GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 5 • Number 2 • 2011

Małgorzata Mendela*

Analysis and Interpretation of Relative Displacements on the Intra-Sudetic Fault

1. Introduction

Geodynamic investigations conducted in the Sudeten Mts. and on the Fore-Sudetic Block indicate contemporary mobility of the geological structures, occurred in this region. The researches of the Intra-Sudetic Fault's geodynamic mobility are conducted on the geodynamic polygon of Janowice Wielkie, in the appropriate measurement and control system [1].

In this paper there are presented the results of analysis of relative displacements, measured with the TM-71 crack gauge in the period from October 2001 till November 2006. It was taken into consideration both the analysis of the investigated phenomenon in time (time series analysis) and the causal-consecutive analysis (the research of causes for registration of the variations of the relative displacement values and the type identification of their occurrence).

The relative measurements, carried out during next years (December 2006 – May 2009), show relative stable values of each three-dimensional relative displacement vector's component. However, they are not of the main interest of this paper.

2. The Location and Geological Structure of the Investigated Object

The Intra-Sudetic Fault is the part of the main polish tectonic structures – the Sudeten Mts. It is one of the most important dislocations in the Central Sudeten [3].

Its origin is timing of the Varsician orogenesis, as a result of the rock mass disruption and their displacement along the fault area [13].

* Wrocław University of Environmental and Life Sciences

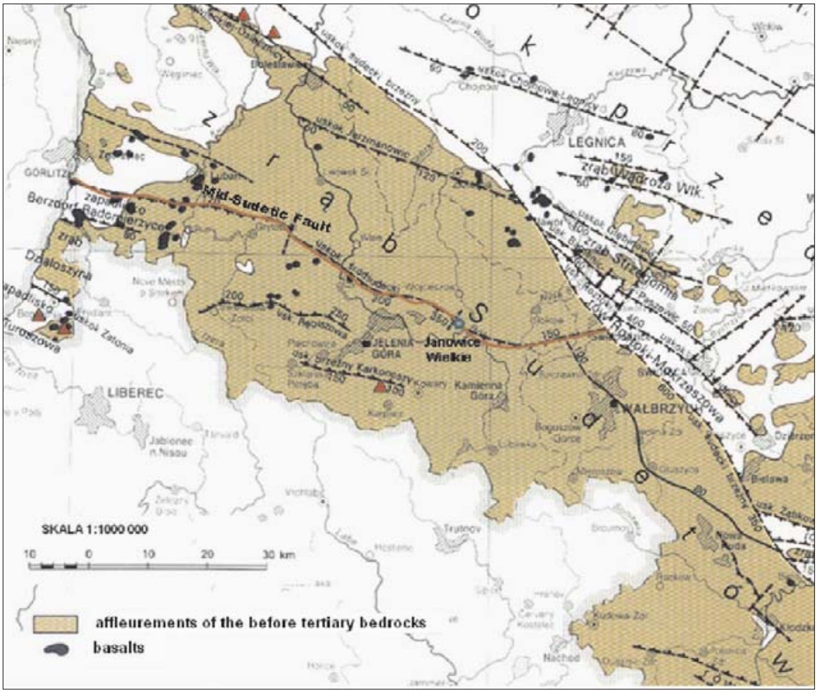

Fig. 1. The location and geological structure of the Intra-Sudetic Fault

Source: the study on the basis of [13]

The Intra-Sudetic Fault (Fig. 1) is the north-west continuation of the main geological-tectonic structure in the Sudeten Mts. – the Sudetic Marginal Fault.

The Intra-Sudetic Fault's geological structure is differentiated. There is a dominance of the before tertiary bedrock's affleurements, e.g. metamorphic rocks, gneisses and tertiary basalt effusions, taken place mainly in the northern and northwestern part of the Fault (Fig. 1). The occurrence of the effusive magma rocks on the study area gives indication of the tectonic mobility of the investigated geological structure.

3. Relative Measurements with the TM-71 Crack Gauge Conducted on the Geodynamic Polygon of Janowice Wielkie

The geodynamic polygon was established in 2000 and is part of the GEOSUD regional network. It is the main area of geodynamic investigations, realized on the Intra-Sudetic Fault (Fig. 1). The values of the three-dimensional relative displacement vector's components (*dx*, *dy*, *dz*) are determined on the basis of the TM-71 crack gauge's measurement data.

