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The paper was published in the proceedings of the 7th International Young Geotechnical Engineers Conference and was edited by Brendan Scott. The conference was held from April 29th to May 1st 2022 in Sydney, Australia.

Changes in silty-clayed soil properties due to hydrodynamic water pressure at excavation of a deep pit

Changements dans les propriétés du sol limoneux en raison de la pression hydrodynamique de l'eau lors de l'excavation d'une fosse profonde

Elena Bragar, Yakov Pronozin & Leonid Bartolomei

Department of Construction Production, Industrial University of Tyumen, Tyumen, Russia, el.bragar@yandex.ru

Elena Bragar

Department of Design of Buildings and Constructions, L.N. Gumilyov Eurasian National University, Nur-Sultan, Republic of Kazakhstan, el.bragar@yandex.ru

Dr. Pulod Aminzoda

Institute of Geology, Earthquake Engineering and Seismology, National Academy of Sciences Of Tajikistan, Tajikistan

ABSTRACT: Designing foundations in open deep pits is a complex engineering challenge. The situation is beginning more complicated in the process of construction on soft soils in severe climatic conditions. The low deformation and strength characteristics of the soil can be fully manifested. The properties of soils are additionally degraded during excavation of a deep pit in conditions of a high groundwater level and possible freezing. A high groundwater level in case underprotection of groundwater cutoff results to a hydrodynamic water pressure on the active soil thickness of the excavation bottom and, as a result, to a change in the deformation characteristics of the soilbase and destructuring of the soil. This, in turn, causes to unpredictable additional settlements of the structure. As part of a laboratory experiment, authors investigated a quantitative changes in the elastic modulus, deformation characteristics of the Soft Soil model under hydrodynamic water pressure on the soil without its destruction. The object of study was low-plasticity clay loam. It was established that the hydrodynamic water pressure significantly reduces the deformation characteristics of the clay loam. Authors recommend to take into account the obtained patterns at designing foundations in deep pits during performing both analytical and numerical calculations aimed to more accurate prediction the settlement of foundations.

RÉSUMÉ : La conception de fondations dans des fosses profondes ouvertes est un défi d'ingénierie complexe. La situation commence plus compliquée dans le processus de construction sur des sols meubles dans des conditions climatiques sévères. Les caractéristiques de faible déformation et de résistance du sol peuvent être pleinement manifestées. Les propriétés des sols sont en outre dégradées lors de l'excavation d'une fosse profonde dans des conditions de niveau élevé des eaux souterraines et de gel éventuel. Un niveau d'eau souterraine élevé en cas de sous-protection de la coupure des eaux souterraines entraîne une pression hydrodynamique de l'eau sur l'épaisseur du sol actif du fond d'excavation et, par conséquent, une modification des caractéristiques de déformation du sol et une déstructuration du sol. Ceci, à son tour, provoque des tassements supplémentaires imprévisibles de la structure. Dans le cadre d'une expérience en laboratoire, les auteurs ont étudié les changements quantitatifs du module d'élasticité, les caractéristiques de déformation du modèle de sol mou sous la pression hydrodynamique de l'eau sur le sol sans sa destruction. L'objet de l'étude était un limon argileux à faible plasticité. Il a été établi que la pression hydrodynamique de l'eau réduit considérablement les caractéristiques de déformation du limon argileux. Les auteurs recommandent de prendre en compte les modèles obtenus lors de la conception de fondations dans des fosses profondes lors de la réalisation de calculs analytiques et numériques visant à prédire plus précisément le tassement des fondations.

KEYWORDS: excavation of a deep pit, hydrodynamic water pressure, clay loam, Soft Soil model, laboratory experiment.

1 INTRODUCTION

The modern requirements of urban infrastructure are based on the maximum usage of urban areas and a clear organization of space. These requirements lead to the development of both separate underground structures and multifunctional complexes with a developed underground part. They are a solution to many infrastructural problems, thereby improving the quality of life of the population.

