Impact of deep excavation on nearby urban area
L’influence d’une excavation profonde sur le terrain urban voisin

G.A. Horodecki & E. Dembicki
Department of Geotechnics and Applied Geology, Gdansk University of Technology, Poland

ABSTRACT
The design and execution of deep excavations in urban areas require knowledge of the expected environmental impact which includes two types of the influence: changes of stress state in a subsoil and technological influence. Unloading and reloading of a subsoil is induced by the excavation and loading by the construction. Technological influence is related to the methods of construction processes and depend on the type of braced wall assumed and the method of installation, type of wall support, wall stiffness, dewatering, soil improvement under nearby structures, change of stress state caused by installation of diaphragm wall, vibrations induced by sheet pile wall installation and the some others. As the results of these influences displacements of braced walls, surrounding ground surface and adjacent constructions are observed.
The examples of deep excavations braced by diaphragm walls localised in city centres in various subsoil conditions are described. Vertical displacements of the soil surface around the excavation and adjacent structures as well as horizontal displacements of braced walls were monitored during construction process.

RÉSUMÉ
Les exemples des excavations profondes renforcées par des diaphragmes et des parois de pieux qui sont localisés dans les centres des cités et dans differentes conditions du sol sont présentés. Les déplacements verticaux de la surface du sol entourant l’excavation et des immeubles voisins ainsi que les déplacements horizontaux des parois ont été enregistrés pendant le procésus de la construction.

Keywords: deep excavation, influence zones, displacements, urban area, geotechnical engineering

1 INTRODUCTION
Deep excavations in urban areas require special measures due to the buildings and other engineering constructions existing nearby. They must be designed in such a way that the elements of bracing system and neighbouring structures meet both ultimate and serviceability limit state requirements. In the first case, there are no major difficulties to meet these requirements whereas in the serviceability limit state, especially for the nearest structures, there are some specific demands which have to be fulfilled by geotechnical engineering. On the one hand, in case of any damage caused, it is related to possible claims of the owners of neighbouring buildings and on the other, to the legal requirements and necessity for determination of impact zones and their environmental influence during execution and operation stages including surrounding constructions.
The environmental impact is usually related to displacements and strains caused by deep excavations. The most common are displacements of retaining structures and settlements of the adjacent buildings together with zones where they occurred.
In the literature one can find also detailed problems related to the displacements caused by the installation of diaphragm wall (Symons & Carter, 1992; Ng & Lei, 2003), corner effect on excavation behaviour (Chang-Yo & Bor-Yuan, 1998), three-dimension effect of deep excavations (Moormann & Katzenbach, 2002a; Zdravkovic et al., 2005), influence of geometrical parameters, zone of displacements caused by deep excavations (Hsieh & Ou, 1998), the influence of the constitutive assumptions on FEM predictions (Viggiani & Tamagnini, 2000), influence of wall stiffness and technology of execution (Long, 2001), unloading of subsoil due to deep excavations (Chan & Morgenstern, 1987; Nash et al., 1996; Chang-Yo et al., 1998), influence of excavation dewatering in urban area (Moormann & Katzenbach, 2002b).

2 ENVIRONMENTAL IMPACT TYPES AND EFFECTS

We can distinguish two types of environmental impact: natural influences (unloading, reloading and additional loading) and technological influences (related to technology applied and solutions assumed). Displacements are the most important effects of these influences. They are usually measured in the frame of monitoring system and correspond to global response of the structure being the effect of all the influences. Separation of the particular influences is usually very difficult and mostly impossible.

2.1 Natural impact

Natural impact includes changes of stress state in a subsoil as a result of unloading process, and then loading by the structure. These influences are basically irrelevant to solutions used and technology of works applied. They are defined under following design assumptions:
- location of investment – geotechnical conditions of a subsoil (arrangement of soil layers, groundwater conditions, strength and strain parameters, initial stress state in a subsoil),
- foundation depth and planar dimensions of the structures (excavation volume – the magnitude of unloading of the subsoil),
- height of the structure (number of storeys – the magnitude of additional loading).