The crack gauge is mounted on the geodynamic polygon of Janowice Wielkie, in the former uranium adit (Fig. 2). There are conducted monthly relative observations with the TM-71 crack gauge.

Fig. 2. The TM-71 crack gauge mounted in Janowice Wielkie (phot. S. Cacoń)

The calculations of the unknown values are carried out according to the algorithm, worked out by Košťák [8], on the basis of the main grid's readings, in the form of Moir'e fringes.

The accuracy of the final data sets, presented in the graphic form (Fig. 3), is order of magnitude of 0.01 mm.

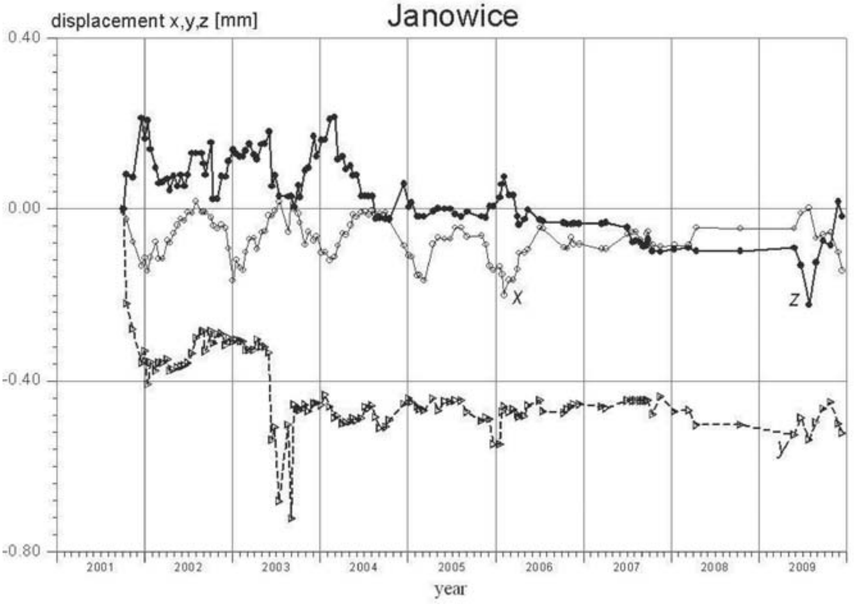

Fig. 3. The graphic results of the relative displacement calculations

Depending on the crack gauge's orientation during measurements (DPN) and the sign of the (*dx*, *dy*, *dz*) components' vaules in each measurement periods, there are drawn the following conclusions:

- the positive values of the *dx* component indicates an opening of the fracture,
- the negative values of the *dy* component points at its dextral movement,
- the positive values of the *dz* component shows the tendency to lift one of the investigated rock blocks (the unstable one).

4. The Statistical Analysis and Interpretation of the Relative Displacement Values with Reference to the Intra-Sudetic Fault

The statistical studies comprise of the time series analysis of the relative displacement vector's components. They were conducted with the use of statistical analysis software – Statistica 7.0. The time series analysis is a passive forecasting method, which one of the aim is to define the nature of the investigated phenomenon, represented by the sequence of observations [7]. The conducted studies are referred to the changes in values of the *dx*, *dy*, *dz* components in time, without taking causes into consideration. There are analysed the structure of the time series of the both horizontal (*dx*, *dy*) and vertical (*dz*) relative displacement vector's components, represented by two elements – trend and periodicity.

4.1. The Analysis of the Relative Displacement's Trend

The analysis of the relative displacement's trend is conducted separately for each component (*dx*, *dy*, *dz*) by two independent analytical methods- linear regression and *M*-estimation.

In table 1 there are presented the estimation results in the form of time series equations for each component. Their graphic display is shown at figure 4.

Table 1. The estimation results for relative displacement vector's components

Linear regression	*M*-estimations
dx	
$y = -0.0001x + 18.6151$	$y = -0.0001x + 18.6404$
dy	
$y = -0.0001x + 84.8827$	$y = -0.0001x + 79.4015$
dz	
$y = -0.0001x + 60.9990$	$y = -0.0001x + 62.6203$

According to table 1 there are noticeable the exact value of estimators for parameter a of the regression line (–0.0001). The differences concern the value of parameter *b,* which is a random element and defines random deflections of the dependent variable's value (values of the *dx*, *dy*, *dz* components).

Therefore, it can be stated, that the occurrence of detached observations in data set do not affect computation results of linear regression.

