

ASSESSMENT OF POSSIBLE UTILISATION OF RESULTS OF GEODETIC MONITORING OF DISPLACEMENTS OF STRUCTURES AND THEIR SURROUNDINGS FOR THE NEEDS OF VERIFICATION OF DIGITAL MODELS

Janina Zaczek-Peplinska, Pawel Popielski

**Faculty of Geodesy and Cartography
Department of Engineering Geodesy and Detailed Measurements
e-mail: j.peplinska@gik.pw.edu.pl**

**Faculty of Environmental Engineering
Department of Water Constructions and Hydraulics
e-mail: pawel.popielski@is.pw.edu.pl**

Warsaw University of Technology, pl. Politechniki 1, 00-661 Warsaw

ABSTRACT

Each well designed project, related to digital modelling for the needs of assessment of conditions of an engineering structure, contains comparison of results of numerical calculations with results of surveying. Usually, results of levelling, which determine differences of elevation of controlled points of the structure, are the subject of such comparison. Results of measurements of a horizontal network may be presented in a similar way. In the course of comparison, functional, structural and accuracy differences of digital models, as well as models based on results of surveying monitoring should be also considered.

Comparison of modelling results with results of surveys may be performed for various purposes. Besides the diagnosis of current conditions of the structure, emergency or non-standard situations, such comparison may be performed for specific demands of geodetic services, and, in particular, the needs of modernisation of the geodetic control network or in the process of the initial control of surveys. Such comparison may be performed in order to assess the digital model, developed basing on archive geological reconnaissance and/or verification of values of parameters of materials.

The paper discusses the demands of verification of digital analysis by means of back analysis, as well as possibilities to utilise the results of geodetic monitoring for the needs of calculations. It should be noticed that the geodetic control network should be consulted with designers of the particular structure and with the entity, which performed numerical analyses. Those issues are illustrated by means of the example of development of the control network and the numerical model for a building, which is located in the densely built-up area, within the direct neighbourhood of the Warsaw underground.

1. INTRODUCTION

Comparison of compliance between the designing and survey data (in the course of construction or exploitation) can be practically applied for the assessment of technical conditions of the structure. The analysis is based on comparison of the quantitative

compliance and the compliance of trends of results of modelling operations performed by the structure. Models (such as models developed by means of modelling using the Finite Element Method – FEM), developed basing on the assumed initial conditions should be verified basing on results of periodical, control surveys; adequacy of the digital model, developed in the phase of design, should be confirmed. Results of geodetic monitoring of the structure displacement are the data obtained from direct observations of the structure, which reflect its conditions at the given moment of exploitation. Considering results of monitoring, performed in the phase of construction and exploitation of the structure, allows for efficient verification of the digital model during successive stages of implementation of the investment. Then, the digital model may be used for the assessment of technical conditions of the structure. An important element of utilisation of digital models is specification of the value of possible, limitary displacements. Displacements greater than the limitary ones will point to the conditions of hazard/breakdown of the structure and neighbouring structures. Measured displacement of the investigated structure or other structures located within the areas of impact of performed investments, are often the first syndrome of the hazard, which should not be disregarded or considered as a result of inaccuracy of the digital model.

2. POSSIBLE UTILISATION OF NUMERICAL MODELLING BY MEANS OF THE FINITE ELEMENT METHOD (FEM)

Digital modelling using the FEM method allows to perform wide analyses of behaviour of geotechnical and hydrotechnical structures. It may be successfully applied for the needs of analysis of displacements and strength of such structures as: foundations of various constructions (reservoirs, machinery, buildings), retaining walls, earth and concrete dams, excavations, tunnels, escarpments and embankments.

The FEM method is applied when conventional methods of calculation of the limitary load capacity or construction settlements fail. Designs aiming at strengthening constructions, forecasts concerning settlements in complicated circumstances or on sensitive organic base, or on consolidating mud or clays, may be successfully analysed by means of the FEM method.

Digital models were successfully applied for analysis of many geotechnical structures, as for example for analysis of settlements of foundations of turbogenerators at the Połaniec Power Supply Plant, for analysis of retaining walls in Czorsztyn-Niedzica and for modelling breakdowns of decanters of industrial waste in Skawina, Połaniec, Stalowa Wola and Krasnystaw.

The FEM method allows to model phenomena, which concern construction of embankments and banks of industrial decanters. Calculations of multi-stage construction or widening of road embankments and banks on consolidating organic bases, were often performed. (Fig. 1).

