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# TOWARD THE RELIABILITY OF GEODETIC SURVEYS IN STUDY OF GEODYNAMICS – A PROBLEM OF INFLUENCE OF SEASONAL VARIATIONS

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**ABSTRACT**
A study of displacements relating to geodynamical processes involves a use of accurate measurement equipment. Better and better accuracy of field surveys neglecting a survey environment can be insufficient in a reliable study. One of the environmental aspects is discussed in the paper. That is a geotechnical condition of a ground – an environment of benchmarks, which changes of position are observed in geodetic surveys. The conditions determine a ground stability affected by weather or geological processes. The main idea of the paper is to consider geotechnical and geological aspects in geodetic reasoning carried on the base of displacement analysis within a study of geodynamics.
There are presented examples illustrating the problem. The first relates to former levelling observations carried in an area of Wieliczka, well geologically surveyed due to mining activity in a salt deposit. There are presented results obtained on the base of a numerical analysis. The seasonal variations of benchmarks' heights are explained in a background of geology. The changes of ground properties induced by atmospheric conditions are suggested as the main cause of the displacements. The survey data processing provided values of displacements caused by seasonally expanding grounds. The second examples concerns ongoing observations in the area of Inowroclaw (located above the salt dome) bring similar variations of heights that can not be related to that cause. The estimated linear trend of height changes proves an uplift process of the salt dome.
Derived conclusions suggest a certain methodology helpful in reliable analysis of geodetic surveys. The conclusions prove that geodetic surveys carried out for investigations of displacements in geodynamics require quite extensive geological data.

**KEYWORDS:** levelling, salt dome geodynamics, seasonal displacements

## 1. INTRODUCTION

The presented paper deals with a problem of a seasonal height changes and their possible influence in estimation of displacements in geodetic studies. This problem was discussed in numerous papers (Madej, 1971; Wolski, 1996; Nicolas, et al., 2004), usually in aspects of geotechnics or installation procedures of benchmarks to provide them as free from ground movements. The influence of shallow factors (as shallow ground water migration, expansive soils etc.) on displacement process of the terrain surface seems to be underestimated in a study of geodynamics. It seems probable that there is no installation technique providing a perfect stability of benchmarks, especially when they are drilled in the ground. Effects of shallow geological or geotechnical factors affecting a displacement process induced by deep geodynamical causes can be expected in any location. A certain methodology in geodetic surveys is needed to filter these effects to derive reliable conclusions in estimation of displacements caused by geodynamical processes.

The presented paper suggests an approach in identification of shallow and deep factors affecting the terrain surface.

There are results obtained from two test fields (Wieliczka and Inowroclaw), where levelling observations were carried out periodically for several years. In the both cases areas of investigations are located over a salt deposits exploited by underground mining methods in the past. Some analysed displacements occurring there could be affected by post mining or subrosion process (in Wieliczka) but most of the benchmarks are located in the areas free of that influence. However, the values of vertical displacements demonstrate uplift and subsidence with seasonal variations. Some displacements can be related with seasonal changes of ground properties as a result of atmospheric or shallow geological process influences. The presented numerical analysis of the displacements enables estimation parameters of the seasonal effects. A noticeable linear tendency in the process of height changes in Inowroclaw can be explained on the base of uplift process of the salt structure. An elimination of seasonal effects enables to estimate a reliable rate of the process.

## 2. BACKGROUND INFORMATION AND SURVEY RESULTS OF THE TEST FIELD IN WIELICZKA

The analysed field is located just behind the northern boundary of the salt deposit, on a hillside of the Cloister Hill (Fig. 1). That area was affected by ground deformations caused by water inflow into a Wieliczka Salt Mine excavation (the Mina heading)

