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SUBSOIL MOVEMENTS FORECASTING USING 3D NUMERICAL MODELING

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The design of new investments with underground floors in the downtown urban fabric calls for determining its impact on existing, often historic, neighboring facilities. The article presents the results of own research on 3D spatial arrangement numerical modeling of this type of investment. The scope of the research includes the analysis of neighboring buildings (including historic buildings), construction of the 3D numerical model, and calibration of the subsoil model taking into account the actual results of geodetic measurements. Own research as well as the completed housing development complex in Poland, downtown Warsaw, including data from project design and implementation documentation serve as the basis for research and analysis. As a result of said research and analysis, it was found that 3D computational models allow mapping of actual impacts within the designed new buildings and neighboring buildings, and as consequence - after appropriate calibration - a good reflection of soil displacements in the area of the planned investment. The knowledge of the anticipated values of soil displacements related to erecting new buildings is necessary at the design and implementation stages to ensure safety in all phases of works of existing buildings.

Keywords**:** soil displacement, 3D numerical modeling, calibration of numerical models, building subsidence, deep building foundations, buildings with multi-story undergrounds.

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1. INTRODUCTION

Buildings with multi-storey underground parts, most often with 2 to 5 such storeys, are more and more often erected in dense urban development. Typically, new investment is a supplementary building, the so-called infill. The erection of a new facility with a deep foundation in the immediate vicinity of the existing buildings causes the displacement of the soil and the buildings situated on it [1-4]. These displacements are caused primarily by the change in the stress state due to the relief and loading of the subsoil, deformation of the excavation support, lowering the groundwater table, and are also dependent on the adopted technology of the excavation support and its height support. It is necessary to determine the range of its impact, as well as to forecast the nature and value of ground displacements at the design stage of this type of investment.

Most of the researchers defined the excavation phase impact ranges and estimated them, mainly on the basis of the results of empirical research, depending on the type of soil forming the subsoil, as a function of the depth of the planned excavation [5-12]. The results showed that the extent of the impact of the excavation depends primarily on the deformability of the soil, the depth of the excavation, the size of the excavation plan, the extent and duration of the possible lowering of the groundwater table (in the case of the excavation below the groundwater level) and the length and bearing capacity of the ground anchor bolts (by securing the stability of the excavation walls with soil anchors). Examples and experiences of implementing such structures were also defined [13-18]. However, during the construction [19], special attention was drawn to the continuous subsoil displacements in subsequent stages of works, i.e. the construction of the underground part, the above-ground part of the facilities, and then works related to the application of the live load. The temporary deformations occurring during the construction of the underground part of the structure are the result of excavation lining deformations, including, in particular, its horizontal displacements. The total deformations are the sum of immediate deformations and rheological deformations of the subsoil, resulting from the "history" of its loading or unloading condition. These deformations arise from the start of building construction until the end of the subsoil consolidation process during the use of the building [19].

It was noted during the construction [20-23] that the development of a numerical model including the layout of the subsoil and the designed building as well as the existing neighboring buildings supports the design of structures deeply seated in dense urban tissue, and also enables the analysis of the impact at all stages of the implementation of this type of investment. In order to represent the actual deformations in the numerical model, it is necessary to calibrate the model, usually using the back-analysis method. It consists in multi-stage modeling of the subsoil parameters, first of all - the modulus of elasticity E, in the zone below the level of the foundation slab, and a comparative analysis of the vertical displacements values at points located on the ground surface in a numerical model and their corresponding points / benchmarks stabilized e.g. on the actual investment obtained from geodetic measurements. The modification of the subsoil parameters takes place until the displacement values from the numerical model and the actual values of vertical displacements obtained from geodetic measurements are consistent. The values that do not differ by more than twice the mean accuracy of geodetic measurements are usually assumed as consistent [19].

During the construction [19] it was assessed that the modeling of the soil modulus of elasticity E in the zone below the level of the foundation slab of the structure is an effective tool for mapping the actual soil deformations.

The analysis of the literature, i.a. [24-27] shows that in terms of the so-called small deformations of the subsoil, which concerns the layers of the subsoil lying deep, usually below the ground recognition level for the purposes of geological and engineering documentation of the designed building, the values of the E module are greater than in the range of large deformations, sometimes even ten times greater. Strengthening (increasing) the modulus of elasticity E of the deeply lying layers of the subsoil in the zone of small subsoil deformations results primarily from their pre-consolidation. An incremental change of this parameter was adopted as the basis for the calibration of numerical models due to the phenomenon of strengthening (increasing) the value of the modulus of elasticity E together with its depth [19].

The 3D computational models presented in this article make the mapping of the real impacts within the designed new development and neighboring buildings possible, and consequently, present a good reflection of the ground displacement of the planned investment area. The awareness of the anticipated displacements of the subsoil related to the new development is necessary at the design and implementation stage to ensure safety in all phases of the existing development works.

