THE PROBLEM OF VALIDITY OF BENCHMARK ELEVATIONS FOR GENERAL ENGINEERING TASKS IN URBANISED AREAS ON THE EXAMPLE OF VERTICAL NETWORK IN THE CITY OF WROCLAW

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ABSTRACT

To carry out many surveying operations, one requires, apart from location determined in horizontal plane also elevation of selected points in a project. In the case of work realised over a large area, particularly if the object to be measured is of elongated shape, these tasks are performed in relation to a greater number of national network benchmarks. At that point control of benchmarks locations in relation to one another and determination of the most reliable reference frame for surveying tasks are required. The need to carry out such control will be proved in this paper on the example of historical changes of benchmark ordinates of vertical network in the city of Wroclaw.

1. INTRODUCTION

Correctly realised geodetic surveys depend on high accuracy of measurements, high professional qualifications of contractors and, first and foremost, adequately accurate and valid geodetic control network used for those surveys. The validity of geodetic network, particularly the vertical one, is of particular importance in case of measuring large and elongated objects for site construction and inventory purposes. The need to tie such measurements to a greater number of benchmarks requires control of their location in relation to one another. Exception to this rule may cause errors that are very costly and sometimes impossible to correct. Permanence of benchmark locations relative to one another acquires particular significance in geodetic surveys aimed at determining vertical movements. In such a case, a good rule is to use existing elevation control points for establishing a fixed reference frame. One may then investigate their relative stability in earlier periods of time. The subject of this paper concerns analysis of benchmarks elevations changes located inside the Wroclaw city limits.

2. POTENTIAL CAUSES FOR VERTICAL MOVEMENTS OF SURFACE IN WROCLAW AREA

The problem of elevation changes in the Wroclaw area has already been raised many times in literature. The main tasks of these research works focused on identifying causes

of surface deformations within the city limits. Analyses were carried out independently for the 1930-1968 (*Ferenc, 1979*) and 1968-1998 (*Grzempowski, Cacoń, 2005*) periods in comparison to various reference frames and for different sets of benchmarks. Accomplished, till that time, research works (*Ferenc, 1979; Grzempowski, Cacoń, 2005*) have shown vertical movements from +10 to –30 mm for the 1930-1968 period and from +24 mm to –69 mm for the 1968 – 1998 period.

The analysis of benchmarks elevations changes for the 1930-1968 period carried out by Ferenc had shown correlation between vertical changes of benchmarks and geological and geo-engineering conditions in the Wroclaw area. He has found that benchmarks set on buildings constructed on Pliocene loams and thin Quaternary deposits showed the smallest movements. Whereas benchmarks located in areas of fluvial accumulations with high fluctuations of ground water level and thick Holocene deposits experienced the greatest movements. Between 1968 and 1998 the values of vertical movements of benchmarks have increased twofold and the main reason for that was drawing up of underground waters from layers isolated by loams and clays. Construction works influenced these changes of benchmark elevations to a lesser extent (the analysed benchmarks are mostly points fixed on buildings with solid foundations). No significant effect of the 1997 flood has been found. Vertical movements of benchmarks located on flooded areas have not differed noticeably from those in areas unaffected by flood. It has been found basing on analysis of elevation changes of vertical control points and benchmarks located on buildings near these vertical control points, that vertical movements of the surface resulted from deformations of deeper ground layers (15 to 20 m below).

In addition to that, looking at a period of several dozen of years, tectonic movements of sub-Cainozoic stratum may also contribute to vertical movements of surface in Wroclaw area The city lies on the Foresudetic Monocline close to the Foresudetic Block, the units separated by the Middle Odra Fault Zone. The analysis of vertical movements of benchmarks along national levelling lines in the Wroclaw part of the Middle Odra Fault Zone is a subject of a separate study by an interdisciplinary group of specialists.