It should be realized, that the time series of each relative displacement vector's component are characterized by linear trend.

As a result, there is known the general direction of the investigated phenomenon's development [10].

The correctness of linear trend function's estimation is determined by multiple regression method. The results of the conducted analysis (Fig. 4) indicate the smaller values of probability level (*p-value)* then the significance level (α-*level*), which is 0.05 [11].

In other words, there is showed the statistically essential linear relationship.

dx

STAT. REGRESJA WIELOKR.	Podsumowanie regresji zmiennej zależnej : dx R= ,27415844 R2= ,07516285 Popraw. R^2= , 03624 F(1,54)=4,3887 p<,04088 Błąd std. estymacji: ,04978					
N=56	BETA	Błąd st. BETA	B	Błąd st. B	t(54)	poziom p
W. wolny			,969128	,495131	1,95731	,055488
VAR1	-,274158	,130869	-,000027	,000013	-2,09491	,040884

dy

STAT. REGRESJA WIELOKR.	Podsumowanie regresji zmiennej zależnej : VAR2 (dy.sta) R= ,67784115 R2= ,45946863 Popraw. R^2= ,44945879 F(1,54)=45,902 p<,00000 Błąd std. estymacji: ,06475					
N=56	BETA	Błąd st. BETA	B	Błąd st. B	t(54)	poziom p
W. wolny			3,943994	,644051	6,12373	,000000
VAR1	-,677841	,100049	-,000115	,000017	-6,77508	,000000

dz

STAT. REGRESJA WIELOKR.	Podsumowanie regresji zmiennej zależnej : VAR2 (dz.sta) R= ,61514421 R2= ,37840240 Popraw. R^2= ,36689133 F(1,54)=32,873 p<,00000 Błąd std. estymacji: ,05422					
N=56	BETA	Błąd st. BETA	B	Błąd st. B	t(54)	poziom p
W. wolny			3,150225	,539338	5,84091	,000000
VAR1	-,615144	,107290	-,000081	,000014	-5,73349	,000000

Fig. 4. The correctness of linear trend function's estimation

The determination coefficient r^2 (1) is used to estimate the quality of linear regression model's adjustment to the actual data.

There is to be determined what part of the integer variability of the dependent variable (*dx*, *dy*, *dz*) is explained in regard to the independent variable (*t*) [7]

$$r^2 = \frac{\sum_{t=1}^{n}(\hat{y}_t - \overline{y})^2}{\sum_{t=1}^{n}(y_t - \overline{y})^2} \tag{1}$$

where:

- $\hat{y}_t$ – actual value of the dependent variable,
- y_t – theoretical value of the dependent variable determined using the model,
- y_t – arithmetic mean of dependent variable's empirical values.

According to the results of the determination coefficient calculations (Fig. 5), the analysed linear regression model explains to the highest degree, that is 42%, the variability of the dy component; whereas it explains to the lowest degree (35%) the variability of the *dx* component.

	dx	dy	dz
$\sum_{t=1}^{n}(y_t - \bar{y})^2$	0,00665	0,17564	0,10251
$\sum_{t=1}^{n}(\hat{y}_t - \bar{y})^2$	0,14468	0,41886	0,25542
r^2	0,35	0,42	0,40

Fig. 5. The values of the determination coefficient, calculated for each component

4.2. The Analysis of the Relative Displacement Residual Values

Both estimation methods, viz. linear regression and *M*-estimation allow to draw a conclusion of the periodicity of relative displacement residual values towards *x*-axis and *z*-axis of the TM-71 crack gauge (Fig. 6).

The time series of the dy component is a stationary and do not show periodic variations.

The conducted analysis shows, that the residual value of the *dy* component is the largest one, viz. 0.3 mm.

