**Asta ANIKĖNIENĖ**

# RESEARCH AND MODELING OF THE RECENT VERTICAL MOVEMENTS OF THE EARTH'S CRUST ON THE BASIS OF GEODETIC MEASUREMENTS (SAMPLES ON LITHUANIAN TERRITORY)

**Summary of Doctoral Dissertation**
**Technological Sciences, Measurement Engineering (10T)**

**1565-M**

**Vilnius** LEIDYKLA TECHNIKA **2008**

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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**Asta ANIKĖNIENĖ**

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## Introduction

***Relevance of the scientific problem.*** The studies concerning recent movements of the Earth's Crust are considered to be significant for solving scientific and practical problems, which many scientists from different fields are interested in. The data on the investigation of the recent movements of the Earth's Crust are used further to analyse the tectonic activity of the Earth, determine seismically active territories and evaluate the degree of their insecurity, derive the field characteristics of the recent geodynamic intensities, search for mineral resources, forecast risks concerning the maintenance of the objects of increased ecological safety and sensors dealing with deformations.

To determine the digital values of the recent movements of the Earth's Crust the repeated geodetic measurements are performed. The benchmarks are consolidated in the upper layers of the Earth's Crust. That is why in the regions where the sedimentary cover of the Earth is thick, the values of the movements of the Earth's Crust determined by applying measurements are considered to be the total result of the deformations caused by tectonic movements and preconditioned by the local sedimentary layers of the cover. Deformations of sedimentary cover act as disturbances, distorting the regularities of the general recent tectonic movements of the Earth's Crust.

Moreover, recent movements of the Earth's Crust are regarded as the modern stage of the tectonic process of the long lasting geodetic periods. Having in mind that the formation of sedimentary cover was influenced by the processes of tectonic development, after determining the data relationship between them and geodetic measurements, there could appear the possibility of compiling generalized models of the recent movements of the Earth's Crust. The model might be applied for forecasting the movements. The territory of Lithuania signifies itself by a qualified network of levelling and data on geo-parameters. Due to that, the territory could be treated as a suitable polygon for investigation of the recent movements of the Earth's Crust by applying geodetic measurements as well as for perfecting the method of simulation and for analysing the possibilities of implementation.

***Objective and tasks of work.*** The objective of the work is to work out the method for simulation and estimation applying geodetic methods of the measured recent vertical movements of the Earth's Crust and to apply the method for compiling the map of vertical movements of the Earth's Crust for the territory of Lithuania.

The main tasks of the work are:

1. To determine the values of the measured recent movements of the Earth's Crust based on the data of repeated levelling.

2. To investigate the regularities of the change of the recent vertical movements of the Earth's Crust.
3. To examine and determine the relationship between the territory geo-parameters and measured recent vertical movements of the Earth's Crust.
4. To analyse the possibilities of applying regression models for forecasting recent vertical movements of the Earth's Crust and work out the recommendations to be able to employ them in compiling maps of vertical movements of the Earth's Crust.
5. To estimate the regression models of forecasting of the recent vertical movements of the Earth's Crust by means of multi-criteria method of analysis.
6. To compile the velocity map of the recent vertical movements of the Earth's Crust for the territory of Lithuania.

***Objective of research***

Earth's Crust recent vertical movements in the territory of Lithuanian.

***Scientific novelty***

1. Based on the values of mathematical statistics it was proved the change of the vertical movements of the Earth's Crust in the sequence of time.
2. The methodology was worked out to be able to compile regression models of the recent vertical movements of the Earths' Crust taking into account the data on geodetic measurements and territorial geo-parameters.
3. By applying the suggested method there were compiled velocity maps of the recent vertical movements of the Earth's Crust for the territory of Lithuania.

***The methods of the research.*** They are geodetic measurements, correlation and regression analysis of geodetic measurements of the territory, multi-criteria analysis.

***Practical value.*** The application of forecasting methods for recent vertical movements of the Earth's Crust precondition the possibilities to elaborate and supplement the maps compiled according to the results of geodetic measurements on the vertical movements of the Earth's Crust.

***Statements for approval***

1. Demonstrations of the characteristics of the movements of the Earth's Crust in the sequence of time.
2. Regression models of the recent vertical movements of the Earth's Crust.
3. The method of compiling maps concerning the recent vertical movements of the Earth's Crust in respect to the geo-parameters of the territory.

4. A new map on the velocities of vertical movements of the Earth's Crust in the territory of Lithuania.

***Structure and size.*** The work consists of six chapters, together with the introduction and conclusions, list of scientific literature, list of publications of the author and supplements.

## 1. Research on the recent vertical movements of the Earth's Crust by geodetic methods and peculiarities of interpreting the results of the investigations

The chapter presents the analysis of the state of research as well as the tendencies of development of the recent vertical movements of the Earth's Crust, geo-tectonic interpreting of the Earth's Crust and peculiarities of maps in compiling them. The possibilities of investigating the recent vertical movements of the Earth's Crust by geodetic techniques are analysed.

The analysis of the scientific sources of the research manifested that the maps available concerning the recent movements of the Earth's Crust of Lithuania and the maps of adjacent territories significantly differ. The reasons of the differences could be caused by the change of the characteristics of vertical movements in the sequence of time, by the peculiarities of the implementation of the territorial geo-parameters in compiling maps. Therefore, it is required to investigate by means of measurements the change of the Earth's Crust within the sequence of time and to suggest the unanimous methodology based on digital indices to be applied in the total estimation of geodetic measurements and territorial geo-parameters. Based on the conception derived, there were analysed the possibilities of implementing the studies in the territory of Lithuania and there were particularized the tasks of the research.