Designing foundations in deep open pits (more than 5 m (SP 22.13330.2016) in difficult geotechnical conditions (low deformation and strength characteristics, heaving, thixotropy, etc.) is a complex engineering task. The principle of conservation of the natural soil structure is preferable for deep pits. Consequently, the following risk factors should be taken into account:

1. Drastic changes in static conditions of base behavior during soil excavation and unloading;

2. Hydrostatic and hydrodynamic water pressure;
3. Local freezing and thawing of the upper part of the soil base
4. Vibrational impact from operating equipment, dynamic impact from transport from installation of excavation shoring and soil excavation

Problems arising during the excavation of deep pits are observed everywhere: both in Russia and abroad. Therefore, the problem of changing the soil characteristics after removing the load, influence of various factors and subsequent loading, was studied earlier (Ulitskiy et al. 2010, Boldyrev & Idrisov 2017, Abelev 2002, Ponomarev et al. 2013, Hong & Wang 2016, Xie et al. 2015). However, the problem is still relevant.

It should be noted that according to (Mangushev et al. 2011) the vertical deformation of foundations on a natural base is determined as the sum of four components (Equation No. 1):

$$S = S_1 + S_2 + S_3 + S_4, \quad (1)$$

where S_1 –calculated settlement, in accordance with building standards.

S_2 – other settlement associated with the unloading of the pit and the next construction of the foundation.

S_3 – settlement of bottom heave associated with the accumulation of shear deformations in the soil, leading to the squeezing out of the soil from under bottom of the foundation.

S_4 – settlement associated with the destructing of the soil, i.e. freezing-thawing of soil, water saturation, vibration loading from working equipment, severe climatic conditions, hydrodynamic water pressure etc. Usually, this part of settlement is not taken into account, however, destructing of the soil during earthworks often leads to significant deformations of the soilbase during the construction and operation of the building (Figure 1).

Authors investigated the hydrodynamic water pressure effect on the deformation characteristic of loam.

Many scientists have studied the processes of changes in the deformation characteristics of clay soils (Kaloshina & Salimgarieva 2013, Averin et al. 2010, Gavshina & Dzintser 1982, Retkhati 1989, Zinoviev 1988).

Researchers have noted a significant effect of moisture content changes on the mechanical properties of silty-clayed soils. The strength of structural bonds in silty-clayed soils is influenced by a few factors: soil density, moisture, mineral composition, degree of dispersion, etc. So, deformation characteristics of full water saturation soils, decrease by 14-25% - for filled soils, by 23-45% - for loams, by 29-42% - for clays (Petrov 2017).

It was established that the soils of the active zone of the deep pit bottom suffer the hydrodynamic water pressure in case of unreliable work of groundwater cut-off (GWC), or in case of turned off dewatering installations at construction.

Such impact can lead to practical **failure** of the surface layer soil and **destructing** of the underlying soils. On the one hand, the assessment of the properties of the **failure** soil is practically not interesting to engineers because the thickness of this soil is relatively low. Therefore, the failure soil must be replaced or modified.

On the other hand, the assessment of changes in the properties of the underlying soils exposed to hydrodynamic water pressure takes considerable interest, because the thickness of the **destructing** soils can be heavy. It significantly affects to the final settlement of the structure.



Figure 1. Flooding of the pit due to insufficient depth of GWC

2 MATERIALS AND METHODOLOGY

The object of laboratory testing was stiff loam. Main physical properties tested soil are presented in Table 1. Deformation properties of soil were determine in accordance with (GOST 5180-2015) by compression test in odometer. Diameter of specimens was 87 mm; height of specimens was 25 mm.

Table 1. Physical properties of soil.

No	Criteria	Unit of measurement	Value
1	Water content	1	19.5
2	Soil density	g/cm ³	1.96
3	Dry density	g/cm ³	1.64
4	Solid particles density	g/cm ³	2.70
5	Void ratio	1	0.65
6	Plasticity limit	%	15
7	Liquid limit	%	27
8	Plasticity index	1	12
9	Liquidity index	1	0.38

The necessary and sufficient deformation characteristics of the soil were determined for Mohr-Coulomb and Soft Soil models (elastic modulus E , modified compression index λ^* , modified recompression index κ^*).

