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INQUIRY INTO VERTICAL MOVEMENTS OF THE EARTH'S CRUST BASED ON SAMPLES FROM EASTERN LITHUANIA

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Abstract. In the research of vertical movements of the earth's crust, examination of statistical correlations between the measured vertical movements of the earth's crust and territorial geo-indexes is accomplished with the help of mathematical statistical analysis. Availability of the precise repeated levelling measuring data coupled with the preferred research methodology offer a chance to determine and predict recent vertical movements of the earth's crust. For the inquiry into recent vertical movements of the earth's crust, a Lithuanian class I vertical network levelling polygon was used. Drawing on measurements made in the polygon, vertical velocities of earth's crust movements were calculated along the following levelling lines. For determining the relations shared by vertical movements of the earth's crust and territorial geo-parameters, the following territory-defining parameters are accepted. Examination of the special qualities of relations shared by vertical movements of the earth's crust and geo-parameters in the territory under research contributed to the computation of correlation matrices. Regression models are worked out taking into consideration only particular territory-defining geo-parameters, i.e. only those parameters which exhibit the following correlation coefficient value of the vertical earth's crust movement velocity: $r \geq 0.50$. A forecast of the velocities pertaining to vertical movements of the earth's crust in the territory under examination was made with the application of regression models. Further in the process of this research, a map was compiled specifying the velocities of vertical movements of the earth's crust in the territory. In the eastern part of this territory, the earth's crust rises at a rate of up to 3 mm/year; while in the western part of it, the earth crust lowers at a rate of up to –1.5 mm/year. In order to pinpoint territories characterised by temperate and regular rising/lowering or intensive rising/lowering, a map of horizontal gradients of recent vertical earth crust movements in the territory enclosed by levelling polygon was compiled.

Keywords: geodetic levelling line, recent vertical movements of the earth's crust, correlation analysis, regression analysis, horizontal gradients of vertical movements of the earth's crust, geo-indexes of the territory, repeated geodetic measurements.

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Introduction

Not only earthquakes account for movements of the earth's crust; slow periodic rising/lowering of the earth's crust is also observed (Schwartz 2007). In addition to geologic methods, the geodetic ones can be used for the research of recent vertical movements of the earth's crust. Data provided by precise repeated geodetic measuring can offer a picture of geodynamic processes taking place within the entire territory of a country. However, measurements taken along the levelling lines may be affected by the influences of non-tectonic origin, such as seasonal fluctuations of the groundwater level (Demoulin 2004) or the factors of anthropogenic origin (Zakarevičius 1994; Tosi *et al.* 2007). When applying various research methodologies, it is vital to distinguish between effects produced by the factors of

either tectonic or non-tectonic origin on the measurements. To gain a better insight into recent vertical movements of the earth's crust obtained by geodetic measuring or for pinpointing more precisely the component of tectonic origin, different methodologies are applied. Besides, the geologic structure of a locality and fractures found in it are taken into account. This not only allows determining the developmental tendencies pertaining to the earth's crust but also settling a number of other issues related to recent tectonic movements and seismic tectonics (Zakarevičius 1994, 2003; Fukahata *et al.* 1996; Bonaccorso, Mattia 2000; Mrlina 2000; Li *et al.* 2001; Bonaccorso 2002; Battaglia *et al.* 2003a, 2003b; Howle *et al.* 2003; Langbein 2003; Nielsen, Bayer 2003; Demoulin 2004; Lanari *et al.* 2004; Amoruso *et al.* 2005; Behncke *et al.* 2006; Gottsman *et al.* 2006; Newman *et al.* 2006; Vestol 2006; Tosi *et al.* 2007).

Availability of the precise repeated levelling measuring data coupled with the preferred research methodology offer a chance to determine and predict recent vertical movements of the earth's crust. They may be represented graphically by maps of recent vertical movements of the earth's crust. These maps are compiled following the estimation of digital values pertaining to recent vertical movements of the earth's crust.

By means of mathematical statistics analysis, the present study purposes to inquire into recent vertical movements of the earth's crust determined with the help of measuring; to predict vertical movements of the earth's crust in a selected territory and to estimate their intensity rate by using territorial geo-parameters (in this study, geo-parameters mean the geologic characteristics observed within a definite territory).

1. Methodology of the research

Vertical movements of the earth's crust are determined by geodetic methods, drawing on the findings provided by repeated measuring of geodetic levelling. Velocities of vertical movements of the earth's crust are estimated by the following equation:

$$v_{ij} = \frac{h''_{ij} - h'_{ij}}{\Delta t}, \qquad (1)$$

where h'_{ij}, h''_{ij} are the altitude differences between i and j geodetic marks recorded during the first and second measuring, Δt is the period of time dividing repeated levelling.