Values of displacements resulting from unloading of the subsoil and the range of zone where they are observed, depend on geotechnical parameters of the subsoil and geometry of excavation (depth, width and length). Thus the unloading effect for small excavations has negligible influence on displacements and most often is not taken into consideration. However, during the execution of deep excavations (Chan & Morgenstern, 1987; Nash et al., 1996; Bolt et al., 1997; Horodecki et al., 2004), positive vertical displacements (heave) of the excavation bottom, retaining walls and first of all the subsoil surface and adjacent constructions are observed (Fig. 2). These displacements significantly contribute to the total values of vertical displacements. For this reason – through reduction of extreme settlements – they have their impact on safety of neighbouring constructions and their conditions. Unloading of the subsoil and connected with it displacements do not depend on the type of bracing system.

Depth of unloading zone depends on geometric parameters of excavation and can be estimated as 2÷3H (H – excavation depth) below the excavation bottom (Chan & Morgenstern, 1987; Nash et al., 1996).

2.2 Technological impact

Technological impact depends on assumed solutions which influence the changes of stress state such as:
- type and technology of bracing system which define its stiffness,
- execution method of bracing,
- changes of stress state during the deepening process for diaphragm wall;
- type of support or anchoring (initial pre-stressing or strutting);
- vibrations during driving/vibrating of sheet pile wall;
- technology of excavation deepening;
- influence of excavation dewatering,
- disturbance of groundwater flow,
– soil improvement under neighbouring structures,
– influence of vehicular traffic.

2.2.1 Type and parameters of bracing system
A choice of a type and parameters of bracing system is essential for its predicted displacements. The displacements of the bracing protecting the deep excavation have direct impact on the settlements of the subsoil observed behind the bracing. The stiffer braced wall and less flexible support, the smaller displacements and deformations of the bracing and subsequently the subsoil around the excavation and the influence zones. The way of bracing supports is also of great importance – in case of top-down method, the stiffness of the structure is greater than at strut or anchored excavation and in consequence the displacements observed are smaller. At the same time, stiffer bracing system with smaller displacements causes higher values of earth pressure acting on the bracing, which in turn forces a necessity to dimension the construction for greater inner forces.

2.2.2 Excavation of trenches
The excavation of trenches supported by bentonite slurry for installation the diaphragm walls causes stress state changes in the subsoil and can induce settlements of the neighbouring constructions. Due to that, the length of braced walls sections, sequence and time space should be chosen in such a way to secure stability of the subsoil under foundations of the nearest structures.

2.2.3 Dynamic impact
Application of the methods causing dynamic impact within the subsoil, e.g. during vibrating-in the sheet pile wall may also cause some damage for the nearest buildings therefore during these works it is necessary to measure the vibrations, enabling to control and secure against exceeding of acceptable values (Adam, 2002; Borel & Guillaume, 2002; Horodecki, 2003).

2.2.4 Technology of excavation
Technology of excavation (open excavation, top-down methods), as well as the sequence and rate of works influence the values of displacements and the range of its presence.

2.2.5 Dewatering
Dewatering in terms of wells localised inside the excavation may cause drawdown of groundwater table around the excavation which may result in changes of stress state in the subsoil. The effect is even greater in case of location of wells outside the excavation. If changes of groundwater table are within the range of natural periodic fluctuations thus they do not significantly influence the value of settlements of neighbouring structures. In case of drawdown of groundwater table significantly below the natural fluctuations, additional, relevant settlements can occur as it was observed e.g. during execution of excavation for Deutsche Bibliothek and under the Main Tower sky-scraper in Frankfurt (Moormann & Katzenbach, 2002a). The settlements occurred directly after drawdown, whereas one month after completing the dewatering there were positive displacements which almost entirely reduced previous settlements. Similar effect – reduction of settlements after dewatering process – was also observed during execution of excavation under Kwiatkowski Centre in Gdynia.

In a case, when values of settlements caused by drawdown of groundwater table would exceed the acceptable values, one can improve the soil under the nearest buildings or abandon dewatering process and sealing the bottom instead (e.g. by jet-grouting) in case of small surface of excavation.

