Utilisation of Geodetic Monitoring for Verification of the Numerical Model of Impact of a Building under Construction on Surrounding Structures

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Key words: geodetic surveys, deep excavation, settlement

SUMMARY

The paper discusses the issue of verification of numerical models with the utilisation of results of geodetic monitoring for that purpose. That issue has been illustrated by an example which presents results of geodetic monitoring versus forecasts of displacements, calculated basing on numerical modelling for a building located in a densely built-up urban area, in the direct neighbourhood of the Warsaw Underground Railway tunnels. Results of 6 geodetic control surveys have been analysed; 3 of them were performed in the period of implementation of the construction, 1 within a period of „as built" acceptance and 2 after completion of construction (6 and 10 months).

Słowa kluczowe: pomiary geodezyjne, głęboki wykop, osiadanie

STRESZCZENIE

W referacie podjęto zagadnienie weryfikacji modeli numerycznych wykorzystując w tym celu wyniki monitoringu geodezyjnego. Zagadnienie zilustrowano przykładem w którym wyniki monitoringu geodezyjnego zestawiono z prognozą przemieszczeń obliczonych na podstawie modelowania numerycznego dla budynku zlokalizowanego w gęstej zabudowie miejskiej w bezpośrednim sąsiedztwie tuneli metra warszawskiego. Przeanalizowano wyniki 6 geodezyjnych pomiarów kontrolnych z których 3 wykonano w okresie realizacji obiektu, 1 w okresie odbiorów powykonawczych i 2 po zakończeniu budowy (6 i 10 miesięcy).

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1. INTRODUCTION

Comparison between results of numerical calculations with results of geodetic surveys may be found in almost every work which utilises numerical modelling to evaluate conditions of engineering structures. Comparison of modelling results with results of surveys may be utilised for many purposes. Besides diagnosis of current conditions of a structure, emergency or non-standard situations, such comparison allows for performing backward analysis and verification of material parameters. Estimation of agreement between calculated and measured displacements may serve for evaluation of correctness of a multi-stage numerical model, not only for consideration of parameter values, but also for an appropriate reflecting of stages of the structure implementation.

The paper presents the impact of deep foundation on buildings located within the zones of impacts, using the example of the „Wolf Marszałkowska Building", located in the dense centre of Warszawa. Due to:

- its location within the neighbourhood of existing buildings,
- foundation in complex geotechnical conditions,
- the excavation made for 5-storey underground part of the building, which implementation forced the lowering of buoyancy of the water bearing layer,

this object was constructed with simultaneous monitoring of displacements of neighbouring buildings. The detailed analysis of the impact of dewatering on displacements of neighbouring buildings and numerical simulations were performed at the Chair of Hydrological Engineering and Hydraulics of the Warsaw University of Technology [Nazarewicz, Popielski 2010]. For the discussed analysis, vertical and horizontal displacements of the building – in the phases of its construction – and neighbouring buildings, as well as ordinates of water level in piezometers, were utilised. In the course of performed investigations stages of the object construction were reconstructed with consideration of lowering the ground water level. Backward analysis was also performed in order to select appropriate modules of deformations for particular, pre-consolidated soil layers, basing on performed measurements of displacements. Besides, measurements of vertical displacements of surrounding objects were performed by the Chair of Engineering Geodesy and Topographic Surveys of the Warsaw University of Technology [Zaczek-Peplinska, Popielski 2010].

2. LOCATION AND IMPLEMENTATION OF INVESTMENTS

The building of 5 underground floors planned as car parking areas and 12 above-ground floors, to be used as trade and services areas, is located at the crossroad of the Marszalkowska and Żurawia Streets, within the City Centre of Warszawa. The building parcel borders the Marszalkowska street to the east; the western tunnel of the first line of the Warsaw

Underground Railway is located along that street, within the distance of 8.0 to 11m from the border. To the south the land parcel borders the Żurawia Street; densely built-up areas with apartments and office are located along that street within the distance of 20.0 m from the border. At the western side, a monumental palace is located within the distance of 18.0 m from the parcel borders; the City District offices are located at that palace. To the north, the PKO BP bank building (partially of 2 and partially of 8 floors), with cellars, adjoins the area of investment. To the southern side of the Bank building, some cracks were noticed before the building works were started. The terrain ordinate at the place of the building location equalled to approx. 35,05 – 35.50 m above the Vistula River (n0W).

