Elasto-plastic FEM model for researching of problematic soil ground of St.Petersburg city

Modèle élasto-plastique de MEF destiné à l'étude des conditions de sol compliquées de la ville de Saint-Pétersbourg

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ABSTRACT
A test pit work was carried out in 2007 in the area of the Extension of Mariinsky Theatre. It was applied to the work to use sheet pile cofferdam. In the work large displacement of sheet pile was measured. We analyzed this work by our elasto-plastic FEM in total stress condision. In this study Mohr-Coulomb type yield function and Drucker-Plager type plastic potential were applied to constitutive equation. We decided the cohesion of each soil layer from the geological colum and the Young's modulus of the strut and sheet pile not to be able to get the detailed soil parameter and the sheet pile and strut data. For this analysis, it was obvious that the ineffective strut progressed the measured large displacement of the sheet pile.

RÉSUMÉ
En 2007, l'excavation des échantillons du sol a été faite sur le chantier d'extension du Théâtre Mariïnsky. Pour effectuer des travaux a été utilisé le caisson des pieux de rainure. Lors du travail on a observé un grand délogement des pieux de rainure. Nous avons fait l'analyse de ce travail au moyen du modèle élasto-plastique dans l'état du sous-sol absolument mis en charge. Le modèle élasto-plastique de Mohr-Coulomb ainsi que le modèle plastique de Drucker-Plager ont été utilisés pendant l'établissement de la formule. L'engrenage de chaque strate du sol dans une coupe géologique ainsi que le modèle d'élasticité de l'étai et du pieu de rainure n'ont pas mis en évidence des paramètres précis du sol et des données du pieu de rainure et de l'étai. D'après les résultats des prélèvement des mesures il était évident qu'en vue d'un grand déplacement des pieux de rainure l'étai ne fonctionne pas de façon efficace.

Keywords : excavation analysis, elasto-plastic FEM, strut and sheet pile

1 INTRODUCTION

A test pit work was carried out in 2007 in the area of the Extension of Mariinsky Teatre. It was applied to the work to use sheet pile cofferdam. The test pit work was carried out to research the behavior of soils in St. Petersburg within cofferdams. The location of test pit was selected in an intermediate internal area at a safe distance from the existing buildings. In the work the large displacement of sheet pile was measured by the inclinometer.

We analyzed this work by our elasto-plastic FEM in total stress condition. It is difficult that the stable limit stress condition is computed well when the rotating failure of the retaining wall occurs (Potts, 2003). There is few effective numerical method against this problem. We developed the elasto-plastic finite element analysis with the implicit-explicit dynamic relaxation method to solve this problem. This finite element analysis is able to stably analyze the limit condition of sheet pile until the back ground of the sheet pile collapse (Tanaka and Okajima, 2001). In this study Mohr-Coulomb type yield function and Drucker-Plager type plastic potential were applied to constitutive equation (Mori and Tanaka, 2001).

We decided the cohesion of each soil layer from the geological colum and the Young's modulus of the strut and sheet piles not to be able to get the detailed soil parameter and the sheet pile and strut data (Okajima, Tanaka, Zhusupbekov, 2009).

a)
b)

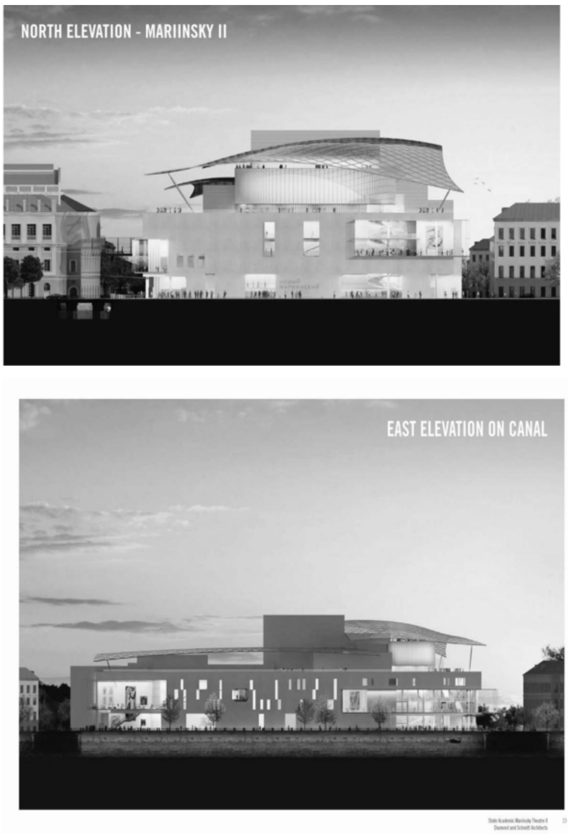

Fig. 1. Conceptual offers of «Diamond&Schmitt Architects»
a) North elevation – Mariinsky II
b) East elevation on canal

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-773

2 FEM MESH AND EXAVATING ANALYSIS

The test pit was about 13m width and 12m depth as Fig.2. Sheet piles of which length were 22.5m were installed. Three struts were installed at 1.5m, 3m and 6m depth in depth direction. Though the layer from 12m to 14m depth is jet-grouting layer, we didn't considered this layer in this study.