1.1. GENERAL DESCRIPTION OF THE DESIGNED INVESTMENT

Own research and the example of a designed and implemented residential complex in the center of Warsaw, Poland, as well as taking into account data from the design and implementation documentation of the investment [33-37] serve as a basis for research and analysis. The subject of the study is a complex of new residential buildings - buildings A, B and C and existing neighboring buildings including (Fig. 1): a baroque church with monastery buildings; classicist salt storage building from 1850; a 5-storey historic modernist building from 1935; multi-family residential building with 17 floors above ground and five residential buildings of various sizes and number of floors above ground ranging from 5 to 9.

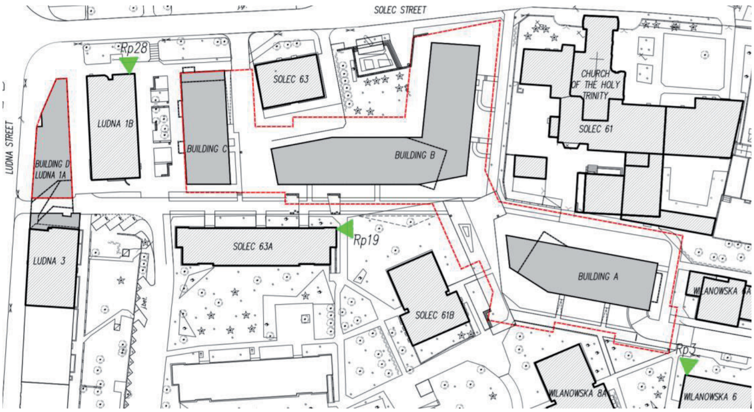

Fig. 1. Site plan of the planned investment and existing neighboring buildings. The outline of the underground part of the new housing complex is marked by a dotted line (own study based on [35]). The location of benchmarks for geodetic measurements is provided - explanations in the text.

1.1.1. SUBSOIL

The subsoil was characterized in the soil investigation report [37] on the basis of field and laboratory research. As part of the field research, 17 boreholes were drilled and 12 research profiles were probed with the static CPT. The physical and mechanical properties of the soil were determined on the basis of in situ tests and laboratory samples taken from the boreholes.

The following geotechnical separations form the subsoil on the investment site (from the top):

- layer I – rubble embankments with an additive of sand and loam with a thickness of 1.0 - 3.8 m;
- layer II – local hard-plastic clay pockets (sub-layer IIa) and sandy clays in a plastic state (sub-layer IIb) with a thickness of up to 2.0 m;
- layer III – medium and coarse sands in the medium compacted state, thickness of 2.5 - 5.0 m;
- layer IV – local fine sands and medium-compacted silty sands;
- layer V – local dusty soil formations in a semi-compacted state;
- layer VI – clays and silty clays in hard-plastic (VIa) and semi-compacted (VIb) state occurring at the level of 5.0 m below the ground surface.

Depending on the season and precipitation, the first level of groundwater can be found at a depth of around 5.5 m below ground level, i.e. below the excavation level. The geotechnical parameters specified in the documentation [37] and adopted in the first phase of the construction of the numerical subsoil model are given in Table 1.

Table 1.Subsoil parameters adopted in the model of the subsoil on the basis of the documentation [37]

Layer No	Compaction index	Plasticity index	Weight/ unit volume	Friction angle	Cohesion	Dilatancy angle	Poisson ratio	Compression modulus based on CPT probing	Modulus of elasticity based on CPT probing
	I_D	I_L	γ [kN/m^3]	φ [°]	c [kPa]	ψ [°]	ν	M [kPa]	E [kPa]
I	–	–	16-18	24	–	–	0.25	–	15,000
IIa	–	0.3	20	–	–	–	0.32	5,000	3,500
IIb	–	0.1-0.2	21.5	15	17	–	0.32	15,000	10,500
IIIa	0.4	–	18.5	32	–	2	0.25	75,000	62,500
IIIb	0.6	–	19.0	34	–	4	0.25	110,000	91,700
IV	0.4-0.6	–	17.5	31	–	1	0.30	90,000-120,000	78,000
V	–	0.0	21	22	40	–	0.29	>45,000	34,400
VIa	–	0.05-0.2	19.5	11	54	–	0.37	20,000-30,000	14,100
VIb	–	0.0	21	13	60	–	0.37	>30,000	17,000
A	–	0.0	21	13	60	–	0.37	–	25,500
B	–	0.0	21	13	60	–	0.37	–	34,000

1.1.2. DESIGNED COMPLEXES OF BUILDINGS A, B AND C

The aboveground construction of buildings A, B and C is a monolithic reinforced concrete frame with infill walls made of ceramic elements. The underground one-story part with an irregular plan with an area of about 5,000 m^2 - is shared by and located under all three A, B and C buildings. The excavation for this 4.0 m deep underground part was carried out using 60 cm thick diaphragm walls housing. (Fig. 2). For the most part, the A, B and C building complexes are founded on a layer of medium-compacted sands, about 2.0 m below the maximum groundwater table. The groundwater level was below the bottom of the foundation slab during the foundation works (no water was pumped out of the excavation) and this level was modeled during the analyses.

