Special Features of Creep of Clayey Soils

Particularités du fluage des sols argileux

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ABSTRACT: The problem of settlement predictions in clays involves the solution of complex engineering challenges associated with the determination of many experimental parameters (modulus of deformation, lateral expansion ratio, coefficients of permeability and consolidation, as well as rheological characteristics). The full analysis of ground behavior during consolidation and creep of the solid soil particles at the time of the construction and operation is only possible if the site investigation and laboratory results are reliable. In this paper the authors present the results of the long-term settlement observations (over 50 years) of large industrial facilities of Karaganda Metallurgical Complex and the soil properties of these sites based on the thorough site investigation program. The underlying soils have sufficient bearing capacity, relatively high values of density and low void ratios. The creep deformations at the constant loads in the saturated state exhibited gradually decreasing character. The actual settlements of the structures and the maximum allowable settlements (by the building codes) are compared. The conclusion is made on the need to amend the recognized formula given by the building codes for the ground analysis by the second group of limiting states.

RÉSUMÉ : Le problème de la prédiction de la base de sédiments est réduite à la résolution des problèmes d'ingénierie complexes associés à la détermination des paramètres expérimentaux (module de déformation, le coefficient de coefficients de dilatation latéraux, du filtre et la consolidation, de fluage et de la rhéologie caractéristiques) des sols argileux. Une analyse complète du comportement de la base pour la consolidation et le fluage des particules solides du sol avec le temps au cours de la construction et l'exploitation n'est possible que si les résultats expérimentaux sont fiables et exacts. Les auteurs de cet article établissent que les propriétés physiques des sols argileux du site de construction dans l'ouest du Kazakhstan se caractérisent par une hétérogénéité et la propagation en assez grand nombre de valeurs de caractéristiques. Les résultats des observations de règlement à long terme des grandes installations industrielles de Karaganda Complexe Métallurgique sont présentés dans le document. Les colonies réelles des structures et les colonies maximales admissibles (codes du bâtiment) sont comparées. La conclusion se fait sur la nécessité de modifier la formule communément reconnue pour l'analyse du sol par le deuxième groupe d'états limitatifs.

KEYWORDS: settlements, foundations, laboratory and in-situ characterization, creep.

1 INTRODUCTION

The long-term settlements of large industrial facilities of Karaganda Metallurgical Complex have been monitored for more than 50 years by geodesic surveying. In order to record the settlements, the survey points were installed during the construction of the blast furnace, charcoal oven battery and 250 meters tall chimney structures of the complex.

It is known that the primary settlements occur during the construction period and after several years of building operation. The settlement stabilization in clays occurs over time. In the central part of Kazakhstan the clayey soils (clay loam) with mostly semi-solid consistency are dominant which turn into a plastic state if the moisture content is increased.

In this regard, it is important to monitor the ground deformations from the moment of foundation installation and application of the loads, as well as to conduct the observations of changes in soil water content and groundwater levels (Tsytovich N.A. et al. 1967, Tsytovich N.A. and Ter-Martirosjan Z.T. 1981, Ukhov S.B. et al. 2002.)

2 PHYSICAL - MECHANICAL PROPERTIES OF SOILS

The physical and mechanical properties of the soils underlying the industrial facilities of Karaganda Metallurgical Complex are presented in Table 1.

Table 1. Physical- mechanical properties of the soils

Properties	Units	Facilities				
		Furnace	Oven battery	Chimney		
				H= 250 м	H= 100 м	H= 150 м
γ_o	kN/m^3	20,0	21,0	21,1	20,6	20,3
γ_s	кN/m^3	26,8	27,0	27,0	26,9	27,2
ω	%	12,5	14,2	18	19	17
J_l		0,25	0,24	0,26	0,21	0,26
e		0,52	0,76	0,49	0,66	0,52
φ	deg.	21	24	21	22	19
c	MPa	0,08	0,06	0,06	0,08	0,06
E_o	MPa	19,5	14,1	15,0	16,9	17,2

These geotechnical investigations and laboratory testing results show that the soils have relatively high density and low void ratios. The laboratory studies confirm an increase in water content of soils and the transition from a semi-solid to a low-plasticity consistency.