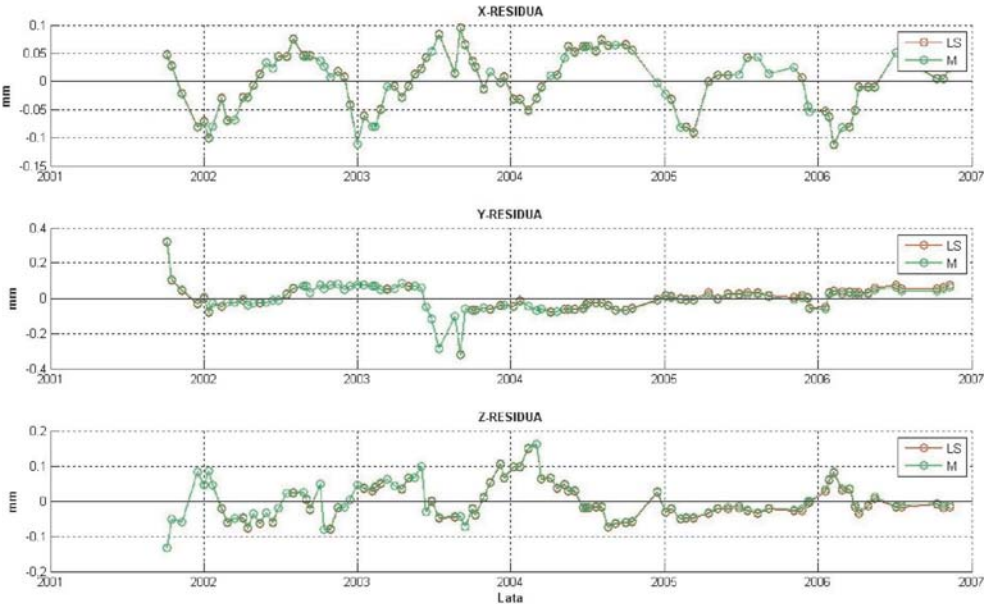

Fig. 6. The residual values of the relative displacement vector's components

The maximum residual values of the *dx* and *dy* components point out, that there is a possibility to be detached values in the analysed data sets (June – September 2003). They are responsible for the changes in values of the model's parameters, which are estimated using the *M*-estimation method (the model of the best adjustment) [9].

4.3. The Analysis of the Relative Displacement's Periodicity

The periodicity is the second of analysed, seasonally repeated component of the time series. Its analysis is conducted using the Fast Fourier Transform (FFT) method. The choice of this analysis method is associated with the high suitability of the frequency domain to the periodicity observation.

On the basis of the signal measured amplitude's graphs, in function of its frequency changes (Fig. 7), there could be noticed the annual periodicity changes of the relative rock blocks' movements towards both x and z-axis of the TM-71 crack gauge. They are probably caused by seasonal moisture variations.

The sinusoidal vibrations are not observable for the time series of the dy component. It is worth to pay attention to the highest signal amplitude's value (0.8 dB) of the time series of the dy component, which allows to clame about the occurrence of the detached observations in the analysed data sets. The time series of the dz component is distinguished by the lowest value of the amplitude spectrum (0.12 dB).

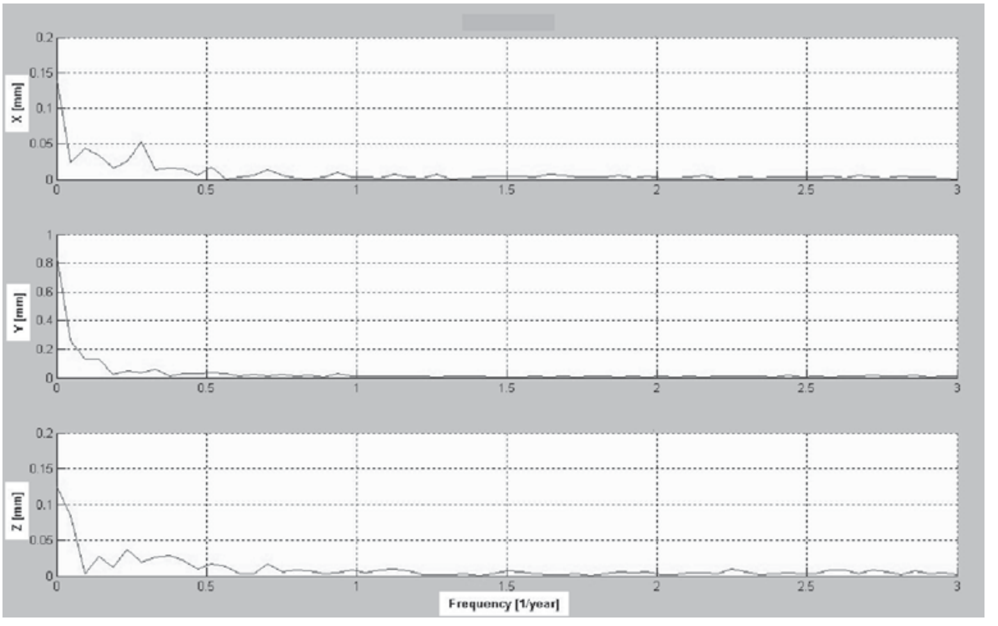

Fig. 7. The results of the quantity analysis of relative dispacements' periodicity

5. The Analysis of the Extreme and Periodic Variations of Relative Displacements

The aim of this analysis is to try to determine the causes of the registered extreme and periodic variations of the relative displacement values in relation to the geodynamic polygon of Janowice Wielkie.