Fig. 2. Implementation of the underground building complex a) construction of the foundation slab, b) construction of the walls and pillars of the underground storey.

1.1.3. EXISTING NEIGHBORING BUILDINGS

The most valuable monument located in the vicinity of the planned investment is one of the oldest churches in Warsaw - the baroque church of the Holy Trinity with the adjacent chapel, catechetical house, monastery buildings and office pavilion [36].

The church and monastery buildings are founded directly on stone and brick continuous footing. Building walls are made of ceramic bricks with cement-lime and lime mortar, brick vaults, and a wooden roof truss. The historic classicist salt building from 1850 is the second valuable structure located in the immediate vicinity of the new investment. The building has a basement and has two floors above ground level and a loft. The building's structure is traditional and longitudinal. The foundation is direct on continuous footing about 3.10 m deep below the ground surface.

The modernist tenement house from 1935 is another monument in the immediate vicinity of the building complex. The tenement has a basement and five floors. Its structure is made of ceramic brick, the load-bearing system is longitudinal, and the ceilings are mainly ceramic (Klein ceiling) on steel beams. The foundation is placed directly on a continuous footing about 3.70 m deep below the surrounding area.

Neighboring residential buildings have various constructional and material solutions and overall dimensions, including:

- 17-storey residential building - monolithic RC structure with a transverse arrangement of load-bearing walls and beam and block floors; 50 m high; RC raft foundation;
- 5-storey above-ground multi-family residential building with transverse basement construction, prefabricated RC construction, set at a depth of 2.70 m below the level of the surrounding area on RC continuous footing;

- two 9-storey multi-family residential buildings of identical dimensions and construction solutions; floor shape similar to the letter 'T', full basement; transverse RC wall construction; foundations on RC continuous footing; prefabricated RC floors.

1.2. RANGE OF DESIGNED INVESTMENT

Expert assessments of the technical condition of the neighboring buildings were carried out prior to the commencement of the investment [36], soil and water conditions were determined, as well as excavation for the complex of buildings A, B and C in diaphragm wall housing. The ranges of the excavation impact zones on the displacement of the land surface and the existing buildings located on the land were determined by taking into account the research results and recommendations provided in [1, 10, 12, 19]. Zone I - direct impact of the excavation and the largest expected subsoil deformations of 2.35 m from the diaphragm wall face and zone II with fading impact - 9.4 m [36] (Fig. 3).

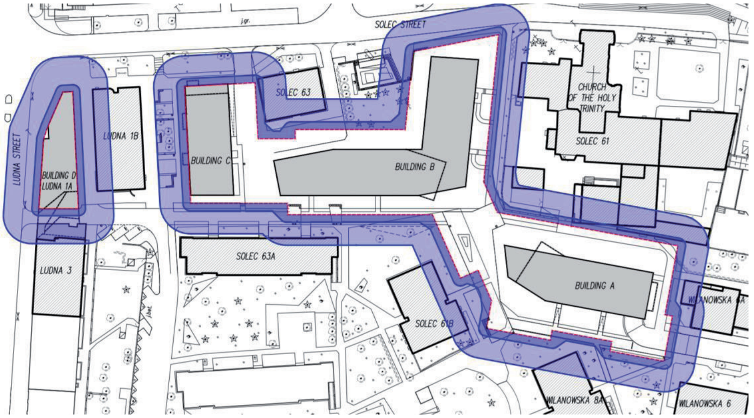

Fig. 3. Range of excavation impact zones at the ground level of the building complex (own study based on [35, 36]). Marking: Zone I - dark purple, Zone II – purple.

There was a historic salt storage building and buildings of the historic church of the Holy Trinity in the direct zone of the first excavation impact. Bearing in mind the construction of the complex in compact downtown buildings, and the historic nature of a significant part of this building, as well as soil and water conditions, the excavation support and the outer walls of the underground were made of 60 cm thick diaphragm walls. Diaphragm walls with a depth of 8.0 to 10.0 m below the ground were placed in cohesive soil to cut off the groundwater supply to the interior of the excavation. During the excavation work to the bottom level of the foundation slab the diaphragm wall stability was ensured by bracing struts with ∅711/12,5, ∅502/12,5 steel pipes and HEB 300 H-sections [33]. After the foundation slab was made and concrete reached the designed strength, the struts were dismantled.

1.3. GEODETIC MONITORING

Geodetic and visual observation of the neighboring buildings located in the zones of influence I and II (cf. Fig. 3) as well as diaphragm walls were carried out during the construction works. Over 70 benchmarks stabilized on neighboring buildings and located in zones I and II of the excavation impact were measured for vertical displacements. The measurements of horizontal displacements of the selected buildings were also carried out, as well as the measurements of horizontal displacements of the diaphragm walls. The frequency of the measurements depended on the stage of the performed construction works.

The maximum benchmark displacements measured on buildings in zone I were: office pavilion - uplift up to +6.0 mm, settlement up to –14.2 mm; catechetical house - uplift up to +2.1 mm, settlement up to –4.9 mm and salt storage - uplift up to +3.0 mm, settlement up to –3.0 mm [34].

