Numerical modeling of structures fencing deep excavations of complex configuration

A. Dvornyk

State scientific-research Institute of building constructions, Kiev, Ukraine

Member of the Ukrainian Society for Soil Mechanics, Geotechnics and Foundation Engineering since 2017

ABSTRACT: The numerical model of the structure-soil system should be selected considering the most significant factors determining the stress-strain state of system elements. In certain cases, especially in cases of dense urban development, one of the most significant factors can be the spatial variability of structures and soil base. There is a widely held view that 2D models are always more "conservative", i.e. the degree of stability is determined with a margin, besides 3D calculations are irrational because of technical difficulties. 3D modeling of the asymmetrically configured excavation in complicated geological conditions combined of dense urban development requires more complex approaches that considers spatial effects and allow significantly improve the safety and the efficiency of design.

This paper shows different situations at examples of real objects, when complicated three-dimensional calculations are rational to use. The main criterion for substantiating the need to consider spatial effects is comparison the calculation results of 2D and 3D model based on finite element method.

KEYWORDS: foundation pit (excavation), retaining pile wall, structure-soil system, stress-strain state, finite element method, variable soil rigidity coefficient method

1 Introduction

Two-dimensional geotechnical modeling procedures and calculations do not always consider all the important factors that determine the stress-strain state of system. The maximum correspondence of 2D model to the real work of structure is achieved by introducing additional boundary conditions, some loads and effects or coefficients in the design model. In some cases the reliable definition of these additional data is comparable in complexity with the creation of a conforming spatial 3D model. The practice of design the retaining walls use methods that consider spatial effects to some extent in calculations with flat schemes. These methods are mainly concerned with determining the parameters of loads if there are any form curvatures of structure (Fig. 1). Alternative solution in such situations is 3D modeling, considering in detail all those important spatial effects.

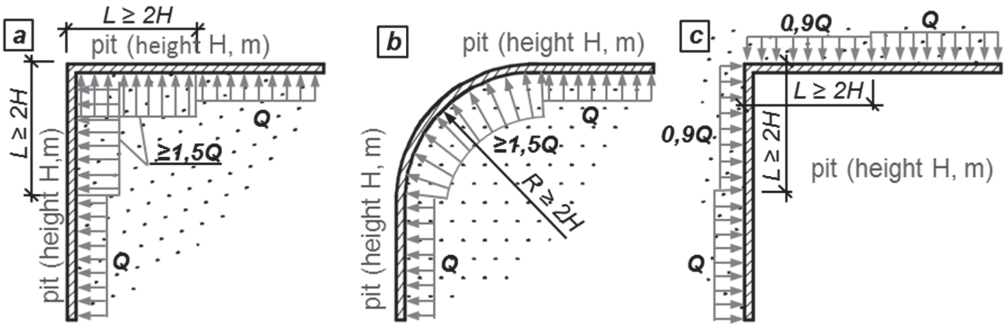

Fig. 1: Form of structures influence for determines the load from ground to retaining wall. Typical schemes

2 Comparative analysis of 2D and 3D modeling in geotechnical calculations

The most significant factors that indicate the need for geotechnical 3D modeling are:

- Complicate and variable configuration of structures or earthworks, including shallow excavations and accounting of digging stages
- Structures consist of elements with different rigidity and geometric parameters
- Geotechnical conditions of areas with high spatial variability of soil properties and the geometry of their location

In general, 3D modeling provides economically more profitable and technically efficient solutions in design of retaining structures for excavation in variable geotechnical conditions.

The considering spatial effects of constructional system gives a solution of two main problems:

- Exhaustive use of potential load bearing capacity of structures and decrease the "reserves" to acceptable values
- Avoidition of design errors associated with the mismatch of the stress-strain state of structure that calculated from 2D models to its real state

3D modeling is a technically complicated process, but it doesn't exclude the using of calculations with 2D models, but only complements them.

The algorithm for designing excavation structures using 3D modeling can be presented in following steps:

Step 1. Determination of the characteristic cross sections, its number depends on the degree of variability the soil properties.

Step 2. Perform calculations with 2d model to determine the main parameters of the excavation in the first approximation. For example, if pit fencing is made of bored piles, then determine the depth of piling and required bending stiffness of the retaining structure (diameter, pile spacing, etc.). Also, in complicate cases, the relationship "pressure-displacement" is calculated for different deformations of the retaining wall in specific ground conditions using the numerical Continuous Medium Model.