In the analysed data set there could be distinguished five episodic periods of the observed data variations in values. There are mainly periodic variations, whereas the extreme ones are identified in the form of "data peaks" (Fig. 8).

The highest deformation values of the investigated object are determined by both the endo- and exogenic factors [4].

In the conducted analysis there are taken into account the influence of the earthquakes (endogenic factors), the occurrence of the episodic incidents, e.g. strong mining shocks, random incidents, e.g. strong rainfalls, strong winters, the exploitations of rocky material in quarries.

In the periods of the analysed intensified the Intra-Sudetic Fault's geodynamic activity, on the basis of the relative displacement measurements with the use of the TM-71 crack gauge, conducted on the geodynamic polygon of Janowice Wielkie, there are stated any important random incidents.

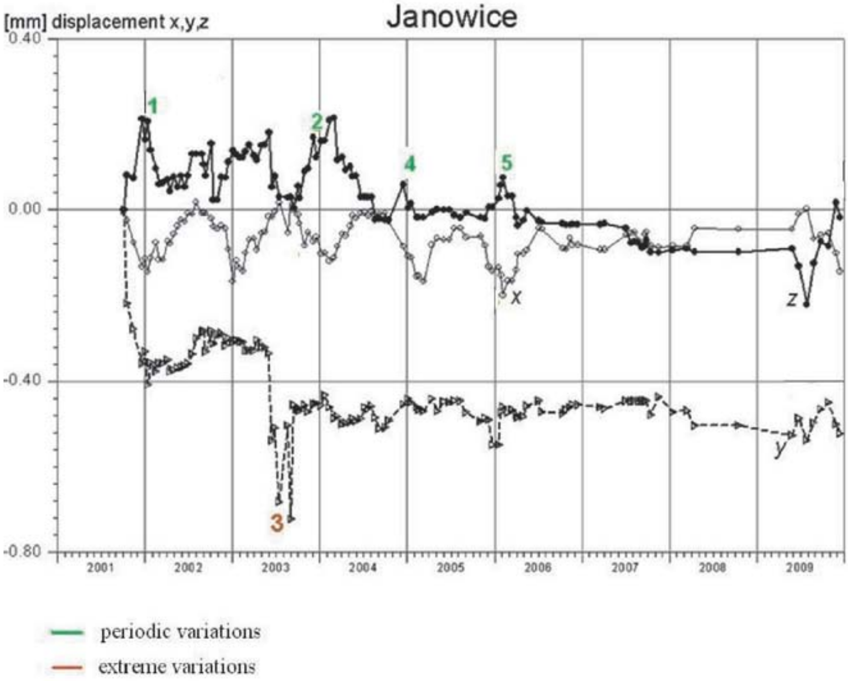

Fig. 8. The graphic presentation of the extreme and periodic variations in values of relative displacement vector's components

At the same time, it is assessed, that the completed exploitation of copper ore in 1954 in the Miedzianka mine, could have the indirect influence on the registration of extreme relative displacement values, because of the subsidence of mining ceiling's excavation [2].

In the perturbation periods, there is not stated the elevated Kwisa and Bobr river's state, flowed near the Intra-Sudetic Fault, that could have potentially an influence on the results of relative displacement measurements, conducted on the geodynamic polygon of Janowice Wielkie.

As a result, it could be maintain that there is a correlation between the extreme relative displacement values and earthquakes, which are the most certain indication of the contemporary tectonic activity of the investigated area.

The results of the relative displacement measurements, conducted in the Sudeten and Fore-Sudetic Block in the Bear Cave and in Zloty Stok from 1989 till 2003 [6], confirm the possibility for the occurrence of the above mentioned dependencies.

There is stated the influence of strong, distant earthquakes, i.a. in Algeria, Turkey, Greece, of the value of 6.0 in the open-ended Richter Scale on the registered relative displacement values.

The increased geodynamic activity of the geological structures could be caused by the relevant for the magnitude's value earthquake. Strong earthquakes may be responsible for occurring temporary changes in the strain field of the earth's crust, that could be noticed in the readings of sensitive measuring instruments, viz. the TM-71 crack gauges [6].