## 2. Methodology of the research

The chapter deals with the submitted methodology on determining the measured velocities of the recent vertical movement's of the Earth's Crust in accordance with the geodetic measurements as well as their analysis, on the integrated treatment of territorial geo-parameters and the velocities of measured movements as well as the methodology of the estimation.

To determine the velocities of the recent movements of the Earth's Crust within the period of the repeated levelling there was applied the comparison of the differences of altitudes of geodetic tides not calculated after the adjustment of the levelling networks but after the measured ones. When applying such a method the results are not influenced by the systems of altitudes of levelling networks, selection of initial points when levelling the network as well as the

errors of their altitudes. To reduce the errors of measurements as well as random unrelated with general regularities anomalies of vertical movements there were applied polynomial regression equations to smooth the measured values. The coincidence of the measurements of smoothing models to the data of measurements was evaluated by applying mathematical statistical indices ($F$ statistics and the coefficient of the determinant) and by calculating the confidence intervals of probability equal to 0,90 and 0,95.

The relationship of velocities of measured vertical movements of the Earth's Crust with the territorial geo-parameters was determined by calculating the correlation matrixes.

To forecast vertical movements of the Earth's Crust there were compiled linear regression models, where territorial geo-parameters served the role of causative variables. The adequacy of models to the results of measurements is evaluated by applying mathematical statistical criteria.

To determine the changes of the characteristics of vertical movements of the Earth's Crust within the sequence of time there were compared various time periods and in accordance with the results of geodetic measurements there were compiled the values of the horizontal gradients of the models of movements, there was considered the importance of the characteristics of changes and estimation of mathematical statistical indices.

To interpret the compiled models of regression forecasting of the recent vertical movements of the Earth's Crust and to range the tectonic multi-criteria there was introduced the multi-criteria analysis.

## 3. Research on recent vertical movements of the Earth's Crust in the northern part of Lithuania

The research in the area of the northern part of Lithuania was carried out in order to prove the suggested methodology of the studies and to justify the peculiarities of its application within the whole territory of Lithuania.

Within the studied area located in Lithuania there were executed 4–5 repeatable levellings along the separate lines of the levelling network. That is why there was a possibility to investigate the modifications of the movements of the Earth's Crust in the sequence of time and by means of the criteria of mathematical statistics to justify it.

To determine the measured vertical movements of the Earth's Crust located in the northern part of Lithuania the data on the accurate levelling in the polygon of *Vilnius–Jonava–Zarasai–Turmantas–Vilnius* for 1935–2006 were employed. The mean square errors of measurements are within the range of 0,27–0,69 mm/km.

The difference of vertical movements in the sequence of time was

analysed by means of comparability of the gradients of velocity models of the compiled movements of geodetic measurements, the significance of their differences when the estimation was made by means of statistical criteria. The comparison of gradients is submitted in Table 1.

**Table 1.** Analysis of the velocity gradient differences for regression models of vertical movements of the Earth's surface

| Time period, year | $\Delta$ | $\sigma(\Delta)$ | $t$ | $t_{q,k}$ , $(q = 0{,}05)$ | Remarks |
|---|---|---|---|---|---|
| *Vilnius – Jonava* | | | | | |
| 1970/71–1948<br>1998–1970/71 | 0,0184 | 0,0013 | 14,2 | 2,08 | $t > t_q$ |
| *Jonava – Zarasai – Turmantas* | | | | | |
| 2005–1980<br>2005–1935/36 | 0,0197 | 0,0016 | 12,3 | 2,06 | $t > t_q$ |
| 1980–1935/36<br>2005–1980 | 0,0334 | 0,0017 | 19,6 | 2,02 | $t > t_q$ |
| *Turmantas – Vilnius* | | | | | |
| 2005/06–1985/87<br>1985/87–1968 | 0,1066 | 0,0033 | 32,3 | 2,02 | $t > t_q$ |
| 1968–1948<br>2005/06–1985/87 | 0,0089 | 0,0031 | 2,9 | 2,03 | $t > t_q$ |

*Conventional markings:* $\Delta$ *– velocity gradient differences of the comparative periods of time,* $\sigma(\Delta)$ *– standard evaluation of gradient differences,* $t = \Delta / \sigma(\Delta)$ *– evaluation of statistics,* $t_{q,k}$ *– theoretical value of statistics, when reliability level* $q$ *and* $k$ *are in the degrees of freedom.*

Judging from the data of Table 1 it is possible to state that the characteristics of the vertical movements of the Earth's Crust within the sequence of time are changing and these variations are statistically significant. The variation of the vertical movements within the sequence of time along the line *Turmantas–Vilnius* is depicted graphically in Fig. 1, 2. The amplitude of the variation of the direction of movements is significantly higher than the confidence intervals of the movement models. The analogous view was derived and along the other lines. When the probability is not lower than 0,95 there is the hypothesis regarding the inversion of the direction of the vertical movements in the sequence of time, and the variation of the gradients within different time periods, when the direction of the vertical movements is the same. Therefore, the studies have to be related with a particular time period when investigating the recent movements of the Earth's Crust.