3 STRUCTURAL FEATURES OF FOUNDATIONS

The foundation of the blast furnace facilities was designed as a monolithic mass of reinforced concrete with the plan area of 27.0 x 27.0 m. The reinforcement of the foundation consisted of welded wire mesh made of steel class A – II. There are three horizontal grids with spacing of 200 mm in both directions in the lower zone of the foundation. In the upper zone there is the grid reinforcement with spacing of 400 mm. The depth of the foundation is 4.0 m. The bearing pressure is 300 t/m^2.

The foundations of the charcoal battery structures consist of box sections with the plan dimensions of 15.0 x 80.0 m. The depth of the foundation is 3.5 m. Each foundation has 4 exhaust ducts and 1 vent groove. The foundations were reinforced with longitudinal and transverse bars with diameter 20 mm, class A - II. The bearing pressure is 18.0 t/m^2.

The foundations of the 250 meters tall chimney structures are made of monolithic reinforced concrete. The foundation base is round with the diameter of 40.0 m and height of 4.0 m. The design load at the base of the chimney is approximately 21.1 t/m^2. The adopted concrete grade for all types of foundations was M300 on the Portland cement. Based on the site-investigation to a depth 30.0 m, the groundwater was not revealed.

4 LABORATORY STUDIES OF CREEP BEHAVIOR

The volumetric creep behavior of clayey soils under hydrostatic compression was investigated on the triaxial testing devices by applying a constant load (Tatsuoka F., Shibuya S. and Kuwano R. 2001).

The results of the studies show that the structural strength of the samples of clay with natural moisture and density content ranged from 25 ÷ 100 kPa; it was established experimentally that the consolidation process of the intact samples taken at different depths is significantly different with respect to time and deformation modes. The intensity of consolidation for the investigated soils under axial stresses of 25 ÷ 100 kPa is practically unchanged. It was mainly determined by the destruction process of the soil structure and the development of creep in the soil skeleton over time at the axial stresses of 100 ÷ 400 kPa. The existence of transient creep in shear has been established experimentally. The shear creep deformations at the given loads in the saturated state exhibited gradually decreasing character (Zhakulin A.S. and Zhakulina A.A., Kropachev P.A. 2011, Nakai T., Shahin H., Kyokawa H., Miyahara Y. 2011.).

The following plots were obtained based on the investigation:

– volumetric strains -time;

-relationship between the hydrostatic pressure and volumetric strain;

– pore pressure-time.

Figure 1 shows the test data volume creep of clay. The values of the hydrostatic pressure in the experiments were: σ_m= 0.10; 0.20; 0.3 MPa.

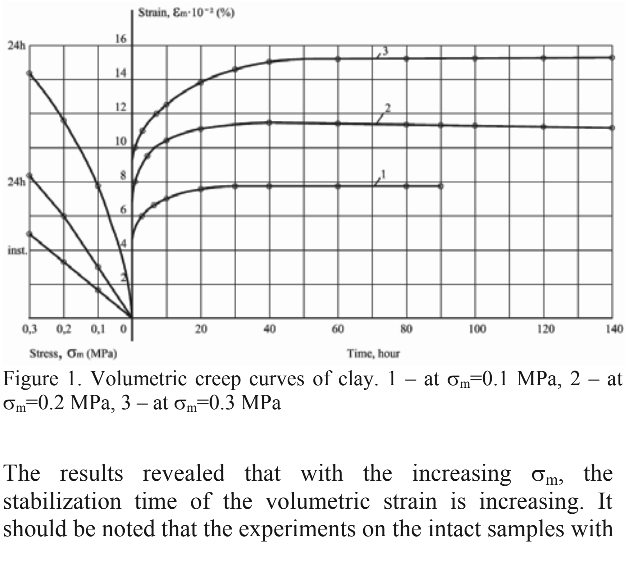

Figure 1. Volumetric creep curves of clay. 1 – at σ_m=0.1 MPa, 2 – at σ_m=0.2 MPa, 3 – at σ_m=0.3 MPa

The results revealed that with the increasing σ_m, the stabilization time of the volumetric strain is increasing. It should be noted that the experiments on the intact samples with natural moisture-density content showed that the volumetric strains were gradually decreasing for 1.5-2.0 days. When σ_m was changed from 0.1 to 0.3 MPa the volumetric strains increased by 2.1 times. During the study of the volumetric deformations of the saturated clay samples, an increase in the time of stabilization with an increase in the hydrostatic pressures was observed. Therefore, at σ_m= 0.1 MPa the full stabilization of volumetric creep deformations was achieved in 3-3.5 days, while at σ_m = 0.3 MPa this time increased to 5-7 days.