The registration of the extreme relative displacement values is also connected with the presence of the local strain changes in the mountain massif.

In Poland, which is basically aseismic area, the increased geodynamic activity of the investigated objects is not only a local phenomenon, but could also result from the increased geodynamic activity of the adjacent tectonic-geological structures.

The redistribution of the strain on a width scale within the earth's crust could lead to the tectonic instability, that is in charge of relevant fault displacements and might cause earthquakes [1].

In the objective analysis of the relative displacement extreme values, registered on the geodynamic polygon of Janowice Wielkie, there is taken into account the influence of both the distant and local earthquakes. Their registration is done before as well as after the occurrence of the perturbation period at the time of 1–1.5 month.

For the analysed geological structures within the geodynamic polygon of Janowice Wielkie, there is to be noticed one of the most essential perturbation period of the value of 0.400 mm, that is identified in the form of "data peaks" (Fig. 8).

The episode is defined by the initial and final date of its occurrence, the location of relevant earthquakes with their magnitude and registration period (Tab. 2).

Table 2. The list of relevant earthquakes for the most outstanding perturbation period (05.06.2003–20.09.2003), taking into account the value of the deformation

Earthqukake's date	Country	Magnitude	Geographical coordinates	
			φ	λ
31.05.2003	Dolny Śląsk	4.2	51.558 N	16.084 E
21.05.2003	Algieria	6.9	36.964 N	3.634 E
05.10.2003	Dolny Śląsk	4.8	51.517 N	16.201 E
25.09.2003	Hokkaido, Japonia	8.3	41.775 N	143.904 E
26.05.2003	Halmahera, Indonezja	7	2.410 N	128.810 E

Source: the study on the basis of the the Seismology Department of the Institute of Geophysics Polish Academy of Sciences and USGS web services

According to table 2 there could be noticed the dominant, potential influence of distant and strong earthquakes on the registered extreme relative displacement values. They do not constitute exact evidences for the increased geodynamic activity of the Intra-Sudetic Fault.

There is to be noticed in the observation data set the episodic period (June 2003 – September 2003), that could be interpreted as an after seismic effect or be determined by strong and distant earthquakes in Algeria and Indonesia.

At the same time, it should be paid attention to the high magnitude value, viz. 8.3 in the open-ended Richter Scale of the earthquake in Japan. It could be assumed, that it could be caused by the attainment of the earth's crust surface's deformation wave to the Intra-Sudetic Fault as well as rock blocks within the geodynamic polygon of Janowice Wielkie.

Besides this, there are also important to mention about the local earthquakes, registered twice during the analysed period in Lower Silesia. Despite the lower magnitude values in comparison to the earthquakes of distant epicenter, their influence on the extreme relative displacement values is more relevant [12].

For the reason of significant location distance of the main earthquakes' epicenters, which are relevant for the surveyed area, it could be assumed, that its geodynamic activity is mostly caused by aseismic factors. They are resulted from i.a. local changes in the Sudeten Massif, as well as the increased geodynamic activity of the adjacent tectonic-geological structures.

As far as periodic variations of the observation data sets (the TM-71 crack gauge) are concerned, the measuring instrument location plays an important role. If the TM-71 crack gauge is mounted outside, the periodicity is mostly strictly connected with the seasonal temperature variations [6].

Because of the fact, that there is an interior TM-71 crack gauge's mounting on the geodynamic polygon of Janowice Wielkie (the former uranium adit), the registered periodicity is not associated with the thermal changes. At the same time, there should be paid attention to the moisture variations, that potentially determine to a high degree the occurrence of the periodic variations in the measured values.

Besides the episodic and periodic variations in values of the analysed observation data sets (the geodynamic polygon of Janowice Wielkie), there should be noticed the relatively stable periods (February 2008 – April 2009), after which there are two perturbation periods of the lower extreme variations in values of the measuring data sets (Fig. 8).

6. Conclusions

The conducted analysis are accomplished out on the basis of the several years' relative observations with the TM-71 crack gauge on the geodynamic polygon of

Janowice Wielkie from October 2001 till November 2006. The analysed rock blocks in Janowice Wielkie are within the study area of the Intra-Sudetic Fault's contemporary mobility.