The „Wolf Marszalkowska Building" is located on the denudated Warsaw post-glacial upland, on which the dual complex of sandy sediments are located – Fig.1. That complex is the pressure, double layer, II water bearing level. The upper layer of the II water bearing level (IIA) consists of interglacial and water-glacial sands with gravels, with the ceiling at the depth of a dozen or so meters and the water stabilisation level at the depth of approx. 9.0 m (26 m n0W). At the depth of approx. 30m, below that layer, the filtering membrane (IIB) of river silts is located. The bottom layer of the II water bearing level (IIC) is located below the filtering membrane.

The pressure II water bearing level was depressioned many times for the needs of construction of deeply founded structures and of the Warsaw Underground Railway. In the course of geotechnical investigations, before the construction was started, the water level was stabilised at the ordinate of 25,0 – 26.0 m n0W.

Due to location of the building with respect to neighbouring buildings and considering the 5-storey underground part, foundation of the building was secured by diaphragm walls of the thickness of 80 and 100 cm, sinked for the minimum of 1,0 – 2,0 m in the filtering membrane layer (IIB) (Fig.1). The excavation was made with the application of the floor method. At the first stage of construction, floors „-1" (-4,75), „-2" (-8,45), „-3" (-11,60) and „-4" (-14,75) were constructed. They were supported by diaphragm walls and by steel temporary pillars, constructed from the -1.30 level and based in barettes.

Additionally, for the time of construction of the underground part, diaphragm walls were spaced using temporary horizontal struts, made of steel pipes and I-sections. Those strengthenings were constructed at the level of -1.50 in the north-east corner, at the PKO BP Bank side (2 angle pipe struts Ø508/12.5 and 1 strut HEB300) and in the north-west corner, at the level of -17.40 (angle struts 2I360).

The „Wolf Marszałkowska Building" was founded on the foundation plate of the thickness of 150 cm with local trims related to the technology of the building technical installations (lift shafts and a separator). The floor of the plate is located at the depth of 19,25 m below the ")" of the building ("0" of the building = 34.85 m n0W).

In the plan of the building, close to the southern wall of the building, at the side of the PKO BP bank, four lift shafts are located. They were constructed on the bottom plate of the thickness of 60 cm and at the depth of 21.35 m below the "0" of the building (13.50 m n0W). Southern trims from the side of the Żurawia Street are the separator constructed on the bottom plate of the thickness of 70cm, at the depth of 20.05 m (14.8 m n0W) and two lift shafts.

Considering results of calculations of required terrain ordinates of lowering of the pressure layer IIC, dewatering was divided into two stages. At the first stage, static waters were pumped off from the excavation interior (IIA layer), catching the possible leakages (dynamic inflows). At the second stage of dewatering, the hydrostatic pressure of the IIC layer was lowered, works were performed in three phases [Nazarewicz, Popielski; 2010].

Table 1 presents characteristic stages of construction of the Wolf Marszałkowska object in time, with consideration of particular dewatering stages and performed measurements of displacements.