Step 3. Analysis the structural scheme of the underground part of building. Selection of geometrical parameters of foundation pit fencing considering the results of performed calculations and features of the construction site.

Step 4. Create the model of "base-underground structures" system. Definition of basic technical parameters of the stress-strain state of structures from the joint calculation of system. At this step it's already possible to estimate the spatial effects on the stress-strain state of structures comparing the results of 2D and 3D calculations for the characteristic cross sections (step 1). Perform preliminary analysis of the results and make a decision of need to correct the design parameters from the first approximation (step 2). Also, the deformed construction scheme is analyzed, and the load from the ground pressure adjusts, if it's necessary, in accordance with the previously defined pressure-displacement relationships (step 2). Thus, by successive iterations in several steps, we obtain an optimal spatially balanced design system, all elements of which are used with maximum efficiency.

The joint work of base and constructions is analyzed by using numerical Contact Model and Continuous Medium Model based on finite element method.

The Contact Model is the main one, which takes into account the interaction of structures with the base on the surface of "construction-ground" contact, but the stress-strain state of the soil massif is not considered. The Continuous Medium Model is an auxiliary one, the construction and the surrounding mass of soil are considered within the design area and their joint stress-strain state is analyzed. The numerical Continuous Medium model is based on Hardening Soil Model and used to determine the calculated "pressure-displacement" relationship for various deformations of retaining structures in specific ground conditions.

Numerical Contact Models use the Variable Soil Rigidity Coefficient method. The distribution of stresses in soil is determined through the Fuss-Winkler model. The stress-strain relationship is described using an ideally elastic-plastic model with a limiting surface determined by the Coulomb-Mohr criterion.

Calculations is performed by iterative method, each step is accompanied by a verification of base stability by the condition of limitation the calculative pressure σ_z that applied to the ground by the lateral surfaces of piles.

Two specific examples that demonstrate the characteristic contradictions with 2D and 3D models calculations are presented below. To compare the results for 2D and 3D calculation methods and initial conditions are chosen the same. Both examples show the effects of considering spatial rigidity of structures in certain conditions. At 1-st example we deal with the complicated geometric configuration of structure, at 2-nd example the geological conditions are characterized by high spatial variability of soil properties. The main criteria for comparing the results of calculations are horizontal displacements (U, mm) and bending moments (M, kNm) in structures, as well as general deformed scheme.

2.1 Example 1

The scheme of foundation pit with complicate configuration and variable depth from 5 m to 8 m is shown in Fig. 2. The engineering geological conditions are uniform for the whole site.

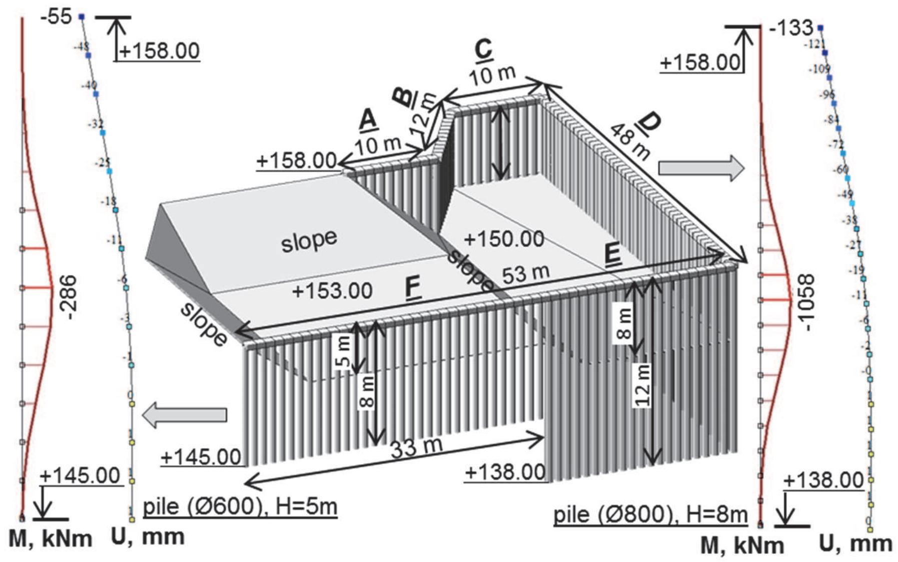

Fig. 2: Foundation pit scheme. Diagrams of horizontal displacements U and bending moments M in piles of retaining wall (2D model results). Example 1