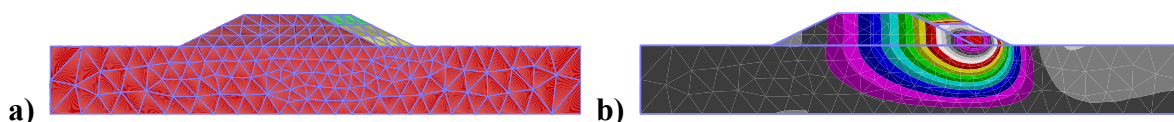


Fig. 1. Digital modelling in the course of construction of a road embankment:
a) a diagram of material zones for analysis of embankment widening on sensitive base,
b) Isolines of vertical displacements in the form of coloured maps.

The discussed method is also utilised for digital modelling of foundations of high buildings in Warszawa, as well as for constructing the Warsaw underground. This type

of calculations should consider phenomena related to the presence of underground waters under pressure, which often occur in several water bearing levels in one profile. Besides determination of settlements of structures, in the case of calculations concerning the deep foundations of a structure, it is necessary to determine impacts on surrounding structures, which are located both, on the surface and below the terrain surface. Those calculations are often required in the process of applying for a building permission. Similar calculations are required, for example, in the case of designing the underground part of a power plant, attached to the existing stage of fall or another structure, located within the zone of impact on a dam.

The example of possibilities to perform analysis of impacts of the designed structure on underground structures, is the case of foundation of a building within direct neighbourhood of route tunnels of the underground. Fig. 2 presents the example model in the form of a diagram of material zones.

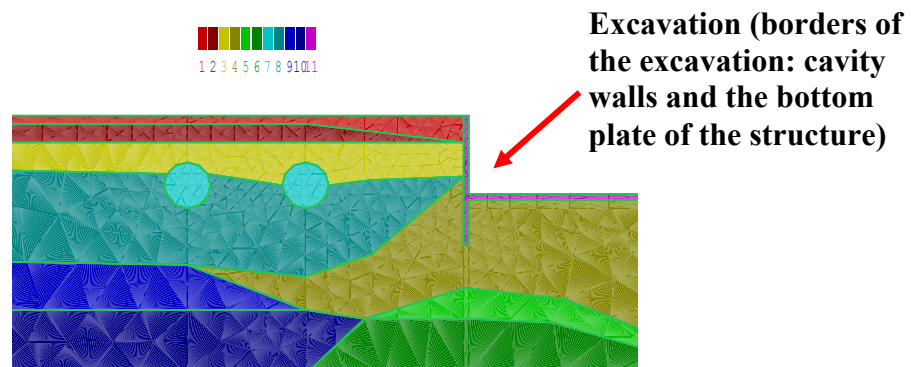


Fig. 2. Diagram of material zones for analysis of deep foundation within the area of underground structures.

3. IMPROVEMENT OF ACCURACY OF THE FEM – BACK ANALYSIS

Back analysis consists of creation of the calculation model of the structure behaviour, with introduction of properties of materials of the construction and the base, assumed in the design or determined basing on tests. Knowing the load acting on the structure at the selected stage of construction, as well as knowing the measured values of displacements, the back analysis should be performed in order to verify parameters of materials contained in the modelled structure. As initial data, parameters resulting from geological investigations or assumed in the design for various material zones, described by the model geometry, should be used.

The model should reflect successive stages of construction of the structure and related changes in load. In the case of the back analysis, the real, observed behaviour or the construction (such as displacements, deformations, the course of filtration) are compared with data obtained from the model. The high and repeating inconsistency of the results of observations (monitoring) with the model calculations, points that the model is not adequate for the reality. In successive iterations, changing the model material properties, and, sometimes, the mode of its load (according to successive stages of construction), consistency of the model with the reality may be obtained, what allows for forecasting the future behaviour or the construction with higher reliability. Such calculations will allow for determination of the average values of parameters of the base or other element of the digital model.

Experiences from analysis of displacements of various structures point, that the determined modules of elasticity are loaded with a small error, what results in the possibility to perform more accurate forecasts of displacements. Implementation of the back analysis may be identified as taring the digital model. Only the digital model, appropriately verified, may be applied in practical issues connected with exploitation of the structure, such as the assessment of technical conditions of the structure or modernisation of geodetic control networks. The back analysis, performed for the needs of a dam – the Besko concrete dam, has been described in (Zaczek-Peplinska, 2008); its results are presented in Fig.3.

