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## THE MODELLING OF EXCAVATION PROTECTION IN A HIGHLY URBANISED ENVIRONMENT

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### MODELOWANIE ZABEZPIECZENIA WYKOPU W ŚRODOWISKU MOCNO ZURBANIZOWANYM

#### Abstract

This paper presents the problem of excavation protection in an 'infill' construction environment surrounded by neighbouring buildings. It presents a method of protecting deep excavation within a palisade of CFA reinforced piles in casing pipes. The 3D model was built using the ZSoil program, in which the neighbouring buildings were taken into account in modelling. The HSs model of the ground base was adopted. Based on the ITB instruction [1], an analysis was performed on the impact of building expansion on neighbouring buildings; this analysis provides guidelines for the first two phases, i.e. the phase of shoring construction and the phase of actual excavation. The study also takes into account the phase of building serviceability. After including the results of numerical analysis in the estimation of the displacements of neighbouring structures, the results were compared with indicative displacement limit values of displacement building structures.

**Keywords:** deep excavation, neighbourhood building, palisade, cased CFA piles, HSs model

#### Streszczenie

W pracy przedstawiono problem zabezpieczenia wykopu realizowanego w środowisku „plombowym”, w otoczeniu sąsiedniej zabudowy. Opisano metodologię zabezpieczenia głębokiego wykopu w technologii palisady z pali zbrojonych CFA w rurach osłonowych. Zbudowany został model 3D w programie geotechnicznym ZSoil, w którym uwzględniono sąsiednią zabudowę. Przyjęto ośrodek gruntowy modelu HSs. Na podstawie instrukcji ITB [1] przeprowadzono analizę wpływu rozbudowy obiektu na sąsiednią zabudowę, która podaje wytyczne dla pierwszych dwóch faz, tj. fazy wykonania obudowy i wykonania wykopu. W opracowaniu uwzględniono dodatkowo fazę eksploatacji obiektu. Włączając uzyskane rezultaty analizy numerycznej do oszacowania przemieszczeń na sąsiednie obiekty, wyniki porównano z orientacyjnymi wartościami granicznymi przemieszczeń konstrukcji budynków.

**Słowa kluczowe:** głęboki wykop, sąsiednia zabudowa, palisada, rurowane pale CFA, model HSs

## 1. INTRODUCTION

Nowadays, one can colloquially say that ‘we build wherever we can’, meaning that it is becoming more and more difficult to find a space to erect buildings in an attractive location and at a good price. We use every possible piece of land, especially in city centres, which costs more and more, and often use neighbouring areas.

With reference to the investment that is the subject of this paper carried out in reality, this paper describes the spatial 3D model of the designed building with the protection of a deep excavation for palisade technology with CFA reinforcement piles in casing pipes. Based on the ITB instruction [1], an analysis was performed of the impact of building extension on neighbouring buildings. To estimate the vertical displacements of neighbouring buildings, numerical results from the second and the third phase were taken into account; this is from the phase at the stage of excavation protection and the phase at the building serviceability stage.

## 2. SOIL AND WATER CONDITIONS

The area under consideration is located within the Polish Uplands in the sub-province of the Śląsko-Krakowska Upland. In terms of morphology, the research area lies on the Katowice Plateau. The plot under investigation is located in the depression of the Rawa river whose regulated bed is located approximately 300 m north of the area in question. The investment area is surrounded by high-density development located in the city centre. The location of the structure is shown in Fig. 1.



Fig. 1. Location of the building

In the ground of the investigated area there are both, man-made soils and native soils with diverse lithology and consistency. Therefore, based on the available soil engineering report, the most unfavourable layer layout was chosen for modelling; this is shown in the V-V' cross section in Fig. 2. The red line marks the bottom of the foundation slab of the designed building, which is 4.5 m below the ground surface. The groundwater level is situated at a depth of approx. 6.2 m below the ground surface.

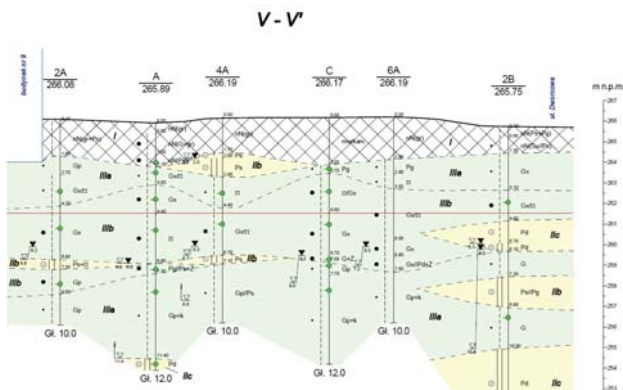


Fig. 2. Geological engineering cross section V-V'

Below the existing layer of man-made soil with a thickness of around 2.0 m, there are clays interbedded with sandy lenses. The clays may be generally characterised as being stiff and firm. The thicknesses of the medium and fine sand lenses range between 0.5 and 1.5 m. The values of geotechnical parameters of individual soil layers are presented in Table 1.