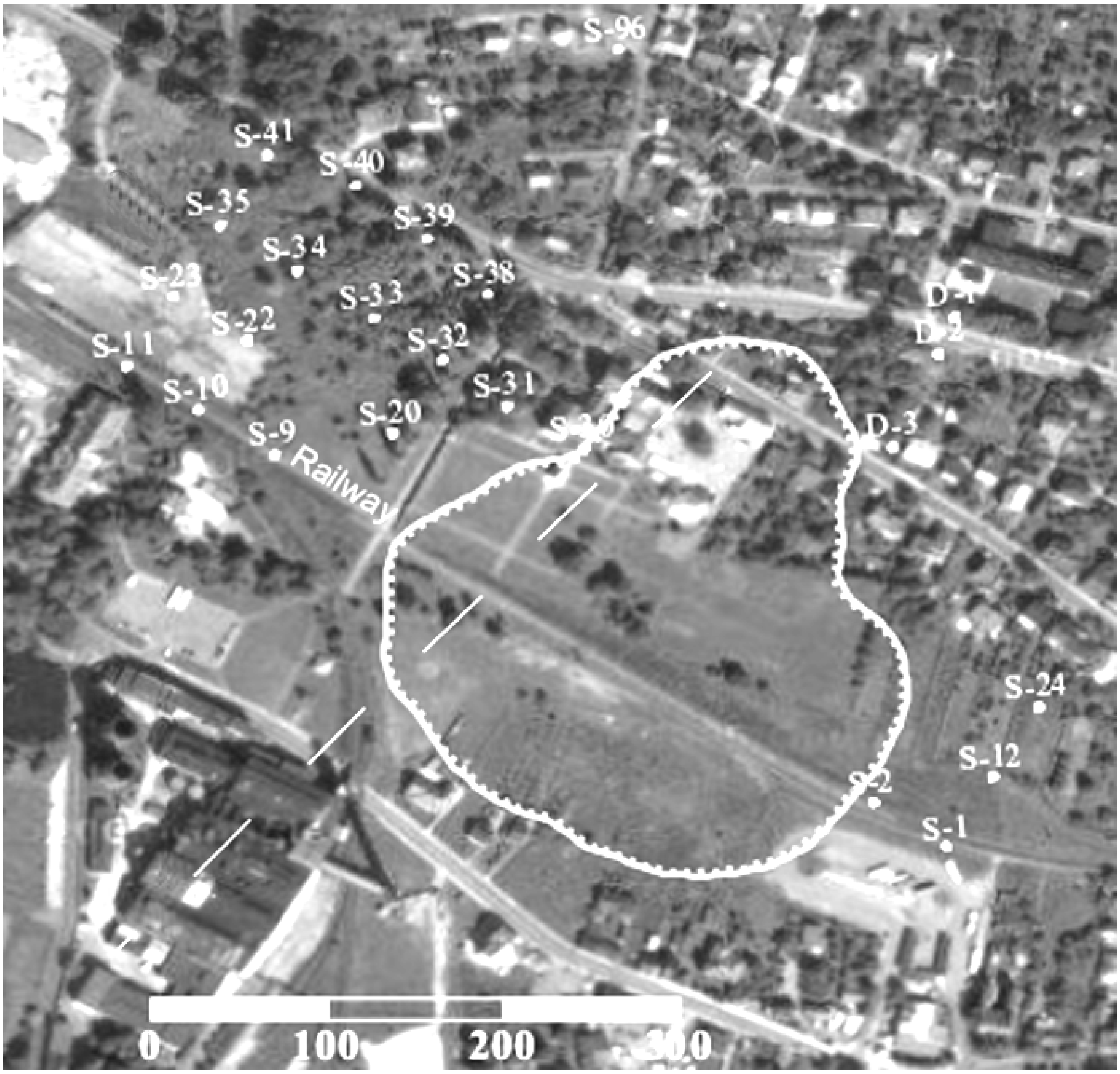


**Fig. 1** The Serafa valley and the Cloister Hill in Wieliczka. Localization of surveyed benchmarks and a boundary of a subsidence bowl caused by water inflow into the Mina heading (white closed line). Dash line represents a localization of the cross section mentioned in the text.

in 1992-1995. The underground water penetrated cap rocks at the northern boundary of the salt body and it initiated a subrosion. A subsidence bowl occurred on the terrain surface as an effect of this deformation process. Intensive geological and geodetic surveys carried out by years provided a lot of information about a detail geological situation and a proceeding of the deformation process. Levelling surveys were carried during over 30 campaigns: in week, month and other periods. Firstly, a regular network of over 50 benchmarks (grounded about 1.5 m deep and every 50 m) was established on the affected area but subsequently it became extended (Szewczyk, 1995). The first survey campaign was 2$^{nd}$ June 1992 and during all campaigns the height error of a single point amounted from ±0.5 mm to ±1.5 mm (Szewczyk, 1995).

A quite complicated geology of the area is illustrated by a crossection in Figure 2. The Chodenice beds formed as sandstones and claystones are dominant formations making a contact (probably a tectonic one) with salt deposit. The outer part of the deposit is made from gypsum cap rocks. The rocks located at the contact of the salt deposit are considered by geologists as deteriorated, and easily penetrated by water migration. The overlying ground is a kind of reflection of deeper rocks: a mixture of sands and clay makes geotechnical conditions difficult for any building action. So, the main elements are waste grounds with places of blind drainage. The most

