Strutting systems for deep excavations – technical challenges

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Abstract. Constant development carried out in town centres causes that many problems related to earthworks and tunnelling must be resolved. Investors are required to ensure respective number of parking bays, which in turn demands 2-3 storeys of underground car parks. This paper presents interesting case studies of deep excavations in Wrocław, Poland. As the geotechnical works in the old city centres may bring some risks to the surrounding area, proper strutting or anchoring systems must be provided. Apart from solving engineering problems, one needs to meet very stringent requirements of heritage conservator supervision. In order to ensure the stability of the excavation walls, it is necessary to examine the foundations of neighbouring structures, and if necessary, to strengthen them for the process of installing the excavation protection walls, progressing the excavations and constructing basement storeys. Another problem refers to constructing underground storeys below the level of groundwater. This requires efficient cutting-off or long-term lowering of water table inside the excavation with a possibly limited intervention in hydrological regime beyond the project in progress. In the typical case of old cities in river valleys such “hoarding off” the excavation and cutting off groundwater leads to temporary or permanent disturbances of groundwater flow and possible local swellings. Contemporary technologies make it possible to protect vertical fault and simultaneously cut-off groundwater inflow by means of steel sheet pilings, diaphragm walls or secant pile walls.

1. Introduction – The need of deep excavations and technical challenges

The expanding urban fabric and rapid increase in population poses challenges to looking for usable space in big cities. Developers want to construct higher and higher buildings on ever smaller plots of land, and as the inhabitants need parking bays, the structures must go deeper and deeper, often including two, three or more underground storeys. Transportation, focused on reducing traffic jams, also is often moved underground and sends the flow of vehicles to tunnels. Each tunnel construction also requires a deep excavation, at least at some part of its length [1]. In order to meet the developers’ expectations, design engineers are faced with challenges to resolve the problems like these specified below:
• limited space of construction site,
• complex structure of soil layers,
• high level of ground water,
• sensitive environment of construction site,
• necessity to run archaeological work,
• complex shapes of the project,
• large depths of excavations,
• thermal effects,
• control of excavation support behavior.

The paper takes a closer look at the enumerated problems and discusses how to resolve them on the example of the system of struts applied in construction site at Nowy Targ Square, Wrocław.

2. How deep excavation affect construction site vicinity

For densely built-up areas, it is often impossible to protect excavations by preparing earth slopes; it is necessary to use excavation supports in form of cavity walls, sheet pilings, palisades, etc. For deeper excavations, such structures are no longer able to serve as cantilever construction and to protect stability, additional supports need to be used, such as struts, anchorages, and also mixed strutting/anchoring systems [2]. Each excavation with vertical walls features some impact zone which determines the area where horizontal and vertical soil displacements may be expected, potentially affecting the neighbouring buildings. In Poland, the most often approach applied to determine this area is that presented by Building Research Institute [3] which defines two zones, $S_I$ – zone of direct excavation impact, and $S$ – zone of excavation impact.

![Figure 1. The range of excavation impact zone $S_I$ and $S$ [3]](image)

The ranges of these zones depend on the soil types found in the subsoil and on the excavation depth $H_w$ [3].

| Type of soil | $S_I$ | $S$       |
|--------------|-------|-----------|
| Sand         | $0.5 \ H_w$ | $2.0 \ H_w$ |
| Silt         | $0.75 \ H_w$ | $2.5 \ H_w$ |
| Clay         | $1.0 \ H_w$ | $3\div4 \ H_w$ |

If the buildings located near the construction site are also within the excavation impact zone, the problems related to deformation of excavation support construction due to soil displacements should be considered in more detail. These deformations depend both on technology used to construct the support itself and also on the way it is propped. According to research made for 18 excavations in Warsaw, the smallest horizontal distortions can be expected for a cavity wall supported by means of underground storey floors (top-down method), while the largest – the anchored sheet piling.