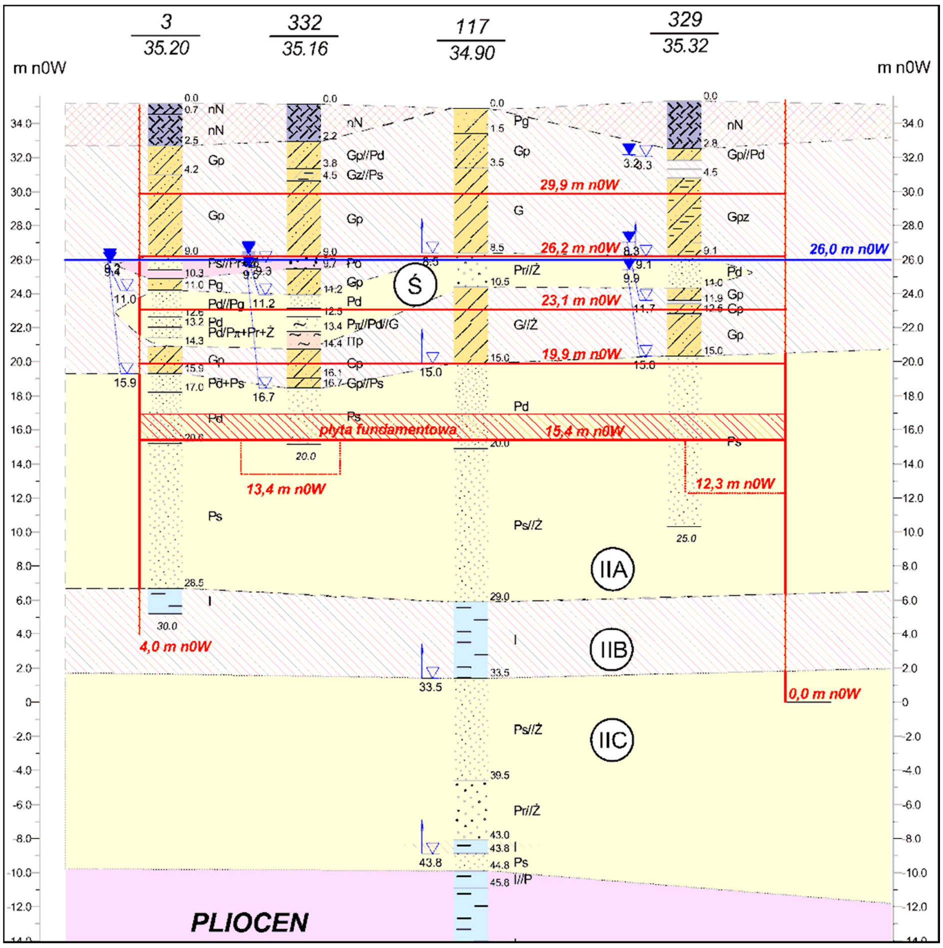

Figure 1 Hydrogeological section of the the Wolf Marszałkowska object background layers

Table 1 Characteristic stages of implementation of the Wolf Marszałkowska object

Stage of construction of the object	Dates		Performed building works	Stages of dewatering works	Control measure-ments
	since	till			
0			Initial condition		
1	22.12.2007	21.03.2008	Building diaphragm walls and barettes		
2	09.04.2008	08.05.2008	Making the excavation, construction of the floor for the storey -1		
3, 4, 5	20.05.2008	04.08.2008	Making the excavation, construction of floors for storeys -2, -3, -4	I	

6, 7	10.08.2008	06.10.2008	Making the excavation, building the foundation plate	II (phase I, II)	
8, 9	21.11.2008	18.02.2009	Building the floor of the storey 0, Transfer of loads on the foundation plate	II (phase II, III)	
10	18.02.2009	10.03.2009	Building the floor of the storey 1		
11	04.03.2009	30.03.2009	Building the floor of the storey 2		20.03.2009
12	04.04.2009	21.04.2009	Building the floor of the storey 3		23.04.2009
13	23.04.2009	29.04.2009	Building the floor of the storey 4		
14	06.05.2009	22.05.2009	Building the floor of the storey 5		21.05.2009
15	15.05.2009	12.06.2009	Building the floor of the storey 6		
16			Completion of building works		30.06.2009
			Turn-key acceptance		02.10.2009
			Exploitation		18.06.2010
			Exploitation		09.10.2010

3. NUMERICAL ANALYSIS

Numerical analysis was performed using the HYDRO-GEO software package of the MES software tool used for the needs of geotechnique, hydrotechnique and environmental engineering [Dłużewski 1997].

The numerical model (Fig. 2) of the area around the Wolf Marszałkowska Building was developed, which covered the surrounding buildings - PKO BP Bank and an office-and-apartment building in the Żurawia Street. The time schedule of the structure development, presented in Table 1, was accurately reconstructed in the course of modelling.