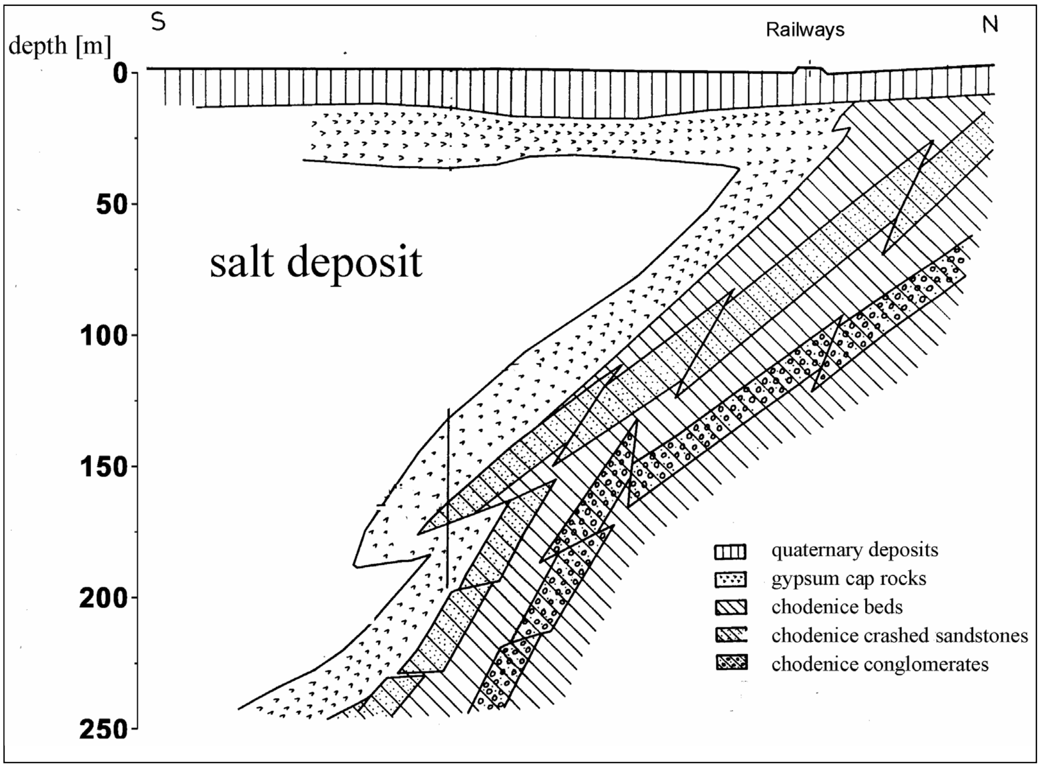


**Fig. 2** Cross-section in vicinity of the Mina (according to Jaworski et al., 1994, modified).

significant urban feature of the test field is monumental building of a cloister being located at the top part of the valley. Railways and a parking place are located at the southern part of the field (Fig. 1). The other part of an area behind is typically urban. Most of the analyzed benchmarks are located behind the boundary of the salt deposit and behind an area of mining influence.

The height changes between following campaigns were analyzed as a result of the surveys to estimate deformations carrying the risks for buildings around (the railway was closed). After years the results were studied again but in this case – jointly (i.e. result of all surveys were put into the analysis). The distribution of benchmark's heights in time looks as a temporal propagation of a signal.

The Figure 3 presents the height changes of analyzed benchmarks. The zero value (in meters) was presumed as the benchmarks' starting height obtained during the initial surveys (2$^{nd}$ June 1992). The rises and falls of heights reveal as sinusoidal course but in several cases a linear or polynomial trend is evident. So, both polynomials of various orders and linear functions were tested in a detrend procedure. A numerical analysis of this distribution is presented further on.

## 3. BACKGROUND INFORMATION AND SURVEY RESULTS OF THE TEST FIELD IN INOWROCLAW

The discussed conclusions were evaluated by three surveying campaigns carried out in the area of Inowroclaw. This is a particular area in mining and geological aspects. Although the area is concerned as post mining (salt mining), there are still terrain surface displacements observed. The salt dome deposit is a specific geological structure with a terrain surface being affected by diapirism (uplift) and hydrogeological processes (subsidence). Affecting processes and former mining influence make a specific combination case forming the topography of this quite small area - a few square kilometres (Fig. 4).

The periodic levelling surveys between a reference benchmark and benchmarks grounded around the Church of the Annunciation of Virgin Mary have been carried quite regularly by years (Szczerbowski, 2004). Localization of the studied area is presented in Figure 4 and Figure 5. Main purpose of the surveys is a monitoring of the performance and behaviour of this historical building and its surroundings. The church construction was affected by old mining and natural processes and still ongoing surveys are carried for renovation purposes.

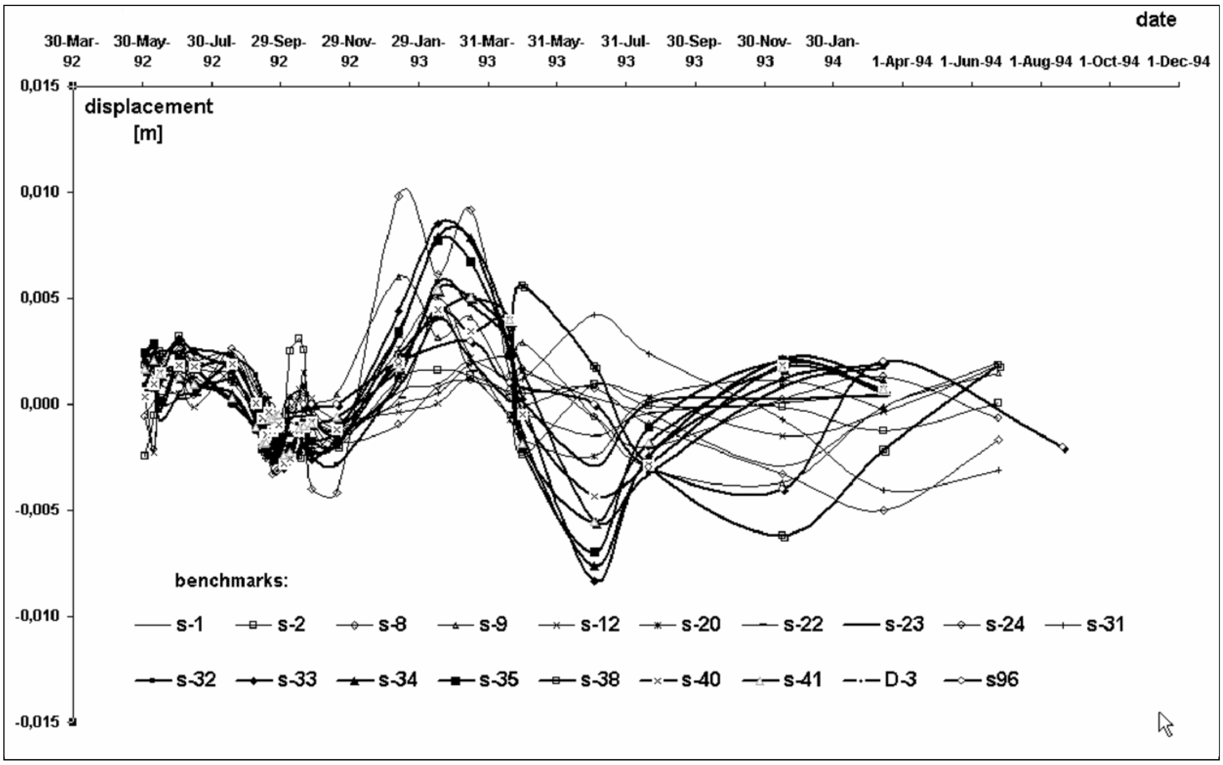


**Fig. 3** The vertical displacements of the benchmarks on the test field in Wieliczka.


**Fig. 4** Inowroclaw. Localization of the test field, mining excavations and a boundary of the salt deposit.

The surveys characterize high accuracy - the height error of a single point is about ±1 mm. The levelling reference measurement concern wall and ground benchmarks located at the survey line that is SW-NE orientated and nearly perpendicularly to north-eastern boundary of the salt deposit.

