ABSTRACT

Surveying measurements, together with accuracy of elevation determinations, which may be currently achieved, remain the more reliable source of information concerning displacements of soils and foundations of buildings located close to newly constructed structures. A numerical model, which is used to forecast such displacements, should be verified basing on surveying monitoring.

The paper presents comparison and analysis of results of surveying monitoring and forecasts of displacements, calculated basing on numerical modelling for a building located within an urban, densely built-up area, within direct neighbourhood of tunnels of the Warsaw underground railway. Results of 7 surveying control measurements: 4 in the period of implementation, 1 – in the period of post-implementation approval and 3 after completion of construction (6 and 10 months), were analysed. Guidelines concerning verification of the numerical model have been presented.

1. INTRODUCTION

Comparison of compliance of design and survey data (in the period of construction or exploitation) may be applied in practice for evaluation of technical conditions of a structure and for determination of its impact on surrounding structures. The analysis is based on comparison of quantitative compliance, as well as compliance of trends of results of modelling the structure’s operations. Models (e.g. Developed by means of modelling using the FEM - finite element method), performed basing on the assumed initial and boundary conditions should be verified basing on results of periodical control surveys and the adequacy of the numerical model developed in the designing phase should be confirmed. Results of geodetic monitoring of displacements of structures are the data obtained from direct observations of those structures, which present their current conditions, for a given moment of exploitation.
Consideration of results of monitoring performed in the period of construction and exploitation of a structure allows for efficient verification of the numerical model, during successive phases of investment implementation. The numerical model may be applied in practice only after calibration. Determination of the values of possible limit displacements is an important element of utilisation of numerical models – greater values would point to emergency/hazard conditions for a particular structure and surrounding structures. Displacements of analysed structure or other structures located within the area of impact of performed investments, which are incompliant with „the model” are often the first warnings about the hazard, which may not be neglected and considered as inaccuracies of the model.

2. COMPARISON OF (FORECASTED AND OBSERVED) VALUES OF VERTICAL DISPLACEMENTS OF AN OBJECT

The described investment – Wolf Marszalkowska Building for offices and services, situated in the very heart of Warsaw, close to the corner of the main transportation routes – Marszalkowska Street and Jerozolimskie Avenue, at the cross-section of Marszalkowska Street and Żurawia Street. Construction of that building was started in winter 2007 and it was completed in December 2009.

The paper presents comparison and analysis of results of geodetic monitoring and forecasts of displacements, calculated basing on numerical modelling for a building situated within an urban, densely built-up area, within the direct neighbourhood of the Warsaw underground railway. Results of 7 surveying control measurements: 4 in the period of implementation, 1 – in the period of post-implementation approval and 3 after completion of construction (6 and 10 months), were analysed.

1.1 Surveys of vertical displacements

In order to verify the numerical model, surveys of vertical displacements were performed using precise levelling methods, for the ceiling of the „0” floor – in the course of construction successive floors (construction stages 10-15, Table 1) and neighbouring buildings (23 benchmarks) – until completion of construction. Benchmarks for the ceiling of the “0” floor were fixed basing the guidelines of the person who performed numerical calculations – 17 benchmarks were added, in three sections parallel to the axis of the tunnel of the underground railway (Zaczez-Peplinska, Popieliski, 2009).

All surveys were performed using the precise, direct levelling from the centre. For each station surveys were performed following the mode: BFFB, i.e. backward, forward, forward, backward and the elevation difference were averaged for two surveys. The value of 0.2mm was assumed as the maximum permitted discrepancies of two, independent determinations of elevation difference at the station. Surveys were performed by means of Leica NA 3003, the precise bar-code level. That instrument is characterised by the mean error of 0.4 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 determined using the method of differences of coordinates, identification of the reference system was performed using the method of successive, free adjustments.

Results obtained for the section marked in Fig. 1 were described in the paper.

![Fig. 1. Location of a section for which the numerical model of soil displacements was developed.](image)

**Teren budowy – construction site**

Besides, monitoring of vertical displacements of heads of temporary pillars situated at the level – 1 was made during the implementation works. It was assumed that, basing on surveyed displacements of heads and with consideration of shortening of pillars, resulting from loading by floors, displacements of barettes located at the level of foundation of the building. The barette located at the central part of the excavation was selected for analysis. It was assumed that the determined displacement describes the minimum relaxation of the bottom of excavation.

The uplift of the head of the temporary pillar equalled to 5.5 mm. Surveys were performed between the 3rd and the 6th stages of construction. Shortening of the pillar resulted from its loading, equalled to 8.3 mm. It was assumed, basing on calculations, that the vertical displacements of barettes located in the central part of the excavation, equalled to 13.8 mm.

### 1.2 Numerical analysis

The numerical analysis was performed using the HYDRO-GEO package from the FEM software tools for geo-technology, hydrotechnology and environmental engineering [Dłużewski 1997].