3. DETERMINATION OF CHANGES OF BENCHMARKS ELEVATIONS AND RATES OF CHANGES BETWEEN 1930 AND 1998 FOR THE AREA OF WROCLAW

3.1 Characteristics of archival materials used in the studies

Vertical movements of points as well as rate of surface vertical movements in Wroclaw has been determined analysing ordinates from the following archival materials:

- **Catalogue of elevation points from the year 1932 containing 1766 benchmarks with elevations established basing on measurements from the 1929-1930 period,**
- **Catalogue of elevation points from the year 1978 containing 2370 benchmarks with elevations established basing on measurements carried out between 1968 and 1977,**
- **Catalogue of elevation points from the year 1998 containing 2032 benchmarks with elevations established from measurements realised in 1998.**

The 1932 catalogue does not contain information on the accuracy of vertical network measured. Ferenc (1979), basing on archival reports, states that the mean error of measurement is close to the mean error obtained for the next period of measurements.

Between 1968 and 1971 the vertical network within the city limits of that time, was measured again. The network's accuracy characterised by mean error after adjustment was ±2.7 mm/km. From 1971 till 1977 the remaining part of vertical network in peripheral districts has been measured. The ordinates of benchmarks measured in the 1971-1975 period are not comparative material of this study.

The accuracy of network measured in 1998 is characterised by mean error after adjustment of ±1.4 mm/km (Szczepanski, 2003).

With the aim to determine surface movements and their rates for the 1930-1998 period 320 benchmarks that had been included in vertical network and measured between 1929-1930, 1968-1971 and in year 1998, have been selected.

3.2 Analysis of catalogue data applicability for calculating the rate of vertical movements

The analysis of vertical movements of points basing on catalogue ordinates is dictated by the lack of field measurements from the 1929-1930 period and changes of levelling lines routes in successive periods of measurements. Corrections for random errors of network measurements and control points errors tying the network had to be included in the adjustment. The catalogue values of benchmarks ordinates had been calculated using different adjustment methods and in relation to various reference points. This undoubtedly affects the values of determined vertical movements of benchmarks. The measured elevation differences were compared with values calculated from catalogue ordinates to test the effect of adjustments on elevation changes. The results for measurements realised in 1968 and 1998 are presented in Tables 1 and 2. The elevation differences were established between benchmarks located at extreme ends of a vertical network tied by levelling lines extending in the S-N and W–E directions with lengths of lines equal to 25 and 30 km respectively.

The measured elevation differences and the ones calculated from benchmark ordinates differ by 2 t 3 mm for the 1968-1971 measurements (Table 1) and by 12 to 14 mm for the measurements in 1998 (Table 2). The differences fall within the limits of accuracy for 3rd class levelling surveys that is ± 4 mm/km.

Table 1. Comparison of measured elevation differences and differences calculated from catalogue elevations for the 1968 measurements.

From benchmark	To benchmark	Measured Δh	l [km]	H_{from}	H_{to}	$\Delta h_k = H_{from} - H_{to}$	$\Delta h - \Delta h_k$	4mm/km * $\sqrt{L}$
3311007	3441004	-12,388	30,5	130,708	118,318	-12,390	0,002	±0,022
3141025	1121056	15,021	25,0	116,705	131,723	15,018	0,003	±0,020

Table 2. Comparison of measured elevation differences and differences calculated from catalogue elevations for the 1998 measurements.

From benchmark	To benchmark	Measured Δh	l [km]	H_{from}	H_{to}	$\Delta h_k = H_{from} - H_{to}$	$\Delta h - \Delta h_k$	4mm/km $* \sqrt{L}$
3311007	3441004	-12,419	28,9	130,716	118,311	-12,405	-0,014	±0,022
3141025	1121056	15,026	23,0	116,706	131,744	15,038	-0,012	±0,019

The accuracy of calculated elevation differences not exceeding ± 4 mm/km is adequate to determine movements with expected value of several centimetres.

3.3 Calculation of vertical movements and their rates

No stable reference frame could be used to determine vertical movements of benchmarks in the Wroclaw network. Therefore, movements have been calculated with reference to one benchmark located in the southwest part of the city. This point met the assumption that the movements calculated in relation to it will not be positive. However, it must be stated that close to this benchmark a group of points with similar movement values is located. Therefore, it is not an isolated case. Results of previous studies of vertical movement in the Wroclaw city limits (*Ferenc, 1979; Grzempowski, Cacoń, 2005*) and currently carried out in the Middle Odra Fault Zone (the analysis of vertical movements of benchmarks along national levelling lines in the Wroclaw fragment of Middle Odra Fault Zone is the subject of a separate work by interdisciplinary group of specialists) indicate subsidence of the whole area of the city in relation to adjacent areas.