Basing on the findings of measuring taken along the levelling line, vertical velocities of movements of the earth's crust with respect to the initial point of the line are estimated by the following equation:

$$v_k = \sum_{i=1}^{k} v_{i-1,i}, \qquad (2)$$

where $i = 0, 1,..., k$ are the numbers of geodetic points.

Movements of the earth's crust measured by geodetic methods are the parameters of the general condition of a natural system. In order to study relations shared by vertical movements of the earth's crust and geo-parameters, all-round research is carried out, including the integrated analysis of territorial geo-parameters and data provided by geodetic measuring of recent movements of the earth's crust.

Initial estimation of relations shared by measured recent vertical movements of the earth's crust and territorial geo-parameters is performed by calculating the correlation coefficients for the values of measured vertical movements of the earth's crust and for the digital values of territory-defining geo-parameters (Rodionov 1981; Draper, Smith 1998; Spiegel, Stephens 2007):

$$r_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii} \cdot \sigma_{jj}}}, \qquad (3)$$

where σ_{ij} are the elements of a covariant matrix; σ_{ii}, σ_{jj} are the dispersions of random values.

Mathematical statistical interactions involving all parameters are defined by a matrix of correlation coefficients (Krumbein, Graybill 1965; Spiegel, Stephens 2007).

Identified with vertical shifts of the earth's crust and shift velocities, the measured vertical shifts of geodetic marks and their respective velocities represent the algebraic sum of movements originating from non-tectonic sources, i.e. movements accounted for by various natural or anthropogenic factors. In order to eliminate local anomalies triggered by accidental causes, to determine the regular trend and to verify its adequacy for the measuring findings, mathematical statistical methods are applied. Well suited for the study of the regular character of earth's crust movements along the levelling lines, regression analysis is one of such methods. A forecast model may be expressed as follows (Draper, Smith 1998; Spiegel, Stephens 2007):

$$V = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_m X_m + \varepsilon, \qquad (4)$$

where $X_1, ..., X_m$ are the values of territory-defining geo-parameters.

The regression model's conformance to the findings obtained by measuring is verified by applying the following regression suitability rates: determination coefficient R^2 and Fisher statistics (Draper, Smith 1998; Spiegel, Stephens 2007).

F statistics are calculated for the estimation of the created regression model's adequacy for the measured velocities of vertical movements of the earth's crust along the route under examination.

$$F = \frac{(\hat{\beta}X^T - n\bar{v}^2)(n-m-2)}{(X^TX - \hat{\beta}X^TV)(m-1)}, \tag{5}$$

where $\bar{v}$ is the mean value of the dependent variable on the line under examination, n is the number of geodetic marks, m is the power of a polynomial.

F statistics have the $k_1 = m-1$ and $k_2 = n-m-2$ degrees of freedom. If $F > F_{q(k_1,k_2)}$, then it is possible to argue, with a probability of $p = 1-q$, that values obtained by using the regression model are adequate for the values of measured vertical movements of the earth's crust, i.e. the trend of movements of the earth's crust described by the regression model is adequate for the actual physical process determined by measuring. If $F < F_{q(k_1,k_2)}$, then it is possible to state, with a probability of $p = 1-q$, that the regression model is out of conformance with the actual movement model, i.e. it fails to reflect adequately the on-going actual movements of the earth's crust; consequently, it is not applicable.

The greater the proximity of the determination coefficient to one and the greater the lower limit of its reliability interval, the greater is the efficaciousness of the regressive model. The lower limit of the determination coefficient is estimated by the following equation (Draper, Smith 1998; Spiegel, Stephens 2007):

$$R_{\min}^2 = R^2(m) - 2\sqrt{\frac{2m(n-m-1)}{(n-1)(n^2-1)}}(1 - R^2(m)). \tag{6}$$

Derivatives of these movements are vitally important for the study of recent movements of the earth's crust. The most important of them is the gradient characterising the velocity of earth's crust deformations.