Geological situation of the test field is quite simple. The part of the analyzed line is over a Permian salt deposit that is being formed as a dome lying 120-190 m below the terrain surface. Both eastern and western sides of the salt structure are seated steeply or even upright (the eastern part). The boundary of the salt deposit in the test field is just below the benchmark GPS2.

Permian salt is surrounded by crushed Jurassic complex which is divided into western permeable sandy rocks and eastern carbonates (dolomites, limestones and marls). Cap rocks are located at a contact between Jurassic or Permian formations and they overlay the salt structure. Gypsum cap rock and gypsum-clay cap rock characterize a different permeability and it makes the main cause of diversity of karst phenomena distributions as sinkholes or caves – most of them occurred in the western part of the city. So, it can be assumed that the analyzed area, which is located at the eastern part of the deposit, is in general free of karst phenomena or erosional processes. The top deposits covering the salt body are post glacial moraines with changeable thickness (from few to 70 m) and the Holocene sands (not significant). The low porosity of those deposits permits only limited transmission of groundwater. That's the main difference between ground conditions in the analyzed areas: there are no significant shallow groundwater layers in the test area in Inowroclaw.

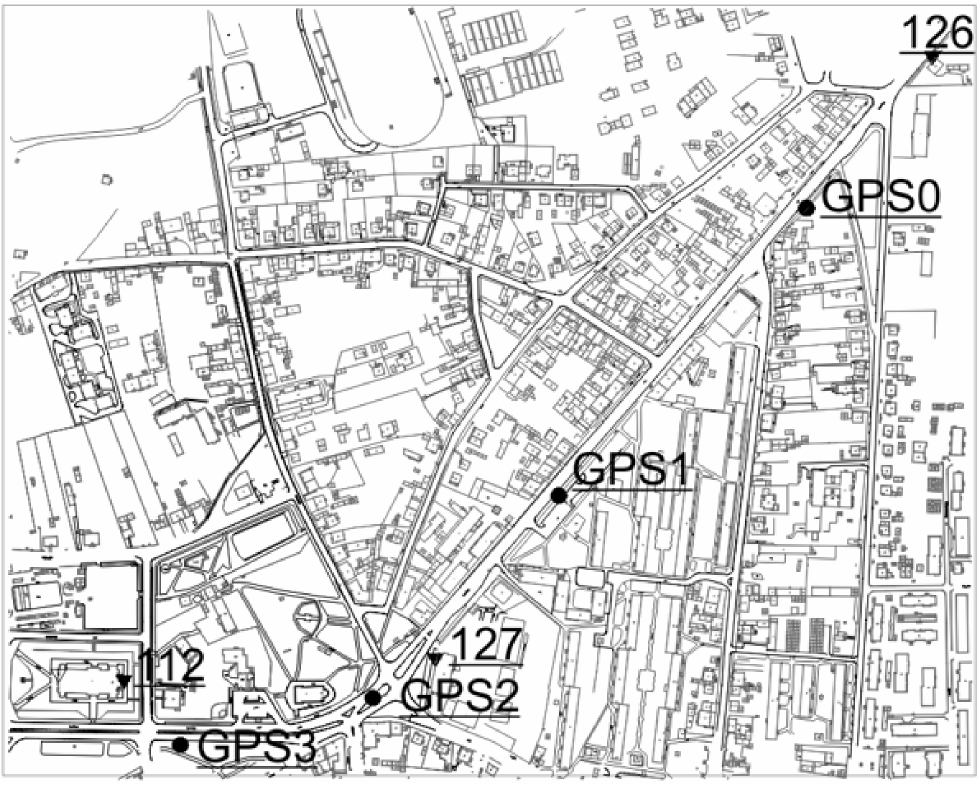


**Fig. 5** The localization of benchmarks of the 126-112 survey line in Inowroclaw.

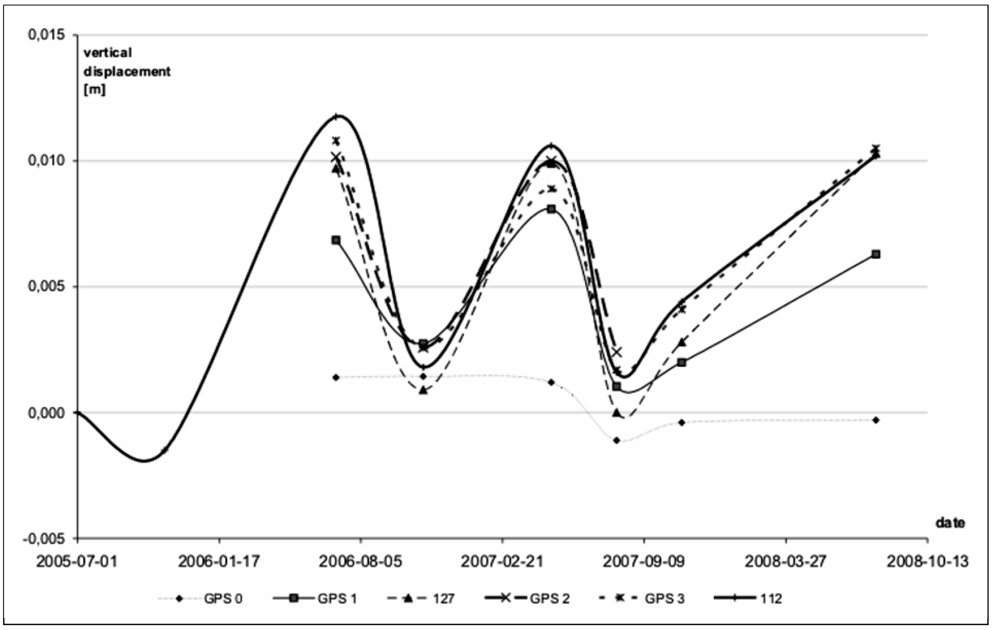


**Fig. 6** The vertical displacements of benchmarks of the 126-112 line.

The wall and ground benchmarks (including the 126 reference point) are placed along a survey line that passes the boundary of the salt deposit and an area of the old mining influences (Fig. 5). But all mining excavations in Inowroclaw were flooded due to the Solno mine closure in 1991. Presently both uplifts and subsidence (not significant) in various areas of the city are observed. The annual rate of the process is a few millimetres and the city area is regarded as a free of post mining influences. There was not so many survey campaigns as it was in the Wieliczka test field, what's more there were carried only 2-3 times a year. In some cases the vertical displacements obtained by spirit levelling were confirmed by GPS observations that were carried once a year (Szczerbowski, 2007).