2. DEVELOPING A 3D NUMERICAL MODEL

2.1. ADOPTED ASSUMPTIONS

The geotechnical parameters from the technical documentation were adopted for modeling the subsoil of the "subsoil - new A, B and C building complex - adjacent buildings" systems;

phases of work resulting from the actual stages of the investment. The values of loads from buildings, as well as the approach and place of their application, were determined based on the analysis of project documentation and own experience. The spatial numerical model was designed in the 2016 ZSoil application by ZACE Services Ltd. [28-30]. The model maps an area of 240 × 150 m, a complex of new buildings including buildings A, B, C, D and neighboring buildings (Fig. 4).

The load of the buildings was calculated based on the actual dead loads as well as their live loads. The loads associated with individual phases of works were modeled as time-variable and included in calculations in accordance with the actual moment of their application - according to the operative construction schedule of individual buildings. The neighboring buildings were entirely modeled using three-dimensional finite elements [31, 32].

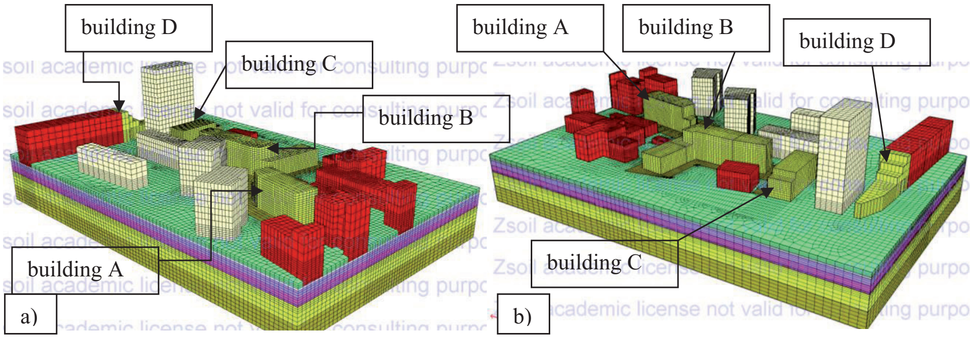

Fig. 4. 3D numerical model covering the designed building complex A, B and C, neighboring buildings and soil: a) view from the south, b) view from the north.

The soil below the buildings was modeled down to 30 m deep below ground level using the Mohr-Coulomb soil model, while the continuation of the last layer of the ground (layer VIb) specified in the documentation [37] was adopted to the full depth of the numerical model divided into two sublayers (layer A and layer B).

The subsoil research included in the geological and engineering documentation [37] determined the parameters of the subsoil reaching up to 12 m below the ground level. Based on the results of the soil investigation report [37], a spatial arrangement of soil layers was modeled on the 29 boreholes (Fig. 5). The parameters of the soil layers below the diagnosis were extrapolated.

The parameters of layer VIb were extrapolated below the identification level of the subsoil [37], dividing it into two layers in the model i.e. layer A - 12-20 m below ground level, layer B - 20-30 m below ground level. (Fig. 5). In the case of individual soil layers, the following parameters were determined on the basis of the soil investigation report [37], i.e.: the soil modulus of elasticity E, Poisson's ratio ν, unit weight γ, angle of repose φ, dilatancy angle ψ and cohesion c (table 1). At the contact point of the diaphragm walls with the ground, contact elements were modeled to reflect the existence of a bentonite slurry layer - occurring in the process of deepening the slots for the walls of the trench housing - with a 5° internal angle of repose. Depending on the soil type of the substrate, the stiffness of the contact elements is automatically generated in the Zsoil program and is automatically modified in the case of changes to soil parameters.

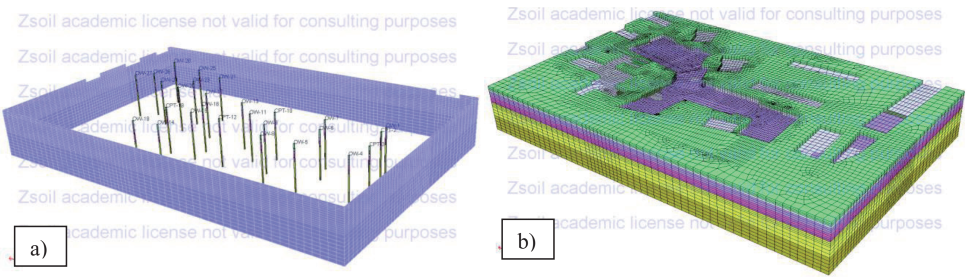

Fig. 5. The modeled subsoil in the place of the boreholes with the external planes of the model - a) and the numerical model of the subsoil in ZSoil 2016 - b).