To determine relative vertical movements, the elevation difference between the reference benchmark to the remaining benchmarks have been calculated separately for 1930, 1968 and 1998 measurements. Next, changes of elevation differences and vertical movements from 1930 till 1998 and from 1968 till 1998 have been calculated. Rates have been determined assuming linear relationship between movement and time as a quotient of movement and period of its incidence.Average rate of vertical movements for the 1930-1998 period amounted to –0.6 mm/year and standard deviation to 0,25 mm/year (maximally –1,5 mm/year). This means that for 68% of points the rates fall within the -0.35 to -0.85 mm/year limits (Fig. 1).

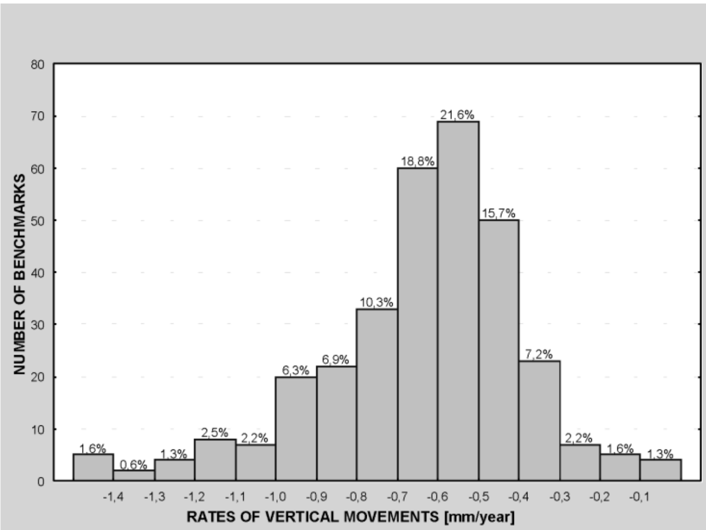

Fig. 1. Histogram of vertical movements rates determined for the 1930 to 1998 period.

The most intense changes for the period of 68 years occurred in area extending from the southern districts of the city through its centre and towards northeast. These changes have reached between –0,8 and –1.1 mm/year (Fig. 2). For a small number of benchmarks (approx. 6% of total) these values exceeded -1.1 mm/year. The smallest rates of relative movements, up to –0,44 mm/year, occurred in the southwest part of the city.

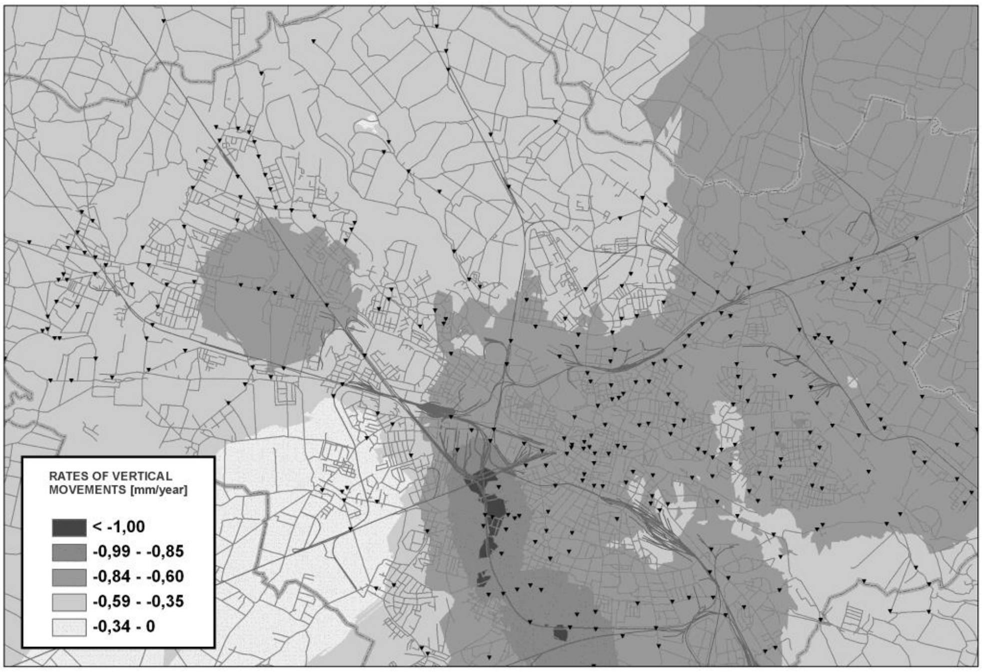

Fig. 2. Rates of vertical movements determined for the 1930 – 1998 period.