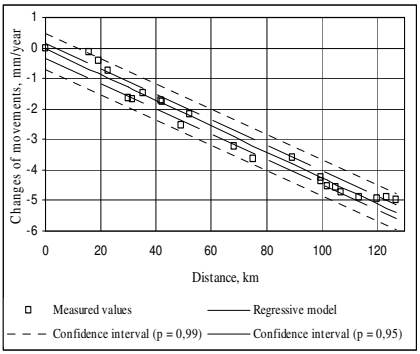


**Fig. 1.** The Earth's surface movements 2005/06–1985/87, along line *Turmantas–Vilnius* (linear model)

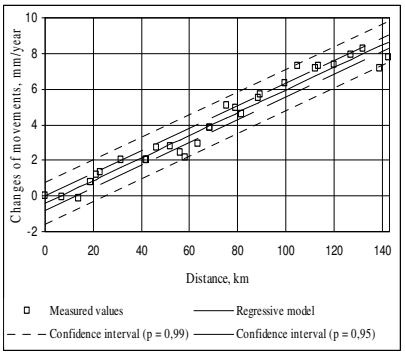


**Fig. 2.** The Earth's surface movements in 1985/87–1968, along line *Turmantas–Vilnius* (linear model)

Following methodology principals that recent vertical movements of the Earth's Crust are the continued tectonic processes of the former geological periods, there were investigated the possibilities of compiling regression models concerning recent vertical movements of the Earth's Crust by means of the territory geo-parameters.

Thus, taking into account the findings of the research on the changes of the characteristics of the vertical movements of the Earth's Crust within the sequence of time, there were applied the data of the two geodetic measurement cycles to compile the model of the Earth's Crust movements for the analysed territory, namely the measurements were employed following along the line *Vilnius–Jonava in* 1998 and in 1970/71, along the line *Jonava–Zarasai–Turmantas in* 2005 and 1980, along the line *Turmantas–Vilnius in* 2005/06 and in 1985/87.

The modelling implied the following geo-parameters: $x_1$ – gravitational field, $x_2$ – magnetic field, $x_3$ – the Earth's surface current relief, $x_4$ – the relief of the crystalline basement, $x_5$ – Pre-quaternary relief (of the main layers), $x_6$ – the thickness of the Quaternary cover, $x_7$ – the thickness of the sedimentary cover, $x_8$ – the thickness of the Pre-quaternary cover (of the main layers).

The coefficients of correlation were computed for the measured movement's velocities of the Earth's Crust and for the geo-parameters of the territory along the separate lines comprising polygon and for the parameters when joining the lines into the total polygon.

The defined findings indicate that the most substantial correlation

relationship of the vertical movements of the Earth's Crust is along the line *Vilnius–Jonava.* Majority of geo-parameters are $0{,}64 \le r \le 0{,}89$, except the gravitational field and magnetic field, where $r \le 0{,}25$. The most substantial correlation relationships are along the line *Jonava–Zarasai–Turmantas* with the current relief of the Earth's Crust and Prequaternary relief (the main layers), $r \ge 0{,}83$. Along the line *Turmantas–Vilnius* the most substantial correlation relationships of vertical movements of the Earth's crust are the gravitational field, current relief of the Earth's surface, the relief of the crystalline basement, the thickness of the sedimentary cover as well as Prequaternary cover (the main layer) $-0{,}94 \le r \le 0{,}95$. After joining all the lines into the total closed polygon, the most substantial correlation relationships are with the gravitational field, the relief of the crystalline basement, the relief of the Prequaternary (the main layers), the thickness of the sedimentary cover and the thickness of the Prequaternary cover (the main layers). In addition to that, it was determined, that the coefficients of correlation of vertical movements along different lines with the same values are different. Meanwhile, the values of correlation dependencies along separate lines are higher, than the values in the total polygon with all the lines connected there. Therefore, it is required to take into consideration the heterogeneous geological structure of the territory when compiling regression models.

Due to the correlation relationship between the measured recent vertical movements of the Earth's Crust and the geological parameters of the territory, there is a possibility to derive the polynomial models of the recent vertical movement of the Earth's Crust.

The polynomial model of the vertical movements of the Earth's Crust is expressed by the linear regression equation

$$v = a_0 + \sum_i a_i x_i \ , \qquad (1)$$

where $v$ – are forecast velocities of the recent vertical movements of the Earth's Crust, $x_i$ – are the values of geo-parameters, $a_0, a_1, ..., a_8$ – are the coefficients of the regression model. The coefficients of the regression model are calculated by means of least squares**.**

To estimate the possibilities of the application of polynomial model (1) and the quality of forecasting, the analysis was carried out along the lines of the repeated levelling and the lines were joined into the total integrity.

The regression models were computed by the following three ways:

1) applying all the geo-parameters exercised for correlation analysis;

2) taking into consideration only these values that describe the territory and the value of the correlation coefficient with the velocities of vertical

movements of the Earth's Crust are $r \geq 0{,}50$;

3) applying reverse stepping regression, until in the regression equation there remain 2–4 values having the strongest influence, when the values of the model adequacy are of satisfying probability.

All three cases along all the lines and polygon have the probability of regression models which corresponds to the data of measurements which is $p \geq 0{,}95$.

Along the line *Turmantas–Vilnius* there were measured and forecasted the velocities of the vertical movements of the Earth's Crust exhibited in Fig. 3. The analogues results are obtained in other lines as well.

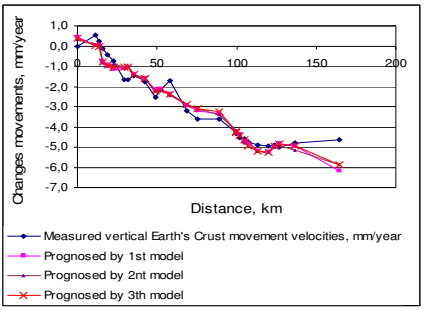


**Fig. 3.** Measured and forecasted vertical movements of the Earth's Crust along the line *Turmantas–Vilnius*

The mean values of the coefficients of determination along the lines are about 93%, but in the polygon are about 87% (with all the variables – 81%, but in the other two cases are 76% and 75%). In the second and third cases along the lines is obtained the diverse structure of the regression models.

