Studying the influence of taking into account the elastic-plastic behavior of strut elements on the retaining system equilibrium

Armen Ter-Martirosyan and Vitalii Sidorov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: vitsid@mail.ru

Abstract. Currently, there is a rapid compaction of urban areas, which inevitably leads to the need for more active and integrated use of the underground space. In conditions of dense urban development, for the construction of underground structures or underground parts of buildings, it is necessary to design and realize deep excavations with vertical walls under the protective of the retaining structures, including supporting systems. The most common support is a system of metal elements - distribution beams and pipes (struts). The article deals with the calculation of the real excavations, taking into account the elastic and elastoplastic behavior of the support elements, the influence of this factor on the resulting internal forces and the stability of entire retaining system. Questions about the correctness of calculations by elastic models for structural elements used in geotechnics, are raised.

1. Introduction
The traditional approach to designing of a retaining structure of the excavation with supporting system made of steel pipes and distribution belts (I-beams) comes down to the adoption of various design decisions with the subsequent calculation of those in specialized software systems [1,2]. Some of these programs are capable of transmitting information about the minimum necessary system parameters to the user, for example, the Wall-3 program gives the value of the retaining structure fixed end length, which is necessary to ensure the stability of the system, but the user is given the freedom to change it. The supporting structures themselves are selected from design experience or simply by selection, and then, based on the calculation results, the user evaluates the received forces in the elements [3-5]. Typically, for struts made of steel pipes, the axial force N, kN is of greatest importance, since such elements are designed for compression work. Based on the calculated design forces, the stresses arising in the sections of the elements are determined and the strength and stability calculation is also performed. As a model of behavior for such strut elements applies a linear elastic, that is, not containing the strength of the elements. The stiffness of such elements is provided by the standard value of EJ, due to the geometric and deformation characteristics of the element’s section.

From the point of view of ensuring the strength of the system, this approach is not satisfactory, because the internal forces obtained are compared with the limit values in accordance with the law:
\[
\left( \frac{N}{A \cdot R_y \cdot \gamma_c} \right)^n + \frac{M}{c \cdot W \cdot R_y \cdot \gamma_c} \leq 1,
\]

(1)

where \( N \) and \( M \) - values of axial force and bending moment, respectively, kN and kNm;
\( n \) and \( c \) – coefficients from E.1 table of SP 16.13330.2011;
\( A \) – cross section area, \( \text{m}^2 \);
\( W \) – cross section resistance moment, \( \text{m}^3 \);
\( R_y \) – compression design resistance, kPa;
\( \gamma_c \) – work condition factor.

The calculation of struts stability [6] is performed according to paragraph 9.2 of SP 16.13330.2011 as for eccentrically compressed (compression with bending) elements of constant cross section in the plane of action of the moment, which coincides with the plane of symmetry according to the formula:

\[
\frac{N}{\phi_e \cdot A \cdot R_y \cdot \gamma_c} \leq 1,
\]

(2)

where \( \phi_e \) - coefficient of equilibrium; other designations are the same as in (1).

However, it is worth considering whether the task of the elastic behavior of the elements of the retaining system will lead to smaller deformations of it and, as a result, to incorrect calculation of the deformations of the soil base of the surrounding buildings. It is also necessary to find out whether the application of an elastic model of soil behavior can lead to unreliable deformations of the retaining structure of the excavation during the dismantling process of struts at the moment of grinding the retaining wall onto the floor disks. To verify this assumption, finite element calculations were performed in PLAXIS in plane strain and three-dimensional formulations in accordance with the initial data of real construction objects [7-11].

2. Methods

To identify the degree of influence of accounting in the numerical calculations of the elastoplastic behavior of soils, calculations of deep excavations were carried out in flat and three-dimensional formulations in accordance with the real design solutions of the objects under construction. In a two-dimensional formulation, when specifying the elastoplastic behavior of the “anchor” element, which defines the strut, it is required to enter the value of the maximum load on the element, at which it can no longer perform the work properly. For struts made of steel pipes 273x8 mm, 377x9 mm, 630x9 mm, 820x9 mm, such forces were 1690 kN, 2635 kN, 4420 kN and 5765 kN, respectively. In three-dimensional formulation, the “beam” element is set to the stress value corresponding to the material flow. In the calculations for steel elements, this value was set to 500000 kPa. After that, the task was calculated for a fragment of the deep excavation, and for the three-dimensional task, separate calculations were performed for dismantling the elements of the strut system (the article contains only a part of the calculations for dismantling).

A plane-strain 2D calculation was carried out for a projected object in St. Petersburg, which has an retaining structure made of a metal sheet pile of the Larsen L-5 type and a three-level strut system made of metal pipes.
Figure 1. Isofields of total displacements during excavation of a excavation in St. Petersburg.