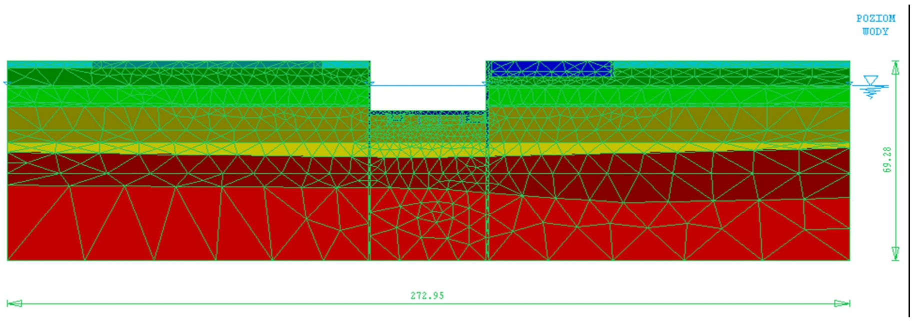

Figure 2. Numerical model of deep foundation

Firstly, calculations based on soil parameters, specified in geo-technical documentation for the Wolf Marszałkowska Building, were performed. Soil parameters, specified in the designing documentation were developed basing on the PN – 81/B-0320 Standard. Those parameters were characterised by lowered values of modules of deformations for deeply occurring soils. Due to that reason, the firstly obtained values of displacements highly diverged from real values, measured at the construction site.

In order to obtain the agreement between modelled values and monitoring of vertical displacements repeated modifications of soil parameters were performed. Calculations were based on modified parameters of deeply occurring soils. Those modifications were introduced basing on literature data (Atkinson, 2000), (Georgiannou, 1991), (Shibuya et al., 1992), as well as own experiences (Barański, Popielski, Szczepański, Wrona, 2007. In order to verify the limit values of the foundation, measurements of the soil stiffness were performed from the bottom of the excavation using the surface seismic method [Barański, Szczepański, 2004].

Initial values and values assumed for calculations are presented in Table 2. Comparison of values of calculated and measured displacements for selected benchmarks of the building being constructed, at the initial stage of building works, are presented in [Nazarewicz, Popielski, 2010].

Additionally, monitoring of vertical displacements of heads of temporary piles, located at the level -1, was performed in the implementation phase. It was assumed that – basing on measured displacements of heads, and with consideration of shortening of piles, caused by loading of floors – displacements of barrettes located at the level of the building foundation may be estimated. Observations were performed between the 3rd and the 6th stages of the building construction. Shortening of a pile, caused b y its load, equalled to 8.3 mm. It was assumed basing on calculations, that vertical displacements of barrettes located at the central part of the excavations, equalled to 18.3 mm. This allowed for additional verification of material parameters of the foundation, during the analysis of elastic recovery of the excavation.

Table 2 Designed and modified parameters of soils

Material no.	Symbol	Description of material	Parameters of layers assumed in accordance to geotechnical documentation (following the standard PN-81/B-03020)					Parameters considering the range of small deformations
			ν	γ	c	ϕ	E_p	E
			[-]	[kN/m^3]	[kPa]	[°]	[kPa]	[kPa]
1	I	Silt	0.25	22	40	30	20 000	650 000
2	Ps	Medium sand	0.3	20	3	35	80 000	400 000
3	Gπ/Π	Dusty clay close to dust	0.25	20.7	35	25	20 000	450 000
4	Ps+Pd	Medium sand with additives of fine sand	0.3	18.5	0	36	80 000	300 000
5	Gp_m	Sandy waterised clay	0.25	22.5	35	23	47 000	68 000
6	Gp_s	Dry sandy clay	0.25	22.5	35	23	47 000	68 000
7	nN	Non-building escarpment	0.25	22	25	19	40 000	40 000

