-1960 were completed in the meantime, thus giving the opportunity for derivation of vertical

crustal velocities for the whole territory of Republic of Serbia. Simple methodology of construction of kinematical network was used. The approach with velocities was driven by the fact that only two epochs of levelling were at our disposal. Currently, the levelling data from epoch 2005 are under consideration, and they will certainly be able to confirm the validity of results and offer the possibility for calculation of accelerations. Since this is the first attempt for the area under investigation, no interpretation of velocity field is given, apart for some very general remarks.

4.8.4.2. Data

Precise levelling data from epochs 1950-1960 (NVT1) and 1970-1973 (NVT2) represent the basic pieces of information on vertical displacements or velocities on the territory of Republic of Serbia, because NVT2 network was intentionally identical to NVT1 network wherever it was possible. That is to say, there is nearly 1500 levelling segments which are common to both networks (Fig. 4.8.4.2.). In order to include them in calculation of vertical velocities, the quality of NVT1 and NVT2 in terms of accuracy has to be assessed.

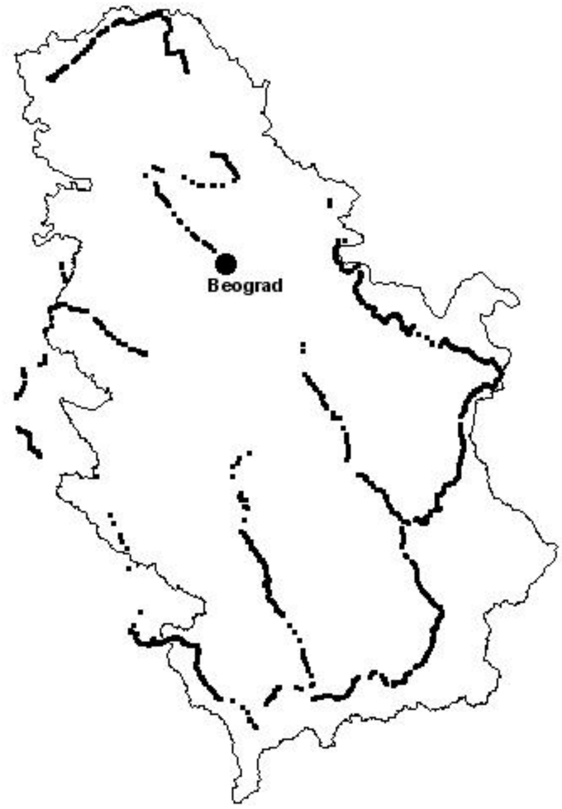

Fig. 4.8.4.2. Relevelling data

The levelling accuracy per kilometer of both networks was estimated using double run (forth and back) levelling differences ρ for levelling segments (average distance *R* of 1 km), double run levelling differences λ for levelling lines (average distance *L* of 50 km), and misclosures φ for levelling loops (average perimeter *F* of 400 km), *n* being the number of data used:

$$\hat{\sigma}_{0\rho} = \sqrt{\frac{1}{4n_\rho}\left[\frac{\rho^2}{R}\right]}, \quad \hat{\sigma}_{0\lambda} = \sqrt{\frac{1}{4n_\lambda}\left[\frac{\lambda^2}{L}\right]}, \quad \hat{\sigma}_{0\varphi} = \sqrt{\frac{1}{n_\varphi}\left[\frac{\varphi^2}{F}\right]}$$

Results are given in Table 4.8.4.1. Accuracy obtained should be considered reliable because of great amount of data. Subsequent adjustment gave almost the same results as accuracy based on misclosures. It can be seen that data contain some systematic components which reveal themselves in longer levelling lines. In spite of this, statistical tests have proved the hypothesis that levelling data are nearly normally distributed for both networks. It is also obvious that NVT2 network has greater accuracy because of more rigorous measurement and processing method.

Table 4.8.4.1. Statistics of levelling data.

Epoch	$\hat{\sigma}_{0\rho}$ $[mm/\sqrt{km}]$	n_ρ	$\hat{\sigma}_{0\lambda}$ $[mm/\sqrt{km}]$	n_λ	$\hat{\sigma}_{0\varphi}$ $[mm/\sqrt{km}]$	n_φ
NVT1 (1950-1960)	**0.65**	**1734**	**1.29**	**38**	**1.57**	**15**
NVT2 (1970-1973)	**0.45**	**973**	**0.83**	**72**	**0.68**	**34**

4.8.4.3. Methodology

There is a multitude of methods for determination and monitoring of recent vertical crustal movements (e.g. ICRCM, 1984, Pelzer, 1986, Zippelt, 1988). The approach adopted here is fairly simple, and essentially based on construction of kinematical network, i.e. network of relative vertical velocities. Such network was formed by approximately 100-150 km long lines consisting of relevelled segments.