Possessing only a graphic image of the field of recent vertical movements of the earth's crust (a map of the velocities of vertical movements of the earth's crust) or the digital values of these movements at relevant points, the values of the horizontal gradients of movement velocities can be found by digital differentiation methods (Ulomov 2004). Assuming that the changes of vertical movements of the earth's crust between iso-lines V_i and V_{i+1} and the distance between them $D_{i,i+1}$ has a linear character, the gradient's digital values are calculated by the following equation:

$$|grad V| = \frac{(V_{i+1} - V_i)}{D_{i,i+1}}. \tag{7}$$

2. Results

For the inquiry into recent vertical movements of the earth's crust, a Lithuanian class I vertical network 4th levelling polygon (as shown in Fig. 1) was selected.
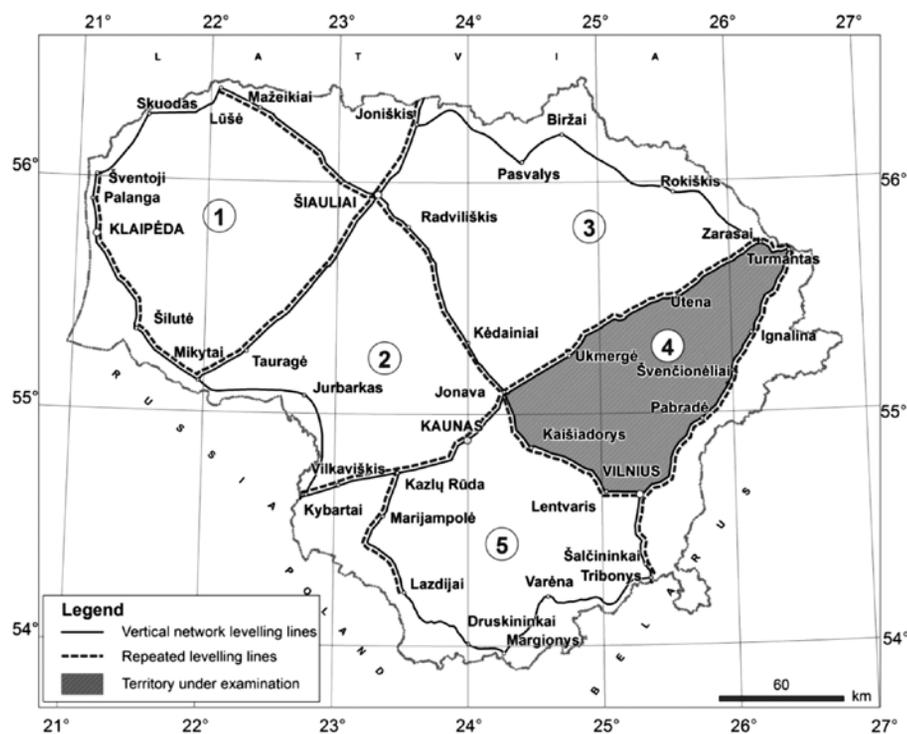

Fig. 1. Accuracy class I network created for the territory of Lithuania over 1998–2006 (with polygons marked on it)

The levelling polygon is composed of the follo-wing levelling lines: Jonava–Zarasai–Turmantas, Tur-mantas–Vilnius, Vilnius–Jonava. They were measured in different years by different enterprises, from 1934 to 2006. A period between the last two repeated levellings was chosen for the research. Characteristics of the le-vellings of this polygon are given in Table 1.

Drawing on data collected by measurements con-ducted in the polygon, vertical velocities of earth's crust movements were calculated along the following levelling lines in the following periods:
– Vilnius–Jonava, 1970/71–1998;
– Jonava–Zarasai–Turmantas, 1980–2005;
– Turmantas–Vilnius, 1985/87–2005/06.

For determining the relations shared by vertical movements of the earth's crust and territorial geo-pa-rameters, the following territory-defining parameters are accepted:
x_1 – gravitational field;
x_2 – magnetic field;
x_3 – current relief of the earth's crust;
x_4 – crystalline basement relief;
x_5 – pre-Quaternary (main layers) relief;
x_6 – Quaternary cover thickness;
x_7 – sedimentary cover thickness;
x_8 – pre-Quaternary (main layers) cover thick-ness.

Values of the geo-parameters were determined on the grounds of benchmark co-ordinates from the digi-tal database.

Availability of data on vertical movements (they are identified with movements of the earth's crust) me-asured along repeated levelling lines and of the digital values of geo-parameters enables the application of a mathematical statistical analysis. Examination of the special qualities of relations shared by vertical move-ments of the earth's crust and geo-parameters in the territory under research contributed to the computa-tion of correlation matrices along the following lines: Vilnius–Jonava, Jonava–Zarasai–Turmantas, Turman-tas–Vilnius, and by bringing these lines into a single unit, i.e. for one common polygon Vilnius–Jonava–Za-rasai–Turmantas–Vilnius.