The main characteristics of the Soft Soil model are:

λ^* – modified compression index (Equation No. 2):

$$\lambda^* = \frac{C_c}{(1+e_0) \cdot \ln 10} = \frac{\varepsilon_2 - \varepsilon_1}{\ln(\sigma_2) - \ln(\sigma_1)} \quad (2)$$

κ^* – modified recompression index (Equation No. 3):

$$\kappa^* = \frac{\varepsilon_1 - \varepsilon_2}{\ln(\sigma_1) - \ln(\sigma_2)} \quad (3)$$

The test scheme included:

- 1) Specimen reconsolidation to confining pressure equal to 100 kPa (for soil at a depth of 5 m);
- 2) Unloading to simulate the excavation of a pit 5 m deep;
- 3) Loading up to 800 kPa and unloading to determine the characteristics of the Soft soil model (Mirny & Ter-Martirosyan 2017, Kempfert & Gebreselassie 2006) [20], [21]. Loading stages and stabilization parameters were taken accordance with GOST 12248-2010.

Laboratory test No. 1 was carried out on low-plasticity clay loam without hydrodynamic action to determine the characteristics of soil compressibility. The number of repeated tests was 6.

Water saturation of soil specimens was carried out under a pressure of 20 kPa (Experiment No. 2) and 40 kPa (Experiment No. 3) to simulate the a hydrodynamic water pressure on the active soil thickness of the excavation. The water saturation of specimens was carried out in compression device through it's bottom by pressure from triaxial compression device. The equipment setup is shown in Figure 2. The water saturation had been continuing for 3 days. The number of repeated tests was 6. It is important to note that the upper and lower surfaces of the soil samples were fixed during the test to prevent the possible destruction of its surfaces by active filtration during water saturation.



Figure 2. The equipment setup for water saturation

3 RESULTS OF LABORATORY TESTS

Table 2 shows the results of laboratory tests. It can be seen that the main deformation characteristic value (elastic modulus) decreased by 9% with a hydrodynamic water pressure $p_w = 20$ kPa. Elastic modulus decreased by 16% with a hydrodynamic water pressure $p_w = 40$ kPa. The relationship between hydrodynamic water pressure and decreasing elastic modulus is linear, that can be approximated firstly for the given type of soil.

Table 2. Comparison of soil characteristics obtained as a result of tests.

No	Criteria	Symbol	Number of test		
			No. 1	No. 2	No. 3
1	Elastic modulus	$E_n, 1$	20,6	18,8	17,4
		$E, 1$	20,3	18,6	17,3
2	Modified compression index	$\lambda_n, 1$	0,0356	0,0348	0,0378
		$\lambda, 1$	0,0350	0,0344	0,0373
3	Modified recompression index	$\kappa_n, 1$	0,00246	0,00116	0,00130
		$\kappa, 1$	0,00214	0,00108	0,00122
4	Maximum deformation of the specimen	$\Delta h, \text{mm}$	2,88	3,11	3,34
5	Maximum relative deformation of the specimen	$\varepsilon, 1$	0,115	0,125	0,134

Experiment No. 2 showed a significant decreasing in the standard values of the Modified compression index λ_n and Modified recompression index κ_n to 2% and 53% respectively. However, Experiment No. 3 showed an increasing in the standard values of the Modified compression index λ_n to 6% and an decreasing in the standard values of the Modified recompression index κ_n to 47%.

4 NUMERICAL MODELING

The work of the “soilbase-foundation-building” system was considered on the example of the construction of a 19-storey residential building with a two-storey underground parking. The foundation of the building is a slab 1.0 m thick with plan dimensions 15.30 x 34.90 m. The standard pressure from the building to the subgrade is 254 kPa, the design pressure is 292 kPa. The used soil models were Mohr-Coulomb (MC) and Soft

Soil (SS). The settlements were also determined by the layerwise summation method (LSM) in accordance with SP 22.13330. An elastic model of the material was used (Elastic model) to describe the work of reinforced concrete structures (the foundation slab, the supporting structures of the building - columns and plates). The strength characteristics of the soil were taken in accordance with Appendix A (SP 22.13330.2016). The deformation characteristics of the soil for the Soft Soil model were taken from the results of laboratory tests. All properties of materials are presented in Table 3.