Average rate of vertical movements for the 1968–1998 period amounted to –1.1 mm/year, standard deviation to 0,42 mm/year and maximum value of –2,8 mm/year (Fig. 3). This means that for 68% of points the rates fall within the –0.7 to –1.5 mm/year limits.

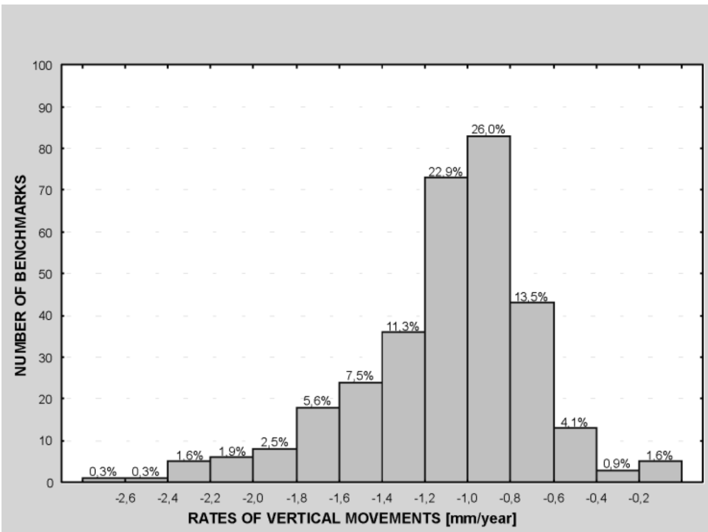

Fig. 3. Histogram of vertical movements rates determined for the 1968 to 1998 period.

In the last 30 years the changes have happened almost twice as fast as for the whole period of 68 years. While areas of maximal and minimal values are located in the same places as for the 1930 – 1998 period (Fig. 4).

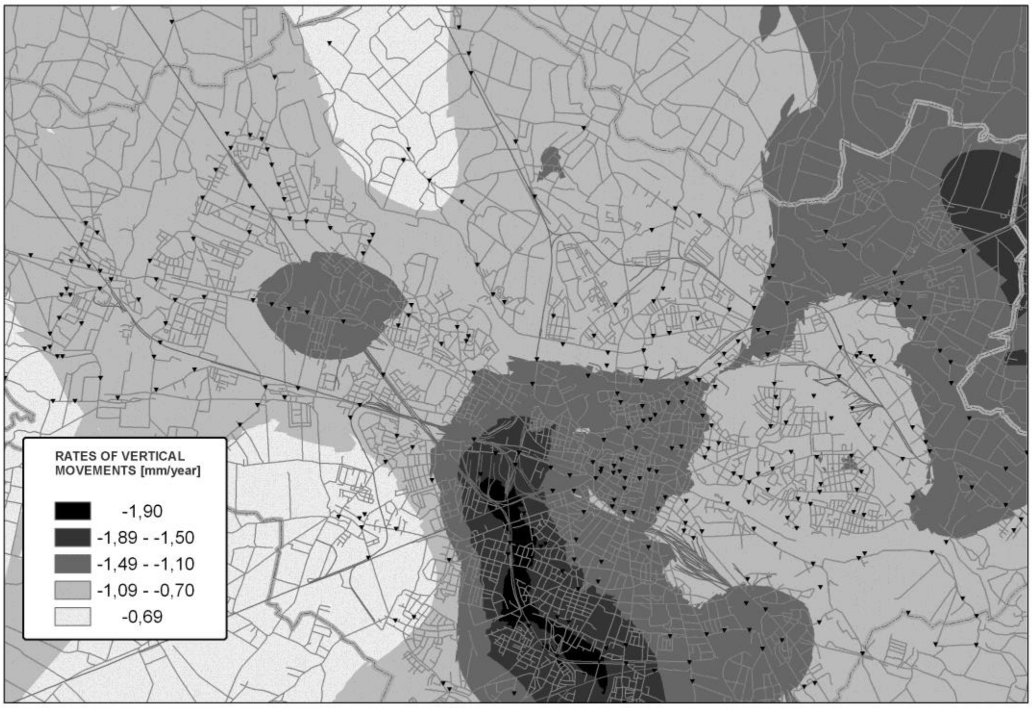

Fig. 4. Rates of vertical movements determined for the 1968 – 1998 period.