Coefficients of correlation between measured ve-locities of vertical movements of the earth's crust and territorial geo-parameters are provided in Table 2.

Findings provided in Table 2 indicate that not all correlation dependencies are sufficiently strong. Obviously, the strongest correlative relationships between vertical movements of the earth's crust mo-vements and all geo-parameters, with the exception of

Table 1. Characteristics of the levelling lines

	Levelling line		
	Vilnius–Jonava	Jonava–Zarasai–Turmantas	Turmantas–Vilnius
Period, years	1970/71–1998	1980–2005	1985/87–2005/06
Measuring duration, years	27/28	25	19/21
Line length, km	103	156	164
Number of repeatedly le-velled geodetic marks	14	26	26
Accuracy, mm/km	0.36–0.53	0.38–0.62	0.68–0.69

Table 2. Findings of the correlation analysis

$r(vx_1)$	$r(vx_2)$	$r(vx_3)$	$r(vx_4)$	$r(vx_5)$	$r(vx_6)$	$r(vx_7)$	$r(vx_8)$
Line / Polygon							
Vilnius–Jonava							
0.25	0.07	0.89	0.88	0.77	0.64	–0.85	–0.85
Jonava–Zarasai–Turmantas							
0.31	–0.11	0.89	0.12	0.80	0.62	0.44	0.32
Turmantas–Vilnius							
–0.86	–0.31	0.69	–0.94	0.22	0.45	0.93	0.95
Vilnius–Jonava–Zarasai–Turmantas–Vilnius							
–0.69	0.02	0.29	–0.57	0.45	–0.03	0.70	0.67

gravitational field and magnetic field $R \leq 0.25$, exist along the *Vilnius–Jonava* line. The *Jonava–Zarasai–Turmantas* line demonstrates the strongest correlative relationships with the current earth's crust relief, pre-Quaternary (main layers) relief, and Quaternary cover thickness $0.62 \leq R \leq 0.89$. Along the *Turmantas–Vilnius* line, vertical movements of the earth's crust exhibit the strongest correlative relationships with the gravitational field, the current earth's crust relief, crystalline basement relief, sedimentary cover thickness and pre-Quaternary (main layers) cover thickness $-0.94 \leq R \leq 0.95$. When all these lines are brought together to form a closed polygon, the strongest correlative relations are obser-ved with the gravitational field, crystalline basement relief, pre-Quaternary (main layers) relief, sedimentary cover thickness and pre-Quaternary (main layers) co-ver thickness $-0.57 \leq R \leq 0.70$.

Moreover, findings provided in Table 2 show that coefficients of correlation with certain identical geo-parameters are significant along all lines; however, along some particular lines they are not significant.

This can be accounted for by the specific qualities of the territory's geological structure.

The following conclusions emerge from the findings of this research: the structure and strength of relations shared by measured vertical movements of the earth's crust and territorial geo-parameters is related to the territorial peculiarities. Along different lines, the coefficients of vertical movements' correlation with the same parameters are different. Along separate lines, the values of correlative dependencies are stronger compared to the values characterising the polygon enclosed by the lines. It is possible to conclude that the working out of regression models demands taking into account the non-homogeneous character of the geologic structure of the territory. From the territorial point of view, the geologic structure of Lithuania is heterogeneous. Thus, it is not possible to interpret geodetic measurements adequately unless parameters characteristic to a particular region and connected with the tectonic development of the territory are taken into consideration. Also, it is possible to argue that recent movements of the earth's crust taking place in the north-eastern part of Lithuania represent a natural continuation of the development of geologic processes. This means that there is a realistic chance to forecast basic features of the on-going tectonic processes and to characterise the current tectonic background basing upon the geologic and geophysical parameters of the territory.

A regression model can be applied for working out a tectonic background forecast for a particular territory. In this model, territorial geo-parameters serve as causal variables. Having vertical movements computed on the grounds of the repeated levelling line measuring data (movements are identified with movements of the earth's crust) and the digital values of territorial geo-parameters, is possible to produce regression models. Regression models are worked out taking into consideration only particular territory-defining geo-parameters, i.e. only those parameters which exhibit the following correlation coefficient value of the vertical earth's crust movement velocity: $r \geq 50$. In order to estimate the adequacy of regression models, determination coefficient $R^2\%$, statistics F and $F_{q(k_1, k_2)}$, where $q = 0.05$ was computed.