Table 1. Values of the geotechnical parameters of the soil models

| Parameters of Coulomb-Mohr model |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
|----------------------------------|----------------|------------|--------|------------|-------------|-------------------|----------------|--------|--------|------|-----------|----------------------|------------|
| Layer I                          |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| $E$                              | $\nu$          | $\Phi$     | $\Psi$ | $c$        | $K_0$       |                   |                |        |        |      |           |                      |            |
| [M Pa]                           | [-]            | [°]        | [°]    | [-]        | [M Pa]      |                   |                |        |        |      |           |                      |            |
| 27.8                             | 0.25           | 20         | 0      | 10         | 0.66        |                   |                |        |        |      |           |                      |            |
| Layer III <sub>b</sub>           |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| 46.7                             | 0.25           | 15         | 0      | 18         | 0.74        |                   |                |        |        |      |           |                      |            |
| Parameters of HSs model          |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| Layer II <sub>b</sub>            |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| $E_{ur}^{ref}$                   | $\sigma_{ref}$ | $\nu_{ur}$ | $m$    | $\sigma_L$ | $E_0^{ref}$ | $\gamma_{0.7}$    | $E_{50}^{ref}$ | $\Phi$ | $\Psi$ | $c'$ | $E_{ocd}$ | $\sigma_{ocd}^{ref}$ | $K_0^{NC}$ |
| [M Pa]                           | [k Pa]         | [-]        | [-]    | [k Pa]     | [M Pa]      | [-]               | [M Pa]         | [°]    | [°]    | [-]  | [M Pa]    | [k Pa]               | [-]        |
| 180                              | 100            | 0.25       | 0.4    | 10         | 440         | $4 \cdot 10^{-5}$ | 60             | 31.5   | 6      | 0    | 60        | 200                  | 0.48       |
| Layer II <sub>c</sub>            |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| 180                              | 100            | 0.25       | 0.4    | 10         | 540         | $1 \cdot 10^{-4}$ | 60             | 31.5   | 6      | 0    | 60        | 200                  | 0.48       |
| Layer III <sub>a</sub>           |                |            |        |            |             |                   |                |        |        |      |           |                      |            |
| 49.5                             | 100            | 0.25       | 0.65   | 10         | 440         | $2 \cdot 10^{-5}$ | 16.5           | 35     | 4.5    | 0    | 16.5      | 232.56               | 0.43       |

### 3. 3D NUMERICAL MODEL IN ZSOIL

This part of the paper presents an example of the modelling of the designed building and the excavation protection for the project which encompasses the addition of floors to the existing building and the addition of a 7-level building (with one underground floor) in the place of a demolished house. The buildings will be independently and structurally connected with each other. The designed building will be based on a piled-raft foundation (CPRF [2]) utilising the CFA reinforced pile palisade technology. In the foundation slab are local thickenings at the column locations. There are also, two pits in the left area of the slab. Figure 3 shows the geometry of a piled-raft system with the locations of columns, the shafts of the building and a system of columns for the palisade protecting the excavation.

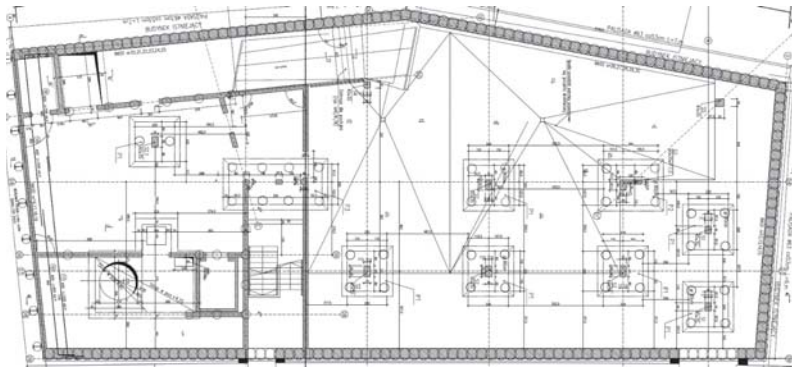


Fig. 3. Sheet of the foundation slab of the designed building

The foundation slab is 50 cm thick. The two pits have a depth of about 2.0 m. The slab is thickened at column locations to a total thickness of 80 cm.