2.2.6 Flow disturbance and the groundwater rise
Execution of permanent or temporary bracing system and structure in case of flow of groundwater can cause its disturbances and rise. This kind of impact may be limited by installation of drainage system under the structure and by the use of temporary bracing.

2.2.7 Soil improvement
In order to significantly reduce predicted displacements (regardless of the impact) of structures situated nearby, which are susceptible to settlements (old buildings without foundations, historical buildings) one can improve the subsoil underneath.

3 DISPLACEMENTS CAUSED BY DEEP EXCAVATION

Rational effect of impact are both vertical and horizontal displacements of (Fig. 2):
– bracing system,
– excavation bottom,
– site surface and structures nearby,
– underground infrastructure around the excavation.

Displacements actually observed are a sum (resultant) of displacements caused by individual types of influences which occur in specific situation. Detailed selection of the impact of particular displacement components is rather difficult issue and the measured values are assumed to be resultant values.

4 IMPACT RANGE

The range of all impact zones and displacements resulting from them is defined empirically or semi-empirically on the basis of measuring data. Most of-
ten the ranges of the given zones correspond to resultant displacements caused by technological impact related to braced wall stiffness, type of support and subsoil conditions. It is mainly related to the fact that the displacements of the soil surface around the excavation caused by wall deformation contribute to the total displacements, the most. However, in the case of relatively stiff bracing system (diaphragm walls) and supports (top-down method), which restrict the values of these displacements, their part definitely decreases at an increase of the significance of the displacements resulting from other influences.

In Peck’s method the values of vertical settlements of the soil behind the wall are between 1%H to over 2%H (where H is a depth of excavation), and for Clough and O’Rourke method from 0.15%H to over 2%H.

Hsieh and Ou (1998) define maximum value of ground surface settlements behind the wall equal to 0.5 ÷ 0.75 of maximum value of the lateral wall movement. Only for very soft clay the maximum value of ground surface settlements behind the wall may be larger than maximum value of the lateral wall movement. In turn, the values of ground surface settlements are equal to 0.5 ÷ 0.7%H.

The impact zones for above mentioned methods—worked out on the basis of great numbers of measurements—amount from 2H to over 4H. They are defined as a function of excavation depth H as they basically apply to the settlements connected with displacements and deformation of bracing system.

In Polish recommendations two impact zones of excavation are given (Kotlicki & Wysokiński, 2002):

- zone I – in the direct vicinity of the excavation, where the displacements may threaten the safety of the structure;
- zone II – where the occurring displacements can cause visible damages of the buildings, which however do not threaten its safety.

Definition of the range of impact zones generated by vibrations during installation the sheet pile walls is however a separate and complex problem and requires further theoretical works and empirical studies in natural conditions. In any particular case, it requires individual analysis and monitoring of vibrations during works in order to adjust parameters of vibrations to the boundary values.

5 SOIL-STRUCTURE INTERACTION ANALYSIS

Analysis of soil-structure interaction should be carried out during whole the investment cycle both at the design stage, execution phase as well as after the back analysis.

Calculation analysis of environmental impact of deep excavations can be done with a use of FEM (Zdravkovic et al., 2005) for 2D or 3D problems. It allows to estimate forces and displacements of bracing system, excavation bottom and the ground surface for specified stages of execution.

For standard data, the important role play numerical code applied and first of all assumed soil model together with respective soil parameters as well as an experience of the person who makes the calculations (Schweiger, 2002).

In numerical calculations of the displacements, of great significance are stiffness parameters of the soil especially the modulus of unloading and reloading, thus its reliable determination is very important.

6 EXAMPLES OF DEEP EXCAVATIONS

6.1 Manhattan Trade Center in Gdańsk.

The excavation was carried out using the top-down method (floor ring at the level –1) of dimensions 80 x 90 m and depth 12.5 m (with local overdepth dredging up to 13.8 m) in gravel, clay sand, sandy clay and fine sand, braced by diaphragm walls.