4 ASSESSMENT OF BENCHMARK ELEVATION VALUES VALIDITY IN TERMS OF TIME OF LAST MEASUREMENT

G-2 technical regulations do not define accuracy criterion for a single 3rd class vertical point. The existing criteria concern:

- **Mean error of adjustment m_0, which for the 3rd class is ± 4.0 mm/km,**
- **Deviation of tying the line to points of higher order, which for the 3rd class is $4\mathrm{mm}/\mathrm{km} * \sqrt{L}$,**
- **Adapting and classifying vertical points basing on previously applying regulations – points are classified as 3rd class if the mean error of levelling surveys after adjustment does not exceed ±4 mm/km.**

The assumption of linear relationship between rate of change and time is an attempt to describe the least unfavourable situation when changes are proportional to time that has elapsed since the last measurement. On the basis of determined rates for 68 year and 30 year time spans it has been found that the changes happened with varying speeds. For this reason two variants for assessing period of losing validity for benchmarks since the last measurement:

- **with the assumption that in the next period (after year 1998) average rate of speed will be equal to the average for the 68-year time period,**
- **with the assumption that in the next period (after year 1998) average rate of speed will be equal to the average for the last 30 years.**

To estimate validity of benchmarks in relation to time of last measurement a criterion has been adapted that the ordinate of 3rd class benchmark loses validity if the value changes by more than 4 mm. This assumption has been made taking into consideration that distances between benchmarks do not exceed 1 km. Loss of validity by 3rd class vertical network points should be understood as change of benchmark's ordinate by the given criterion resulting in not counting a given point to 3rd class vertical network if adapted for the accepted time since the last measurement. Basing on determined rates of change of benchmarks' elevations the time when the ordinates change exceeds 4 mm has been estimated. Assuming that the changes after 1998 will happen with the rate of speed equal to the average rate for the 1930-1998 period, within the first 5 years 21% of benchmarks will lose validity, in the 6 to 10 years period next 66% of benchmarks (Fig. 5, 6). It is expected that in the period between 1998 and 2003 benchmarks located in the city's centre towards south have lost validity. While in the 2003-2008 period in remaining part of the city with the exception of districts located in western and south-western parts where the expected time for this to happen is more than 10 years since last measurement.

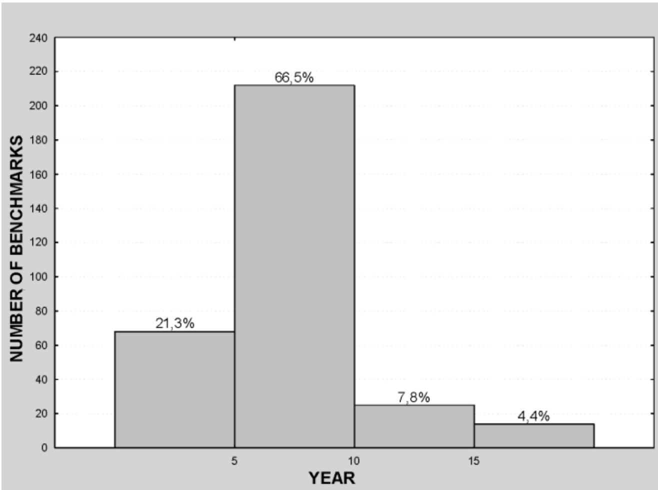

Fig. 5. Expected loss of validity by benchmarks' ordinates since last measurement assuming rate of change calculated for the 1930 – 1998 time period.

Fig. 6. Expected time of losing validity by benchmarks' ordinates since last measurement assuming rate of change calculated for the 1930 – 1998 time period.