2D calculations are made for characteristic sections of the retaining structure:

- Retained height – 8 m. Pile wall parameters: pile diameter – 800 mm, length – 12 m, piles spacing – 1 m. Cross-section design is typical for walls in sections A-E, number of piles – 100
- Retained height – 5 m. Pile wall parameters: pile diameter - 600 mm, length – 12 m, piles spacing – 1 m. Cross-section design is typical for walls in section F, number of piles – 33

The results of calculations with flat schemes (2D model) – diagrams of horizontal displacements U and bending moments M in piles of the retaining wall are presented in figure 2. The calculated moment in piles Ø800 mm (sections A-E) M = 1058 kNm, displacement of the pile top U = 133 mm, displacement of piles in excavation bottom level U = 38 mm. The moment in piles Ø600 mm (section F) M = 286 kNm, displacement of the pile top U = 55 mm, displacement of piles in excavation bottom level U = 18 mm.

Such picture of the stress-strain state is clearly characteristic to the middle cross-sections of linear part of the retaining wall with sufficient length. For example, 2D calculations would be valid for the middle part of sections D and F. The picture of stress-strain state in other parts of the retaining wall received by 2D calculations is absolutely unrealistic, the configuration of the pile cap combining piles heads and changes the nature of piles work, so it can't allow such big deformations.

The results of the 3D calculations of the retaining pile wall with the cap 1000×600 mm (b×h) that combines piles heads are shown in Fig. 3.

The maximum absolute values of strain and bending moments vary relatively insignificantly:

- Maximum horizontal displacement for piles Ø800 decreased by 15% from 133 mm to 103 mm, piles Ø600 – increased by 23% from 55 mm to 68 mm (at the boundary of the E-F sections)
- Maximum bending moments for piles Ø800 decreased by 11% from 1058 kNm to 939 kNm, piles Ø600 – increased by 20% from 286 kNm to 344 kNm (at the boundary of the E-F sections)

If confine the comparing of maximum values, we can make a false conclusion that considering the joint work of the spatial 3D model didn't lead us to essential changes of the results. However, the nature of distribution the forces and deformations values in definite sections of the pile wall radically differs from the diagrams obtained by 2D calculations.

Let's regard in detail how horizontal displacements (U) and bending moments (M) values changes for piles from different sections of retaining wall:

- Sections A-C: U=5...35 mm (-75%), M=410 kNm (-60%)
- Section D: U=9...113 mm (-15... -90%), M=255...939 kNm (-11...-75%)
- Section E: U=9...68 mm (-50...-90%), M=278...627 kNm (-41...-74%)
- Section F: U=25...68 mm (-55...+24%), M=180...344 kNm (-37...+20%)

For some sections, in addition to changing the values of the moments, the shape of the moments diagram along the pile length also changes. The spatial effect for sections D and F dissolves from a distance L>2H from the edge of the section and in the central part is almost completely absent. For the other sections of retaining pile wall, with much less length than 4H, the spatial effects are especially clear.

In this particular case, the 3D calculations of retaining pile wall have the following advantages in comparison with the 2D calculations:

- Sections A-C (number of piles 32) – the length of piles may be reduced by 2 m; reinforcement area can be reduced by 40% or increasing the piles spacing from 1.0 m to 1.3 m
- Section D (number of piles 49) – calculated reinforcement area of 20 piles (for 10 piles on both boundary sites - left and right) can be reduced by 45%
- Section E (number of piles 20) – calculated reinforcement area of piles can be reduced by 40%; for 10 piles located closer to section E the piles spacing can be increased to 1.3 m
- Section F (number of piles 33) – calculated reinforcement area of piles must be increased by 35% for 14 piles located closer to section E
- Arising of significant strains in the concrete pile cap uniting the pile heads (fig. 3b), that must be considered in the design development

Thus, 3D modeling of structure-soil system gives a significant economic effect; it allows eliminating design errors that connected with low capacity of structures on local areas.