The designed building complex was built of finite elements - shell and beam, which were used to model the diaphragm walls, the strutting of diaphragm walls, the internal walls, the columns, the foundation slab, the floor above the level -1 in the underground part of the A, B, C, D buildings. The elements were given thickness and material characteristics in accordance with the design assumptions. The ground part of the buildings was mapped as three-dimensional finite elements (continuum). These elements were given the value of the reduced modulus of elasticity, taking into account the stiffness of the above-ground parts of the buildings resulting from the used construction materials and material data, including Poisson's ratio. The presented method of modeling above-ground parts of buildings resulted in the simplification of the model and reduction of the number of finite elements, which in turn allowed for the adaptation of this model to the computational capabilities of the computer [31, 32]. The adopted dimensions of the finite elements of the underground part are 1.0 × 1.0 m and 2.0 × 2.0 m, and the dimensions of the above-ground finite elements are 2.0 × 2.0 × 1.0 m. The load on the buildings was assumed by taking into account the actual weights of structures and finishing elements as well as live loads. The loads, related to individual phases of works, were modeled as variable in time and included in the calculations according to the actual moment of their application - according to the construction schedule of individual buildings (A, B, C and D, i.e. the initial phase zero - before the commencement of works); and subsequently the construction work phases - for each building - in the order of execution (Fig. 6): the guide wall construction (Fig. 6a), the diaphragm walls (Fig. 6b), the preliminary excavation and installation of wall struts (Fig. 6c), the full depth excavation (Fig. 6d), the foundation slab (Fig. 6e), the disassembly of struts, the construction of columns and walls of the underground part (Fig. 6f), the ceiling above the underground floor (Fig. 6g), the construction of the above-ground part (Fig. 6h), the application of the live load (Fig. 6i).

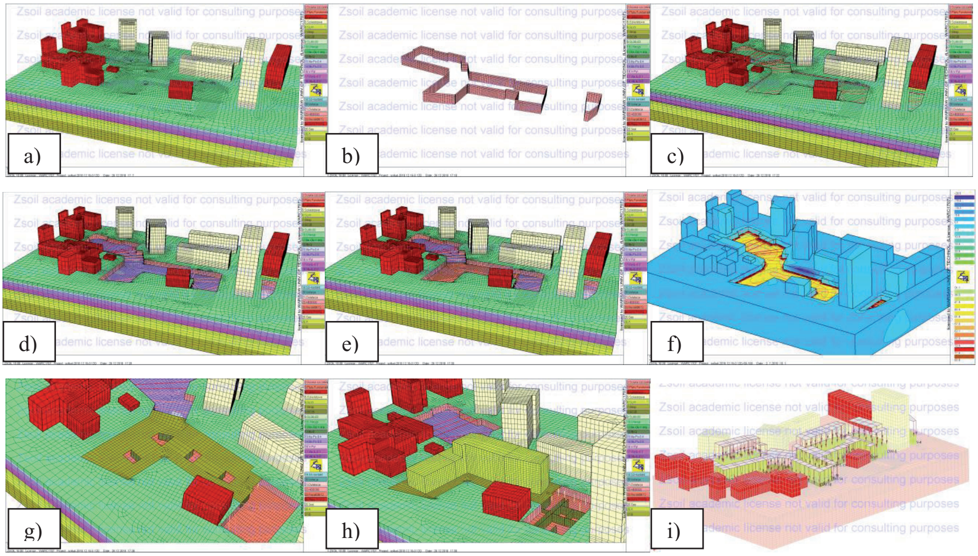

Fig. 6. Numerical models of selected phases of the construction complex implementation - explanations in the text.

The neighboring buildings were entirely modeled (together with the underground parts) using three-dimensional finite elements (continuum). These elements were given the value of the imported modulus of elasticity, taking into account the stiffness of the buildings. The adopted dimensions of finite elements are up to 2.0 × 2.0 × 1.0 m. The parameters of the spatial elements modeled on the existing neighboring buildings were estimated on the basis of own analyses and varied depending on the type of structure, e.g. in the case of tenement houses with masonry structures, the adopted Young's modulus was: $E = 675{,}000$ kN/m^2, $\nu = 0.25$, $\gamma = 6.0$ kN/m^3, and for buildings with reinforced concrete skeleton structure - $E = 2{,}000{,}000$ kN/m^2, $\nu = 0.2$, $\gamma = 5.0$ kN/m^3. The spaces between the individual buildings of the modeled area were filled, in their actual locations, with dilatation elements enabling independent deformation of these buildings in this respect.

2.2. CALIBRATION OF THE NUMERICAL MODEL

Multiple computer simulations were carried out and the results obtained in terms of displacement and model integrity were analyzed as part of the soil model calibration. The calibration consisted in increasing the value of the soil modulus of elasticity located at depths below the recognition level in the geotechnical documentation, i.e. 12 m below ground level [6, 12, 21, 24-26]. The increase in the modulus of elasticity was performed in relation to two separated soil layers located at the depths of 12 – 20 m (layer A) and 20 – 30 m below ground level. (layer B). The soil in these layers was adopted - from the soil investigation report [37] - as clay with the value of the angle of repose amounting to 13°, cohesion 60 kPa and the modulus of elasticity E amounting to 17,000 kPa. The increase in the value of this modulus by 50, 100, 150, 200, 300 and 400% in relation to the initial parameters for layer A was analyzed - up to 51,000 kPa (up to plus 200%), and for layer B - up to 85,000 kPa (up to plus 400%).