However, the structure of the regression models varies, but when the lines are connected into the polygon, the statistical values of the model adequacy for the measurements are better when evaluating all the geo-parameters, it is recommended to estimate all the geo-parameters when modelling the movements in the polygon as if in the case of a plotted object.

The experimental studies carried out in the north-eastern part of Lithuania prove that it is possible to employ regression models of forecasting in compiling recent maps of the Earth's Crust movements. Having in mind, that from the point of view of significance of the correlation coefficients, the same correlation dependences along separate lines are not adequate, it is advisable also to consider the values of the regression models which could be insignificant along the separately chosen lines, when carrying out the studies in the larger territories.

## 4. Compiling of the map of the recent vertical movements of the Earth's Crust in the territory of Lithuania by applying regression models

Taking into consideration the results of the work presented in chapter four and recommendations described on applying the method of the research, the

investigations were provided within the whole territory of Lithuania and the map on the velocities of the recent vertical movements of the Earth's Crust was compiled. It was determined that even in the other regions of Lithuania the change of the movement characteristics in the sequence of time is analogues to the experimental object. That is why in compiling the map of the vertical movements of the Earth's Crust there were used the data of the last two cycles of geodetic measurements. Along the line *Jonava–Gaižiūnai–Palemonas–Kaunas–Kazlų Rūda–Kybartai* in 1998–1970, along the line *Kazlų Rūda–Šeštokai–Lazdijai–Lenkijos siena* in 1998–1982, along the line *Šiauliai–Kužiai–Mažeikiai–Lūšė in* 2004–1965, along the line *Šiauliai–Tauragė–Mikytai* in 2002–1976, along the line *Mikytai–Šilutė–Klaipėda–Palanga–Būtingė* in 2003–1973/75, *Jonava–Šiauliai–Joniškis* in 2002/2004–1970/71. The accuracy of levelling is within the ranges of 0,37–0,63 mm/km.

However having in mind that in various territories the structure of regression forecasting models is not the same, the method of fragmentation is provided when compiling the map of vertical movements of the Earth's Crust, and then the territory of Lithuania is divided taking into consideration the structure of the repeated levelling polygons, the area was divided into five fragments (Fig. 4).

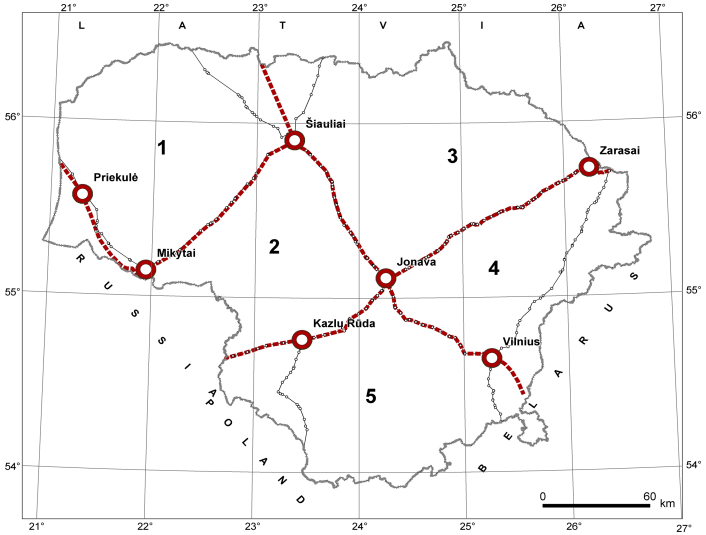


**Fig. 4.** Division of the territory into fragments

The regression models for repeated lines of levelling were derived applying all the three methods described in chapter four both for polygons and

for the whole territory of Lithuania. The probability of adequacy of regression models along the lines and in polygons is equal to the data of measurements $p \geq 0{,}95$. The data of statistical analysis in polygons (fragments) are submitted in Table 2.

**Table 2.** Results of regression analysis

| Unit No. | Method used | $R^2$,% | $F$ | $F_{q(k_1,k_2)}$ $q$=0,05 |
|---|---|---|---|---|
| *1 polygon* | | | | |
| 1 | 1 | 61,78 | 10,91 | 2,06 |
| 2 | 2 | 48,64 | 13,73 | 2,50 |
| 3 | 3 | 45,43 | 24,98 | 3,15 |
| *2 polygon* | | | | |
| 4 | 1 | 44,91 | 5,20 | 2,01 |
| 5 | 2 | 24,06 | 5,91 | 2,71 |
| 6 | 3 | 22,84 | 17,17 | 4,01 |
| *3 polygon* | | | | |
| 7 | 1 | 78,66 | 17,97 | 2,17 |
| 8 | 2 | 78,62 | 21,02 | 2,25 |
| 9 | 3 | 76,23 | 47,02 | 2,79 |
| *5 polygon* | | | | |
| 10 | 1 | 57,11 | 8,99 | 2,03 |
| 11 | 2 | 37,65 | 8,75 | 2,50 |
| 12 | 3 | 51,38 | 20,78 | 2,74 |
| *Total Lithuania* | | | | |
| 13 | 1 | 27,89 | 9,38 | 1,94 |
| 14 | 2 | 12,12 | 27,71 | 3,84 |
| 15 | 3 | 27,02 | 24,56 | 2,60 |

From Table 2 we find out that by applying all the analysed geo-parameters, the results of statistic quality of models are better, than in other two methods, the values of separate polygons are better than the values of the regression forecasting model applied for the total territory of Lithuania. By that it was proved that in compiling maps it is advisable to use the method of fragmentation.