Fig. 3 shows the layout of the FEM mesh of Test pit. The node number is 4615. The element number is 4480. The object domain is 32.9m wide and 35m depth including test pit domain. There are three struts which were set at 0.5m depth, 3.5m depth and 6.5m depth in test pit domain. The excavation analysis was performed by deleting one layer at a time of test pit domain of the soil elements from above. The deletion of one layer was regarded as one stage of excavation. Elements in the part of struts were installed after elements under elements to install the strut were deleted. We decided that the length of domain out of test pit was 32m. This length is over two times of the excavated depth 12m.

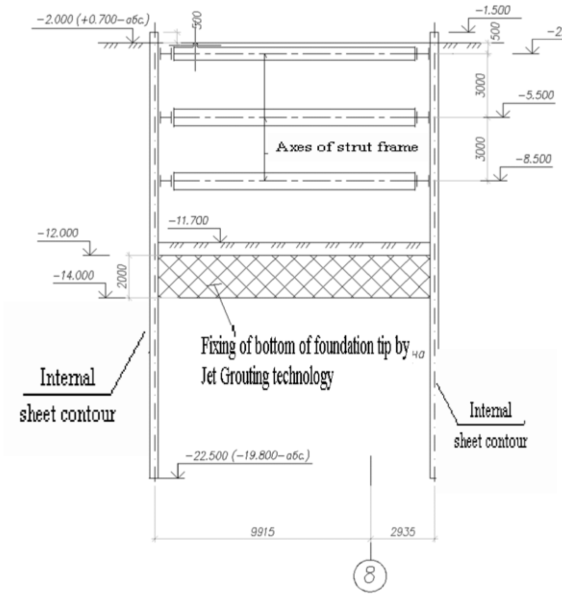

Fig. 2. Layout of the cross section of test pit

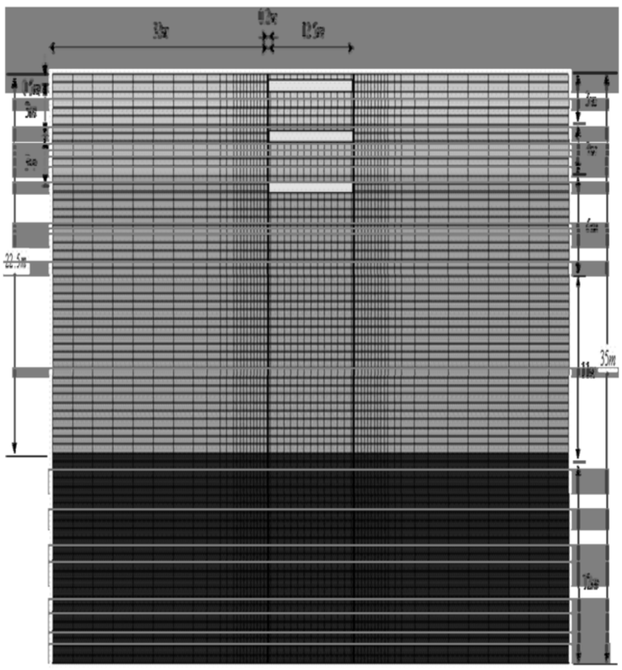

Fig. 3. Layout of FEM mesh and description of modeled soil

3 DEFINED PARAMETERS

In this study we have assumed that the soil were all cohesive soil (internal friction is zero) and applied the total stress analysis. We have determined the soil parameter from soil boring log in Fig. 4**.** The rough cohesion of soil is determined by Terzaghi (Table 1). We devided the ground to five soil layers for Fig. 3. We determined that the shallowest soil layer was from ground level to 3m depth. This soil layer cohesion was set to 0.1kgf/cm^2 for very soft clay. We determined that the secondarily shallower soil layer was from 3m depth to 6m depth. This soil layer cohesion was set to 0.5kgf/cm^2 for medium. We determined that the thirdly shallower soil layer was from 6m depth to 12m depth. This soil layer cohesion was set to 0.2kgf/cm^2 for soft. the forthly shallower soil layer was from 12m depth to 23m depth. This soil layer cohesion was set to 1.0kgf/cm^2 for stiff. the thirdly shallower soil layer was over 23m depth. This soil layer cohesion was set to 2.0kgf/cm^2 for very stiff. The Poisson's ratio was assumed to be 0.3.