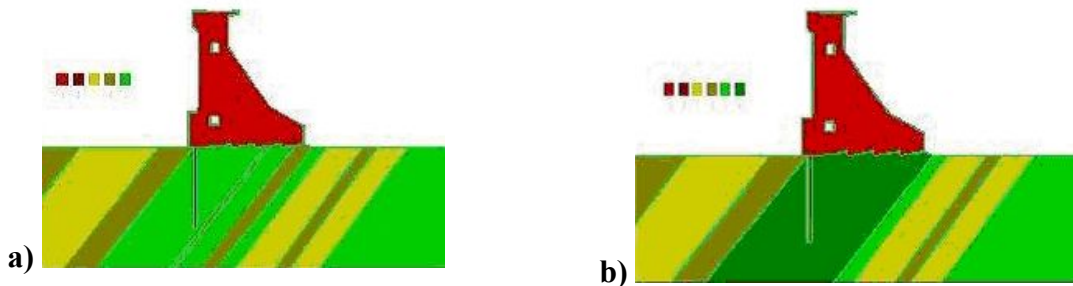


Fig. 3. Diagrams of material zones used for digital models of a dam
a) according to geological reconnaissance, b) after the back analysis.

The back analysis is also helpful for stating the reasons of untypical behaviour of the structure, and, in particular cases, for reconstruction of the process of breakdowns and exceptional values of load, which results in untypical behaviour of the structure (Fiedler at al. 2007), (Popielski, 2000), (Zaczek-Peplinska, 2008).

4. UTILISATION OF RESULTS OF SURVEYING MONITORING FOR BACKWARD ANALYSIS

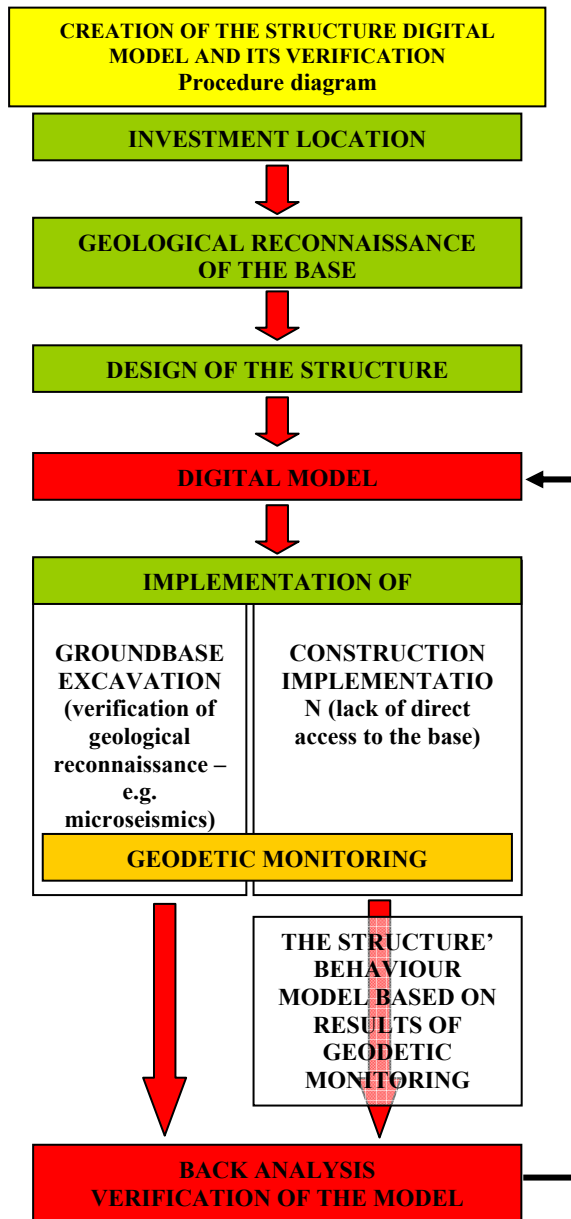
Together with development of survey technologies, possibilities of higher reliability and accuracy of geodetic monitoring of changes of an engineering structure, are increased. In the course of implementation of the design of a new structure, all recent technical achievements may be immediately introduced.