The values of volume strains when tested on clay samples for volumetric creep upon application of step-increasing loads were slightly less than upon the step application. This indicates that the step-increasing loading contributes to hardening of soil at each step and causes less strain than applying the same magnitude of a constant load.

However, the deviation was not more than 12.5%, which allows the use of the Boltzmann deformation imposition law. The laboratory results indicate that the soils exhibit gradually decreasing creep behavior (Vyalov S.S. 1978, Bulychov N.S. 1989).

5 SETTLEMENTS OBSERVATION RESULTS AND THEIR ANALYSIS

The elastic deformations of the magnitude of 12 mm were recorded during the dismantling of the blast furnace in 1985. The settlements stabilized in 2 months after the erection of the blast furnace. A similar pattern was observed in the reconstruction of the most blast furnaces.

The graph of the settlements of the blast furnace in time is shown in Figure 2. Upon the complete replacement of the oven batteries in 1986, the elastic deformations of 9 mm were observed which represented the one fifth of the total settlement. The graphs of settlements over time for charcoal oven batteries are shown in Figure 3.

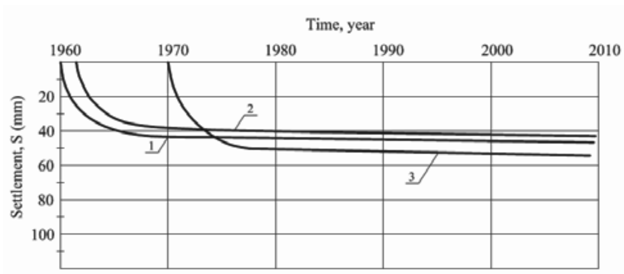

Figure 2. Settlements of blast furnaces over time. 1 - furnace #1, 2 - furnace #2, 3 - furnace #3.

The foundation base of the chimney is underlying by red-brown clay with semi-solid consistency. The stabilization of foundation settlement occurred in 5 years after the construction of the reinforced concrete stem.

The graphs of settlements of concrete chimneys in time are shown in Figure 4. It was found that the deformations of the foundations of blast furnaces and oven batteries were occurring for 2-3 years after their commissioning. The foundation settlements of the chimney structures faded immediately after the completion of construction work.

The comparison of the theoretical solutions and the long-term field settlement observations for 50 years provides a great deal of scientific and practical interest. In order to compare the design values with the actual and maximum allowable values of settlements (by building codes), the settlements of the foundations of the blast furnaces, charcoal oven batteries and 250 meters tall chimneys were re-analyzed.

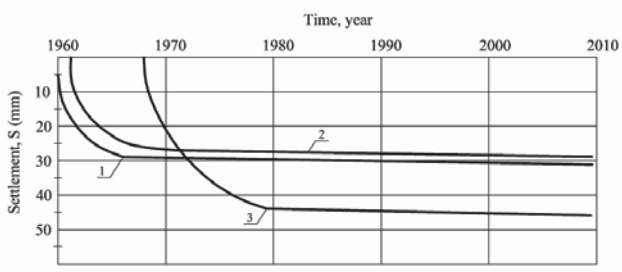

Figure 3. Settlements of charcoal oven batteries over time. 1 – battery #1, 2 – battery #2, 3 – battery #3.

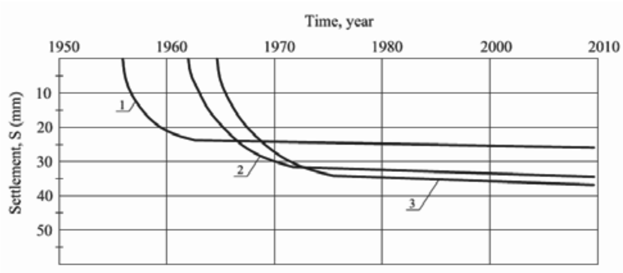

Figure 4. Settlements of chimneys over time. 1 - Chimney H=100m, 2 - Chimney H=250m, 3 - Chimney Power Station.

The settlements were calculated based on the design load: for the blast furnace - 300 t/m^2, for the chimney - 21.1 t/m^2, for charcoal oven battery - 18.0 t/m^2 at the upper edge of the foundation. The settlements were calculated by the method of summing the elementary layers and the method of the equivalent layer in accordance with the building code RK 5.01-01-2002 "Foundations of buildings and structures." Table 2 provides the comparison of design, actual, and maximum allowable (by the building codes) settlements.