Rates of the regression models for separate levelling lines and the polygon enclosed by these lines as well as the rates of models' adequacy to the findings of measuring are given in Table 3.

Data from Table 3 allow making a conclusion that uneven distribution of geo-parameters along separate levelling lines substantiate the assumption that relations shared by geo-parameters and movements of the earth's crust are not homogeneous all over the territory. Estimation of regression models' adequacy to the findings provided by measuring in *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* levelling polygon shows that estimation results are somewhat poorer compared to the ones supplied by separate lines. In all cases, the determination rate is higher than 76%.

Since regressive models of vertical movements of the earth's crust are adequate to the findings provided by measuring, the models can be applied for the forecasting of movements of the earth's crust not only along repeated levelling lines but also in polygons enclosed by the repeated levelling lines, i.e. in areas where geodetic measurements are missing. Such methodology allows avoiding subjective estimation of geo-parameters when a map of vertical movements of the

Table 3. Results of the regression analysis

| Pos. No	Regression models	$R^2,\%$	F	$F_{q(k_1,k_2)}$ $q=0,05$
	Vilnius–Jonava			
1	$V = 2.914 - 7.705 \cdot 10^{-2} \cdot x_3 + 10.016 \cdot 10^{-2} \cdot x_4 - 3.148 \cdot 10^{-2} \cdot x_5 + 3.297 \cdot 10^{-2} \cdot x_6 + 3.846 \cdot 10^{-2} \cdot x_7 + 5.757 \cdot 10^{-2} \cdot x_8$	94.84	21.46	3.87
	Jonava–Zarasai–Turmantas			
2	$V = -1.499 + 7.895 \cdot 10^{-2} \cdot x_3 - 4.980 \cdot 10^{-2} \cdot x_5 - 4.709 \cdot 10^{-2} \cdot x_6$	80.27	29.84	3.05
	Turmantas–Vilnius			
3	$V = -5.378 - 5.065 \cdot 10^{-2} \cdot x_1 - 1.436 \cdot 10^{-2} \cdot x_3 + 0.880 \cdot 10^{-2} \cdot x_4 - 3.727 \cdot 10^{-2} \cdot x_7 + 6.070 \cdot 10^{-2} \cdot x_8$	96.00	96.04	2.71
	Vilnius–Jonava–Zarasai–Turmantas–Vilnius			
4	$V = -6.562 - 3.333 \cdot 10^{-2} \cdot x_1 - 0.251 \cdot 10^{-2} \cdot x_4 + 3.405 \cdot 10^{-2} \cdot x_6 + 1.390 \cdot 10^{-2} \cdot x_7 - 0.909 \cdot 10^{-2} \cdot x_8$	76.20	39.06	2.35
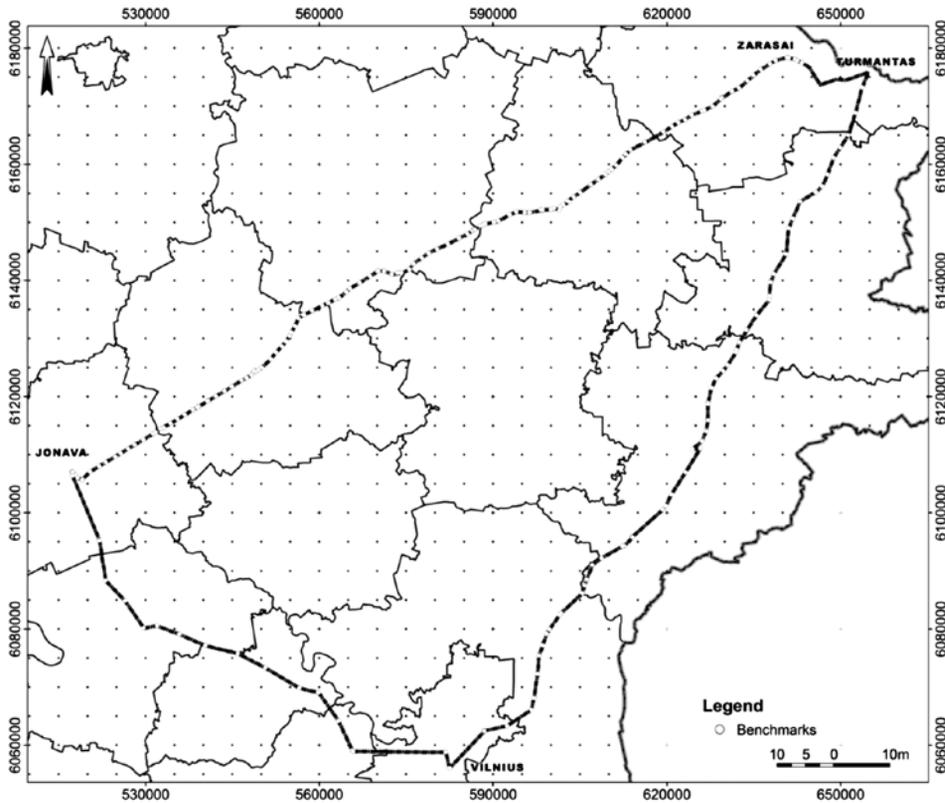
Fig. 2. In *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* polygon, points are spread using a 5´5 km pattern. At these point values of vertical movement of the earth's crust velocities were predicted