It may turn during observations of the structure (in the periods of implementation and exploitation) that the geodetic control network should be extended (amended) with points located in places, which were not previously controlled. Those places may be determined by means of analyzing the behaviour of the structure basing on the previously gathered data. Surveys which were performed earlier should be the base for calibration of the mathematical model of behaviour of particular sections of the structure.

One of elements of data preparation for the back analysis, or for the assessment of technical conditions of the structure is comparison of results of numerical calculations with results of geodetic surveys. Usually, this concerns the comparison of foreseen displacements of points controlled using geodetic methods with their real displacements, determined basing on periodical surveys of the geodetic control network.

Comparison of model data, calculated for a control point under the assumption of the momentary conditions of the structure (compliant with conditions recorded during geodetic surveys) with the result of surveys shows only the partial relations between the assumed model of the structure's behaviour and results of individual measurement. The individual measurement is not the bases for verification of the model adequacy – correctness of results of numerical simulation, which describes the conditions of the

structure. The model should reflect successive stages of the structure erection and related load changes. Geodetic measurements should be closely co-ordinated with the process of structural works. The real, observed behaviour of the structure (such as displacements, deformations, the process of filtration) is compared with data obtained



from the model. Substantial inconsistency of the observation results (monitoring) and the results of model calculations proves, that the model is inadequate for the reality. The diagram of procedure in the course of creation of the digital model and its verification is presented in Fig.4.

In the course of analyses, which aim at verification of the correctness of the digital model (its basic assumptions: geometry of calculation diagrams, parameters of soils and materials, assumed load values, consideration of external conditions, such as thermal conditions), differences between digital models and models, which are based on results of periodical, geodetic surveys of displacements, should be considered.

Fig. 4. Creation of the digital model and its verification – the procedure diagram.

5. THE DIGITAL MODEL VERSUS THE MODEL OF THE STRUCTURE'S BEHAVIOUR BASED ON RESULTS OF SURVEYS OF DISPLACEMENTS

The basic differences are connected with various technology used for obtaining the results (numerical calculations and geodetic surveys), discretization of the structure (the network of FEM nodes and individual points of the geodetic control network) and with the accuracy of obtained values. The accuracy is influenced by different components, which are not only connected with relation between the assumed theoretical parameters and the reality (such as parameters of soils and materials in the digital model), but also

with specific practical operations (such as the accuracy of identification of target and of targetting itself/setting the levelling staff in the process of implementation of geodetic surveys).

The basic differences between both models, with respect to functional aspects and simplification of terms in relation to hydrotechnical issues, are presented in Fig.5.

It should be remembered that the digital model is mostly created in the designing phase of the investment implementation; therefore it is the theoretical model based on the concept of the structure and that control surveys reflect the real conditions of the structure. Unfortunately, the scope of a model based on geodetic surveys is limited; it mostly covers only several points of the structure, located in places specified by the investor's supervising services, often based on results of the preliminary digital modelling.

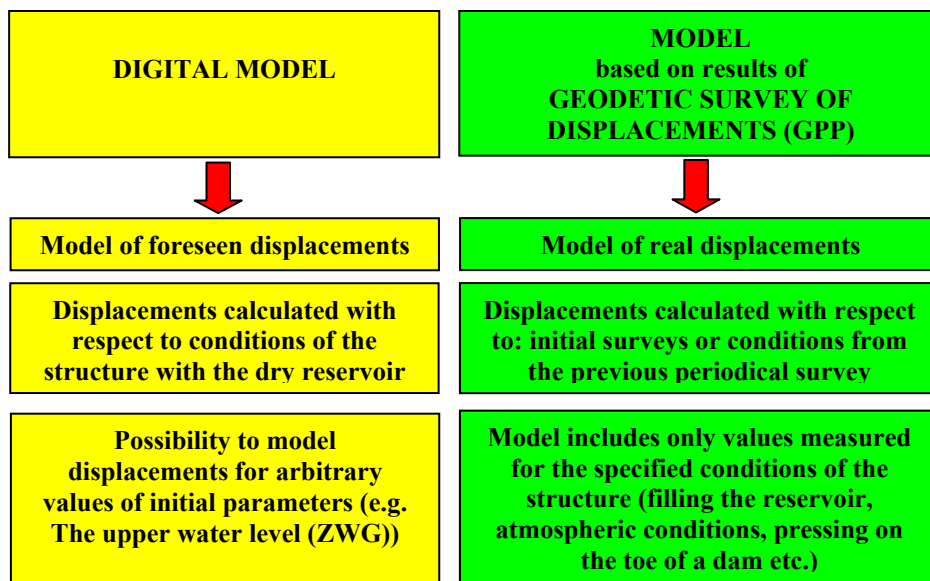


Fig. 5. Basic differences between the digital model and the model based on geodetic surveys of displacements (functional approach).