Table 3. Used material models and their parameters

Symbol	Criteria	Model of material		
		Mohr-Coulomb	Soft Soil	Elastic
ν	Poisson's ratio	0,36	0,36	0,2
c, kPa	Cohesion	28	28	–
$\varphi, \text{degrees}$	Internal friction angle	22	22	–
$\psi, \text{degrees}$	Dilatancy angle	0	0	–
$\gamma, \text{kJ/m}^3$	Relative density	19,6	19,6	24,0
$\gamma_{\text{sat}}, \text{kJ/m}^3$	Relative density of soil at total water saturation	20,3	20,3	–
$e_0, 1$	Initial void ratio	0,65	0,65	–
$k, \text{m/day}$	Coefficient of permeability	0,01	0,01	–
$\lambda^*, 1$	Modified Compression Index	–	0,0350	–
$\kappa^*, 1$	Modified recompression index	–	0,00214	–
E, kPa	Elastic modulus	20310	20310	$3e7$

The construction object is a 19-storey residential building with a two-storey underground parking being built in Tyumen. The building is rectangular in plan with plan dimensions 14.30m x 33.90m. The building has monolithic reinforced concrete frame; bearing elements are reinforced concrete pylons with dimensions of 200mm x 900mm. Center distance between columns is 3200-3850 mm in the transverse direction and 5700 mm in the longitudinal direction. The foundation is a slab 1.0 m thick with plan dimensions 15.30 x 34.90 m.

The numerical modeling was carried out in Midas GTS NX in a 2D setting (Figure 4). The subgrade has dimensions of 160.0 m to 30 m, the dimensions of the computational area are taken based on the depth of the compressible depth, calculated by the layerwise summation method.

The pit has a depth equal to 7.0 m. A width of the pit at the level of the foundation is equal to 17.3 m, a width of the pit at the level of the day soil surface is equal to 31.9 m. The construction of the pit was carried out with berms 2.0 m wide at a depth of 3.5 from the day soil surface.

At numerical modeling the changes in the soil deformation characteristics from the day soil surface to a depth 1.0 – 5.0 was taken into account due to the hydrodynamic water pressure, which can effect to the pit bottom after deactivation of dewatering devices or insufficient reliability of the GWC. Filtration was used as the type of calculation, the staging of the work was taken into account (Table 4). The groundwater level was set at -3,000 or -5,000 from the day soil surface, which

corresponds to the hydrodynamic pressure $p_w = 40$ kPa and $p_w = 20$ kPa, respectively.

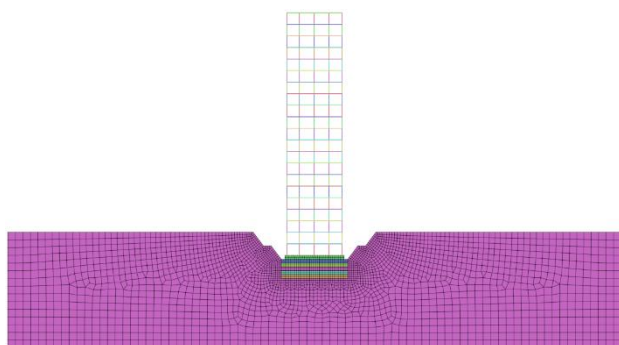


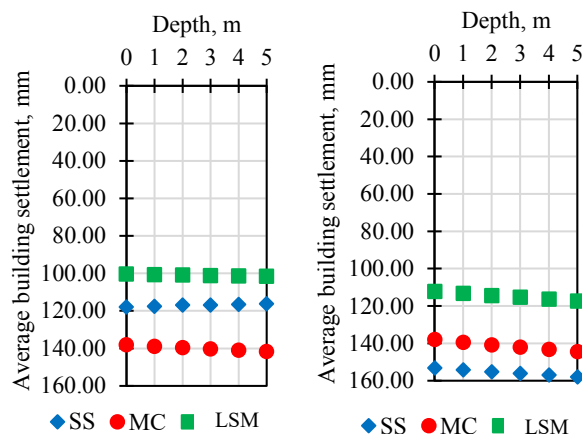
Figure 4. Model of building in Midas GTS NX

Table 4. Stage of numerical modeling into Midas GTS NX

No	Stage	Justification
1	Initial-Filtration	Establishing the groundwater level at -3,000 or -5,000
2	Initial – SSS (Stress-strain state)	Calculation of the stress-strain state of the soil in-situ
3	Dewatering	Dewatering to bottom of the pit
4	Zeroing-1	Reset of deformations of the soil in-situ due to the application of its own weight and dewatering
5	Excavation-1-4	Excavation of the pit to a depth -1,750; -3,500-5,250; -7,000.
6	SSS (Stress-strain state)	Calculation of the stress-strain state of the soil in-situ.
7	Zeroing-2	Zeroing of the deformations of the soil in-situ due to the significant rising of the bottom of the pit after excavation in the Mohr-Coulomb model. For comparison, a similar stage was introduced for the Soft Soil model.
8	Changes in properties	Change in deformation characteristics accordance with laboratory test results (Table 2).
9	Foundation, load application	Construction of the foundation slab, underground and aboveground parts.