In order to create a three-dimensional numerical model using the ZSoil program (2016\_16.04), the following assumptions were made for the structural elements:

- ▶ The foundation slab is modelled as a 50 cm thick discrete 3D continuum element.
- ▶ The palisade is modelled around the circumference as discrete beam elements – piles with a cross section of  $\Phi$  50 cm, spaced at 45 cm and with a length of 7.0 m from the bottom of the foundation slab. Above the bottom of the slab, 3D continuum elements were used. The total height of the palisade is 11.75 m from ground level.
- ▶ Piles/columns under the slab were modelled using discrete beam elements – piles with cross sections of  $\Phi$  50 cm and with a length of 7.0 m from the bottom of the foundation slab.
- ▶ In pit locations, vertical elements with a length of approx. 2.50 m were built with the use of discrete 3D continuum elements. Under these elements, beam-like elements were placed as piles with a cross section of  $\Phi$  50 cm and 3.0 m long. The total height of the vertical wall elements in the pits measured from the bottom of the slab is 5.50 m.

This solution allowed the authors to go with the base of the modelled palisade and the piles tip into the load-capacity layer of the  $II_c$  sands

- Floor slabs and structural shafts were modelled using discretised elastic isotropic shells with thicknesses from 0.2 m to 0.35 m

Adjacent buildings were taken into account by modelling the foundations of individual buildings at an appropriate depth. Discrete 3D continuum elements were used with material parameters corresponding to the concrete class C30/37. The estimated system of forces was collected from the whole structures and applying to the foundations.

The ground base was created in the model in which the underground part of the building was created and then the entire building. An elastic-plastic model with Coulomb-Mohr yield conditions was used to define the subsurface soil layers, while the hard plastic clay deposits ( $I_L = 0.17$ ), i.e. layer  $III_a$  and sand layers  $II_b$  and  $II_c$ , were parameterised using the HSs model.

A view of the 3D model with the adopted layout of layers in ZSoil is shown in Fig. 4.

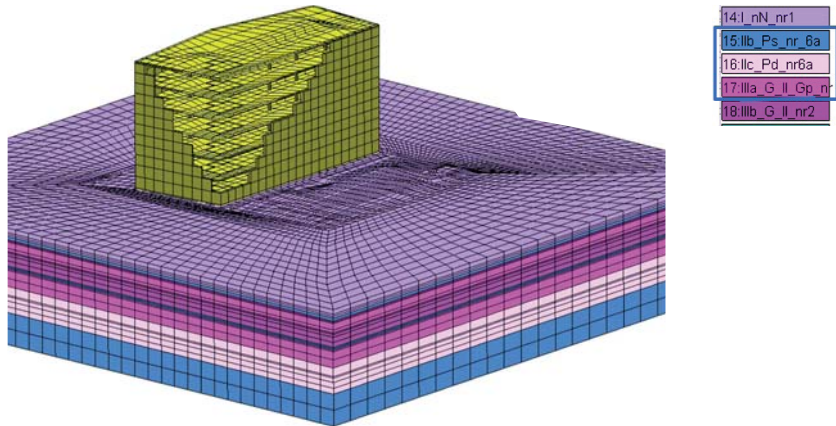


Fig. 4. 3D view of the ZSoil model; the designed building with the adopted layout of layers

#### 4. NUMERICAL ANALYSIS AND RESULTS

The conducted analysis concerns the impact of the extension of the designed structure on the neighbouring buildings. There are three phases each of which generates an impact on the environment. The calculations are divided into three suitable stages.

To specify the maximum displacements in direct contact with the excavation shoring  $max v_o$ , we should determine the sum of the maximum displacements caused by excavation shoring  $v_i$  and horizontal displacement of the wall  $v_u$ :

$$max v_o = v_i + v_u$$

Figure 5 shows a simplified distribution of soil displacements in the vicinity of a deep excavation [1].