Various factor influence the accuracy of displacements calculated from the digital model and the accuracy of results of geodetic surveys. Some of them are presented in Fig.6. It may be assumed that results of digital modelling of location of the same point, assuming various loads, will be charged with the same error; unfortunately the same cannot be stated with respect to successive surveys, which are performed in the course of implementation of the structure. The accuracy of determination of location of a point, which is often incorrectly identified as the accuracy of surveys, is influenced by many, the so-called, instrumental factors (e.g. factors connected with the utilised technology of surveys), as well as environmental factors (e.g. atmospheric pressure, surrounding temperature).

An example may be the comparison of forecasts of displacements of the FEM network node in a model of behaviour of e section of the Besko concrete dam with real displacements of a geodetic target, located in a place, which corresponds to that node. For various levels of the upper water (ZWG), recorded in the course of periodical geodetic surveys in the period 1991-1999, calculated forecasted values are practically characterised by the same accuracy, however, the mean errors of displacements determined from geodetic surveys are included in the interval { 0.2 ; 0.5} mm. This issue has been discussed in details in (Zaczek-Peplinska, 2008).

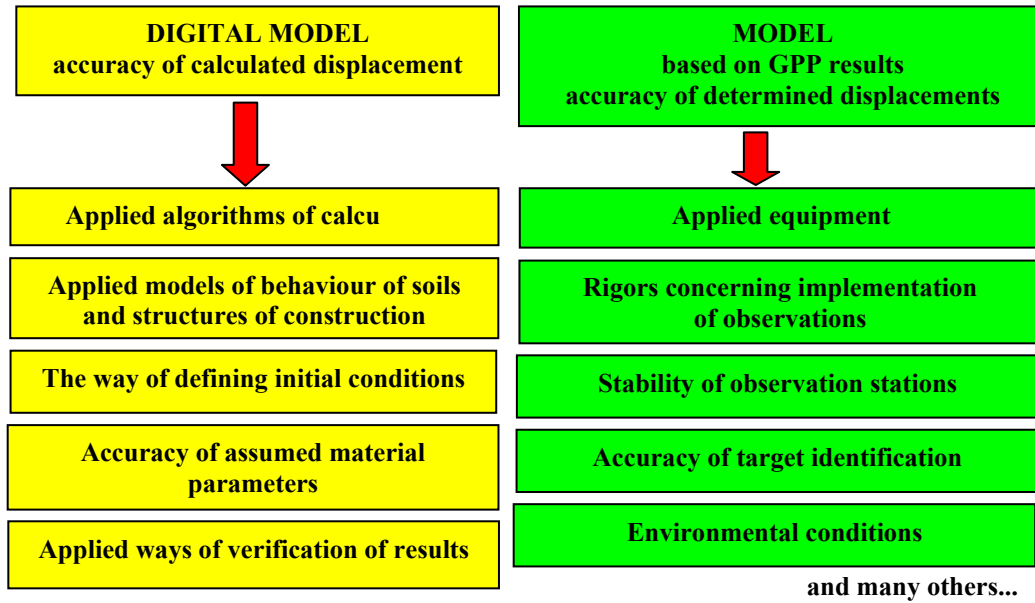


Fig. 6. Factors which influence the accuracy of determined displacements, the digital model and the model based on results of geodetic surveys of displacements.

6. VERIFICATION OF THE DIGITAL MODEL BASING ON RESULTS OF SURVEY MONITORING USING THE EXAMPLE OF THE WOLF MARSZAŁKOWSKA BUILDING

6.1. Characteristics of the structure

The office and service building Wolf Marszałkowska (Fig. 7) is located in the very centre of Warszawa, close the crossroad of the basic arterial roads – the Marszałkowska Street and the Jerozolimskie Avenue. The structural works were commenced in 2008 and their completion is planned in the 4th quarter of 2009.