It needs to be mentioned that properly selected systems of struts provide results close to those in top-down method. Numerical methods enabling to determine subsoil deformations and to select the appropriate method of excavation protection which will minimize the probability of excessive displacements seem to be helpful during the design stage [4].
Also interrupting the level of ground water table, practically inevitable during making deep excavation, may be of essential effect on the construction site vicinity. When we need to run earth work below the ground water table, we need to lower its level. In general, while designing the excavation support, assumption is made that it will be sunk into impermeable layers to avoid the problem with infiltration of groundwater into excavation, causing in this way a depression cone which could adversely affect the surroundings. In case of permanent constructions, such as cavity walls or palisades, this, however, generates another problem, namely the change in groundwater flows, i.e. clogging on water inflow side and lowering its level on the other side. Apart from obvious impact on the excavation support itself, it may adversely affect the vicinity for large projects causing appearance of groundwater in cellars of nearby buildings when water level rises, and soil consolidation where this level goes down [5,6].

The vicinity of the construction site is affected by excavation support as early as during its execution; for instance, deepening the cavity wall may lead to considerable soil displacements, while ramming or vibrating the sheet pilings may cause vibrations, which adversely affect people and neighbouring structures [7,8]. It is important to control all of these impacts by means of geodetic survey or inclinometer measurements [9]. It is also essential to control possible effect of impacts, such as cracks in nearby buildings. For this purpose, specialized reports on nearby structures are often carried out prior to starting with the project [10-17].

3. Selecting the type of excavation support propping

From the perspective of the contractor responsible for the making of the excavation, the best method of propping the support is to use ground anchors, which ensure open space inside the excavation. However, it is often impossible to apply such solution due to several reasons. Firstly, due to small distance of the excavation from neighbouring lots, it would be necessary to obtain a relevant permission to make ground anchors in the neighbouring area. Secondly, the high level of groundwater can create a serious problem with ensuring the tightness of the connection between the anchor head and the support. An alternative solution includes struts, which ensure support tightness and do not go beyond the excavation area, however, they may create some hindrances for the works carried out inside the excavation. Among the possible solutions we find horizontal struts with both ends based on the excavation support, or the ones which are installed at a certain angle and based on the already completed foundation part.

Struts are generally made with pipe sections or the HEB shapes. They are selected according to the compression forces. When the design engineer makes calculations for the excavation support, he assumes some static scheme of the wall wherein the struts must be actually placed in points of supports. These calculations provide the values of internal forces derived from the excavation support load. However, these are not all the forces acting on the struts. A very large impact on the axial forces comes from the thermal effects depending on the season in which they were installed and on the operation of the strut construction. The increase of temperature in time after installation causes the lengthening of struts, and thus the growth of axial forces, while with the decrease of temperatures comes the shortening of the struts, which could cause displacement of the construction into the excavation. In order to determine the real effect of temperature on the strut construction, the susceptibility of their props needs to be determined, i.e. the susceptibility of excavation support to horizontal displacements at points of propping. Once again, numerical methods are useful here for modelling the excavation support together with surrounding ground [18-19]. Potential effects of temperature variation on the construction are discussed in the paper [13] where the use of strain gauges was described. Additionally, while designing the struts, other possible loads are taken into account, like hits by the excavator or resting a ladder against the strut, as a concentrated force of specific value in the middle of the strut span. As mentioned, the construction of struts may include both horizontal and skew elements braced against a part of foundation. These construction may however take different forms. Depending on the depth of the excavation, many levels of struts may be
used. In case when the length of a single strut exceeds 20 m, it could be necessary to use an intermediate prop reducing its buckling length.

4. Exemplary construction of struts

4.1. Project located at Nowy Targ Square, Wrocław.

Here the excavation 130 × 35 m and 8.0 m deep was designed to house a two-story underground car park under the office building. The project is in the centre of Old Town, so over the areas where the archaeological/architectural examinations are mandatory. Nearby the construction site are also buildings sensible to any displacements covered by heritage conservator supervision, like Town Office or St Catherine’s church. The subsoil is consecutively composed of anthropogenic soil 4.5 m thick, then coarse-grained soil (medium sands, gravels) 11.1 m to 12.3 m thick, then the strata of glacial clays at the depth about 13.3 m to 16.0 m constituting the impermeable layer. The groundwater is a depth of about 4.0 m below the ground level.