4. PERFORMED MONITORING OF DISPLACEMENTS

Considering conditions of the object location, described above, as well as its construction technology, an independent (additional) geodetic monitoring was performed, which standard objective was to control vertical displacements of neighbouring structures. In order to verify the correctness of the numerical model (assumed stages and material parameters) and predicted settlement, geodetic surveys were applied. It was decided to perform those surveys for four cycles more, performed after completion of the basic building works. Geodetic measurements of vertical displacements were performed using the precise levelling method, covering 17 benchmarks located on the floor of the storey „0” and neighbouring buildings (23 benchmarks). Benchmarks located on the floor of the “0” storey were located basing on guidelines of a person responsible for numerical calculations, in such a way that it should be possible to analyse results of settlement for three cross sections, parallel to the axis of the underground railway [Zaczek-Peplinska, Popielski, 2009]. Displacements of benchmarks at the “0” storey were determined in the course of construction of successive storeys (stages of construction 10-15, Table 1), on the neighbouring buildings, until the time of completion of construction and for one year after commissioning of the building. Reference benchmarks – 5 benchmarks of the state elevation network – were selected outside the range of impacts of the investigated object.

Measurements were performed using the Leica, NA 3003 precise bar-code level. That instrument is characterised by the mean error of 0.4 mm per 1 km of double levelling (using precise bar-code rods). For the discussed surveys one, 2-meter Leica bar-code rod was used, what allowed to completely eliminate the influence of the zero point of the pair of rods.

Displacements of benchmarks were calculated using the method of differences of ordinates, identification of the reference system was performed using the method of successive, free adjustments.

In total, 7 observation cycles were performed; the first four of them served for determination of impact of the performed construction on surrounding objects and the last four of them served for practical verification of numerical models. The average mean error of vertical displacement determination of controlled benchmarks equalled to approx. 0.8 mm.

The subject of the presented work is not to analyse settlement of object hazarded by impacts of construction works, and therefore, detailed results in that field will not be presented.

The objective of the presented work is to analyse the possibilities to apply results of geodetic surveys for verification of the numerical model; that is why only selected controlled benchmarks, located on the section presented in Fig.3, were utilised.

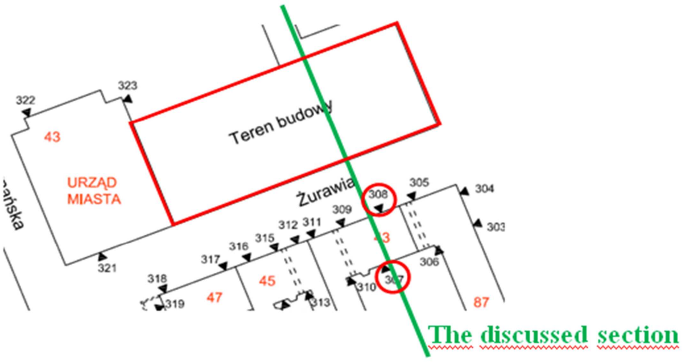

Figure 3 Benchmarks location drawing

5. COMPARISON OF OBTAINED DISPLACEMENT VALUES AT LAST STAGES OF CALCULATIONS

At the stage of designing works the impact of deep foundation onto neighbouring objects was evaluated [Popielski P. 2003]. The maximum permitted values of relative displacements between benchmarks were assumed basing on the guidelines of the Institute of Building Technology (ITB) [Kotlicki, Wysokiński 2002]. In the course of implementation of the object, the varying values of displacements were controlled and it was tested, whether they fall within specified intervals. Displacements observed in the area of the object construction were smaller than permitted values. Displacements of benchmarks 308 and 307 were compared in the paper; they were located on the building, within the neighbourhood of the construction site (Żurawia Street), at the final stages of construction of the object. Those benchmarks were marked in Fig.3.

During the analysis of obtained results, the planned time schedule of implementation was compared with the implementation time schedule. The one-stage delay of works was noticed (in accordance with stages presented in Table 1).

The list of displacements determined basing on the numerical model, developed in accordance with the planned time schedule of works, the modified time schedule and geodetic surveys for benchmarks 307 and 308, are presented in Fig. 4 and 5.