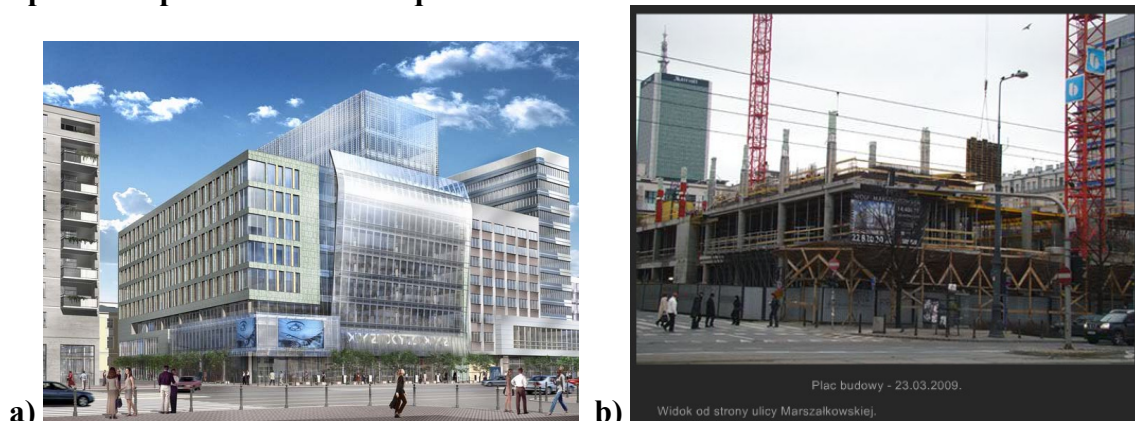


Fig. 7. The WOLF MARSZAŁKOWSKA Building as seen from the Marszałkowska Street: a). the design, b). construction site – placing the concrete on above-ground storeys (March 2008) [source: the investor's archives].

The size of the land parcel equals to 2,116 sq.m. The total size of the 17-storey building (12 above-ground and 5 underground storeys) will equal to 31,707 sq.m. (the useful space 25,095 sq.m., including office space of 11,052 sq.m., and the space for commercial and recreation activities - 3.361 sq.m.). 149 car parking places are planned. The level of

foundation of the building is deeper than the bottom level of tunnels of the Warszawa underground.

The excavation was made by means of the under-ceiling method; at present the concrete is placed on above-ground storeys (completion of the 3rd storey is planned for the end of April 2009).

6.2. Surveying for the needs of verification of the digital model

Additional, precise levelling surveys are performed for the needs of verification of the digital model; they also include surrounding buildings (23 benchmarks) and the ceiling of the „0” storey. The benchmark on the building were localised basing on indications of the employee dealing with numerical calculations – 17 benchmarks were added, placed in three cross sections, parallel to the axes of the Warszawa underground tunnels. Location of the benchmarks is presented in Fig. 8 and 9.

Surveys are performed every month. Beside comparison of results of geodetic surveys and numerical forecasts, data concerning the progress of the investment implementation are currently updated. It is highly important to co-ordinate the moment of surveys with the conditions of structural works; implementation of surveys within periods, which correspond to particular stages of erection of the building, as well as the access to complete data related to works performed at the structure during surveys, are more important than implementation of surveys within equal time intervals.

Three surveys of the control network were performed by the end of April 2008; preliminary analysis and appropriate comparison have already been performed. Obtained results confirm the possibility to utilise the results for the needs of verification of the digital model of mutual impacts between newly constructed and already existing structures (buildings and tunnels of the underground).