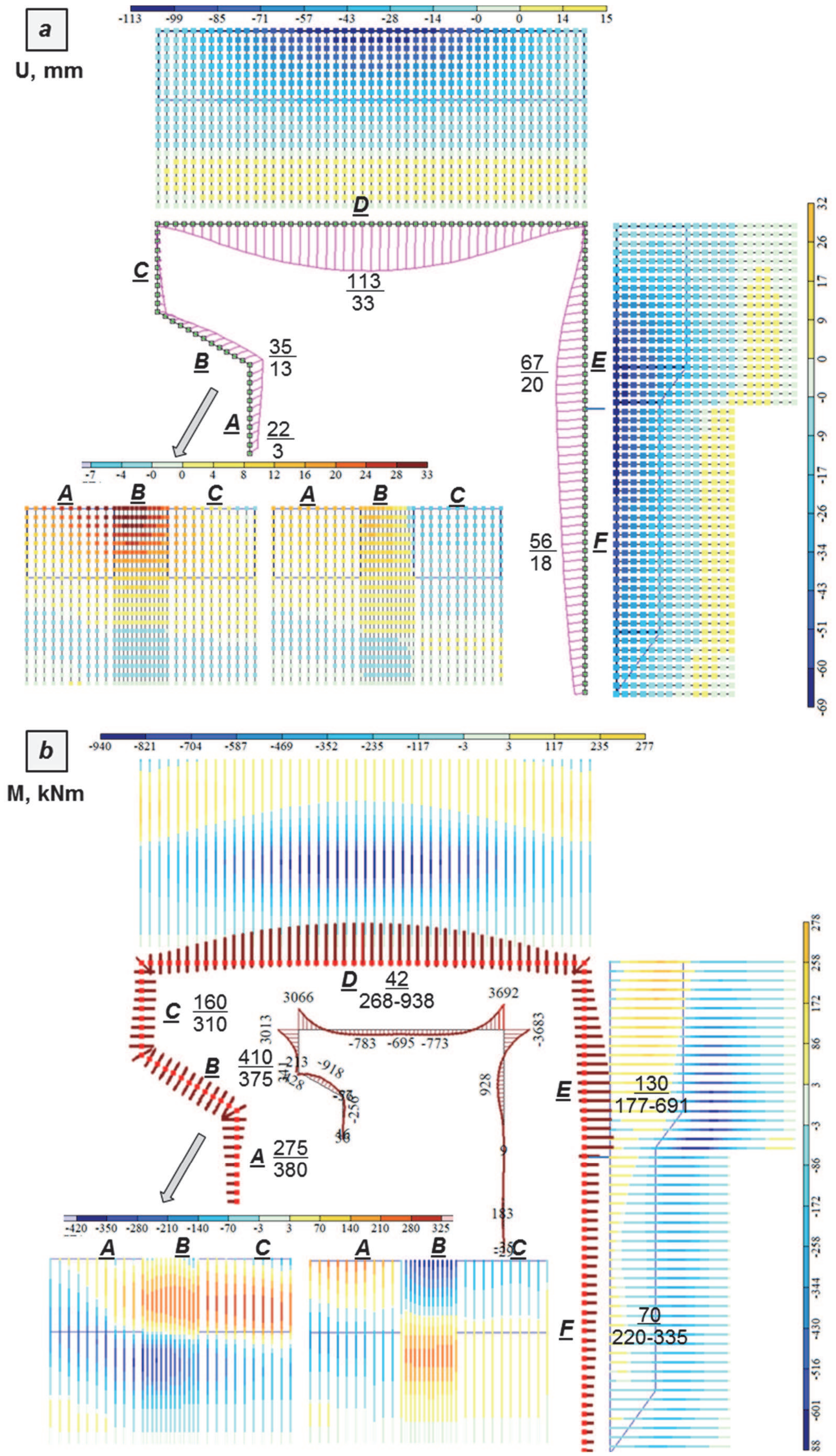

Fig. 3: Diagrams of bending moments M and horisontal displacements U of the retaining pile wall (3D model results). Example 1

2.2 Example 2

The scheme of excavation that designed in complicated engineering geological conditions is shown in Fig.4 and 5. The area is characterized by high spatial variability of strength and deformation properties of soils. Dangerous engineering-geological appearances are represented by landslides and erosion of slopes by surface waters. To retain the soil mass 10 m high the two-row retaining wall of bored piles were designed.