To rank the regression models, namely to determine which model confirms better to the hypothesis on the tectonic nature of the determined movements of the Earth's Crust, there has to be exercised the multi-criteria analysis. The method of multi-criteria analysis TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was applied to determine ranking. The initial data of the analysis are the correlation coefficients of the geological parameters of the territory of the vertical movements. The regression models of separate polygons are arranged in the following order 4, 3, 2, 1, 5 in accordance with the priority values.

By applying the compiled models there were forecasted according to the geo-parameters the values of the velocities of the recent vertical movements of the Earth's Crust computed not only at the points of geodetic measurements along the levelling lines but also within the whole area of the polygon at the corners of the grid 15x15 km. The procedure allows the forecasting of the recent vertical movements of the Earth's Crust to expand into the territories which have no geodetic measurements.

At the nodal points of the models the forecasted values from various models due to errors of measurements or other random reasons do not coincide. That is why there is required the smoothing and adjustment of the models.

To relate the models at the nodal points, the mean values of the velocities of the recent vertical movements of the Earth's Crust were computed and they were obtained from the adjacent lines bordering with the point. These velocity values of the movements of the nodal points are used in the further stages of map compiling.

When the fragmental models are connected in the nodal points it is necessary to transform the calculated values according to the values of the regression models of the polygons. The transformation is carried out by deriving the equation of errors for regression forecasting model for each polygon. The coefficients of the equations of errors are calculated when the deviations of the values of the vertical movements of the Earth's Crust determined in accordance with the regression models and at the known nodal points deviate from the approved final mean values of the velocities of the vertical movements and the coordinates of the planes of the nodal points:

$$\Delta v_i = a_{0,i} + a_{x,i}x + a_{y,i}y\,, \qquad (2)$$

where $i = 1,2,3,4,5$ – are numbers of polygons, $a_{0,i}$, $a_{x,i}$, $a_{y,i}$ – are the coefficients of the equations of correction, $x$, $y$ – are the plane coordinates of the LKS 94 coordinate systems.

The reduced values are derived when to the calculated values of the regression models are added to calculated errors. Following this method there was compiled the map of the recent vertical movements of the Earth's Crust for the territory of Lithuania (Fig. 5).

The velocity values of the recent vertical movements of the Earth's Crust for the compiled map are related with the velocity values of the compiled map meant for the territory of Poland. The velocities of the recent vertical movements of the Earth's Crust measured for the territory of Poland were calculated from Wladyslawowo tide-gauge station, the value of velocities of vertical movements of which was determined after having analysed the data of the tide-gauge stations of Wladyslawowo, Ustka, Kolobrzeg and Swinoujscie.

The amplitude of the velocities of the recent vertical movements of the Earth's Crust in the territory of Lithuania is from –3.5 up to +2.5 mm annually. The most intensive increase of the Earth's Crust and the greatest change of the gradients of velocities of the movements is located in the north eastern part of Lithuania, but the sinking is located in the south-eastern and western areas of Lithuania.

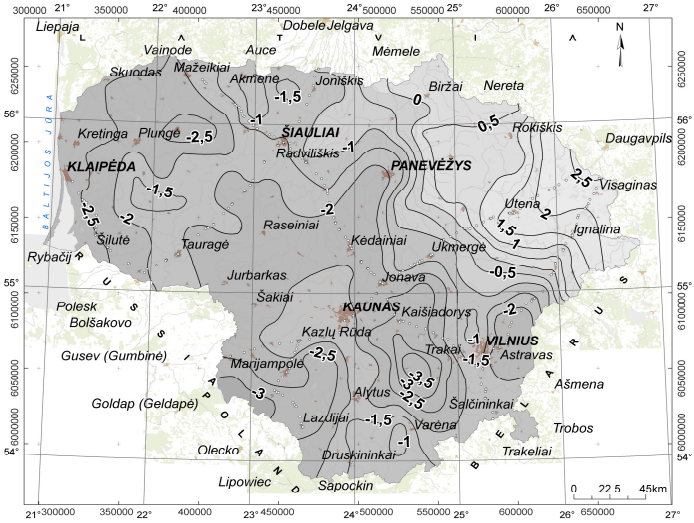


**Fig. 5.** Map of the recent vertical movements of the Earth's Crust for Lithuania

In order to explain the reliability of the compiled map as well as its correspondence to the data of measurements the study was made along the lines *Jonava–Gaižiūnai–Palemonas–Kaunas–Kazlų Rūda, Jonava–Zarasai–Turmantas, Jonava–Šiauliai.* The measured values of the recent vertical movements of the Earth's Crust along these lines were compared, the measured values were smoothed by multi-criteria, confidence intervals of their probabilities were 0,95 and 0,99 and the values of the compiled map of vertical movements of the Earth's Crust were structured (Fig. 6).