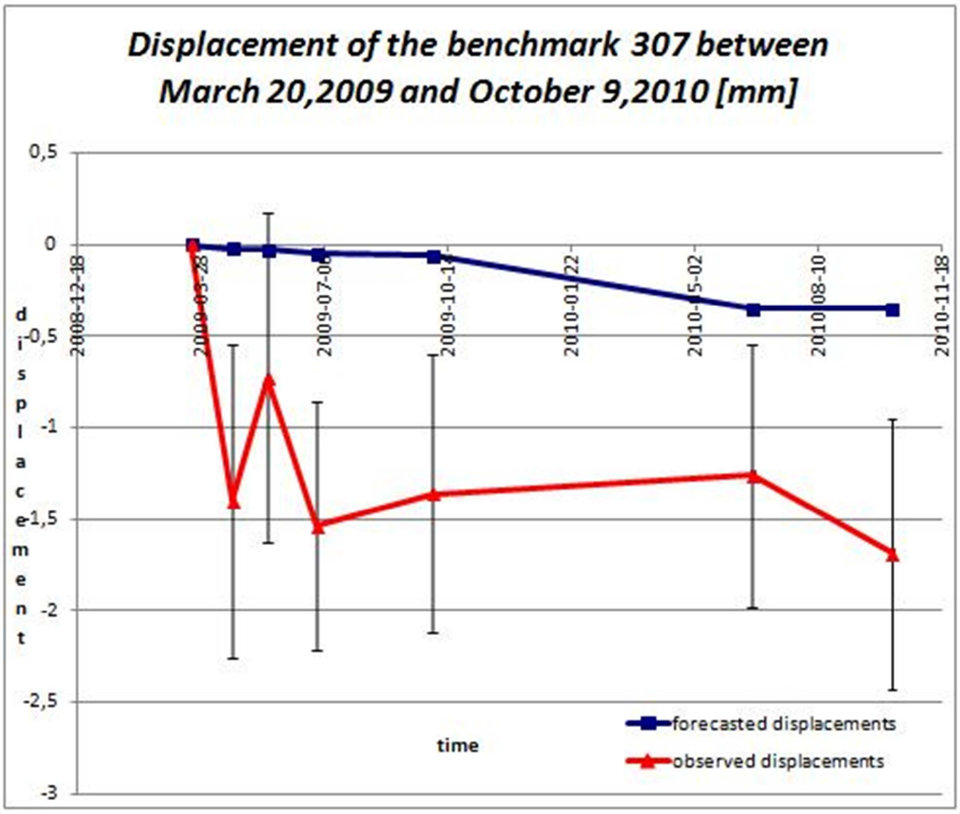

Figure 4 Comparison of predicetd and observed displacements, benchmark 307

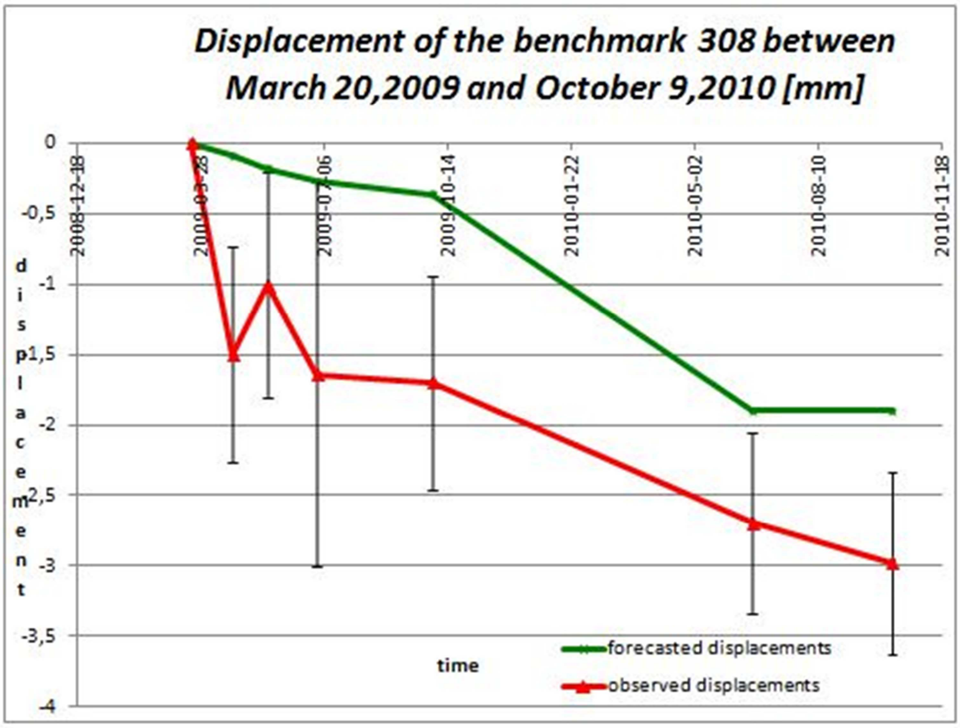

Figure 4 Comparison of predicted and observed displacements, benchmark 308

On the diagrams which present displacements of particular benchmarks the compliance of trends of variations of observed and forecasted displacements may be observed. (Fig. 4 and 5).

Intervals between diagrams of displacements predicted basing on the numerical model and measured displacements are of the 1 mm order – they basically result from displacement observed during the initial measuring cycle. Continuation of the trend and agreement of changes in successive observation periods also confirm the correctness performed verification of the numerical model.

The differences, which have been stated, may be caused by at least two reasons:

- firstly, they may the effect of instability of an identified reference system, caused by reasons other than impacts of the constructed object. In order to confirm the instability of the reference system the analysis of the impact of building works performed in neighbouring areas should be made
- secondly, the difference of obtained results may be also influenced by discrepancies in time schedules of the object implementation – the planned one, which was the basis for calculation of predicted (model) values and the implementation time schedule, which was the basis for geodetic measurements.

The agreement of observed and predicted values of settlement are also seen on the diagram which presents displacements of the benchmark 308 with respect to the benchmark 307 (Fig.6). Those benchmarks are located on both sides of the building and they allow for observation of behaviour of its foundation. Although both benchmarks are located within a short distance, it is possible to draw conclusions concerning the correct modelling of changes of loads and resulting displacements of benchmarks – this points to changes of the “shape” of the basement of the building located in 43 Żurawia Street, in accordance with the model. Analyses of such type may become one of elements of calibration, verification of the numerical model and the values of soil parameters. In that case they confirmed the correctness of the developed numerical model and parameters of materials assumed for calculations.