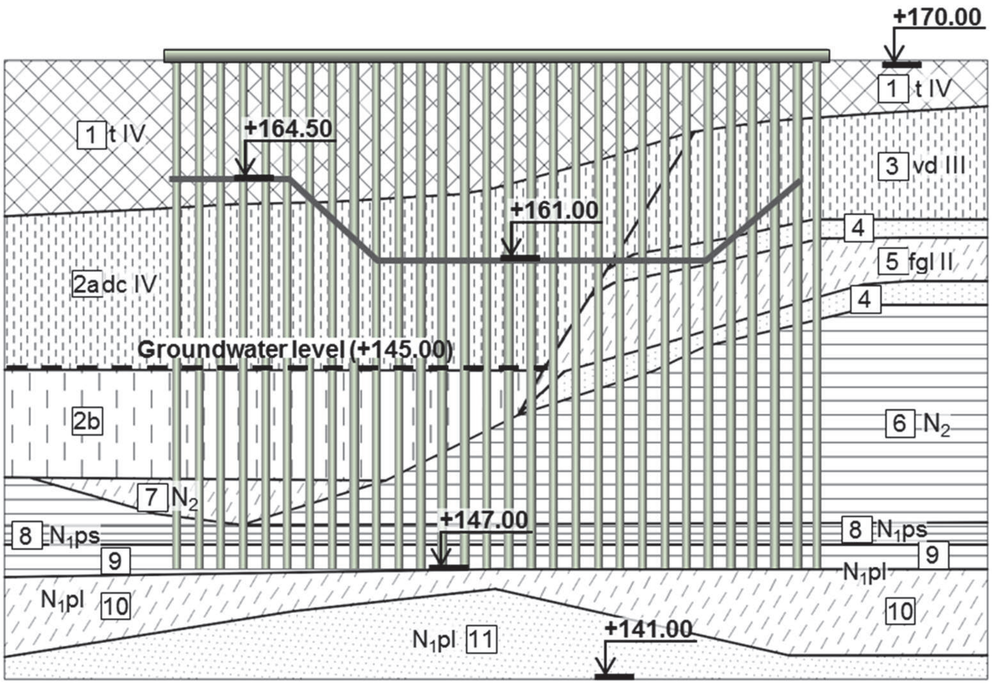

Fig. 4: The retaining pile wall on engineer geological profile. Example 2

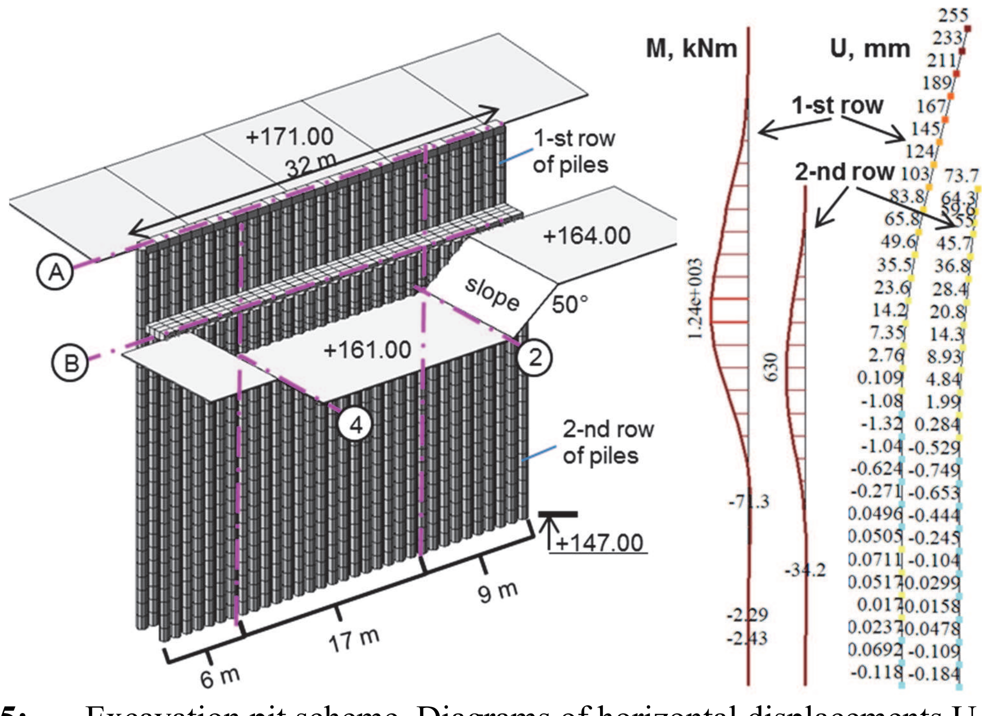

Fig. 5: Excavation pit scheme. Diagrams of horizontal displacements U and bending moments M in piles of retaining wall (2D model results). Example 2