earth's crust is compiled. A forecast of the velocities of vertical movements of the earth's crust in the territory under examination was made with the application of regression models (as shown in Table 3, model (4)). In order to forecast velocities of vertical movements of the earth's crust, the values of independent variables (geo-parameters) involved in the regression equations were determined with the help of digital geologic databases at discrete points positioned at the apexes of a 5×5 km square grid (as shown in Fig. 2). In total, 469 digital values ranging from –1.84 to 3.18 mm/year were computed.

Scatter of the digital values of vertical movement velocities throughout the territory enclosed by *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* polygon is shown graphically in Fig. 3. As can be seen, dispersion of the digital values of velocities is rather even. Scatter range is 5.0231.

As can be seen from the histogram (Fig. 3), the greatest number of digital values representing vertical movements of the earth's crust fluctuates within the range from –1.3 to 2.7 mm/year. This circumstance invites a conclusion that in the territory enclosed by the polygon, the digital values of recent vertical movements of the earth's crust vary within these limits, i.e. they are the
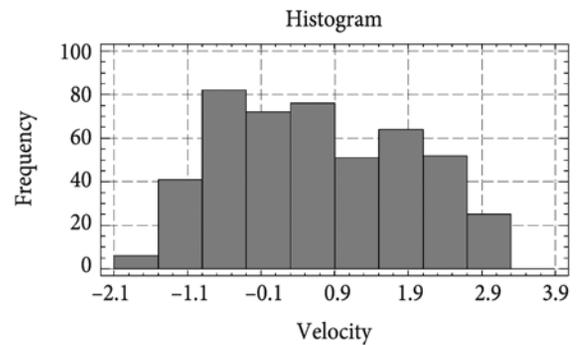

Fig. 3. Frequency of the repetition of digital values of velocities in *Jonava–Zarasai–Turmantas–Vilnius* polygon

dominant movement velocities in the territory. Mean digital value of the velocities of vertical movements of the earth's crust in the territory enclosed by the levelling polygon is 0.66 mm/year; median is 0.5128 mm/year. Dispersion of the existing movement sample is 1.54556, and the standard error is 1.2432.

Further in the process of this research, a map of the velocities of vertical movements of the earth's crust in the territory enclosed by *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* polygon was compiled (as shown in Fig. 4). As indicated in Fig. 4, in the eastern part of this territory, the earth's crust rises at a rate of up to 3 mm/year takes
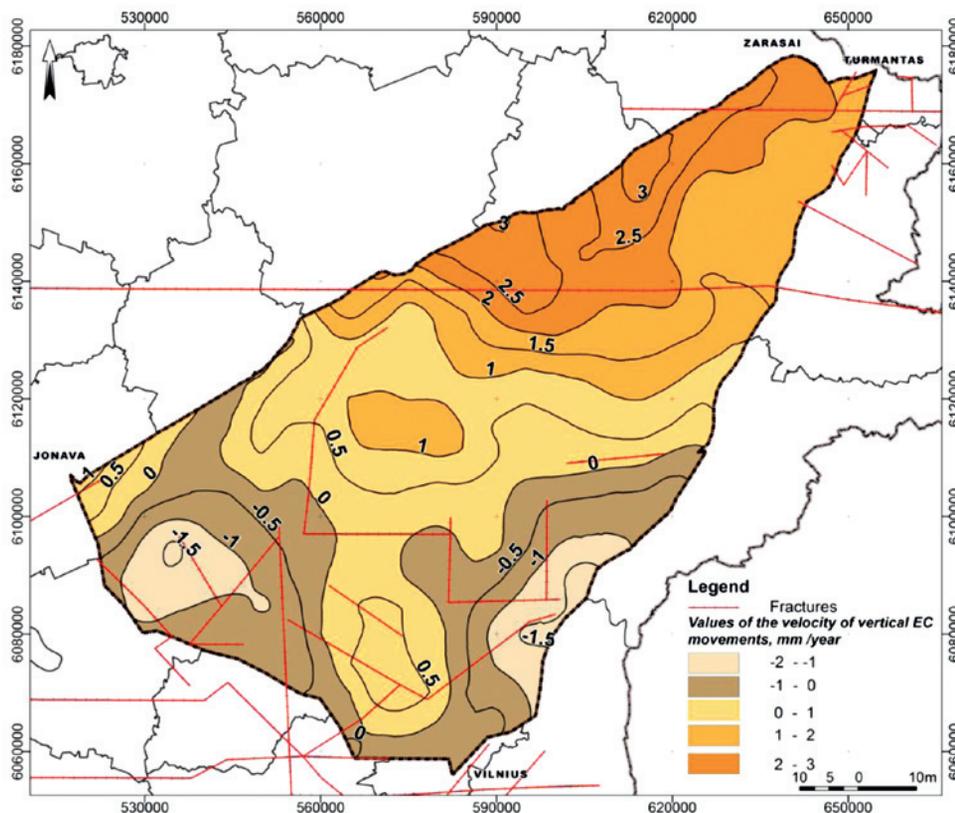
Fig. 4. Velocities (mm/year) of recent vertical movements of the earth's crust in the territory enclosed
by *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* levelling polygon