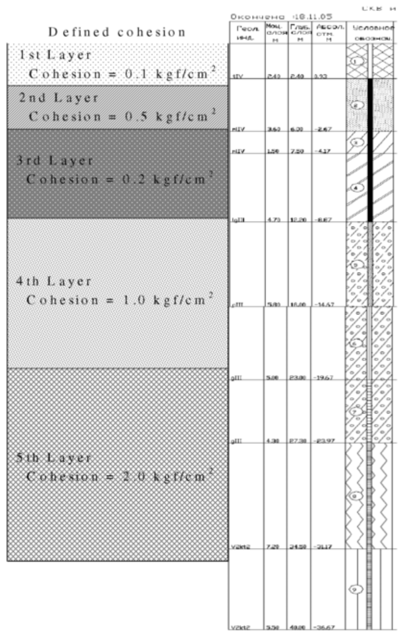

Fig. 4. Geological profile as shown in borehole 4762 and defined cohesion

Table 1. Proposed allowable bearing values for clay

№	Description of clay	N	q_u	C
1	Very soft	less than 2	less than 0.27	less than 0.14
2	Soft	2 to 4	0.27 to 0.54	0.14 to 0.27
3	Medium	4 to 8	0.54 to 1.08	0.27 to 0.54
4	Stiff	8 to 15	1.08 to 2.15	0.54 to 1.08
5	Very stiff	15 to 30	2.15 to 4.31	1.08 to 2.16
6	Hard	over 30	over 4.31	over 2.16

N is number of blows in standard penetration test.
qu is unconfined compressive strength in kgf par square centimeter.
C is cohesion in kgf par square centimeter.

The thickness and the unit weight of elements in the part of the sheet pile was determined in the following way. We regarded the thickness of elements in the part of the sheet pile as the thickness that had the same EI value as the sheet pile. The Young's modulus (E) of the sheet pile (FSP-5L) is 2,100,000kgf/cm^2 and the geometric moment of interia (I) per unit length is 63,000cm^4/m. The shape of elements in the part of the sheet pile was rectangular solid. When these elements had the same EI value as the sheet pile, the thickness of sheet pile's elements was calculated to be 20cm from the geometric moment of interia ($I = bh^3/12$). We considered that elements in the part of the sheet pile consisted of sheet pile and the soil. The unit weight per unit square of the sheet pile is 210kgf/m^2 and the area per unit length of the sheet pile (FSP-5L) is 267.6cm^2/m. The unit weight of the soil was regarded as 0.002kgf/cm^3. The unit weight of elements in part of the sheet pile was calculated to be 0.003kgf/cm^3 in the area ratio of the sheet pile and the soil. We devided the part of the sheet pile into three layers in the mesh.

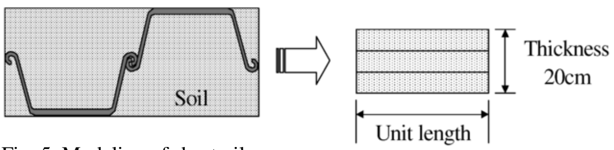

Fig. 5. Modeling of sheet pile

The Young's modulus and unit weight of elements in the part of strut was determined in the following way. The shape of the strut of test pit was sylindal type in the picture. We assumed that the diameter of the strut was 0.5m, the radial thickness was 0.008m, the material was steel and the strut was located every 4m. We thought that there was the rectangle (12.5m*4m *0.5m) of which the EA value is equal to the one of a strut because a strut beared 4m long. The EA value of a strut was 5.3*10^8 kgf. The cross section area of the rectangle was 2.0m^2. For these value the Young's modulus was calculated to be 26,000kgf/cm^2. This Young's modulus was applied to the plane strain analysis.

However, the measured horizontal displacement of the sheet piles in the test pit was 12-13cm. This result shows that the effect of struts was little. We computed the excavation works in three paterns which had different Young's modulus 26,000 kgf/cm^2, 2,600 kgf/cm^2 and 260 kgf/cm^2.

For the above we compared "Strut E=26,000 kgf/cm^2" as designed condition with the results of test pit work. And we compared between "Strut E=26,000 kgf/cm^2", "Strut E=2,600 kgf/cm^2" and "Strut E=260 kgf/cm^2" to estimate the effectiveness of strut. In addition we compared between "Strut E=26,000 kgf/cm^2(Defined cohesion)" and "Strut E=26,000 kgf/cm^2(8 times defined cohesion)" of which each layer cohesion is eight times of defined condition to estimate the impact of soil condition.