5 RESULTS OF NUMERICAL MODELING

The results of the settlements calculating of the foundation slab in the Midas GTS NX are presented in Figure 5.



a)

b)

Figure 5. The dependence of the average building settlement from the engineering and geological conditions where *Depth* is the depth of change in the deformation characteristics of soils due to hydrodynamic effects at excavation from the day soil surface

a - the groundwater level is at an elevation of -5,000 from the day soil surface; b - the groundwater level is at an elevation of -3,000 from the day soil surface.

It was found out that the soil model used in numerical modeling significantly affects the calculation results (Figure 6). So, the Mohr-Coulomb model showed almost identical results of soilbase settlements with ground water level equal to -5,000 and -3,000, the maximum settlement was 142 and 144 mm, respectively. Thus, the MS model is insensitive to changes in hydrodynamic pressure, which proves the insufficient reliability of this model for calculating buildings and structures located in deep pits (Ulitskiy 2014).

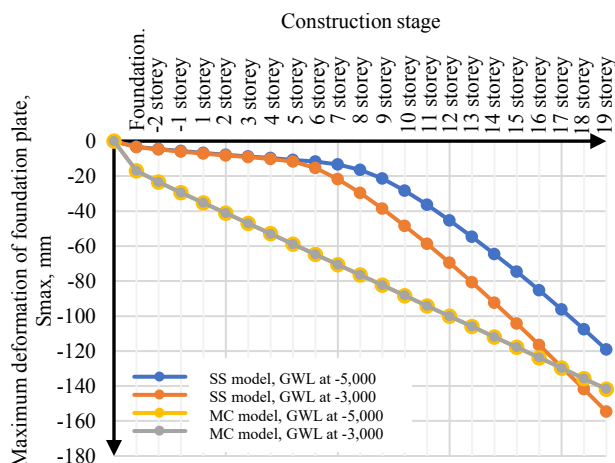


Figure 6. The dependence of the building settlement from the construction stage

Geotechnical numerical modeling with the Soft Soil model showed a significant change in the settlement of the building due to changes in the deformation characteristics and the groundwater level. Consequently, with the groundwater level at -5,000 m and -3,000 m, the maximum settlements were 120 and 160 mm, respectively. However, the Russian building standards (SP 22.13330.2016) delimitate the maximum settlements as 150 mm.

6 CONCLUSIONS

The following conclusions can be drawn from the experimental results analysis above:

1. Buildings with slab foundations, the soilbase of which is highly compressible silty-clayed soils, can have significant, poorly predictable settlements due to the hydrodynamic water pressure on the active soil thickness of the excavation bottom. In this case, the upper part of the active soil thickness can be generally collapsed and must be replaced or modified, while the deeper part will have reduced deformation characteristics.
2. It was established by experimental studies that the standard value of the elastic modulus of low-plasticity clay loam with a porosity coefficient of $e = 0,65$, water content of ($w = 19,54\%$ and soil density $\rho = 1,96 \text{ g/cm}^3$ under hydrodynamic water pressure $p_w = 20 \text{ kPa}$ decreased by 9%. The standard value of the elastic modulus decreased by 16% with a hydrodynamic water pressure $p_w = 40 \text{ kPa}$. The relationship between hydrodynamic water pressure and decreasing elastic modulus is linear, that can be approximated firstly for the given type of soil.
3. Experiments showed a significant decreasing in the standard values of the Modified compression index λ_n and Modified recompression index κ_n to 2% and 53% respectively under hydrodynamic water pressure $p_w = 20 \text{ kPa}$. However, it was also established that the standard values of the Modified compression index λ_n to 6% increased and the standard values of the Modified recompression index κ_n to 47% decreased with a hydrodynamic water pressure $p_w = 40 \text{ kPa}$. That parameters are usually used in Soft Soil numerical model.
4. The Mohr-Coulomb soil model can give significant errors and is not reliable for settlement calculating of the base of buildings and structures erected in deep pits, due to not taking into account plastic deformation of soils. In this case, it is more correct to use more complex soil models, for example, Soft Soil, taking into account other deformation characteristics of soil such as Modified compression index and Modified recompression index.
5. The study of the influence of hydrodynamic water pressure on the deformation properties of cohesive soils makes it possible to more correctly predict the total settlement of structures erected in deep pits and make reliable engineering decisions.