Calculations on a flat scheme were made for a section with the most adverse ground conditions; it's located in the middle of the excavation pit.
The results of 2D calculations showed that initially accepted parameters of piles don't provide the required deformation and load bearing capacity: the bending moment in piles M=1238 kNm, horizontal displacements U=255 mm.
In this regard, there was decision to use the potential bearing capacity of soil outside the excavation with better characteristics. It was realized by extending the retaining wall beyond the boundaries of excavation (Fig. 5).
The length of left and right extending of the retaining wall is selected by spatial 3D calculation to get maximum deformations less than 15 sm and provide the load bearing capacity of the pile Ø800 mm. Considering the spatial rigidity in 3D model of structure gives a significant redistribution of loads and change of the stress-strain state of constructions. The bending moment is reduced by 25% M=916 kNm, horizontal displacements are reduced by 45% U=138 mm (Fig. 6). Spatial effect is equally apparent throughout the retaining pile wall, the pit excavation width is less than 2H.

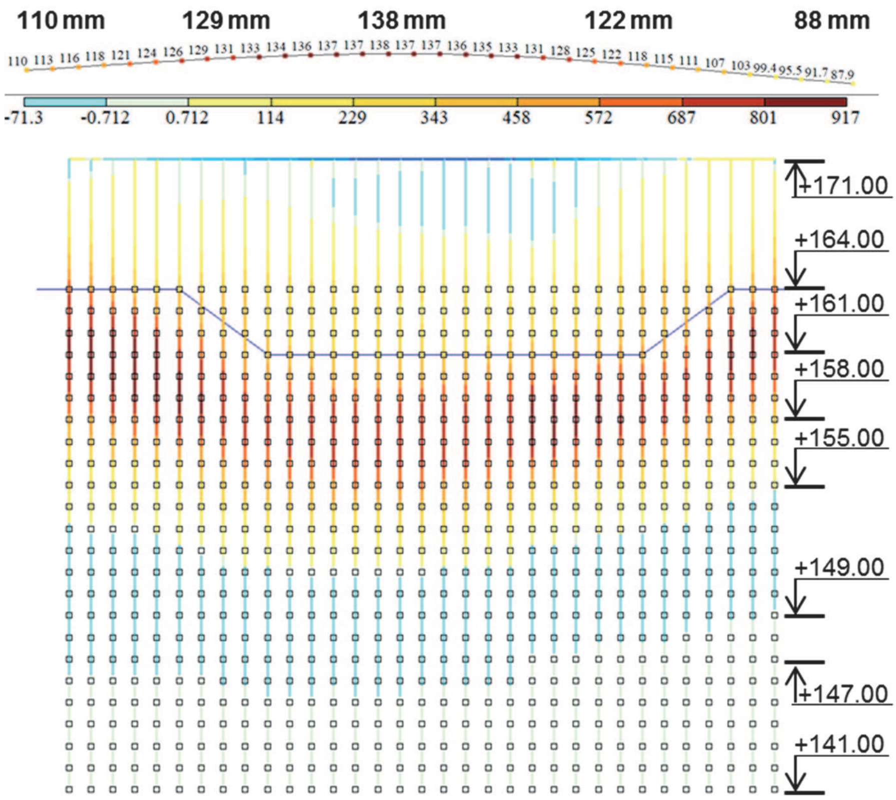

Fig. 6: Diagrams of horizontal displacements U and bending moments M in piles of the retaining wall (3D model results). Example 2

At this example the main advantage of 3D modeling is next: when designer is limited in choosing the retaining wall structural scheme (pile diameters, etc.), the use of the spatial rigidity potential of structure can significantly increase its stability and load bearing capacity.
In examples above, 3D calculation give a possibility to optimize and improve the design solutions. Usually, building practice deals with all those complicating

factors described in examples at the same time at one Object (bad engineer geological conditions, spatial variability of soil properties, slopes, asymmetric configuration of structures, special sequence of excavation, etc.). In such cases, 3D modeling is an integral part of the design, since 2D calculation does not consider all the essential features of specific Object. Examples of such objects we spoken above are structures that simultaneously serve as landslides protection, pit fencing and foundations at the same time (Fig. 7). These are real objects currently building in Kiev. Design of these structures was performed with complex set of calculations, including 2D and 3D modeling. Unfortunately, the analysis of modelling results does not fit into the format of this article.