The results of displacement of buildings from the 3D model were compared with the results of displacement measurements during the implementation of the investment [34]. The displacement results that were the same as the actual displacement measurement results obtained from geodetic measurements, by more than a double geodetic measurement accuracy, i.e. ±0.6 mm, were considered convergent. The following factors of building 3D numerical models were analyzed in the calibration process: soil parameters – taking into account the modulus of elasticity, dilatancy angle, the variable coefficient of the contact element stiffness.

As part of the subsoil model calibration, multiple computer simulations were carried out and the obtained results in terms of displacement and model integrity were analyzed. The model with the smallest possible modification of the subsoil stiffness, which met the convergence assumptions, i.e. in which the modulus of elasticity E of layer A was increased - by 50% (up to 25,500 kPa) and the stiffness of layer B - by 100% (up to 34,000 kPa), was adopted as calibrated.

The comparison of the vertical displacement results of the selected points of the calibrated numerical model located at different distances from the edge of the excavation (see Fig. 1) of the erected building and corresponding to the results obtained from geodetic measurements is shown in Fig. 7. Taking into account the adopted convergence assumptions of the geodetic measurements results and the previously characterized vertical displacements read from the numerical model - a satisfactory agreement of comparative analysis of the results was confirmed in this respect, except for one case - the result of the geodetic measurement of the Rp19 benchmark (Fig. 7). Due to the significant difference in the results of geodetic measurements of the Rp19 benchmark uplift, obtained from only one measurement on July 1, 2016 (results of subsequent geodetic measurements on May 14 +1.8 mm; July 1 +3.3 mm; July 8 +1.6 mm and July 15 +1.4 mm), the subsequent measurements of this benchmark, i.e. July 8, 2016 and July 15, 2016, were not confirmed - the result of this measurement was considered probably encumbered with an error.

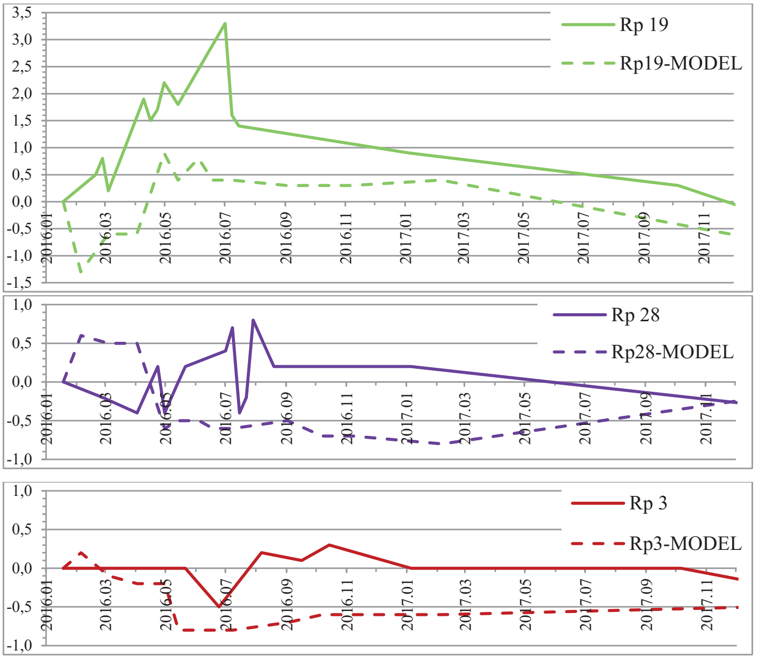

Fig. 7. Comparison of the vertical displacement results from the numerical model and the corresponding ones obtained from geodetic measurements (location of geodetic benchmarks - see Fig. 1). The distance of the benchmark from the edge of the excavation: Rp19 - 7.2 m; Rp28 - 13.8 m; Rp3 - 8.5 m.

2.3. RESULT OF NUMERICAL ANALYSES

In all phases of the erection of the multi-family housing complex displacement, analyses of the calibrated 3D model were carried out. Figure 8 shows the deformed model in the final stage of implementation (deformations scaled 100 times).

As a result of repeated numerical simulations aimed at calibrating the subsoil model, it was found that in the case of 3D models the most important factors affecting the efficiency of numerical modeling are in particular: the appropriate determination of the soil modulus of elasticity *E*, as well as precise modeling of underground parts of buildings and also taking into account the relevant contact elements in the ground - building contact point. Limiting the size of the model by limiting the depth of the subsoil results in obtaining model displacement values significantly different from the values measured during the implementation of the investment, as well as from the values obtained for the calibrated model of the subsoil.