Fig. 6. The struts of construction site of Mariinsky Theatre

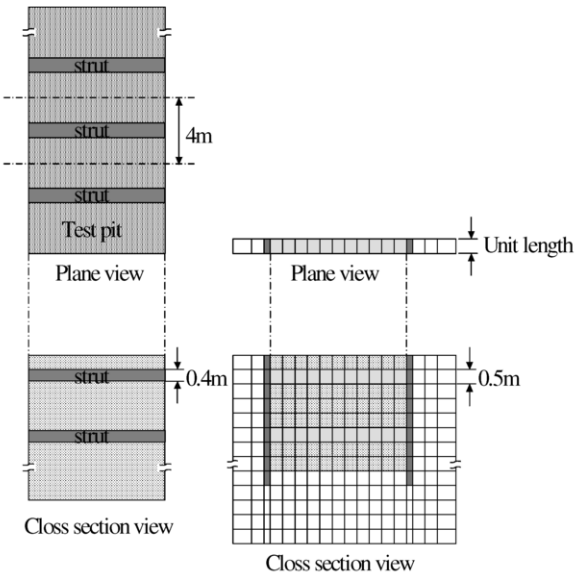

Fig. 7. The modeling of struts

4 RESULTS AND DISCUSSION

Fig. 8 shows that comparison of the displacement of the sheet pile between the result of FEM at some excavation stage and test pit work. The displacement of each excavation stage computed by this FEM expressed the measured displacement of the test pit well on the trend of shape. However the amount of displacement computed by FEM was less than the measured displacement. It was considered that the difference of the amount of displacement between the FEM and the test pit was due to the effectiveness of the strut and soil parameter.

We computed the excavation work in different conditions of the strut. Fig. 7 shows that comparison of the displacements of the sheet pile which have deferent Young's modulus of strut at the last excavation stage. We estimated the impact of the strut when the strut Young's modulus had 26,000kgf/cm^2 and 2,600kgf/cm^2 and 260kgf/cm^2. In the test pit the maximum displacement measured about 130mm. For Fig. 9 larger displacement of sheet pile was computed in lower strut Young's modulus. The maximum displacement in which the strut have 260kgf/cm^2 was computed to be 115mm. Next we computed the excavation work to have different soil parameter. Fig. 10 shows that comparison of the displacements of the sheet pile in deferent cohesions of soil at the last excavation stage. We defined the cohesion as the soil parameter from the ground colum. We estimated the impact of the strength of soil by computing the excavation work when the ground soil have the defined cohesion and 8 times defined cohesion. For Fig. 8 the displacement to be set to the 8 times defined cohesion was almost similar as one to be set to the defined cohesion. Instead in shallow depth the displacement to be set to the 8 times defined cohesion was slightly larger than one to be set to the defined cohesion.

From Fig. 9 and Fig. 10 it was obvious that the impact of the strut strength was larger than the soil strength against the horizontal displacement of the sheet pile in this excavation work. This result shows that there is the possibility that the strut was not enough effective in the test pit work. We need analyze this problem in more detailed case when we get the detailed soil parameter and data of the strut and sheet pile.

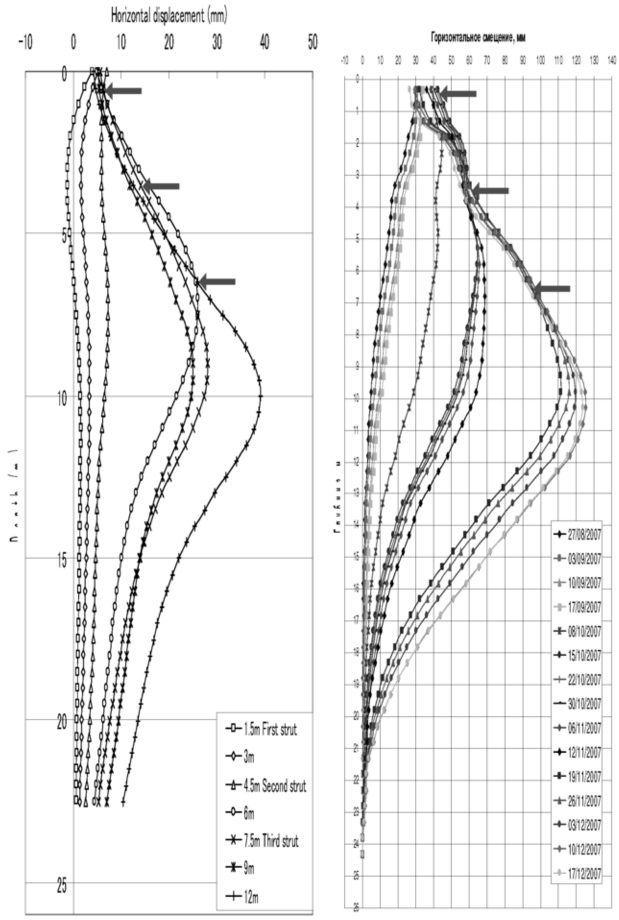

Fig. 8. Comparison of the displacement of the sheet pile between the result of FEM and test pit work