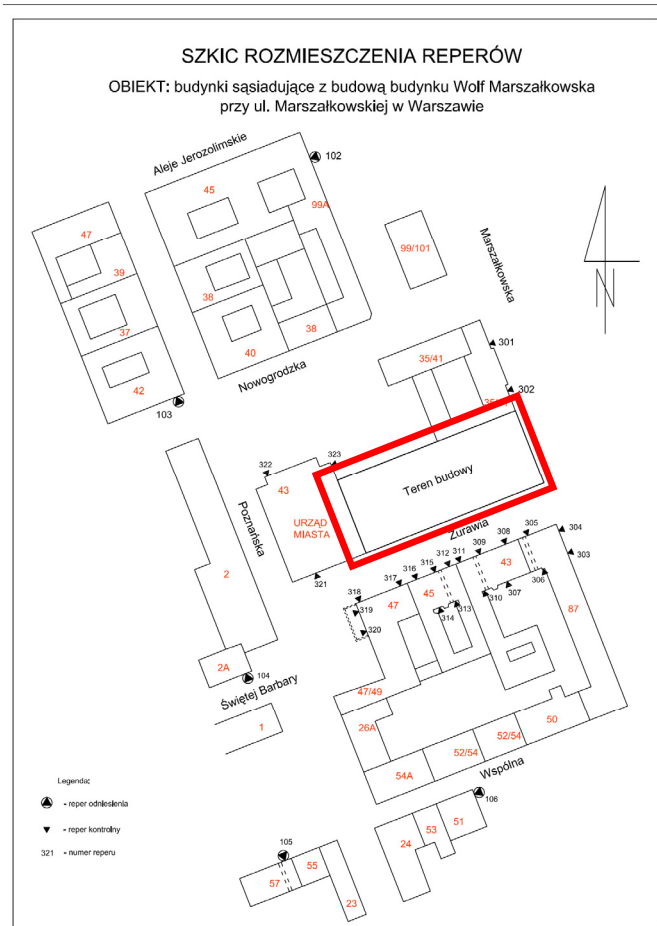


Fig. 8. The diagram of location of benchmarks on buildings surrounding the construction of the WOLF MARSZAŁKOWSKA Building (the construction site has been delineated in red).

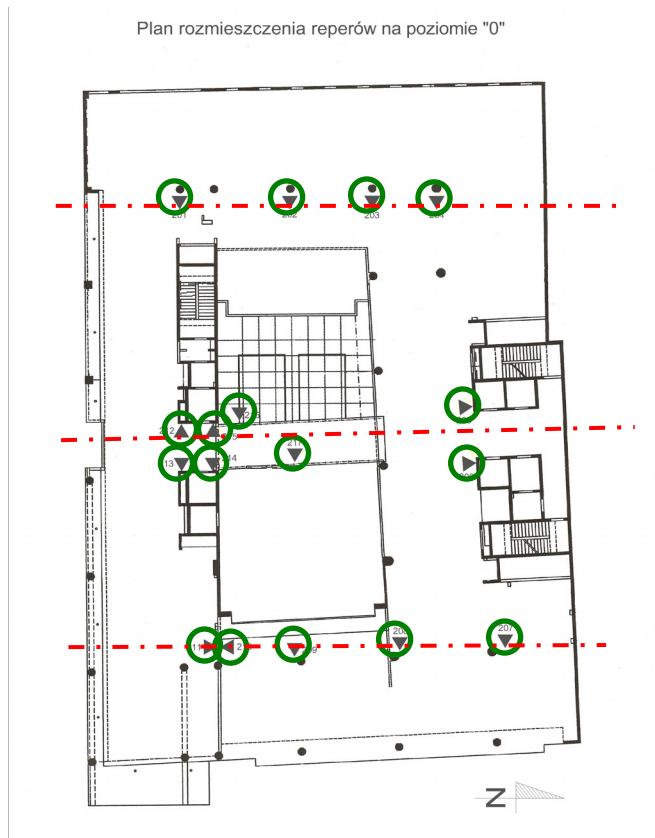


Fig. 9. The diagram of location of benchmarks at the „0” storey of the WOLF MARSZAŁKOWSKA Building – red lines mark the calculation cross sections, the green lines mark the location of controlled benchmarks.

6.3. Numerical modelling

Following the investor's order, the digital model of behaviour of the base and walls of the excavation in the course of the investment implementation, was developed before commencement of structural works. The numerical analysis specified impacts of the building under construction with consideration of the presence of cavity wall, the bottom plate and barettes. The variant analyses was performed, with changed values of lengths of cavity walls and the length and the number of barettes, in order to develop the optimum arrangement considering foundation of the building. Since the building is located next to the route tunnels of the underground, the developed model concerned also the mutual impacts of both investments. Fig. 10. presents the diagram of material zones, developed for that structure. The initial conditions assigned to cavity walls result from the number of storeys constructed in the course of the modelled, "under-ceiling" implementation of the structure.