The height changes of the benchmarks located along the 126-112 line are presented in Figure 6. This

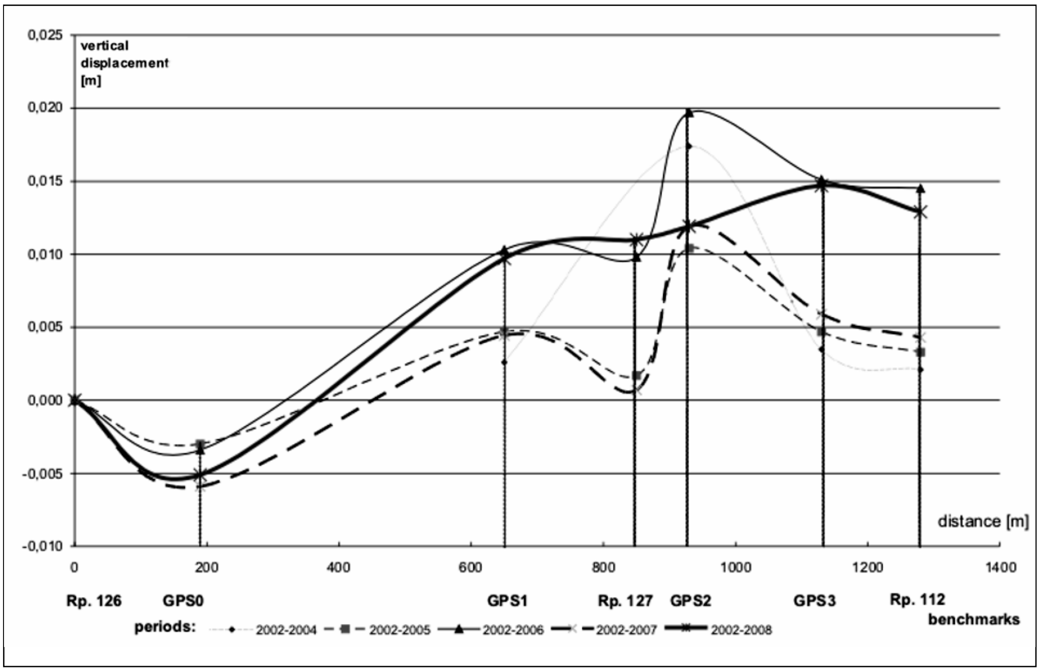


**Fig. 7** The vertical displacements of the 126-112 line in various time periods.

distribution remaining a sinusoidal course looks as a common error resulted from an instability of reference benchmark. The displacements can be illustrated in a different way showing that there is another reason of their characteristic. Another graph presents vertical movements of the profile line passing the benchmarks (Fig. 7). This outline emphasizes displacements of the control points accordingly to their distance of the salt dome.

## 4. ANALYSIS OF THE SURVEY DATA

Presented analysis is based on an assumption that variations of the observed height changes are not accidental and there are deterministic components in distributions of benchmark displacements. The real physical model of the changes is hard to obtain because of hidden factors but it can be estimated by presumed function that respects sequences of uplift and subsidence. Since the data hadn't been taken at equally spaced time intervals, time series analysis couldn't be considered. The approximation of the height changes distribution by sine function was used as a simple method that could prove certain regularity in observed values. The basic aim of the presented analysis is to prove that consistent increases and decreases of observed heights are not random, quite regular and they are a representation of a model with parameters that could be estimated. This numerical model should describe sequences of measurements with a characteristic of the data that consist of a systematic pattern. It will make an opportunity to achieve other goals of the analysis:

(a) identifying the nature of the phenomenon represented by the sequence of observations,

(b) forecasting (predicting future values of the height changes).

Insufficient data enables only to make initial identification of the causes inducing the discussed vertical displacements. Reliable prediction of future movements will be possible with a collection of results of observations carried out by years.