First, the relative vertical velocities were calculated for every relevelled segment along the line:

(1) $$\Delta b = \frac{\Delta h(t_2) - \Delta h(t_1)}{t_2 - t_1},$$

and then the cumulative relative vertical velocities were derived for every common benchmark on the line according to:

(2) $$b_k = \sum_{i=1}^{k} \Delta b_i \,.$$

Fig. 4.8.4.3. depicts the typical kinematical line. Cumulative vertical velocities were processed by piecewise linear regression in order to find benchmarks i.e. locations with significant profile slope changes. These benchmarks were adopted as characteristic or representative, and relative vertical velocities between them were taken into consideration in subsequent procedures. In such a way, many local irregularities and instabilities were filtered out, in order to get reasonably smooth vertical velocity field.

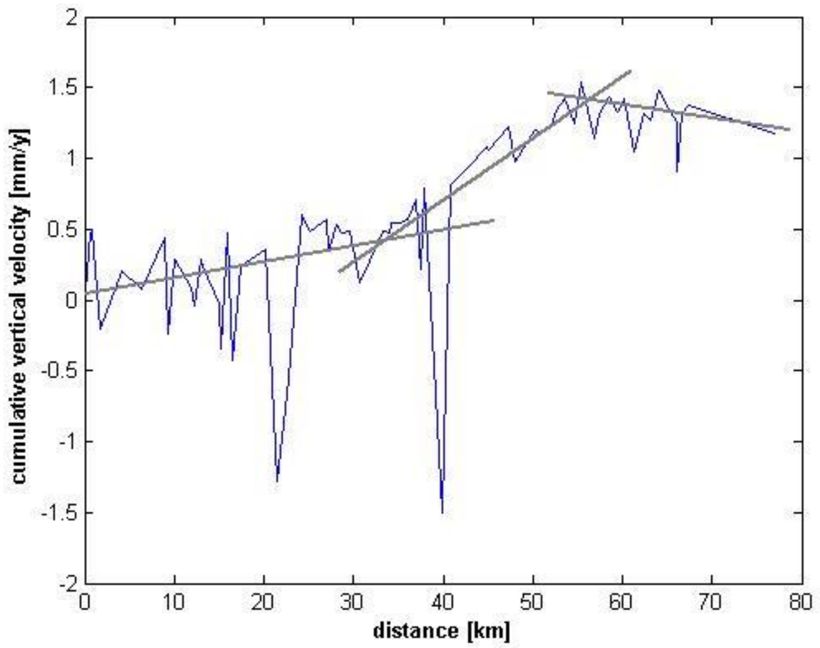

Fig. 4.8.4.3. Typical cumulative vertical velocity profile

For determination of "absolute" vertical velocities least squares estimation method was employed. Functional and stochastical models were formulated as follows:

(3) $$\mathbf{v} = \mathbf{A}\mathbf{x} - \mathbf{l}, \quad \mathbf{C}_{\mathbf{l}},$$

where v denotes the vector of residuals, A is a design matrix, x is vector of unknown absolute vertical velocities that have to be estimated for every representative benchmark, and l is vector of relative vertical velocities between representative benchmarks. Matrix C reflects stochastical features of relative vertical velocities, with diagonal elements representing their dispersions which depend on accuracies of two levelling campaigns, time elapsed, and distance *D* between representative benchmarks:

(4) $$\sigma_{\Delta b}^2 = \frac{(\sigma_{0,1}^2 + \sigma_{0,2}^2)D}{(t_2 - t_1)^2}.$$

Least squares solution for unknown vector x reads:

(5) $$\mathbf{x} = (\mathbf{A}^{\mathrm{T}}\mathbf{C}_{\mathbf{l}}^{-1}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{C}_{\mathbf{l}}^{-1}\mathbf{l},$$

with estimated accuracy of vertical velocities given by diagonal elements of:

(6) $$\mathbf{C}_{\mathbf{x}} = (\mathbf{A}^{\mathrm{T}}\mathbf{C}_{\mathbf{l}}^{-1}\mathbf{A})^{-1}.$$

For estimation of vertical velocities of 37 representative benchmarks, totally 45 relative vertical velocities was used. In order to avoid datum deficiency, average vertical velocity for all benchmarks was arbitrarily set to zero. Model fitting was confirmed by statistical test.

4.8.4.4. Results

To get the first insight into vertical velocity surface represented by vertical velocities of 37 representative benchmarks, they were interpolated in the form of regular grid with grid spacing of approximately 30 km. Ordinary Kriging interpolation procedure was used for that task, because it was found as adequate enough.