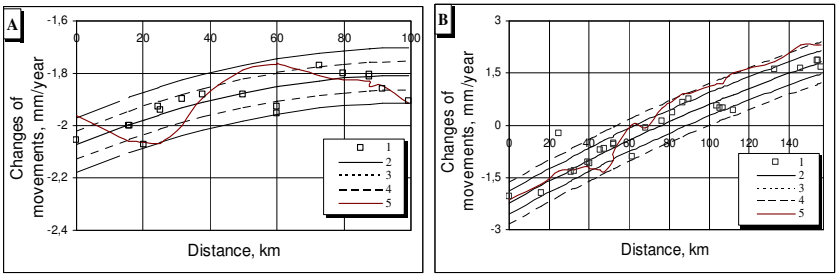


**Fig. 6.** Comparison of the measured results with the map of the vertical movements of the Earth's Crust*: A – is along the line Jonava–Gaižiūnai–Palemonas–Kaunas–Kazlų Rūda, B – is along the line Jonava–Zarasai–Turmantas, C – is along the line Jonava–Šiauliai*

*Conventional markings: 1 – are the measured values, 2 – are the smoothed values, 3 –is confidence interval of probability 0,99, 4 – is confidence interval of probability, confidence interval of probability 0,95, 5 –are the values of the map.*

From these figures it is clear that velocity values of the recent vertical movements of the Earth's Crust depicted on the map are included into the confidence interval of the measured values of probability 0,99. That is why it is possible to state that according to the applied methodology of forecasting there was compiled the map of the recent vertical movements of the Earth's Crust from the point of view of mathematical statistics which doesn't contradict the results of direct geodetic measurements.

**Based on the research carried out, the following conclusions were derived**

1. The methodology is prepared on simulation and estimation of the recent vertical movements of the Earth's Crust, based on the treatment of the general mathematical statistics of geo-parameters characterizing geodetic measurements and the region.
2. Having carried out the mathematical statistical analysis of the velocities of vertical movements of the Earth's Crust measured at different intervals of time when probability is $p \geq 0{,}95$, there was determined that in the sequence of time not only the velocity of the movements undergo the change but direction as well. That is why the models of the movements of the Earth's Crust and the results of the research have to be related with a particular period of time.
3. Regression models of forecasting recent vertical movements of the Earth's Crust when probability is equal to $p \geq 0{,}95$ are adequate to geodetic measurements.
4. There was determined that the dependencies of geo-parameters on the recent vertical movements of the Earth's Crust and territory geo-parameters are not equal everywhere. The type and structure of the relationship bear a regional character. That is why in compiling regression models of forecasting it is required to use fragmental models.
5. Regression models of forecasting could be applied not only along the lines of the repeated levelling but also in the prescribed polygons bounded by the lines of repeated levelling where geodetic measurements are missing .
6. To evaluate regression models of forecasting of the recent vertical movements of the Earth's Crust from the point of view of geo-tectonics it is possible to apply the multi-criteria method of analysis.

7. When applying the suggested method there was compiled a new map of the velocities of recent vertical movements of the Earth's crust for the territory of Lithuania.
8. There was determined that the amplitude of velocities of the recent vertical movements of the Earth's Crust in the territory of Lithuania is from –3.5 up to +2.5 mm annually. The most intensive increase and greatest change of the gradients are in the Eastern part of Lithuania and the sinking is in the south east or west areas.
9. By applying the suggested methodology the velocity map was compiled of the recent vertical movements of the Earth's Crust. Then it was compared with the map compiled based on the data of geodetic measurements, which appeared to be more detailed, with better expressed tectonic peculiarities of territory.
10. By summarizing the results carried out in the territory of Lithuania it is possible to state that the proposed methodology is adequate enough to investigate recent vertical movements of the Earth's Crust, to simulate and compile maps.

**The list of scientific publications**

**In the reviewed scientific journals**

1. Zakarevičius, A.; Anikėnienė, A. 2007. The research on the present geodynamic processes in the north – west part of the territory of Lithuania, *Geodesy and Cartography,* 33(2): 41–46 (in Lithuanian). ISSN 1392–1541 (Compendex).
2. Zakarevičius, A.; Anikėnienė, A. 2007. The regression models of the present Earth crust movements in the north – east part of Lithuania, *Geodesy and Cartography*, 33(4): 91–97 (in Lithuanian). ISSN 1392-1541 (Compendex).

**In proceedings and theses of international and Lithuanian conferences**

3. Zakarevičius, A.; Šliaupa, S.; Puzienė, R.; Anikėnienė, A.; Būga, A.; Dėnas, Ž. 2005. Tectonic interpretation of measured recent movements of the earth surface of sedimentary basin, in *Proceedings of the 6th International Conference „Environmental Engineering" Selected Papers, Vol. II, 26–27 May, 2005, Vilnius, Lithuania.* Vilnius: Technika, 1034–1040. ISBN 9986-05-851-1 (Thomson ISI Proceedings).
4. Zakarevičius, A.; Šliaupa, S.; Dėnas, Ž.; Stanionis, A.; Anikėnienė, A.; Puzienė, R. 2008. Inheritance of the recent vertical movements of the Earth's crust and relationship to the topography in Lithuania, in *Proceedings of the 7th International Conference „Environmental*

*Engineering" Selected Papers, Vol. III, 22–23 May, 2008, Vilnius, Lithuania.* Vilnius: Technika, 1508–1513. ISBN 978-9955-28-265-5 (Thomson ISI Proceedings).