### *4.1. NUMERICAL PROCEDURES*

The distribution of height changes is sinusoidal but there are benchmarks demonstrating displacements with a general systematic linear component. This steady reduction or increase of height values over time is a subsidence induced by post mining or influence of deep geological processes. Non-linear component can be regarded as seasonal influence of unknown factors.

A linear trend being observable in many cases was estimated by fitting procedure of a linear function. Consequently after removal of the trend values the displacements amounted to values that were free of a general tendency representing a different processes. The final effect of the numerical analysis was a collection of the function parameters.

Because of trend elimination there is no vertical offset of the data and the formula of analyzed sine function is as follows:

$$y = a \cdot \sin\left(\frac{2\pi \cdot x}{c} + b\right)$$

which describes a wave-like function of time (x) with:

*a* - peak deviation from center – amplitude (distance a point oscillates up and down), in presented analysis the distance is in mm;

*b* - phase, the fraction of a complete cycle corresponding to an offset in the displacement from a specified reference point at time x = 0 (in days);

*c* - wavelength (the length of each cycle – a number of days).

Coefficient of determination ($R^2$) was examined as a measure of fit of the model. It reflects the goodness of fit of the model relationship between the dependent and independent variables:

$$R^2 = 1 - \frac{SSE}{SSM}$$

where *SSE* - Sum of Squares due to Error (Sum of Residuals Squared), *SSM*- Sum of Squares about Mean.

The numerical analysis of displacements was carried with the use of various options specifying the fitting procedures (Least-squares fitting or Robust methods) to obtain the highest value of coefficient of determination. Although high $R^2$ value does not guarantee that the model fits the data well, it is regarded as a useful measure of the goodness of fit in statistics.

The sine function fitting procedure involves an elimination of a linear component (detrend data). After this removal where the values fluctuate about zero and it is possible to fit sine function to obtain its parameters for all analyzed cases. Hence, the analysis involves the following steps:

1. Fit a trend line to the data, using least squares regression.
2. Detrend the data by subtracting the trend component from the data.
3. Fit a sine function.
4. Examination of the residuals.
5. Examination of the obtained parameters and residuals of the fitting process.

Extracted residuals were to examine their statistical properties. The following methods enable estimation of the trend and the seasonal components. Observed sinusoidal characteristic of the height changes (vertical displacements) is obvious in the most cases, so a basic assumption was that the distributions can be approximated by Sine function.

Time series analysis, being a typical statistical method, requires quite numerous data points, measured typically at successive times, spaced at usually uniform time intervals. So, in fact that limitation precluded time series analysis in the presented study. However, undertaken approach considered as an initial and to present a sense of frequent geodetic observations for a study of geological processes.

### *4.2. WIELICZKA TEST FIELD*

The number of selected benchmarks that satisfied assumption of the analysis was 25. They were points measured in all campaigns and obviously located behind mining or subrosion influence. Distributions of point height changes of the points in the Wieliczka test area were used in trend adjustment as the first step of the analysis. Both 6$^{th}$ order polynomial and linear function were used to detrend data. Nevertheless, most of the examined data values fluctuated around zero. The estimated values of the linear trend represent the tendency in vertical displacements and they are not really significant. The average rate of the displacements is -4 mm/year (extremely – -13 mm/year). The non-linear trend characterizes a polynomial appearance with decreasing values. It can be considered as something between linear dependency caused by “for all time” existing factor and “seasonally” changing factor.

The detrended data were used to determine parameters of sine function representing non-random long term cyclic influence. The number of points do not allow to present single results of the analysis. So, Tab.1 presents average values of the estimated parameters and relative frequencies for categorized values of each parameter. The examination of residuals from a fitted model was the first step in analysis of the sine model validation. The obtained values of residuals revealed a random structure, so the next analysis concerned estimated coefficients of determination for each distribution of displacements.

The average value of obtained coefficients of determination amounted to 0.60, what is interpreted in statistics as a model strongly representing data. Several data demonstrated week dependency ($R^2$ was about 0.35) but in most cases $R^2$ value was between 0.55 − 0.70.

It must be emphasized that presented values of displacements are close to error of measurements, so the estimated parameters should not be analyzed strictly in a numerical sense. However, most of them amount to average values presented in Table 1. Most likely real errors are higher than statistical but a certain tendency is clear and more important is a physical sense following from obtained values. Parameter *a* show ground condition i.e. its susceptibility to react to a seasonal factor influence. In presented analysis the values of the parameter are between 1 mm to 5 mm. It means that there are points displacing even 10 mm per cycle. The average value 2 mm is not really significant but it must be considered in certain studies based on precise levelling surveys. The length of this cycle is expressed in a value the *c* parameter. The most of points demonstrated an annual or nearly annual time period of the cycle changes. According to the most estimated values of phase *b* expressing the start of point displacements this moment is a beginning of wintertime (the end of December). No point revealed the start of a cycle in