The design allowed for archaeological research over the full depth of anthropogenic soil, i.e. 4.5 m below the ground level. For the sake of the nature of archaeologist work, the excavation support could not be propped from the inside until the end of research; also the ground anchors could not be used due to the vicinity of lot borders. Hence, the supporting operation of the structure was assumed until the excavation depth of 4.5 m. So, a 60 cm thick cavity wall was necessary. Figure 2 shows the construction site during archaeological works. Struts were installed after the excavation was made down to the planned depth and when the archaeologists left the site.

![Figure 2](image)

*Figure 2. Archaeological works in the excavation – Nowy Targ Square in Wrocław*

To facilitate deeper excavations, design engineers applied struts seated relatively high in the cavity wall cap. Calculations showed that the struts should be made out of pipes dia. 711/12.5, spaced each 5.0 m. However, due to their length of about 35 m, intermediate props were necessary. The pairs of struts in the form of the letter X, i.e. were situated at a certain angle to the cavity wall. This made it possible to reduce twice the number of supports; additionally the free space in excavation was enlarged. The solution applied is shown in Figure 3. The cavity wall at its shorter edge was supported by corner struts, i.e. the ones installed at 45 degrees to the wall axis. Considering ground arching at excavation corners and making the cap in a form of rigid frame considerably reduced internal forces in struts. This enabled application of smaller cross sections, such as the pipes diameter 508/12.5, or HEB 300 shapes. The situation in the corner is shown in Figure 4.
4.2. Case study 1 - Retention tank – New Gliwice

The first example refers to a rain water retention tank construction. An over 11.5 m high vertical slope supported by sheet piles and struts was constructed in several phases. The wall was designed and built with steel sheet piles sunk 15 m below the terrain level and with intermediate supports made from steel pipe struts (see Fig. 5) placed on two levels. The subsoil profile within the earthwork area was composed of various soils, being a mix of shale, mudstone and sandstone fractions. The lower portions, below 8 m of depth, featured admixtures of shale fractions, which gave the bank certain properties typical of cohesive soils. In general, the geological conditions were quite complex and a proper design calculation of required sheet pile profiles was difficult. Each step of the excavation had to be preceded by the analysis of previous deformations. Such a procedure, called an observational method, seems to be rational as long as valuable and reliable data are provided to the structural engineer at every step of construction.

The inclinometer measurements of sheet pile wall deformation were carried out at individual stages of trench cutting. The “baseline” measurement was made directly after sinking the sheet piles and served as a reference for the measurements during further trenching phases:

- Stage 1: following the trench cut down to the depth of the first strut level;
- Stage 2: following the installation of struts and cutting the trench to the depth of the second strut level;
- Stage 3: following the installation of the 2nd strut level and reaching the target pit dimensions.
Figure 6. Retention tank – New Gliwice. Localization of inclinometer's pipes

Figure 7. New Gliwice - comparison between measured and calculated deformations

The measurement stations – steel pipes were located within the middle section of the retention and at one of the corners (see Fig. 6). The diagrams on Figure 7 show the obtained inclinometer results from every individual stage of the earthworks. The resulting differences in sheet pile wall deformation confirm the presence of the “corner effect”. The measurement results from the corner area are definitely different regarding the shape and scale of wall deformation. This is indicative of a significant reduction in soil pressure on the wall in the corner area resulting from the “arching” effect, which is a major increase in stiffness caused by the retention with the square section of the sheet pile wall. A high level of compliance in shape and scale of deformation was derived from the measurements at the station within the wall middle section in comparison with the calculations which had been made during the analysis of the deformation flat state at the design stage. The design stage calculations were based on the substrate reaction modulus (GEO5 software) with Schmit's nomogram applied. The nomogram establishes the dependence between the consolidometric module and the structural stiffness. To estimate the structural effort reduction found with the retaining wall deformation measurements, a numeric simulation was performed, consisting in a modification of soil strength parameters: internal friction angle (ϕ) and cohesion (c). The values of ϕ and c of the soil substrate were increased in each iteration of the numerical analysis to produce the wall bending line form approximate to that produced by inclinometer measurements.