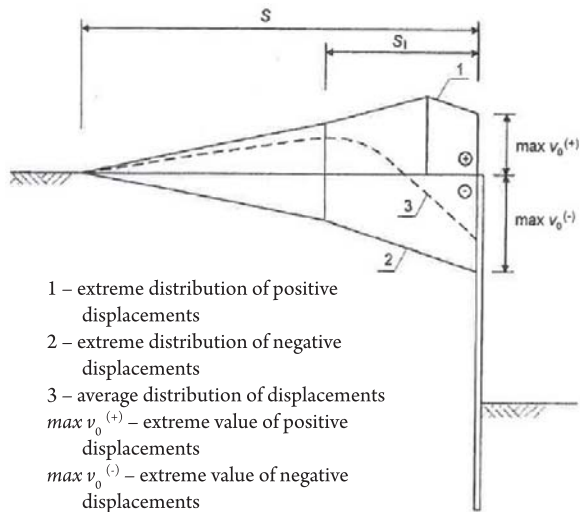


Fig. 5. Simplified distributions of soil displacements in the vicinity of a deep excavation [1]

## FIRST PHASE OF EXCAVATION SHORING

The excavation shoring will be made from level of the work platform, situated at 1.3 m below the ground level. Cased CFA piles combine the quality of classic CFA piles with piles made in casing pipes. This technology of piles is known as CFP (Cased Flight Auger Piles) or VDW (Vor der Wand – in front of the wall) [3]. The piling machine is equipped with a double rotary head that rotates the auger and the casing pipe independently and in opposite directions. In the process of drilling with the auger, the hole drilling is simultaneously by inserting a casing pipe which ensures hole stability during drilling. When an assumed depth is reached, the auger is pulled out together with the pipe, while at the same time, a well-formulated concrete mix is pumped through the auger core pipe. Reinforcing cages or steel sections are inserted by pressing and vibrating.

Maximum vertical displacement caused by construction of the excavation shoring  $v_i$  is determined using formula (1) suggested by instruction [1].

$$v_i = \alpha (H_w)^{\frac{1}{2}} \quad (1)$$

By inserting the following values into formula (1)

$H_w = 7.3$  m – excavation depth,

$\alpha = 1.3$  – empirical coefficient

we get the value  $v_i = 3.51$  mm

## SECOND PHASE OF EXCAVATION

The excavation stage has been included in the model. The protection of the palisade includes one level of strutting with steel pipes. The excavation phases are schematically presented in Fig. 6. Horizontal displacements of the retaining wall were read from the map of

horizontal strain of the palisade for the different excavation phases. The maximum horizontal displacement of the excavation shoring is shown in Figure 7.

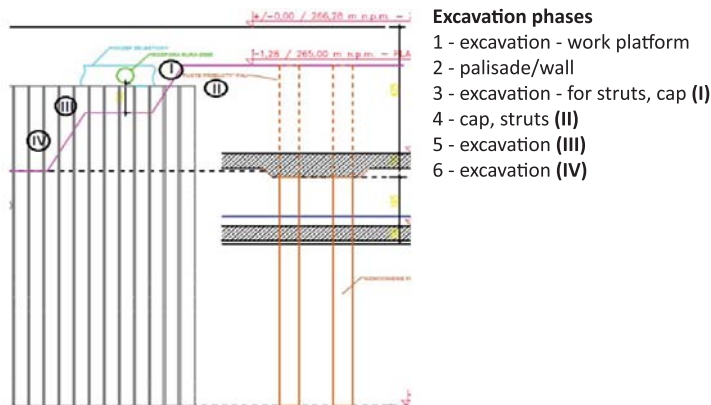


Fig. 6. Excavation phases

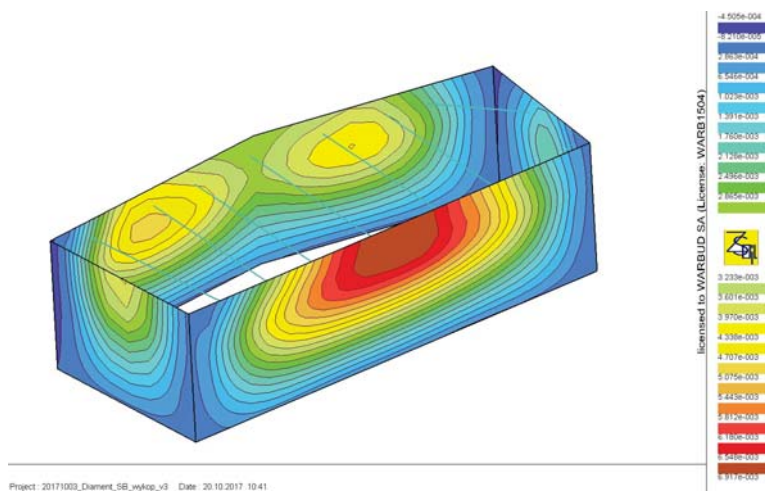


Fig. 7. Horizontal displacement map of excavation shoring

Vertical displacements  $v_u$  caused by deformation of the excavation shoring wall are calculated from formula (2).

$$v_u = 0.75(\max u_k) \quad (2)$$

When entering the obtained value of maximum horizontal displacement of the excavation shoring  $\max u_k = 6.92$  mm into formula (2), we get the value  $v_u = 5.19$  mm.