place; while in the western part of it, the Earth crust lowers at a rate of up to –1.5 mm/year.

For the purpose of examining the intensity of changes in the velocities of recent vertical movements of the Earth's crust, the digital values of their horizontal gradients were computed. Higher digital values of gradients in the territory may point to places of more intense tectonic activity, i.e. the places where the movement velocity changes are more intense, or where the movement velocity contrasts are sharper or where the earth's crust rises or lowers more abruptly.

Changes of the digital values of horizontal gradient modules in the territory enclosed by

Fig. 5. Frequency of the gradient digital value repetition in *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* polygon

Vilnius–Jonava–Zarasai–Turmantas–Vilnius polygon range from 0.00006 to 0.20 (mm/year)/km. Scatter of the digital values of gradients over the territory is represented graphically in Fig. 5. As can be seen, dispersion of digital values changes not too evenly: the greatest concentrations occur in places where digital values range from 0 to 0.09 (mm/year)/km. Scatter range is 0.20.

The histogram indicates the dominance of the gradient module digital values ranging from 0 to 0.10 (mm/year)/km in the polygon. Other largely sporadic values do not cover any significant part of the territory. Mean of the digital values of recent vertical earth's crust movement gradients is 0.06 (mm/year)/km, median is 0.05, dispersion of the sample is 0.0017, standard error is 0.04. As is indicated by the findings, the intensity of changes in the velocity of movements of the earth's crust is not high throughout the territory under examination, with the exception of some regions.

Findings of the research enable us to make the following conclusion: the range of the digital values of vertical movement gradients is quite diverse; however, the territory is dominated by rather moderate values. This allows assuming that the region contains some areas with moderate vertical movement changes. In order
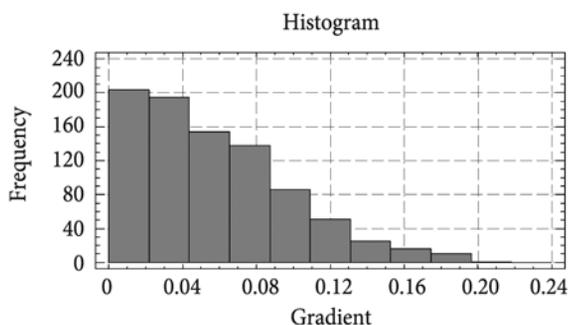
to pinpoint territories characterised by temperate and regular rising/lowering or intensive rising/lowering, a map of the horizontal gradients of recent vertical movements of the earth's crust in the territory enclosed by *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* levelling polygon was compiled (as shown in Fig. 6).

Fig. 6 shows particular regions contained within the territory under examination where the rising/lowering of territory is uniform; however, the territory also contains regions in which the changes in recent movements of the earth's crust are rather distinct. In the western part of territory under research, the earth's crust rising is replaced by the earth's crust lowering; in this particular place, fractures are observed; this evidence coincides with increased digital values of modules of recent earth's crust movement gradients observed in this place. Besides, there is a fracture crossing the middle of this territory, and from this place, intensive rising of the territory starts (as shown in Fig. 4); higher digital values of gradients are also observed here.