The closest approximation of the wall bending line form resulted from the increase of ϕ and c values by 30% (see Fig. 7). This change of the parameters gave the following effort reduction values for the deep trench retaining structural components: sheet pile walls down by 59%, top strut down by 33% and the bottom strut down by 49%. The following table (see Table 2) provides a comparison of the maximum internal forces, i.e. the bending moments within the retaining wall and the compression forces within the struts.
Table 2. Retention Tank – New Gliwice. Comparison of the maximum internal forces, i.e. the bending moments within the retaining wall and the compression forces within the struts

| Internal forces in sheet pile wall | Calculated in 2D analyses | Calculated after modification of “ϕ” and “c” |
|----------------------------------|---------------------------|--------------------------------------------|
| Bending moment [kNm]             | 193.6                     | 79.9                                       |
| Compressive force in upper strut [kN] | 934.8                | 623.3                                      |
| Compressive force in lower strut [kN] | 1920.8               | 981.5                                      |

4.3. Bridge structure – Intercity Road, Gliwice

A similar analysis was made for a retaining wall installed in a trench for a bridge structure made during the construction of the Intercity Road at the intersection with Motorway A1 in Gliwice, Poland. The terminus of the road viaduct was designed as located within a bank along the Motorway. In order to secure the retention stability of the 7 m deep trench and the Motorway bank stability, the sheet pile wall needed to be sunk down to 14 m and supported on two levels with steel struts installed in successive phases of trench cutting, not unlike the previous case. The actual construction phase: protection of deep excavation - following the installation of the 2nd strut level and reaching the target trench dimensions can be seen on Figure 6. The Motorway bank is formed by condensed sand and gravel. Ground profile is composed from cohesive and non-cohesive soils – clays, silty clays and fine and medium sands. The horizontal deformation of sheet pile walls was measured at two station along the retaining wall on the Motorway bank side: within the retention middle section and the retention corner (Figure 10).

Figure 8. Bridge structure – Intercity Road, Gliwice

Figure 9. Inclinometer pipe on sheet pile wall - DTS1

Figure 10. Protection of bridge structure – Intercity Road, Gliwice. Location of inclinometer's pipes
In this case, on the stage of 2D calculations receive similar shape of sheet pile wall deflection as compared with the shape measured in inclinometers. The calculated value of maximum horizontal wall deformation – 48 mm – was very close to the measured value – 51 mm. Similarly to the second case, to estimate the influence of corner effect, the values of soil strength parameters \( \phi \) and \( c \) were increased. A similar shape of the sheet pile wall deflection was received when the values of parameters were increased by 15%. The obtained results are shown in the diagrams (Figure 11). The reduced deflection causes reduced effort of structures elements – 35% for the sheet pile wall, 10% for first level of steel struts and 22% for the second strut's level. The obtained results of calculations are showed in Table 3.

**Table 3.** Intercity Road, Gliwice. Comparison of the maximum internal forces, i.e. the bending moments within the retaining wall and the compression forces within the struts

| Internal forces in sheet pile wall | Calculated in 2D analyses | Calculated after modification of \( \phi \) and \( c \) |
|----------------------------------|--------------------------|-----------------------------------------------|
| Bending moment [kNm]            | 206                      | 132.8                                         |
| Compressive force in upper strut [kN] | 1086                     | 983.2                                         |
| Compressive force in lower strut [kN] | 1483.8                   | 1152.4                                        |

### 5. Summary and conclusions

Executing deep excavations in centres of large cities poses the risk of the impact exerted by the excavation on the vicinity. The changes of stresses in the ground may cause its displacements, also those occurring in nearby buildings. A special care should be taken in case of sensitive structures, like for instance the ones under conservator’s supervision. The analysis made during the design stage should also take into account the behaviour of nearby buildings, and numerical methods could be used for this purpose. As it was shown in this paper, the method used for excavation support is often dependent on the requirements imposed on its maximum displacements, while specific scheme of support is the compromise between meeting the requirements of the assumed static scheme and ensuring sufficient space to run the works inside the excavation. The presented examples demonstrate that even the optimization of the static scheme must often give way to the needs of archaeology endeavours, in case of which the appropriate adaptations of the strutting scheme need to be implemented.
References

[1] Mitew-Czajewska M 2015 Evaluation of deep excavation impact on surrounding structures – a case study Underground infrastructure of urban areas 3, eds. Cezary Madryas, Taylor & Francis Group, London, pp 161-72