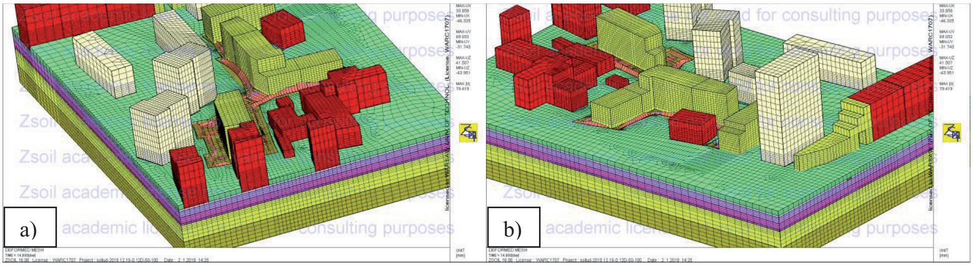

Fig. 8. Numerical 3D model deformed in the final phase (deformations scaled 100 times): a) view from the south, b) view from the north.

3. FINAL CONCLUSIONS

An important element is to determine the extent and expected impact of this investment on the ground displacement and neighboring buildings at the design stage of new investment in compact downtown buildings. The largest observed impact arises during the excavation and underground floors of new investments of this type. The information from the stages of pre-design and design works was used to develop the output model of this system in the numerical analyses of the "subsoil - new building complex - adjacent buildings" systems. The results of displacement measurements of neighboring buildings from the stages of implementation and geodetic monitoring constituted the basis for model calibration. The compliance (assuming an acceptable error of analysis) in the scope of compared vertical displacements from numerical calculations and geodetic measurements in selected benchmarks was treated as identical to calibration, i.e. obtaining the final model. A spatial numerical model of the real investment was presented related to the construction of a new residential building in the center of Warsaw along with an extensive underground part constructed with diaphragm walls. The numerical model was calibrated to map real ground displacements and displacements of neighboring buildings, including historic buildings situated on it. The calibration includes the results of architectural, historical and conservation analyses, as well as the functional and spatial layout; structural and geotechnical conditions in the pre-design, design and implementation phases.

Based on the performed tests and analyses, the following conclusions were made:

The scope of geotechnical soil investigation report should include both the area of the planned new development, as well as the area of the investment impact.

3D modeling of complex investments related to the construction of new facilities with underground parts in dense downtown buildings is a useful tool for forecasting soil displacement and buildings situated on it at the design stage.

3D calculation models allow for mapping of real impacts within the planned new buildings and neighboring buildings, and as a consequence - after appropriate calibration - a good reflection of ground soil displacements of the planned investment. The knowledge of the ground soil displacements estimated at a value related to new buildings is necessary at the design and implementation stages to ensure safety in all phases of works of existing buildings.

The obtained displacement analyses resulting from the 3D numerical model are useful at the stage of designing the network of geodetic measurements of displacements of neighboring buildings crucial for ongoing monitoring of neighboring buildings during investment implementation.

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Rys. 8. Model numeryczny 3D odkształcony w fazie końcowej (odkształcenia przeskalowane 100-krotnie): a) widok od strony południowej, b) widok od strony północnej.

SUBSOIL MOVEMENTS FORECASTING USING 3D NUMERICAL MODELING

Keywords: soil displacement, 3D numerical modeling, calibration of numerical models, building settlements, deep foundations, buildings with multi-story undergrounds.

SUMMARY

The design of new investments with underground floors in the downtown urban fabric calls for determining its impact on existing, often historic, neighboring facilities. The article presents the results of own research on 3D spatial arrangement numerical modeling of this type of investment. The scope of research includes the analysis of neighboring buildings (including historic buildings), construction of the 3D numerical model, and calibration of the soil subsoil model taking into account the actual results of geodetic measurements. Own research as well as the completed housing development complex in Poland, downtown Warsaw, including data from project design and implementation documentation serve as basis for research and analysis. Phases of work resulting from the actual stages of investment implementation were adopted for modeling the subsoil of the "subsoil - new building complex A, B and C buildings - adjacent buildings" geotechnical parameters from the technical documentation of the facility. The loads from buildings, as well as the manner and place of their application were determined on the basis of the analysis of project documentation and own experience. The spatial numerical model was built in the ZSoil 2016 application. The model reproduces an area of 240 × 150 m. The soil below the buildings was modeled to a depth of 30 m below ground level using the Mohr-Coulomb ground model. As part of the soil model calibration, multiple computer simulations were carried out and the results obtained in terms of displacement as well as model integrity were analyzed. The calibration consisted in increasing the value of the soil modulus of elasticity located at depths below the recognition level in the geotechnical documentation. The results obtained from displacement of buildings in the 3D model were compared with the results of displacement measurements during the implementation of the investment. The displacement results that were the same as the actual displacement measurement results obtained from geodetic measurements, by more than a double geodetic measurement error, i.e. ±0.6 mm, were considered convergent. As a result of repeated numerical simulations aimed at calibrating the subsoil model, it was found that the most important factors affecting the efficiency of numerical modeling are, in the case of 3D models, in particular: appropriate determination of the soil modulus of elasticity, precise modeling of the soil medium taking into account additional parameters such as dilatancy angle, but also precise modeling of underground parts of buildings taking into account the appropriate contact elements in the contact ground - building. 3D modeling of complex investments related to the construction of new facilities with underground parts in dense downtown buildings is an effective tool for forecasting - at the design stage - of the displacement of soil and buildings situated on it. 3D calculation models allow for mapping of real impacts within the planned new buildings and neighboring buildings, and as a consequence - after proper calibration - a good reflection of ground soil displacements of the area of the planned investment. The knowledge of the predicted values of ground soil displacements related to new buildings is necessary at the design and implementation stages to ensure safety in all phases of works of existing buildings.