Considering the second assumption 80% of benchmarks will lose validity within the first 5 years and between 6 to 10 years from last measurement another 18% (Fig. 7, 8). It is expected that in the period from 1998 to 2003 benchmarks located in the city's centre towards south have lost validity. While in the 2003-2008 period in remaining part of the city. In a 10-year time since last measurement only 2% of points will remain valid.

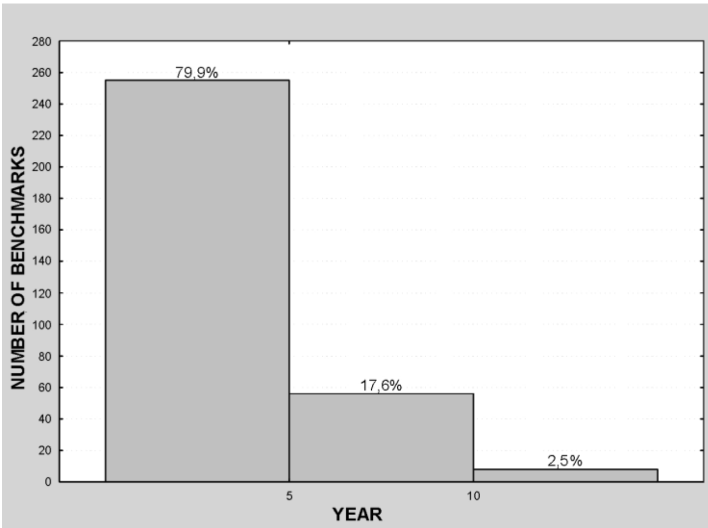

Fig. 7. Expected loss of validity by benchmarks' ordinates since last measurement assuming rate of change calculated for the 1968 – 1998 time period.

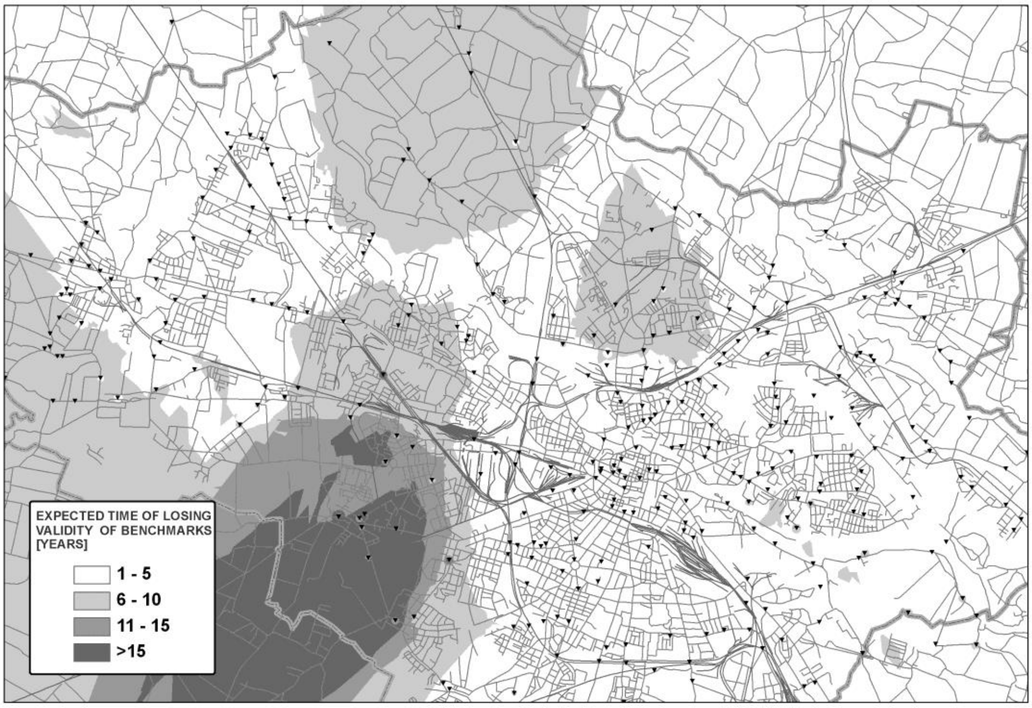

Fig. 8. Expected time of losing validity by benchmarks' ordinates since last measurement assuming rate of change calculated for the 1968 – 1998 time period.