**Table 1** Average values of the estimated parameters of sine function fitted to the data from Wieliczka test field.

| parameter | categories of the data | percentages of total number | average value |
|---|---|---|---|
| | a <= 0.001 | 8.3 | |
| | 0.001 < a <= 0.002 | 41.7 | |
| *a* | 0.002 < a <= 0.003 | 16.7 | 0.002 |
| | 0.003 < a <= 0.004 | 25.0 | |
| | 0.004 < a | 8.3 | |
| | b <= 60 | 12.5 | |
| | 60 < b <= 120 | 12.5 | |
| | 120 < b <= 180 | 62.5 | |
| *b* | 180 < b <= 240 | 0.0 | 159 |
| | 240 < b <= 300 | 0.0 | |
| | 300 < b <= 360 | 4.2 | |
| | 360 < b | 8.3 | |
| | c <=245 | 8.3 | |
| | 245 < c <= 270 | 0.0 | |
| | 270 < c <= 295 | 0.0 | |
| | 295 < c <= 320 | 0.0 | |
| *c* | 320 < c <= 345 | 8.3 | 370 |
| | 345 < c <= 370 | 29.2 | |
| | 370 < c <= 395 | 25.0 | |
| | 395 < c | 29.2 | |

summer or in autumn time. Considering the phase and cycle values presented in Table 1 and their dispersion it can be pointed out that obtained results are quite unambiguous. It shows that the survey results are strongly related with the seasons even when the values of displacements are not really significant. What's more, high statistical dispersion of the *a* values shows the particular actions of each point in the specific time periods. So, this characteristic and the number of points enable a spatial data analysis of distribution of this parameter. Fig. 8 presents a base map with contours illustrating the distribution of amplitudes (*a)*. The distribution doesn't appear to behave randomly; it suggests that there is a relation between the amplitude and a location of the points. The maximum value is located on the top of the slope and at its bottom (the Serafa valley).

### *4.3. INOWROCŁAW TEST FIELD*

Few points of the survey line in Inowroclaw test area demonstrate specific vertical displacements. The sinusoidal oscillations of displacements around a trend line are clear in the most cases (Fig. 6). Anyway estimation of the trend enables characterization of such oscillation but the analysis concerns quite small values and it could bring ambiguous results. So, any assessment should be drawn with caution. Therefore many fitting procedures were tested in the carried out numerical analysis to derive the most probable values of parameters. The linear trend was important in the analysis of the both test fields but Inowroclaw is a specific area due to expected displacements caused by halokinesis process. The linear trend coefficient shows in fact a rate of displacements that can be identified with effects of deep geological processes (systematic component). The Table 2 illustrates annual values of the rates derived from the trend analysis. Two features of their distribution are noticeable: all of them are positive (uplift displacements) and the rate values decrease accordingly to a distance of the salt deposit.

Although the number of analyzed points and the number of surveys were much fewer than in the former analysis, the obtained coefficients of determinant of detrended data were high. They ranged from 0.72 to 0.90. Hence these values and normality of errors illustrate a strong relationship between the model and the data. A collation of the parameter and elevations of the points are presented graphically as a chart in Figure 9. The visible relation between the both distribution lines suggests that existing relief is strongly affected by the uplift process. Although the values of the rates and their differences are small they are very probable. The obtained values of the Sine function parameters are presented in Table 3.

The values of *c* are quite distinctive. The parameter shows that the period of changes is not annual as in previous examples. Moreover, values of *b* denote that the starting moment of the changes is in the middle of summer time. The amplitude of height


**Fig. 8** The distribution of amplitudes (a).

**Table 2** Average values of the estimated linear trend parameter of the vertical displacements in Inowroclaw test field.

| | Benchmarks | | | | |
|---|---|---|---|---|---|
| | GPS1 | 127 | GPS2 | GPS3 | 112 |
| *Rate [mm/year]* | 0.0005 | 0.0016 | 0.001 | 0.0016 | 0.0026 |

**Table 3** Average values of the estimated parameters of sine function fitted to the data from Inowroclaw test field.

| Parameter | Benchmarks | | | | |
|---|---|---|---|---|---|
| | GPS1 | 127 | GPS2 | GPS3 | 112 |
| *a [mm]* | 0.0030 | 0.0045 | 0.0042 | 0.0040 | 0.0045 |
| *b [days]* | 34 | 18 | 29 | 28 | 39 |
| *c [days]* | 270 | 270 | 278 | 268 | 270 |