Because all velocities refer to overall average which was initially and arbitrarily set to zero, they don't have much importance in an absolute sense. It is the shape of vertical velocity surface that matters. In the first step, its detailed features were found removing the quadratic trend of the form:

(7) $$b_{TREND} = a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2,$$

with *x* and *y* being rectangular coordinates of grid nodes, and *a* denoting polynomial coefficients which were estimated using least squares method again. Both absolute and residual vertical velocities are shown in Fig. 4.8.4.4.

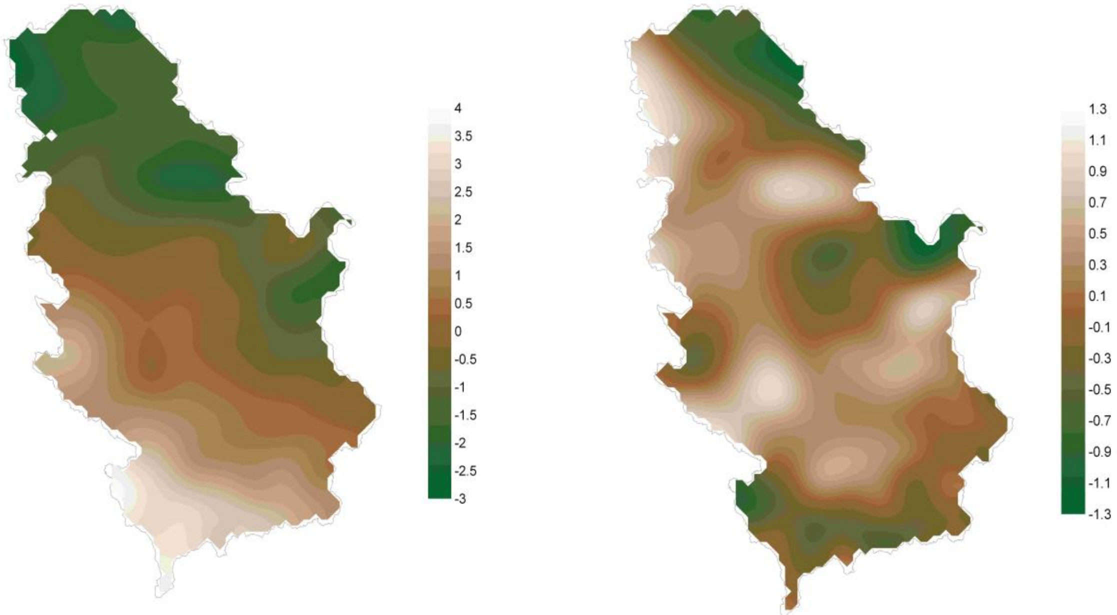

Fig. 4.8.4.4. Absolute (left) and residual (right) vertical velocities. Units: mm/y

In the second step, grid of residual vertical velocities was transformed into grid of horizontal gradients. To make the transformation, gradients along both coordinate axes were computed in every grid node according to:

(8) $$grad_x = \frac{\Delta b_x}{\Delta x}, \quad grad_y = \frac{\Delta b_y}{\Delta y},$$

where Δb denotes difference between residual velocities in adjacent grid nodes along *x* and *y* coordinate direction, while Δx and Δy represent grid spacing in the same directions. Resulting maximum horizontal gradient surface, which is one of the most relevant quantities for geophysical interpretation, is shown in Fig. 4.8.4.5.