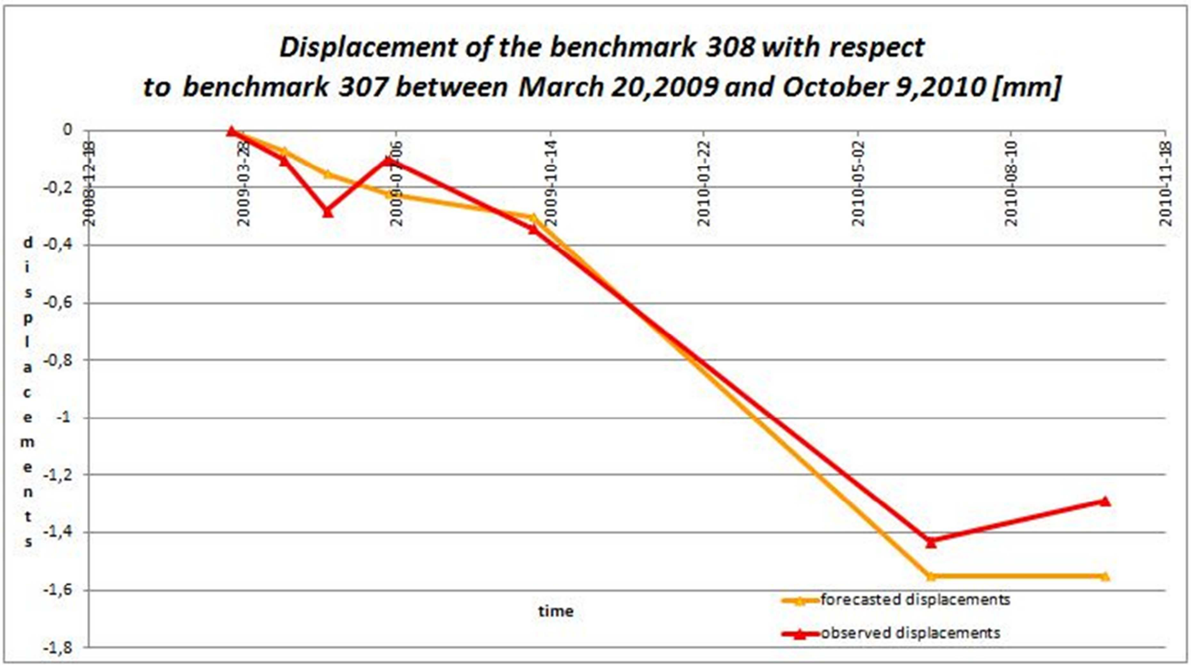

Figure 6 Diagram of predicted and observed displacements of the benchmark 308 with respect to the benchmark 307

6. CONCLUSIONS

- Reliability of results of numerical calculations depends of the accuracy of geological recognition and the correctness of determination of parameters of materials,
- Designing and implementation of building objects in difficult conditions (complicated composition of background, neighbourhood of existing buildings, deep excavations etc.) cannot be based on typical estimation of parameters and standard methods of static calculations,
- Utilisation of non-standard methods of calculations (numerical modelling) forces the development of the monitoring network and utilisation of modern investigations of soils,
- Performed surveying observations allow for verification of the correctness of the FEM model with respect to the reality,
- The difference of obtained results may be influenced by discrepancies in time schedule of the construction implementation – the designing time schedule, which was the basis for calculating forecasted (modelled) values and the time schedule of implementation, being the basis for geodetic surveys,

- Application of relative analysis of displacements between chosen points of measurement network and similar nodes on the MES model allows for assessment of the correctness of the conducted numerical simulation, regardless of possible displacements of the reference benchmarks.

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BIOGRAPHICAL NOTES

Janina Zaczek-Peplinska, Surveying Engineer, is Assistant Professor at the Department of Engineering Geodesy and Detailed Measurement at the Warsaw University of Technology (Poland), Faculty of Geodesy and Cartography. She studied Geodesy at the Warsaw University of Technology and reached her PhD on “A concept of modernisation of conventional horizontal control networks for determination of displacements of hydrotechnical structures” at the Institute of Applied Geodesy at the Warsaw University of Technology in 2008. Specializes in geodetic measurements of displacements of hydrotechnical objects, utilisation of geodetic monitoring for verification of the numerical model of soil and structure behaviour, application of Terrestrial Laser Scanning for measurements of displacements. Author and co-author of 31 publications, research and expert’s reports. Member of Association of Polish Surveyors.

Paweł Popielski, Civil Engineer, is Assistant Professor at the Hydro-Engineering and Hydraulics Department at the Warsaw University of Technology (Poland), Faculty of Environmental Engineering. He studied Civil and Hydro-Engineering at the Warsaw University of Technology and reached his PhD on “Numerical model of mechanical suffusion in terms of Finite Element Method” at the Institute of Water Supply and Hydraulic Engineering at the Warsaw University of Technology in 2001. Specializes in numerical FEM modeling of hydraulic objects and diagnostic investigations of technical and safety conditions of hydraulic structures as well as utilization of geodetic monitoring for “back analysis” and verification of the numerical model of hydraulic structures, deep foundations, soil and structure interactions. Author and co-author of 55 publications, research and expert’s reports, user of FEM programs HYDRO-GEO (also developer), Plaxis, Z_SOIL. Member of Polish Geotechnical Committee and Hydrotechnical Structure Division of the Committee on Civil Engineering and Hydroengineering of the Polish Academy of Sciences.

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