Table 1. 2D calculation results. Maximum axial forces in struts

| Strut      | Strut level | N, elastic behavior | N, plastic behavior |
|------------|-------------|---------------------|---------------------|
| 377x9mm    | 1st         | 621                 | 622                 |
| 630x9mm    | 2nd         | 1107                | 1107                |
| 820x9mm    | 3rd         | 1263                | 1264                |

The three-dimensional calculation takes into account the distribution of forces in the elements of the strut system, taking into account the complex shape of the excavation, the influence of distribution belts and other factors that cannot be taken into account in 2D. For the calculation, a deep excavation was chosen in Moscow, which has a retaining structure made of metal pipes filled with concrete with a wooden filling between them. The dimensions of the retaining structure pipe elements vary from 377x10 mm to 920x10 mm.

The excavation process was modeled taking into account the elastic and elastoplastic behavior of the struts.
Figure 2. Isofields of vertical displacements at the end of excavation process.

Figure 3. Diagrams of axial forces in strut system at the stage of complete excavation (elastic calculation).
3. Results and discussion

The calculations performed showed ambiguous results. When calculating in a plane strain setting, the design model is a section, the spacing of the struts in which is set only in the form of adjusting the stiffness in the parameters of the element itself. Comparison of the calculation results in the plain strain and elastic formulations showed practically the same results. It should be noted that a change in the behavior of the elements of the strut system or their disconnection during dismantling would not lead to a redistribution of forces between all elements, since only one section and only one element with the stiffness reduced to the step of its placement is calculated. It can be concluded that in a plane strain setting it is permissible to restrict ourselves to elastic behavior. In addition, the resulting deformed state of the soil massif in the two calculation cases turned out to be identical and is shown in Figure 1. The total maximum displacements of the soil massif near the retaining structure were 13.4 and 13.6 mm for elastic and elastoplastic problems, respectively.

The results of three-dimensional modeling showed a significant difference in the operation of the strut system with elastic and elastoplastic behavior. The maximum longitudinal forces occurring in the strut elements differ by one third - 1562 kN for elastic behavior and 1049 kN for elastoplastic behavior. Such a drop in the value of the mobilized axial force is due to the fact that, under the condition of elastoplastic behavior, the struts turned out to be more pliable and allowed a greater movement of the retaining structure. At the same time, efforts were redistributed to all elements of the system at each level. However, at the same time, the displacement values of the excavation retaining wall are quite close: along the X axis they are equal to 22 mm and 18.9 mm, along the Y axis - 18.2 and 16.5 mm (elastic and elastoplastic formulations, respectively).

Figure 4. Phase displacements due to the local struts dismantling.

However, when considering the problems with modeling the process of dismantling the strut system (for example, when sequentially removing three struts of the first level when the retaining wall
is expanding with the floor plate of the second underground floor), no effect of taking into account the inelastic behavior of the elements of the strut system was revealed. Summing up the calculation part, we can say that it is desirable to take into account the elastoplastic behavior of the strut system in the case of modeling construction processes involving large changes from phase to phase, which leads to a significant change in the internal forces in the struts and a different redistribution in the system than in the case of their elastic work.

On the contrary, the modeling of successive stages involving a slight change in the stress-strain state (for example, dismantling several struts, a fragment of a small and shallow soil section in the excavation), may practically not affect the redistribution of forces in the system, since all the change in forces lies in the interval of their elastic work.

4. Conclusion
Based on the results of numerical studies, the following conclusions were drawn.
1. The results of solving the problems showed that modeling the elastoplastic behavior of the elements of the strut system in a plane strain setting has practically no effect on the redistribution of forces in the system and on the deformed state of the retaining structure.
2. When simulating the operation of a deep excavation retaining system with a complex shape in terms of elastoplastic behavior, large differences in the mobilized forces were obtained, in contrast to similar calculations, taking into account the elastic behavior of the elements of the strut system. The difference in the maximum values of the axial forces obtained was 500 kN, which reaches one third of the total force. In this case, the resulting displacements of the retaining structure may have slight differences when modeling struts in elastic and elastoplastic formulations.
3. When calculating the effects that do not imply a large change in internal forces in the elements of the strut system, such as staged dismantling of structures, there are practically no differences in the simulation results when using the elastic and elastoplastic formulation. When modeling large changes in the stress-strain state as a whole (for example, due to deep excavation), a significant difference can be observed in the redistribution of internal forces between the strut elements of the retaining structure.
4. To make a final decision on the admissibility of the design of excavation retaining structures, presenting their work with elastic behavior, it is necessary to perform a large number of careful calculations, the results of which must be compared with the data of geotechnical monitoring carried out at the facilities.

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