[2] Gorska K, Wyjadłowski M 2015 An analysis of excavation support safety based on experimental studies, Studia Geotechnica et Mechanica, 37 (3) pp 19-29

[3] Instrukcja ITB Nr 376/2002: Ochrona zabudowy w sąsiedztwie głębokich wykopów, Warszawa 2002. (in Polish)

[4] Siemińska-Lewandowska A, Mitew-Czajewska M and Tomczak U 2012 The study of displacements of diaphragm walls built in Warsaw Quaternary soils, Geotechnical aspects of underground construction in soft ground, 7th Int. Symp., pp 605–10

[5] Siemińska-Lewandowska A, Mitew-Czajewska M 2009 The effect of deep excavation on surrounding ground and nearby structures, Geotechnical Aspects of Underground Construction in Soft Ground - Proceedings of the 6th International Symposium, IS-SHANGHAI 2008, pp 201-6

[6] Rybak J, Ivannikov A, Kulikova E and Žyrek T 2018 Deep excavation in urban areas – defects of surrounding buildings at various stages of construction, MATEC Web of Conferences, vol. 146, art. 02012

[7] Oliveira F, Fernandes I 2017 Influence of geotechnical works on neighboring structures, 17th Int. Multidisciplinary Scientific GeoConference. SGEM 2017. vol. 12, Science and technologies in geology, exploration and mining, pp 993-1001

[8] Sobala D, Rybak J 2017 Steel sheet piles - applications and elementary design issues, IOP Conference Series - Materials Science and Engineering, vol. 245, 022072, pp 1-10

[9] Gorska K, Muszyński Z and Rybak J 2013 Displacement monitoring and sensitivity analysis in the observational method, Studia Geotechnica et Mechanica, 35 (3), pp 25-43

[10] Muszyński Z, Rybak J and Szot A 2012 Monitoring of structures adjacent to deep excavations, Underground infrastructure of urban areas 2, eds. Cezary Madryas, Beata Nienartowicz, Arkadiusz Szot. Leiden: CRC Press/Balkema, cop. 2012, pp 177-83

[11] Segalini A, Chiapponi L, Drusa M and Pastarini B 2014 New inclinometer device for monitoring of underground displacements and landslide activity. Komunikácie 16 (4), pp 58

[12] Muszyński Z, Rybak J 2017 Evaluation of terrestrial laser scanner accuracy in the control of hydrotechnical structures, Studia Geotechnica et Mechanica. vol. 39 (4), pp 45-57

[13] Wyjadłowski M, Kozubal J 2016 Strain gauges as element of effective system for forces control in temporary sheet wall, 16th Int. Multidisciplinary Scientific GeoConference SGEM 2016, Albena, Bulgaria, 30 June-6 July 2016. 3, Sofia, STEF92 Technology, pp 301-7

[14] Bednarski Ł, Sieniko R and Howiacki T 2016 Supporting historical structures technical condition assessment by monitoring of selected physical quantities, Procedia Engineering 195, pp. 32-39

[15] Sienio R, Bednarski Ł and Howiacki T 2017 Continuous structural health monitoring of selected geotechnical quantities within Kosciuszko Mound in Cracow, MATEC Web of Conferences, vol. 117, 00157

[16] Wyjadłowski M 2017 Methodology of dynamic monitoring of structures in the vicinity of hydrotechnical works - selected case studies, Studia Geotech. et Mechanica, 39 (4), pp 121-9

[17] Bialic S, Malek B and Rybak J 2017 Design of braced excavations with an analysis of enlarged passive earth pressure, XX Mezdunarodnaa mežvuzovskaa naučno-praktičeskaa konferencii studentov, magistrov, aspirantov i molodyh učenyh, Moskva, 26-28 aprêlî 2017: sbornik trudov konferencii. Moskva: MGSU, pp 1140-42,

[18] Mitew-Czajewska M 2016 Evaluation of hypoplastic clay model for deep excavation modelling, Archives of Civil Engineering, vol. 62 (4), pp 73-86

[19] Mitew-Czajewska M 2017 FEM modelling of deep excavation - Parametric study, Hypoplastic Clay model verification, MATEC Web of Conferences, vol. 117, 00121