7 REFERENCES

- Abelev K.M. 2002. Features of the technology of the device of foundations and foundations of civil buildings on weak water-saturated clay soils: dis. Cand. tech. Sciences: 05.23.08. - Moscow, 215 p.
- Averin I.V., Rakitina N.N., Bukreev D.S. 2010. Potential flooding and forecast of changes in the level of groundwater of construction sites. *Industrial and civil engineering*, 1,41-42.
- Boldyrev G.G., Idrisov I.Kh. 2017. Influence of cyclic freezing-thawing on the strength and deformability of frozen soils: state of the art. *Engineering geology* 3, 6-17.
- Gavshina Z.P., Dzintser E.S. 1982 Conditions of flooding by groundwater. *Moscow: Stroyizdat*, 1982, 116 p.
- GOST 12248-2010. Soils. Methods for laboratory determination of strength and deformation characteristics.
- GOST 5180-2015 Soils. Methods for laboratory determination of physical characteristics.
- Hans-Georg Kempfert, Berhane Gebreselassie. 2006. Excavations and Foundations in Soft Soils. *Springer*, 576 p.
- Hong Y., Wang L. 2016. Deformation and Failure Mechanism of Excavation in Clay Subjected to Hydraulic Uplift. *Advanced Topics in Science and Technology in China*, 156 p. DOI 10.1007/978 3 662 46507 3.

- Kaloshina S. V., Salimgarieva N. I. 2013. Influence of flooding on obtaining additional sediment of buildings and structures. *Bulletin of PNRPU. Construction and architecture*, 1, 104-113.
- Mangushev R.A., Karlov V.D., Sakharov I.I., Osokin A.I. 2011. Foundations and soilbases: Textbook for bachelors of construction. *M.: Publishing house ASV; SPb.: SPbGASU*, 394 p.
- Mirny A.Yu., Ter-Martirosyan A.Z. 2017. Fields of application of modern mechanical soil models. *Geotechnics*, 1, 20-26.
- Petrov V.V. 2017. Nonlinear incremental structural mechanics. *M.: Infra-Engineering*, 480 p.
- Ponomarev A.B., Kaloshina S.V., Salimgarieva N.I. 2013. Influence of the process of flooding on the physical and mechanical properties of soils. *Academic Bulletin URALNIIPROEKT RAASN* 1, 67-70.
- Rethati L. 1989. Ground waters and construction. *Moscow: Stroyizdat*, 432 p.
- Sheng-bo Xie, Qu Jian-jun, Lai Yuan-ming, Zhou Zhi-wei Xu Xiang-tian. 2015. Effects of freeze-thaw cycles on soil mechanical and physical properties in the Qinghai-Tibet Plateau. *Journal of Mountain Science*, 12, 999-1009.
- SP 22.13330.2016 Soil bases of buildings and structures. Updated edition of SNiP 2.02.01-83 *. *M.: Standartinform*, 2016, 227s.
- Ulitskiy V.M., Shashkin A.G., Shashkin K.G. 2010. Geotechnical support of urban development (a practical guide to the design of buildings and underground structures in a densely built environment). *SPb: Stroyizdat North-West*, SPb, 2010, 561 p.
- Ulitskiy V.M., Shashkin A.G., Shashkin K.G. Shashkin V.A. 2014. Fundamentals of joint calculations of buildings and soilbases. *SPb: "Georeconstruction"*, 328 p.
- Zinoviev M.L. 1988. Influence of the depth of freezing of soils on the formation of the process of flooding. *Hydrogeological research in the built-up areas: collection of articles of the USSR Academy of Sciences*, 25-31.