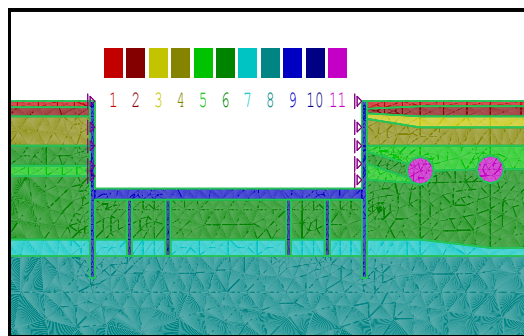


Fig. 10. Diagram of material zones for analysis of deep foundation of the WOLF MARSZALKOWSKA Building and analysis of mutual impacts of underground structures.

The objective of the performed back analysis is to verify the material parameters assumed for calculations. This process was performed basing on the existing monitoring of displacements. Initial parameters of soils were assumed basing on the geological-and-engineering documentation. In successive approximations, made with the use of the „test and error” method values of the elasticity module of selected layers of soils were changed, until such displacements were calculated, which were compliant with the results of performed geodetic surveys. Taring of the digital model was performed this way.

Increasing the value of elasticity modules in successive approximations was based on the assumptions of the, so-called, „small deformations”, for which the values of elasticity modules are greater than in the case of large deformations (Satoru, 1992), (Georgiannou 1991). The change of elasticity concerned only materials which occurred in the zone of small deformations, i.e. below $1 \text{ E-}04$.

Material parameters, verified basing surveys performed in the course of erection of structures and archive data from similar works may be utilised for development of digital models of newly constructed structures. It should be noticed that values obtained by means of the back analysis, do not consider settlement resulting from consolidation of the base, as well as from soil creep (rheological deformations).

The described analyses have not been completed. Each periodical, geodetic survey, performed during the successive stages of implementation of the investment, results in data for successive computational analyses. Presentation of results of monitoring,

calculations and performed back analysis after completion of the investment, as well as conclusions resulting from applied solutions will be the subject of a separate publication.

7. CONCLUSIONS AND REMARKS

- Reliability of results of numerical calculations depends on the accuracy of geological reconnaissance and correctness of determination of material parameters.
- In most cases material parameters are determined using simplified methods, specially developed for soils deposited at small depth, what results in underrating their values. Consequences of this are reflected in the standard method of estimation of settlement of direct foundations.
- Parameters determined basing on the back analysis may be even several times higher than parameters assumed basing on standard tests and norms.
- In the case of considering practical issues of foundation of structures, results of calculations performed basing on values of measured displacements should be considered.
- The back analysis, performed basing on the existing monitoring of displacements, allows for verification of the soil parameters assumed for calculations.
- The back analysis and tests performed in the course of implementation of the structure allow for the efficient verification of the digital model assumed for calculations.
- It seems reasonable to create a data bank concerning implemented projects,, containing material parameters from geological documentation and parameters verified by means of results of the geodetic monitoring. Those data may become the basis for verification of information about the geological base, applied for the needs of designing and implementation of new structures.
- The above results of analysis are compliant with expectations and point to the possibility of utilisation of the geodetic monitoring results for verification of initial assumptions of the FEM modelling with respect to the soil properties and material parameters.
- It would be reasonable to investigate the possibilities of calibration of a digital model basing on results of horizontal and vertical measurements. Due to independency of the horizontal (angular-and-linear) network and the levelling network the way of data integration should be discussed.
- Availability of software used for modelling the structures' behaviour in the three-dimensional (3D) space and introduction of calibration in two planes X, H will allow for higher accuracy of obtained forecasts of the structures' behaviour.

REFERENCES

- Fiedler et al., *Awarie i katastrofy zapór – zagrożenia, ich przyczyny i skutki oraz działanie zapobiegawcze*, IMGW Warszawa 2007.
- Popielski P.: *Model sufozji mechanicznej w ujęciu metody elementów skończonych*, rozprawa doktorska, Politechnika Warszawska, Warszawa 2000.
- Satoru Shibuyaet.: *Elastic deformation properties of geomaterials; Soil and Foundations*, Journal of the Japanise society of Soil Mechanics and Founation Engineering, pp. 23-46, Vol. 32, No. 3 Sep. 1992.

Georgiannou V.N., Rampello S., Silvestri F.: *Static and Dynamic measurements of undrained stiffness on natural overconsolidated clays*, Proc. 10th Firenze Vol. 1, 91 – 95, 1991.

Zaczek-Peplinska J., *Koncepcja modernizacji klasycznych sieci poziomych do wyznaczania przemieszczeń obiektów hydrotechnicznych*, rozprawa doktorska, Politechnika Warszawska, Warszawa 2008.