According to the data provided, the actual foundation settlements of the industrial projects were several times less than the design values. As can be seen from Table 2, the actual settlements of the industrial objects are much lower than the design and maximum allowable ones: for the blast furnaces 6 ÷ 17 times; for the oven batteries 2.5 ÷ 7.0 times; for the Chimney in 2.5 ÷ 3.0 times.

It should be noted that the building codes do not take into account the processes of consolidation and creep of the soil skeleton over time. The analysis by the method of summing the layers is based on the half-space elastic models.

The Eurocode 7 "Geotechnical Design" assumes taking into account the elastic, consolidation and creep components of the foundation settlements.

The settlements analysis that takes into account creep is the following:

$$S = S_0 + S_1 + S_2 \qquad (1)$$

where S – total settlements; S_0 – instantaneous-elastic settlements; S_1 – consolidation settlements; S_2 – creep settlements (secondary);

Table 1. Comparison of design, actual, and maximum allowable (by building codes) settlements

Facility	Settlements, s, mm			
	Actual	Design		s_u
		Method #1 (layer summing)	Method #2 (equivalent layer)	
Blast furnace #1	45	156	210	400
Blast furnace #2	43	163	310	400
Blast furnace #3	55	178	200	400
Oven battery #1	27	138	144	250
Oven battery #2	26	120	132	250
Oven battery #3	44	140	149	250
Chimney (Power Station)	34	92	103	200
Chimney H=250 m	32	149	210	200
Chimney H=100 m	23	83	90	200

The total instantaneous foundation settlement can be determined by using the elastic theory:

$$s_0 = pbf / E_m \qquad (2)$$

where E_m – elastic modulus for calculations;
f – influence factor;
p – linearly distributed bearing pressure.

The components of the total settlements that take into account consolidation and creep:

$$s = s_1 + s_2 = Hm_v p + Hb_k \ln(t / t_v) \qquad (3)$$

To characterize the intensity of soil creep the creep parameter b_κ is used; it is determined by the compression tests from the formula:

$$b_\kappa = \Delta\varepsilon_{kt} / \ln(t / t_v) \qquad (4)$$

where $\Delta\varepsilon_{\kappa t} = \Delta s_{kt} / h$ - creep deformation; Δs_{kt} - creep settlement accumulated during the time *(t-t$_v$)*, cm; *h*- sample height, cm; *t* - compression time of the sample from the beginning of its loading, days; t_v – end of consolidation, days.

During the construction period ($t<t_e$) the applied load is varying over time. It is appropriate to use the theory of hereditary creep of Boltzmann-Voltaire for the prediction of creep settlements under the variable loads (Vyalov S.S. 1978, Tsytovich N.A. & Ter-Martirosjan Z.T. 1981)

For the complex load growth pattern and complex core type of creep, it is convenient to solve the integral equations of the theory of hereditary creep by the numerical method of Krylov-Bogoliubov (Ukhov S.B. et al. 2002, Tsytovich N.A. & Ter-Martirosjan Z.T. 1981, Z.G.Ter-Martirosyan. 1990, Zaretskyi Y.K.1988, Fadeev A.B. 1987, Zhusupbekov A.Z, Zhakulin A.S, Orazaly E.E, Popov. V.N. 2001).

6 CONCLUSIONS

1. The long-term field settlement observation for 50 years provides a great deal of scientific and practical interest.
2. The geotechnical investigations and laboratory testing results show that the soils underlying the site have relatively high density and low void ratios. The laboratory studies confirm an increase in water content of soils and the transition from a semi-solid to a low-plasticity consistency.
3. The laboratory results indicate that the soils exhibit gradually decreasing creep behavior.
4. The actual foundation settlements of the industrial projects were up to 2.5-17 times less than the design and maximum allowable values based on the building codes.
5. The settlement analysis should take into account the elastic, consolidation and creep components of the settlements, as well as make use of elasto-plastic models of the ground.

6. The results show the need for additional research to collect and systematize data and new amendments to generally accepted formula in the building codes for determining the foundation settlements with creep. The amendments to the basic calculation formulae may bring the theoretically derived results to more practical values on the depth of the main distribution of compressive stresses, settlement values and the intensity of creep.

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