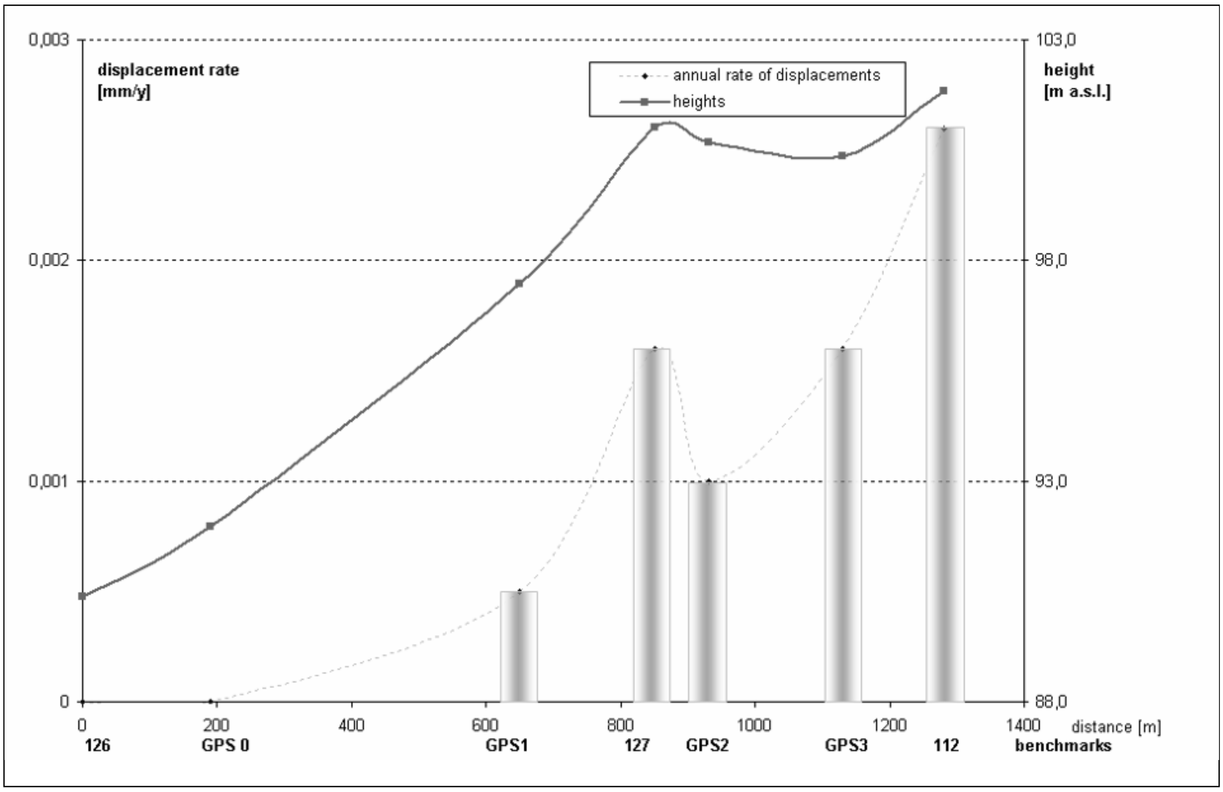


**Fig. 9** The vertical displacement rates of the benchmarks of the 126-112 line and topographical profile of the line.

changes oscillates between 3.0 and 4.5 mm. Generally, the values are equal. They don't increase clearly along the profile accordingly to the location of the salt dome as annual rates of displacements. Furthermore, the 127 and the 112 points placed in huge building demonstrate a high values as ground benchmarks being usually strongly affected by shallow geological factors or seasonal changes of ground physical properties. It shows that the grounding method doesn't affect the results.

## 5. CONCLUSIONS

Most of the presented data obtained in two different test areas demonstrate seasonal variations of height changes with a regularity of displacements that can be estimated by a linear trend and wave function (sine). Obtained results - values of the sine function parameters - enabled to drawn some conclusions.

Remarks concerning the test area in Wieliczka suggest that dominating value of estimated period of the function sine (parameter *c*) is an annual cycle and the amplitude of seasonal height changes (parameter *a)* amounts to 7 mm. Most of estimated values of the parameter *b* show that a process of seasonal displacements starts in December. It can be presumed that ground activity (expansions and shrinkages) starts in that time.

A spatial distribution of analyzed parameters was possible only for test field 1. The most essential is parameter *a* as that one having a physical sense – it denote a ground mobility. Of course such an analysis has a general sense but obviously the locations of the highest values of the parameter *a* are not accidental. In the most cases all derived values of the sine function parameters in Wieliczka test field point out seasonal effects related to ground condition.

Results obtained from the test area in Inowroclaw have a different sense. Although the number of analyzed points was fewer than in Wieliczka test area, their linear location along near 1 km long line allows investigation of larger area. In this case the parameter *a* is less than before and its average value 271 days doesn't correspond to annual period as before. This shows that seasonal changes have a different cause than weather conditions of the area. The amplitude of height changes amounts to 4 mm and the displacement process starts in the end of spring time. The process of ongoing alternately uplifts and subsidences is systematic and there is no other influence to displacements of benchmarks than effects of deep geological structures. This remark concerns as well benchmarks being grounded in walls of large buildings with deep foundations (as presented benchmark 127).

Unfortunately, a number of points and a number of observations in the Inowroclaw test area were fewer but the evaluated values of $R^2$ demonstrate a high goodness of fit. Although, the calculated values of parameters are very probable, they are strongly depended on time of measurements and they should be considered as having a general sense. More accurate values of the analysis will be possible after more survey campaigns. Nevertheless, the initial results are quite remarkable. The main feature of the displacement variations is that the changes don't reveal in annual periods. What's more evaluated linear trend coefficients correspond to the location of the benchmarks in relation to the salt deposit boundary and the distribution of the values relates to the point elevations. The distributions of the parameter and their positive values obviously demonstrate the uplift process of the salt dome. By the way, the area of Inowroclaw demonstrates a diversity of vertical displacements in a spatial distribution as well: there are uplifting and subsidizing sites and this process of movements corresponds to a geological activity of the salt structure (Szczerbowski, 2004).

Presented analysis is informal and obtained values do not demonstrate a strict characteristic of the ground movements. It must be considered that a change of survey frequency could affect the values of the parameters. Anyway they show certain regularity in general view. This regularity is a periodic pattern of height changes, where alternate uplift and subsidence is predictable. The determination of precise values of model parameters needs long-term and frequent observations. The discussed test field in Inowroclaw is a part of a research area for ongoing and henceforward observations of the terrain surface displacements.

## 6. SUMMARY

Repeated, precise levelling surveys provided reliable information about vertical displacements of benchmarks that can be caused both by deep geological processes and natural, seasonal changes of geotechnical properties of ground.

Tectonic movements can be detected with the use of geodetic surveys based on long-term and frequently carried observations of the stabile benchmarks. The simplest method that estimates seasonal height changes is a fitting procedure with a use of sine function. This function was presumed in the presented analysis because of its parameters having a physical sense. Having long-term observations carried out in equal time intervals a time series analysis is suggested as well. The most important is amplitude and period that characterize ground susceptibility to seasonal vertical expansion. So, by this means geodetic survey results bring physical information about a ground environment. The linear trend of displacements can be considered as a tectonically induced process (free of seasonal effects).

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