Discussions and conclusions

Basing on the findings provided by measuring, vertical movements of the earth's crust and correlated geodetic parameters ($-0.94 \le R \le 0.95$) were computed. Shared relationships between movements and territorial geo-parameters differ along different levelling lines; it is possible to pinpoint regional peculiarities. When making regression models for the prediction of vertical movement velocities it would be worthwhile to take into consideration the specific features of geologic structure and to apply fragment-based simulation; this implies taking separate levelling lines for examination without bringing them together to form a closed polygon.

In order to forecast vertical movements of the earth's crust, regression models adequate to the data provided by measuring were worked out. In all cases, the determination rate exceeded 76%, $F > F_q$, consequently, it is possible to argue, with a probability of $p = 1 - q \ge 0.95$, that values predicted by regression models are adequate to the vertical earth's crust movement velocity values.

A map of recent vertical earth's crust movement velocities for the territory enclosed by Vilnius–Jonava–Zarasai–Turmantas–Vilnius levelling polygon was compiled; it allows judging the qualities of movements over the past 19–28 years. The amplitude
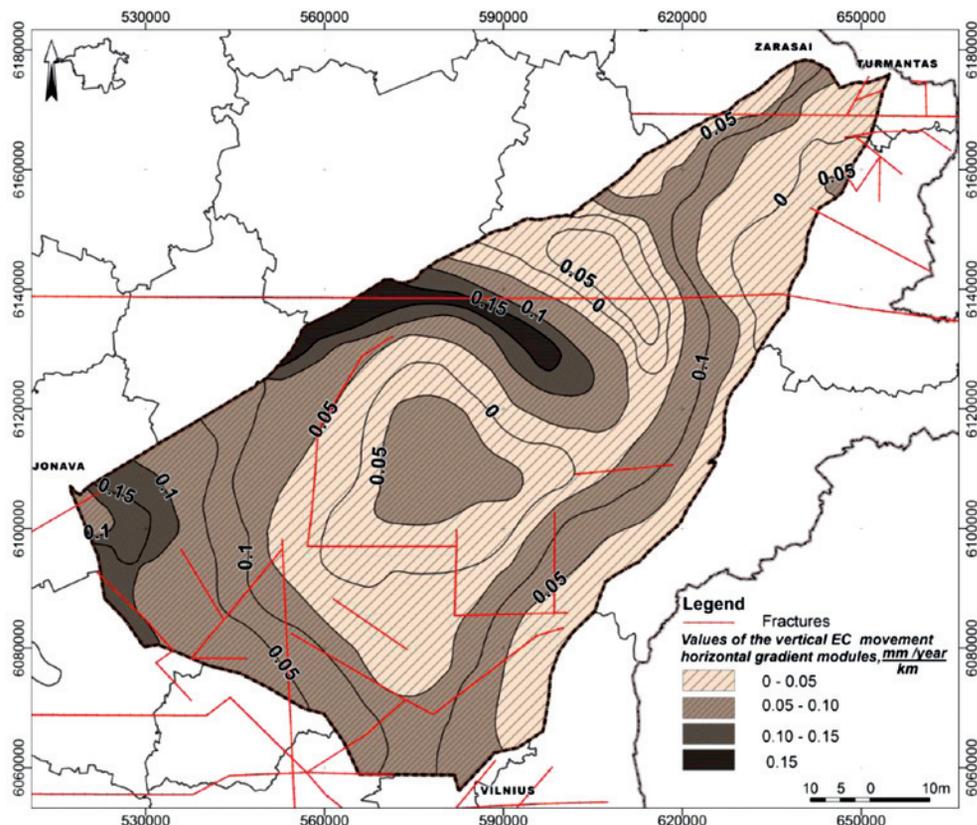

Fig. 6. Modules of horizontal gradients of recent vertical earth's crust movement velocities
in *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* levelling polygon

of movements ranges from –1.3 to 2.7 mm/year, the mean value in the territory enclosed by the levelling polygon amounts to 0.66 mm/year. In the eastern part of the territory, the rising of earth crust takes place, however in the western part the territory, it is moving downwards.

Changes in the digital values of horizontal gradient modules in the territory enclosed by *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* polygon fluctuate between 0.00006 to 0.20 (mm/year)/km; the mean of digital values of gradients amounts to 0.06 (mm/year)/km. The present research enabled pinpointing areas on the territory in which uniform rising/lowering of the territory takes place as well as areas demonstrating sharp changes in the velocity of movements.

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