The cross-sectional numerical terrain model (Fig. 2.) around the Wolf Marszalkowska Building was developed, which covered the surrounding buildings - PKO BP Bank and an office-and-apartment building in the Żurawia Street. The schedule of the structure development was accurately reconstructed in the course of modelling (due to the limitations of this paper, only a simplified schedule is presented in Table 1).
Fig. 2. A sectional model of areas around the Wolf Marszalkowska Building.

Table 1. Simplified schedule of implementation of the Wolf Marszalkowska investment

<table>
<thead>
<tr>
<th>Stage of construction</th>
<th>date from</th>
<th>to</th>
<th>Performed construction works</th>
<th>Stages of land drainage works</th>
<th>Compared control surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>Initial conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>22.12.07</td>
<td>21.03.08</td>
<td>Construction of diaphragm walls and barettes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.04.08</td>
<td>8.05.08</td>
<td>Making the excavation, construction of the ceiling of the floor -1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3, 4, 5</td>
<td>20.05.08</td>
<td>4.08.08</td>
<td>Making the excavation, construction the ceiling of the floors -2, -3, -4</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>6, 7</td>
<td>10.08.08</td>
<td>6.10.08</td>
<td>Making the excavation, construction of the basement plate</td>
<td>II (phase I, II)</td>
<td></td>
</tr>
<tr>
<td>8, 9</td>
<td>21.11.08</td>
<td>18.02.09</td>
<td>Construction of the ceiling of the floor 0, undertaking the loading by the basement plate</td>
<td>II (phase II, III)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>18.02.09</td>
<td>10.03.09</td>
<td>Construction of the ceiling of the floor 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>04.03.09</td>
<td>30.03.09</td>
<td>Construction of the ceiling of the floor 2</td>
<td></td>
<td>20.03.09</td>
</tr>
<tr>
<td>12</td>
<td>4.04.09</td>
<td>21.04.09</td>
<td>Construction of the ceiling of the floor 3</td>
<td></td>
<td>23.04.09</td>
</tr>
<tr>
<td>13</td>
<td>23.04.09</td>
<td>29.04.09</td>
<td>Construction of the ceiling of the floor 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>6.05.09</td>
<td>22.05.09</td>
<td>Construction of the ceiling of the floor 5</td>
<td></td>
<td>21.05.09</td>
</tr>
<tr>
<td>15</td>
<td>15.05.09</td>
<td>12.06.09</td>
<td>Construction of the ceiling of the floor 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>Completion of building works</td>
<td></td>
<td>30.06.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Post-construction acceptance</td>
<td></td>
<td>2.10.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Utilisation</td>
<td></td>
<td>18.06, 9.10.10</td>
</tr>
</tbody>
</table>

Firstly, calculations basing on soil parameters, specified in geo-technical documentation for the Wolf Marszalkowska 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 soils occurring very deeply. Due to that reason, the firstly obtained values of displacements highly diverged from real values, measured at the construction site.

In order to correctly reflect the history of setting, calculations were made basing on modified parameters of selected, deep 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 get those experiences, the “backward analysis” was performed.

In order to obtain the compliance between model setting with monitoring of vertical displacements, multiple modification of soil parameter was introduced. Comparison between selected benchmarks of values of measured displacements and displacements calculated in the first stage of construction are presented in (Nazarewicz, Popielski, 2010).

Surveys of rigidity of soils, with the use of the surface seismic method were performed from the excavation bottom level, for the needs of verification of limit parameters of the foundation (Barański, Szczepański, 2004).

1.3 Comparison of obtained values of displacements

Displacements of benchmarks 308 and 307, situated on the building neighbouring the construction site (Żurawia Street) were compared in the particular stages of the construction implementation. Those benchmarks were marked in Fig.1. The maximum permitted values of relative displacements between benchmarks were determined in the Guidelines of the Building Research Institute (ITB) (Kotlicki, Wysokiński 2002). In the course of the construction implementation, changing values of displacements were controlled and it was tested whether they fallen within specified limits. Within the area of implementation observed displacements were lower than permitted values. The list of displacements determined basing on the numerical model and geodetic surveys for benchmarks 307 and 308.

**Przemieszczenia reperu... – displacements of the 307 benchmark in the period 20.03.09-09.10.10 [mm]**

![Fig. 3. Comparison of forecasted and observed displacements](image)

a) benchmark 307
Compliance of the observed and forecasted values may be seen on the diagram which presents displacements of the benchmark 308 with respect to the benchmark 307 (Fig. 4.); such analyses may be one of the elements of calibration and verification of the numerical model and values of soil parameters.

2. CONCLUSIONS

- Reliability of results of numerical calculations depends of the accuracy of geological recognition and the correctness of determination of parameters of materials,
- The design and implementation phases of constructions in difficult conditions (complex composition of background soils, neighbouring of existing buildings, deep excavations etc.) should not be based on typical estimation of parameters and on statistical calculation methods, applied according to specified standards,
Non-standard methods of calculations (numerical modelling) force 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.

Measured values of setting may differ from real values due to the impact of water melioration on setting of reference benchmarks.

The differences 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.

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