Three impact zones were distinguished. The isolines of maximum vertical displacements were shown in Fig. 4, and example of the vertical displacements measured, in Figure 5. Vertical displacements were observed in the range of 5 ÷ 6H (where H – depth of excavation). Figure 6 shows the
movement (heave) of ground surface behind the dia-
phragm wall measured in different distances from
excavation.

Figure 6. Vertical displacements at points of 0 m, 5 m, 20 m,
27 m, 41 m distant from the wall

6.2 Kwiatkowski Center in Gdynia

Excavation carried out by the top-down method
(floor at the level –1) with dimensions 33 m x 65-75
m and depth about 7.5 m with local overdepth
dredging up to 8.5 m in medium sand, fine gravel
and sandy gravel braced by diaphragm walls.

Figure 7. Excavation layout with three impact zones and meas-
urement points

Dewatering has been carried out inside the exca-
vation. Three impact zones were assumed – zone II
at the distance of 4.5H (Fig. 7). Actually the dis-
placements occurred at the distance over 5H.

Clear compensation effect has been observed af-
after completing the dewatering process on the oppo-
site side to the groundwater flow where there was
the greatest lowering of groundwater and resulting
from it settlements (Fig. 9).

Figure 9. Settlement during compensation of settlements after
dewatering

6.3 A-13 Warsaw Underground Station

Excavation anchored at five levels, with the dimen-
sions 45 x 215 m and depth 17.8 m, made in quater-
nary formations (uncontrolled embankments, mo-
raine sandy clay and clayey sand, locally layer of
silty clay and silt, sandy sediments, fluvioglacial
sand, locally clay and sandy clay, fine sand and me-
dium sand) braced by diaphragm walls. Due to ear-
lier lowering of groundwater table within the site
excavation did not require to be dewatered. Example
of ground surface displacements around excavation
resulting from the ground unloading effect are pre-

dented in the Fig. 10.

During the execution process of the station, val-
ues of positive displacements of the ground around
excavation reached 10 mm. Due to too small meas-
urement range around excavation it is difficult to
define the actual range of impact zones.

Figure 10. Examples of ground surface displacements behind
the wall

Back analysis made for the above case showed
acceptable compatibility of displacements measured
and calculated. On that basis the calculation analysis
has been carried out by the PLAXIS numerical code
for various excavation widths. The relation of verti-
cal displacements calculated at different distances from the edge of the wall in the function of excavation depth is presented in Fig. 11.

7 CONCLUSIONS

Environmental impact of deep excavation on surroundings in urban areas includes natural impact (connected with unloading, reloading and additional loading) and technological influence (including impact of technology assumed on possible displacements of the excavation bottom and braced walls, ground surface and structures around excavation), and the resulting displacements are the sum of all mentioned factors. Basic problem in those cases are conditions of serviceability limit state.

While analysing the specific design or execution situations one should take into consideration individual influences, which can occur, as well as corresponding to it impact zones. These zones must consider all the limitations resulting from:

– conditions of serviceability limit state for bracing system with supports and neighbouring structures,
– character of nearby urban infrastructure and the impact on inhabitants and installations:
  – vibrations (rate, frequency amplitudes),
  – vertical displacements,
  – horizontal displacements,
  – difficulties for inhabitants.

Defining the range of impact zones as well as possible ground surface displacements behind the wall (especially positive displacements) one should take into account individual influences such as local conditions and experience. Since the methods defining range of impact zones and values of displacements are mainly based on measurements of various specific structure, it is appropriate to carry out back analyses together with the analysis of measurement results for existing structures. It may be a basis for verification and improvement of these methods both for local and national conditions. However, it requires to carry out the monitoring with the use of more and more advanced measurement methods and within the range appropriate for a structure. It is intentional then to consider the impact zone including the area monitored, where displacements can occur.

Application of FEM analysis for estimation of possible displacements at various distances from excavation requires reliable geotechnical parameters of the soil, adequate constitutive model, reliable numerical code and experience in this type of calculations.

REFERENCES