5. Zakarevičius, A.; Anikėnienė, A. 2007. Peculiarities of present geodynamic processes in the North eastern Lithuania, *Baltic surveying'07: transactions of the Estonian University of Life Sciences*, *May 9–11, 2007*. Ministry of Agriculture of Lithuania, Lithuanian University of Agriculture. Tartu: Estonian University of Life Sciences, 224: 122–147. ISSN 1406–4049 (Thomson ISI Master Journal List).
6. Zakarevičius, A.; Puzienė, R.; Anikėnienė, A. *2005.* Geotectonic interpretation of recent earth crust movements in sedimentary basins, *international symposium on „Modern technologies, education and professional practice in geodesy and related fields": papers: 3–4 November, Sofia, Bulgaria.* Union of surveyors and land managers in Bulgaria. 225–235.
7. Anikėnienė, A.; Zakarevičius, A. 2005. The multi – criterion evaluation of recent Earth surface movements related to geologic indexes, in Proceedings of the VIII Conference of Lithuanian Young Scientists *„Lithuania without science – Lithuania without future",* held in Vilnius on 25 March, 2005. Environmental Protection Engineering. Vilnius: Technika, 35–39 (in Lithuanian). ISBN 9986-05-876-7.
8. Anikėnienė, A.; Zakarevičius, A. 2006. Influence of weights indices on interpretation of the earth surface geotectonic interpretation applying method of multi – criterion analysis, in Proceedings of the IX Conference of Lithuanian Young Scientists *„Lithuania without science – Lithuania without future",* held in Vilnius on 30 March, 2006. Environmental Protection Engineering. Vilnius: Technika, 108–113 (in Lithuanian). ISBN 9955-28-037-9.
9. Anikėnienė, A.; Zakarevičius, A. 2007. Oscillating movements of the earth's crust in the northeastern part of the Lithuania, in Proceedings of the X Conference of Lithuanian Young Scientists *„Lithuania without science – Lithuania without future",* held in Vilnius on 29 March, 2007. Environmental Protection Engineering. Vilnius: Technika, 270–278 (in Lithuanian). ISBN 978-9955-28-162-7.
10. Anikėnienė, A.; Puzienė, R. 2006. Vertical Earth's crust movements geotectonic interpretation using statistic and multi–criteria analyse, in Republic scientific – practical conference *„Measurement engineering and GIS", Mastaičiai*, 4–9. ISBN 9955-586-97-4.
11. Zakarevičius, A.; Anikėnienė, A. 2007. Correlation of present vertical Earth's crust movements and geologic structure at East part of Lithuania,

in Republic scientific – practical conference *„Measurement engineering and GIS“,Mastaičiai*, 97–99. ISBN 978-9955-27-033-1.

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## DABARTINIŲ VERTIKALIŲJŲ ŽEMĖS PLUTOS JUDESIŲ TYRIMAS IR MODELIAVIMAS TAIKANT GEODEZINIUS MATAVIMUS (LIETUVOS TERITORIJOS PAVYZDŽIU)

***Mokslo problemos aktualumas.*** Dabartinių Žemės plutos judesių tyrimas yra svarbi ne tik mokslinė, bet ir praktinė problema, kuri domina ne vienos mokslo srities ir krypties mokslininkus. Dabartinių Žemės plutos judesių tyrimų duomenys naudojami tektoniniam Žemės aktyvumui tirti, seismiškai aktyvioms teritorijoms nustatyti ir jų pavojingumo laipsniui įvertinti, dabartinių geodinaminių įtampų laukų charakteristikoms nustatyti, naudingųjų iškasenų paieškai, sudėtingų deformacijoms jautrių didesnio ekologinio pavojingumo objektų eksploatacijos rizikai prognozuoti.

Dabartinių Žemės plutos judesių skaitmeniniams rodikliams nustatyti atliekami kartotiniai geodeziniai matavimai. Matavimo ženklai įtvirtinami viršutiniuose Žemės plutos sluoksniuose. Todėl regionuose, kuriuose yra stora Žemės nuosėdinė danga, matavimais nustatytos Žemės plutos judesių reikšmės yra tektoninių judesių ir įvairių priežasčių sukeltų lokalių nuosėdinės dangos sluoksnių deformacijų suminis rezultatas. Nuosėdinės dangos deformacijos veikia kaip trikdžiai, iškreipiantieji bendruosius dabartinių tektoninių Žemės plutos judesių dėsningumus.

Dabartiniai Žemės plutos judesiai yra ilgus geologinius periodus trunkančio tektoninio proceso šiuolaikinis etapas. Tad žinant, kad nuosėdinei dangai formuotis įtakos turėjo tektoninio vystimosi procesai, nustačius jų ir geodezinių matavimų duomenų sąsajas, atsirastų galimybė sudaryti apibendrintus dabartinių Žemės plutos judesių modelius. Šiuos modelius būtų galima taikyti judesiams prognozuoti. Lietuvos teritorijoje yra kokybiški kartotinių niveliacijų tinklas ir georodiklių duomenys. Todėl ši teritorija gali būti tinkamas poligonas geodeziniais matavimais nustatytų dabartinių Žemės plutos judesių tyrimo ir modeliavimo metodikai tobulinti bei taikymo galimybėms nagrinėti.

***Darbo tikslas ir uždaviniai.*** Darbo tikslas – parengti geodeziniais metodais išmatuotų dabartinių vertikaliųjų Žemės plutos judesių modeliavimo bei vertinimo metodiką ir, ją taikant, sudaryti Lietuvos teritorijos dabartinių vertikaliųjų Žemės plutos judesių žemėlapį.