5 IMPORTANCE OF THE RESULTS FOR CARRYING OUT SURVEYING OPERATIONS IN URBANISED AREAS

The problems and need to modernise vertical control networks have been signalled many times in literature (*Dudek and others, 2002; Kmiecik., Sierdzan, 1994; Zaremba, 2000*) in relation to various geodetic surveys requiring different levels of accuracy.

In general, the following geodetic surveys and required accuracies of vertical ordinates can be distinguished (*Wolski, Toś, 2003;* technical regulations):

- **For topographical maps – accuracy level of several cm,**
- **For basic maps and site surveys – accuracy of 5 to 10 mm,**
- **For deformation studies – accuracy of 0.1 to 1 mm.**

Carrying out vertical surveys in accordance with the G-4 technical regulations one is required to keep ± 20 mm/km*$\sqrt{L}$ accuracy in relation to higher order points. Permissible error for average distance of 350 m between reference benchmarks is ±12 mm. For the 1930 - 1998 period average rate of benchmarks elevations changes after approx. 20 years since last measurement the reference criterion based on vertical movements will not be met. While for the 1968 - 1998 average rate of change it may happen after approx. 10 years since last measurement. With regard to vertical surveys carried out to produce topographical and basic maps the changes of benchmarks elevations may gain practical significance within 10 to 20 years since last measurement. The problem may be already noticed several years since last measurements in zones characterised by major elevation differences but remain unnoticed for surveys in areas

of uniform subsidence. Individual sub-areas within the city experience various levels of subsidence but inside these sub-areas changes of elevation differences are insignificant. Vertical surface movements have major effect on results of engineering objects deformation measurements in the city. The fundamental issue concerns establishing a reference frame to determine movements of an observed object. Geodetic methods used to identify stable points cannot detect translation of an entire reference frame because of uniform subsidence in sub-areas where engineering objects and networks used to study them are located. Very often incorrect values of movements are determined for monitored objects. Therefore periodic control surveys of reference benchmarks tied to points located outside area of deformation are required to establish translation of an entire frame. In Wroclaw such measurements can be tied to vertical satellite GPS network made up of 12 points inside the city and 5 reference points located at distances of up to 30 km from the city limits. Measurement accuracy for this network has been comparable to accuracy of 2nd class precise levelling network.

Vertical changes of benchmarks elevations may also be of importance during surveying ordinates of elongated objects (Zaremba S., 2000). In such cases, elevation differences between benchmarks along the entire section of a planned route must be checked.

6 SUMMARY

The results of analysis concerning changes of benchmarks ordinates in the 1930 – 1998 period in Wroclaw have shown changes of up to 10 cm in some areas and maximum the calculated rate of elevations change for this time has reached –1.5 mm/year. Basing on assumed criterion of ± 4 mm most of benchmarks ordinates lose validity (from 88% to 98% depending on assumption) within 10 years since last measurement. Changes of benchmarks elevations may remain undetected during site levelling surveys (in accordance with the G-4 technical regulations) and treated as error of tying levelling lines to vertical points of higher order for about 10 years since last measurement. After this time (depending on rates of changes in particular districts of the city) the number of benchmarks with invalid ordinates will increase systematically to a degree when the accuracy criterion of linking the levelling lines to 3rd class vertical points is not met. The problem may develop even after a few years since last measurement in areas characterised by maximum rates of change and in border zones of deformation sub-areas where large changes of elevation differences between benchmarks exist.

Periodic control of elevation differences between benchmarks is required for them to be used as reference points in measurements of vertical movements of engineering objects. Periodic control in relation to points located in relatively stable areas (outside densely build-up areas, construction sites, cones of depression caused by water drainage, etc) is also advised.

Presented research results indicate the need to carry out control measurements in selected districts of the city, particularly levelling lines extending from southern and south-western parts of the city towards centre and from centre in the north-east direction. Predicted values of benchmarks ordinates changes after 10 years since last measurement exceeding 1 cm are an argument for a new measurement of the vertical satellite GPS network established in the city in 1998 (*Cacon and others, 1999*) and detection of potential translation of the entire network inside the Wroclaw limits.

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