PROGNOZOWANIE PRZEMIESZCZEŃ PODŁOŻA GRUNTOWEGO Z WYKORZYSTANIEM MODELOWANIA NUMERYCZNEGO 3D

Słowa kluczowe: przemieszczenia gruntu, modelowanie numeryczne 3D, kalibracja modeli numerycznych, osiadania budynków, głębokie posadowienia, budynki z wielokondygnacyjnymi podziemiami.

STRESZCZENIE

Projektowanie nowych inwestycji z kondygnacjami podziemnymi w śródmiejskiej tkance miejskiej wymaga określenia jej oddziaływania na istniejące, często zabytkowe, obiekty sąsiednie. W artykule przedstawiono wyniki badań własnych dotyczących modelowania numerycznego w układzie przestrzennym 3D tego rodzaju inwestycji. Zakres badań obejmuje, analizę sąsiedniej zabudowy (w tym zabudowy zabytkowej), budowę modelu numerycznego 3D, kalibrację modelu podłoża gruntowego przy uwzględnieniu rzeczywistych wyników pomiarów geodezyjnych. Podstawę badań i analiz stanowi przykład zrealizowanego zespołu zabudowy mieszkaniowej w śródmieściu Warszawy uwzględniający dane z dokumentacji projektowej i realizacyjnej inwestycji oraz doświadczenia własne. Do modelowania podłoża gruntowego układów „podłoże gruntowe – nowy kompleks budynków A, B i C – zabudowa sąsiednia" przyjęto parametry geotechniczne z dokumentacji technicznej obiektu, fazy prac wynikające z rzeczywistych etapów realizacji inwestycji. Wartości obciążeń od budynków, sposób i miejsca ich przyłożenia określono na podstawie analizy dokumentacji projektowej oraz doświadczeń własnych. Przestrzenny model numeryczny zbudowano w programie ZSoil 2016. Model odwzorowuje obszar o wymiarach 240 × 150 m. Podłoże gruntowe pod budynkami zamodelowano do głębokości 30 m poniżej poziomu terenu z wykorzystaniem modelu podłoża Mohra-Coulomba. W ramach kalibracji modelu podłoża gruntowego prowadzono wielokrotne symulacje komputerowe i analizowano uzyskiwane wyniki w zakresie przemieszczeń, a także integralności modelu. Kalibracja polegała na zwiększaniu wartości modułu odkształcenia pierwotnego gruntu znajdującego się na głębokościach poniżej poziomu rozpoznania w dokumentacji geotechnicznej. Otrzymane wyniki przemieszczeń zabudowy z modelu 3D porównywano z wynikami pomiarów przemieszczeń w trakcie realizacji inwestycji. Jako zbieżne uznawano wyniki przemieszczeń nie różniące się wyników pomiarów rzeczywistych przemieszczeń, uzyskanych z pomiarów geodezyjnych, o więcej niż podwójny błąd pomiaru geodezyjnego, tj. ±0,6 mm. W wyniku przeprowadzonych wielokrotnych symulacji numerycznych mających na celu skalibrowanie modelu podłoża gruntowego stwierdzono, że najistotniejszymi czynnikami wpływającymi na efektywność modelowania numerycznego są w przypadku modeli 3D w szczególności: odpowiednie określenie modułu odkształcenia pierwotnego gruntu, precyzyjne zamodelowanie ośrodka gruntowego z uwzględnieniem dodatkowych parametrów, takich jak kąt dylatancji, ale ponadto precyzyjne zamodelowanie części podziemnych budynków z uwzględnieniem odpowiednich elementów kontaktowych w styku podłoże gruntowe – budynek. Modelowanie 3D złożonych inwestycji dotyczących budowy nowych obiektów z częściami podziemnymi w zwartej zabudowie śródmiejskiej stanowi efektywne narzędzie służące do prognozowania – w fazie projektowania – przemieszczeń podłoża gruntowego i zabudowy na nim usytuowanej. Modele obliczeniowe 3D umożliwiają odwzorowanie rzeczywistych oddziaływań w obrębie projektowanej nowej zabudowy i budynków sąsiednich, a w konsekwencji – po odpowiedniej kalibracji – dobre odzwierciedlenie przemieszczeń podłoża gruntowego obszaru projektowanej inwestycji. Znajomość wartości przewidywanych przemieszczeń podłoża gruntowego związanych z nową zabudową jest niezbędna na etapie projektowym i realizacyjnym do zapewnienia bezpieczeństwa we wszystkich fazach robót istniejącej zabudowy.

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