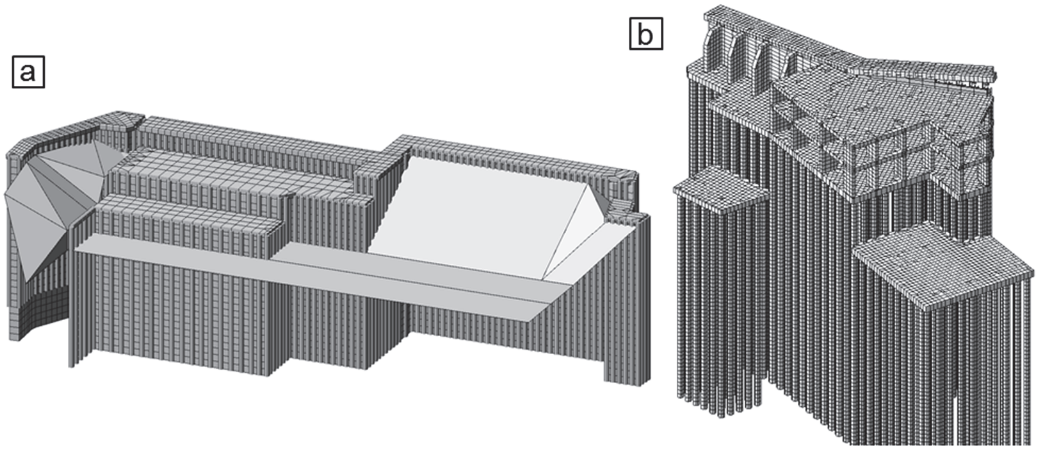

Fig. 7: 3D models of structures simultaneously serve as landslides protection, pit fencing and foundations

3 Conclusion

This article focuses on the necessity and importance of using 3D modeling of calculations the foundation pit excavation in complicated geotechnical conditions. Ignoring the factors considered in the examples leads to excessive margin of safety and stability of the retaining wall, as well as dangerous errors in design.

In general, there can be identified some parameters of the excavation, at which 3D modeling gives the expected economic and technical effect with a high degree of probability:

- Length of linear sections of complicatedly configured excavation doesn't exceed 4H
- Technology of excavation includes gripping with length L≤2H, as well as different depths (H_1, H_2) of adjacent sections when $H_1/H_2>1.5$
- Spatial rigidity of the adjacent sections of the retaining walls changes more than two times during the section of length L<2H;
- High variability of mechanical soil properties (degree of variation K>2) on length section L<2H

However, the final decision of need to use 3D geotechnical modeling is always depends on the specifics of individual object, the main task and available resources. An individual approach is required, the interaction features of the retaining structures and soil base are diverse, and so each case deserves a separate concern.

4 References

Federalnoe dorojnoe agenstvo ROSAVTODOR (2015)
Metodicheskie rekomendacyi po raschetu i proektirovaniyu svaino-ankernyh soorujeniy injenernoi zaschity avtomobilnyh dorog. Otraslevoi dorojniy metodicheskiy dokument ODM 218.2.026-2012, 17-21

Kievskiy otdel VNIIGS (1984)
Metodicheskie rekomendacii po proektirovaniyu i raschetu podpornih sten iz buronabivnih svai, 8-24

Maciy, S. (2010)
Protivoopolznevaya zaschita. Monografiya, 97-202

Ulickiy V., Shashkin A. & Shashkin K. (2010)
Geotehnicheskoe soprovojdenie razvitiya gorodov. Prakticheskoe posobie po proektirovaniyu zdaniy i podzemnyh soorujeniy v usloviyah plotnoi gorodskoi zastroiki, 119-133