Vertical displacements of the neighbouring terrain caused by the excavation can also be obtained directly from the results of numerical calculations by reading the value of displacements from the vertical displacement map shown in Fig. 8.

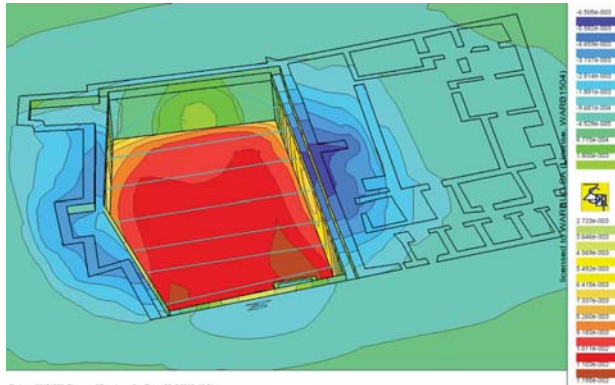


Fig. 8. 3D map of vertical displacements from the ZSoil model after phase II – excavation

The maximum value of the vertical displacement of the adjacent area in the immediate vicinity of the excavation shoring, read from the map in Fig. 8 is  $\nu_u = 6.5$  mm.

### PHASE III BUILDING SERVICEABILITY

The results from the building serviceability phase were obtained directly from the calculations made in the 3D model using the FEM algorithm.

Modelling phases:

- ▶ existing buildings in the form of strip footings and foundations were assumed
- ▶ estimated load values were applied to the strip foundations of the neighbouring buildings
- ▶ execution of a wide excavation in order to take into account the influence of soil relaxation on the neighbouring buildings – excavation phase in accordance with Fig. 6
- ▶ construction of the target structure
- ▶ applying a configuration of forces to the structure

Figure 9 shows a settlement map for the foundation slab and the neighbouring buildings.



Fig. 9. Map of settlement of the foundation slab and neighbouring buildings in the building serviceability phase



The obtained value of settlement of the neighbouring foundations in the phase of serviceability of the designed building is 9.1 mm.

## RESULTS

The maximum vertical displacements behind the excavation shoring amount to:

$$\max v_0 = 3.51 + 5.19 = 8.70 \text{ mm (phases I + II)}$$

The area displacements at distance  $d_{min} = 0.25 \text{ m}$  – the minimum distance between the adjacent foundations and the excavation shoring – estimated on the basis of linear interpolation is:

$$v_0 = 8.5 \text{ mm}$$

The obtained value is contained within the range of approximate characteristic limit values of building structure displacement according to Table 2.

| Rodzaj konstrukcji   | $[s_k]_u, \text{ mm}$ | $[s_k]_n, \text{ mm}$ |
|--|-----------------------|-----------------------|
| Budynki murowane bez wieńców, ze stropami drewnianymi lub ceramicznymi typu Kleina       | 5–7                   | 15–18                 |
| Budynki murowane ze stropami gęstożebrowymi lub żelbetowymi, albo budynki prefabrykowane | 7–9                   | 20–25                 |
| Budynki o konstrukcji monolitycznej  | 9–11                  | 25–35                 |

Table 2. Limit values for building structure displacements [1]

Taking into account the results obtained in the third phase – the serviceability of the structure – we get:

$$\max v_0 = 3.51 + 5.19 + 9.1 = 17.6 \text{ mm (phases I+II+III)}$$

The obtained value is not contained within the range of approximate characteristic limit values of building structure displacements, see Table 2. It can be said that we are even at the limit of design/ultimate values of structure displacements which may result in the loss of load capacity and lead to structural failure.

## 5. CONCLUSIONS

There was conducted the spatial analysis the impact of the extension of the designed building on the neighbouring buildings. The phase regarding the deep excavation work estimated with the use of empirical formulas and numerical tools gives convergent results.

Taking into account the results obtained at the building serviceability stage, it is suggested not to limit the analysis of the impact on the neighbouring environment to only the first two phases.



The application of numerical tools which take into account all the discussed elements may prove to be a solution for conducting a comprehensive analysis of a spatial geotechnical-design problem.

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