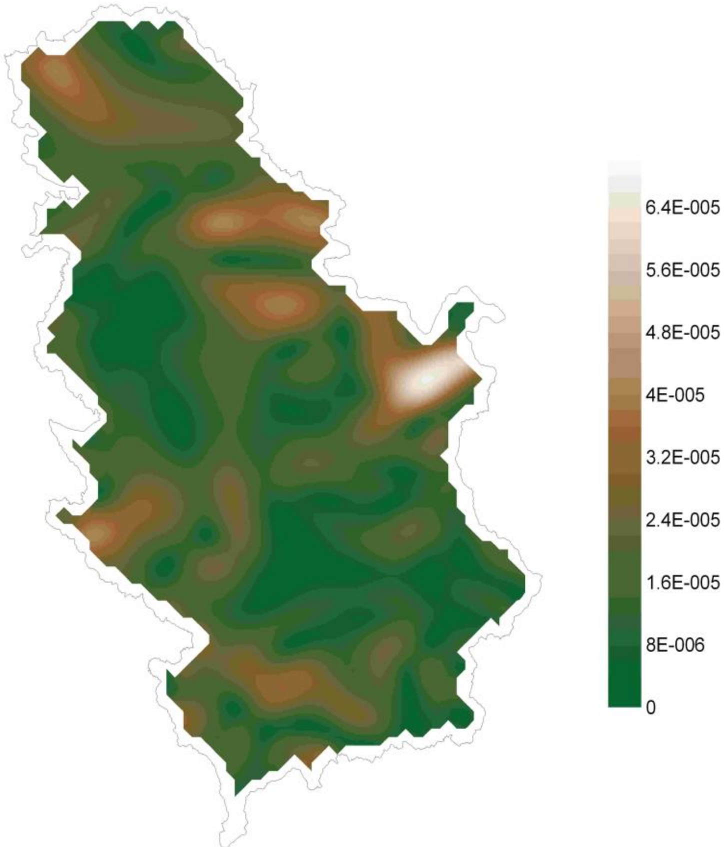

Fig. 4.8.4.5. Horizontal gradients. Units: ***mm/y/m***

Although the detailed interpretation of vertical velocities and horizontal gradients is beyond the scope of this work, some remarks concerning correlation with heights and Bouguer anomalies still can be made (Fig. 4.8.4.6.).

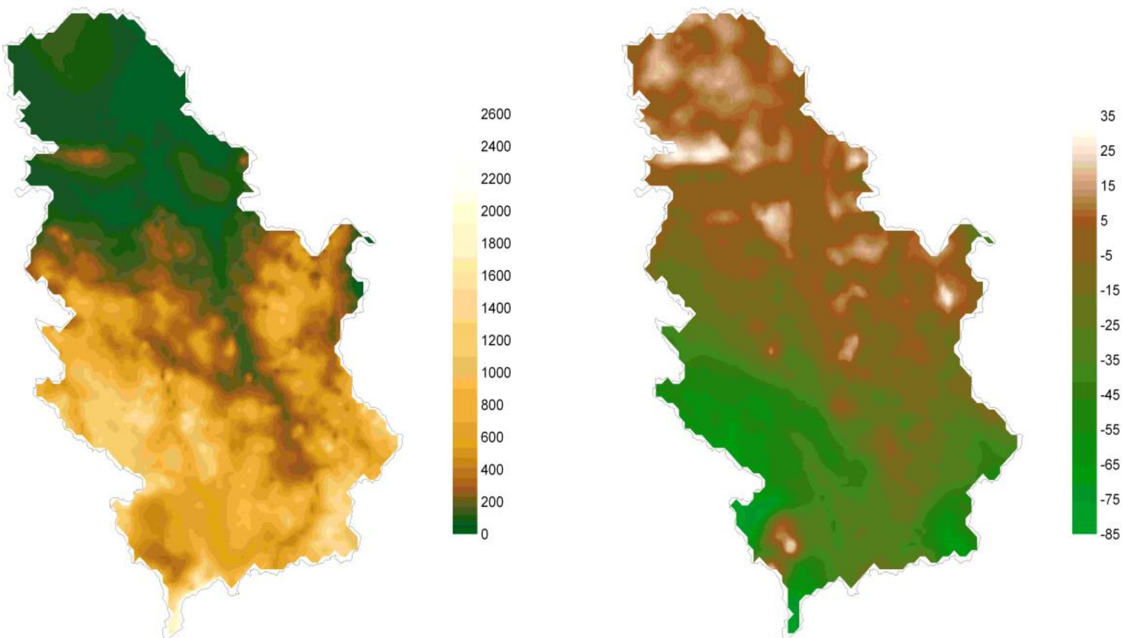

Fig. 4.8.4.6. Heights (left) and Bouguer anomalies (right). Units: m and mGal

First of all, it is evident that surface of absolute vertical velocities closely resembles the surface of terrain heights. Relative sinking and uplift match the lowland and mountainous areas respectively. This is sensible result under assumption on ongoing orogenic process and absence of height dependant systematic levelling errors (like e.g. rod scale error). As a consequence, prominent features on the map of residual vertical velocities mainly reflect locations of big river valleys.

On the other hand, inspection of horizontal gradient surface reveals several areas characterized with values greater than 0.5 mm/y/km. Beside being situated in some of the well known seismic zones, and areas of big open pit mines with decades of exploitation, it is also evident that high values of horizontal gradients can be mainly identified as areas with positive anomalies on the Bouguer map.

4.8.4.5. Conclusions

Recent vertical crustal movements in Republic of Serbia were derived with levelling data from two epochs spanning approximately 15-20 years. These results will hopefully contribute to understanding the complex geodynamical situation on Balkan Peninsula, but they have to be considered as entirely preliminary. Further investigation on the territory of Republic of Serbia is necessary, and it will be focused on inclusion of new levelling data from 2005, careful screening of all available data, integration into results of neighbor countries, and most importantly the correlation with other important geophysical parameters like Mohorovicic's depth, heat flow, geological maps, neotectonic and seismic situation etc.

4.8.4.6. References

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