The statistical relative displacement analysis of the time series structure of the *dx*, *dy*, *dz* components allow to draw following conclusions:

- the linear trend of relative displacements in all directions (the *x*, *y*, *z* axis of the TM-71 crack gauge);
- the greatest residual values of the *dx* and *dy* components at the same time, that is from June 2003 till September 2003; it points out at the occurrence of detached observations in the analysed data sets;
- the stationary time series of the dy component, presenting the lack of periodic variations;
- the periodic time series of the *dx* and *dz* components.

The causal-consecutive analysis include the analysis of the extreme and periodic variations of the relative displacement values, measured on the Intra-Sudetic Fault.

There is identified the most relevant perturbation period (from 5th June 2003 till 20th September 2003) (Fig. 8). Its occurrence is associated with the influence of both the local (the magnitude's value of more than 3.0 in the open-ended Richter Scale) and the distant (magnitude's value of more than 6.0 in the open-ended Richter Scale) earthquakes.

At the same time, there is paid attention to the redistribution process of the strain within the earth's crust as a result of the increased geodynamic activity of the adjacent tectonic-geological structures and the possibility to occur some local strain changes in the Sudeten Massif.

The periodic variations of the relative displacement values are dominant among the analysed data sets. It could be assumed, that they are mainly determined by relevant moisture changes and not by thermal factors – it is connected with the interior TM-71 crack gauge's mounting on the geodynamic polygon of Janowice Wielkie.

However, the computation results of the relative displacement values, referred to the Intra-Sudetic Fault, indicate the dextral movement (the negative values of the dy component) of the surveyd rock blocks within the polygon of Janowice Wielkie.

The conducted analysis confirm the geodynamic activity of the adjacent to the Intra-Sudetic Fault tectonic-geological structures. At the same time they have an influence on its mobility, which is determined by both the endo- and exogenic factors.

References

[1] Cacoń S., Kontny B.: *System of survey,analysis and interpreattion of rocky blocks deformations in the mountains.* Proceedings of the 1st International Symposium FIG-IAG on Applications of Geodesy to Engineering, Stuttgart, Springer Verlag, Berlin – New York – Heidelberg 1993, pp. 157–165.

[2] Cacoń S., Mąkolski K.: *Współczesna geodynamika Karkonoszy w odniesieniu do Sudetów i obszarów przyległych*. [in:] Mierzejewski M.P. (Ed.), *Karkonosze. Przyroda nieożywiona i człowiek*, Wrocław 2005, pp. 306–321.

[3] Cymerman Z.: *Uskok śródsudecki a regionalne strefy ścinań podatnych w Sudetach.* Przegląd Geologiczny, nr 7, 1998, pp. 609–616.

[4] Jaroszewski W.: *Tektonika uskoków i fałdów.* Wyd. Geologiczne, Warszawa 1980.

[5] Klóska R., Hundert M., Czyżycki R.: *Wybrane zagadnienia z prognozowania.* ECONOMICUS, Szczecin 2007.

[6] Kontny B., Cacoń S., Košťák B., Stemberk J.: *Methodic analysis of data obtained by monitoring micro-tectonic movements with TM-71 crack gauges in the Polish Sudeten*. Acta Geodynamica Geomaterialia, vol. 2, no. 3 (139), 2005, pp. 57–67.

[7] Koronacki J., Mielniczuk J.: *Statystyka dla studentów kierunków technicznych i przyrodniczych.* WNT, Warszawa 2009.

[8] Košťák B.: *Combined indicator using moiré technique*. Balkema, Rotterdam 1991.

[9] Namysłowska-Wilczyńska B.: *Geostatystyka. Teoria i zastosowania.* Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2006.

[10] Rabczenko B., Wojtyniak B.: *Metody analizy szeregów czasowych w ocenie wpływu zanieczyszczeń powietrza atmosferycznego na umieralność ludzi.* Przegląd Epidemiologiczny, vol. 59, 2005, pp. 961–968.

[11] Sobczyk M.: *Statystyka.* Wyd. Nauk. PWN, 2008.

[12] Stemberk J., Košťák B., Cacoń S.: *A tectonic pressure pulse and increased geodynamic activity recorded from the long-term monitoring of faults in Europe*. Tectonophysics vol. 487, issue 1–4, 2010, pp. 1–12.

[13] Zuchiewicz W.: *Neotektonika Polski*. VI Ogólnopolska Konferencja "Neotektonika Polski" – "Aktywne uskoki Europy Środkowej", Srebrna Góra 26–28.09.2005.