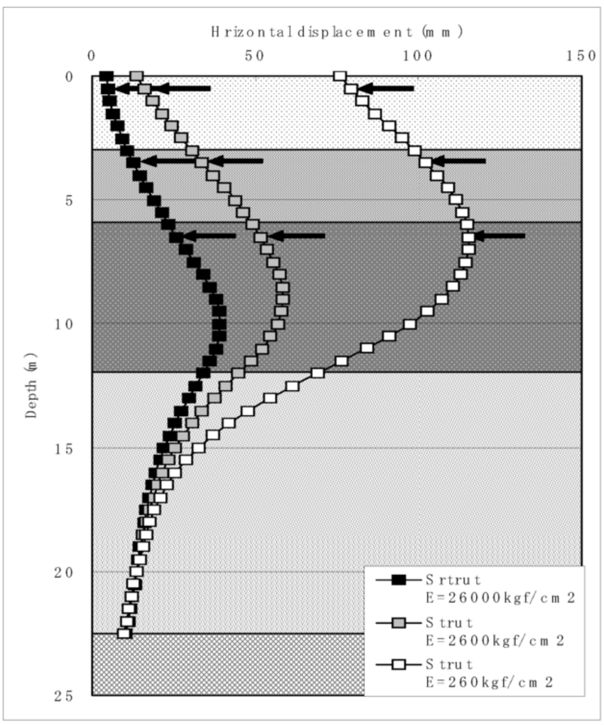

Fig. 9. Comparison of the displacements of the sheet pile which have deferent Young’s modulus of strut

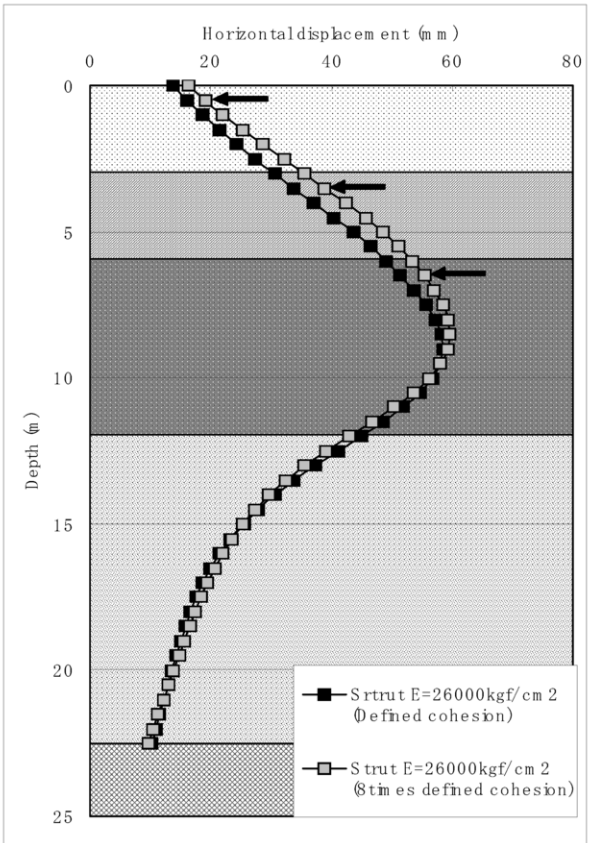

Fig. 10. Comparison of the displacements of the sheet pile in deferent cohesions of soil

5 CONCLUSION

We analyzed the test pit of the excavation work in St. Petersburg soft clay by our elasto-plastic FEM in total stress condition. In the test pit work large displacements of sheet pile were measured. We defined many parameter by our self because we couldn’t get the detailed data. For the result our FEM could compute the trend of displacement of the sheet pile. If we could get more detailed parameters of soils and structures, we might discuss the large displacement of the sheet pile in more detail. Though we cannot say for certain from just this paper, it was obvious that that the ineffective strut progressed the measured large displacement of the sheet pile for some pattern of analyses which compared the effectiveness of struts and soil cohesion.

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