Pagrindiniai darbo uždaviniai:

1. Remiantis kartotinių niveliacijų duomenimis, nustatyti išmatuotų dabartinių Žemės plutos judesių reikšmes.
2. Ištirti dabartinių vertikaliųjų Žemės plutos judesių kaitos dėsningumus.
3. Ištirti ir nustatyti išmatuotų dabartinių vertikaliųjų Žemės plutos judesių ir teritorijos georodiklių sąsajas.
4. Išnagrinėti regresinių modelių taikymo dabartiniams vertikaliesiems Žemės plutos judesiams prognozuoti galimybes ir parengti rekomendacijas juos taikyti sudarant vertikaliųjų Žemės plutos judesių žemėlapius.
5. Įvertinti dabartinių vertikaliųjų Žemės plutos judesių regresinius prognozavimo modelius taikant daugiakriterinės analizės metodiką.
6. Sudaryti Lietuvos teritorijos dabartinių vertikaliųjų Žemės plutos judesių greičių žemėlapį.

***Tyrimų objektas.*** Dabartiniai vertikalieji Žemės plutos judesiai Lietuvos teritorijoje.

***Tyrimų metodika.*** Geodeziniai matavimai, geodezinių matavimų ir teritorijos georodiklių koreliacinė ir regresinė analizė, daugiakriterinė analizė.

***Mokslinis naujumas***

1. Remiantis matematiniais statistiniais rodikliais, įrodyta vertikaliųjų Žemės plutos judesių kaita einant laikui.

2. Parengta metodika dabartinių vertikaliųjų Žemės plutos judesių regresiniams modeliams sudaryti, įvertinant geodezinių matavimų duomenis ir teritorijos georodiklius.
3. Taikant pasiūlytą metodiką sudarytas Lietuvos teritorijos dabartinių vertikaliųjų Žemės plutos judesių greičių žemėlapis.

***Praktinė vertė.*** Dabartinių vertikaliųjų Žemės plutos judesių prognozavimo metodų taikymas sudaro galimybes detalizuoti ir papildyti pagal geodezinių matavimų rezultatus sudaromus vertikaliųjų Žemės plutos judesių žemėlapius.

***Ginamieji teiginiai***

1. Žemės plutos judesių savybių kaitos einant laikui įrodymas.
2. Dabartinių vertikaliųjų Žemės plutos judesių regresiniai modeliai.
3. Dabartinių vertikaliųjų Žemės plutos judesių žemėlapių sudarymo metodika, atsižvelgiant į teritorijos georodiklius.
4. Naujas Lietuvos teritorijos vertikaliųjų Žemės plutos judesių greičių žemėlapis.

***Darbo apimtis.*** Darbą sudaro šeši skyriai, iš jų – įvadas ir išvados, literatūros sąrašas, autoriaus publikacijų sąrašas ir priedai.

**Remiantis atliktais disertaciniame darbe tyrimais, gautos šios bendrosios išvados**

1. Parengta dabartinių vertikaliųjų Žemės plutos judesių modeliavimo ir vertinimo metodika, paremta geodezinių matavimų ir regioną apibūdinančių georodiklių matematiniu statistiniu apdorojimu.
2. Atlikus išmatuotų skirtingais laiko tarpais vertikaliųjų Žemės plutos judesių greičių matematinę statistinę analizę, su tikimybe $p \geq 0{,}95$ nustatyta, kad einant laikui kinta ne tik judesių greitis, bet ir kryptis. Todėl Žemės plutos judesių modeliai ir tyrimų rezultatai turi būti siejami su konkrečiu laikotarpiu.
3. Dabartinių vertikaliųjų Žemės plutos judesių prognozavimo regresiniai modeliai su tikimybe $p \geq 0{,}95$ adekvatūs geodeziniams matavimams.
4. Nustatyta, kad dabartinių vertikaliųjų Žemės plutos judesių ir teritorijos georodiklių sąsajos ne visur vienodos. Sąsajų pobūdis ir struktūra turi regioninių ypatumų. Todėl, sudarant regresinius prognozavimo modelius, reikia remtis fragmentiniais modeliais.
5. Regresinius prognozavimo modelius galima taikyti ne tik kartotinių niveliacijų linijose, bet ir kartotinių niveliacijų linijomis apribotuose poligonuose, kur nėra geodezinių matavimų.

6. Regresiniams dabartinių vertikaliųjų Žemės plutos judesių prognozavimo modeliams vertinti geotektoniniu požiūriu galima taikyti daugiakriterinės analizės metodiką.
7. Taikant siūlomą metodiką, sudarytas naujas Lietuvos teritorijos dabartinių vertikaliųjų žemės plutos judesių greičių žemėlapis.
8. Nustatyta, kad dabartinių vertikaliųjų Žemės plutos judesių greičių amplitudė Lietuvos teritorijoje yra nuo –3,5 iki +2,5 mm per metus. Intensyviausias Žemės plutos kilimas ir didžiausia judesių greičių gradientų kaita yra šiaurės rytų Lietuvoje, o grimzdimas – pietrytinėje ir vakarinėje srityje.
9. Taikant pasiūlytą metodiką sudarytasis dabartinių vertikaliųjų Žemės plutos judesių greičių žemėlapis, palyginti su žemėlapiu, sudarytu tik pagal geodezinių matavimų duomenis, yra detalesnis, geriau išreiškia tektoninius teritorijos ypatumus.
10. Apibendrinant Lietuvos teritorijoje atliktų tyrimų rezultatus galima teigti, kad siūloma metodika tinka dabartiniams vertikaliesiems Žemės plutos judesiams tirti, modeliuoti ir žemėlapiams sudaryti.

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**RESEARCH AND MODELING
OF THE RECENT VERTICAL MOVEMENTS
OF THE EARTH'S CRUST
ON THE BASIS OF GEODETIC MEASUREMENTS
(SAMPLES ON LITHUANIAN TERRITORY)**

**Summary of Doctoral Dissertation
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TAIKANT GEODEZINIUS MATAVIMUS
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