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PARAMETERS OF OVERCONSOLIDATION OF JURASSIC CLAY SOILS IN THE MOSCOW REGION

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Abstract
Jurassic clay deposits are distributed almost everywhere in the Moscow region. Overconsolidation parameters characterize the initial stress-strain state of the soil. Jurassic deposits may be in the zone of influence of the designed structures, for the calculation of settlements of which nonlinear models of soil behaviour are used. As a result of the study, the behaviour of these soils was studied and processed using various graphical constructions. Soil samples were collected from various sites in Moscow, at depths ranging from 7.7 to 23.8 m, belong to the Jurassic system, being marine sediments. The mineral composition is dominated mainly by smectites (38.5-46.5%). The soils under study are classified as non-saline to slightly saline stiff clays (degree of salinity D_{sal} 0.40-0.71%, plasticity index I_p 15-58%, liquidity index I_L from 0.07-0.26). The overconsolidation ratio *OCR* for Jurassic clays at Desenovskoye ranged from 2.1 to 8.1, which corresponds to overconsolidated and highly overconsolidated soils, and in Fadeev street 1.2-1.9, classifying them as normally consolidation soils according to GOST 25100-2020 standards. The preoverburden pressure *POP* ranged from 115 to 831 kPa and from 69 to 372 kPa, respectively. Thus, the data obtained indicate that historical stresses exceeded modern ones and large thickness of the eroded soils is due to the proximity to the river.

Key words
preconsolidation pressure, salinity, swelling, Jurassic clays, Moscow

1 Introduction

To Jurassic clay deposits are distributed almost everywhere in the Moscow region, with the exception of river valleys and its southern and western sides. Jurassic deposits may be in the zone of influence of the designed structures, for the calculation of settlements of which nonlinear models of soil behaviour are used. Due to the history of geological development of the Moscow region, which includes several glaciations, an important characteristic of clayey rocks is their degree of overconsolidation.

Approaches to studying the effects of overconsolidation vary in stratigraphy, oil and gas geology, soil mechanics, and engineering geology. Meanwhile, the study of overconsolidation using engineering geology methods can provide interesting and important information for other branches of geology, for example, for stratigraphy (Kudryashova, 2002).

Soils are considered overconsolidated if their overburden stresses are less than the historical ones, which were maximum during the existence of the soil; the tested stresses are called preconsolidation stresses σ'_p. For the formation of the properties of pre-Quaternary clay, their density, strength and deformability, the depth of occurrence and position within certain geological structures or zones are of great importance, i.e. the duration of the impact of gravitational, geochemical and tectonic compaction during lithification (Kudryashova, 2002). Such soils differ greatly from similar ones in genesis and composition in their physical and mechanical properties.

The main quantitative indicators of soil overconsolidation are preoverburden stress *POP* and overconsolidation ratio *OCR*. Preoverburden stress *POP* is the difference between the effective preconsolidation stress σ'_p and the vertical effective overburden stress σ'_{vo}. The overconsolidation ratio *OCR* is the ratio of the effective preconsolidation stress σ'_p to the existing vertical effective overburden stress σ'_{vo}. Preconsolidation stress σ'_p is the conditional maximum effective stress on the soil during its existence (GOST R 58326-2018). Thus, this is a pseudo-elastic limit which separates 'elastic' pre-yield from 'plastic' post-yield behaviour of a soil (Umar, Sadrekarimi, 2016). The estimation of the preconsolidation stress σ'_p is usually carried out on the basis of the results of one-dimensional consolidation tests. According to Kudryashova (2002), for Jurassic clay of the Moscow region, *OCR* varies from 2 to 12.6.

2 Methods

The tests were carried out in general according to ASTM D 2435 and GOST R 58326-2018 with some deviations from the standard, since the current edition does not apply to swelling and saline soils. The dimensions of the cutting rings for oedometers were 50 × 20 mm and 42 × 13.5 mm (according to ASTM D 2435 no less than 50 × 12 mm, GOST 12248.4-2020 no less than 71 × 20 mm), which made it possible to carry out tests on equipment of Geotek standard series up to higher maximum values of vertical stress 5.0 and 7.2 MPa (according to GOST R 58326-2018 no less than 8.0 MPa). The loading scheme was compiled with a step increment coefficient *LIR* of 0.75 (according to GOST 12248.4-2020 *LIR* is 1.0), which allows one to obtain more experimental points and, therefore, more accurately carry out graphical constructions. The criterion for conditional stabilization was 0.01 mm in 4 hours; the completion of filtration consolidation was monitored using a graph of deformation versus the square root of time, excluding creep deformation (ASTM D 2435, Method B and GOST 12248.4-2020). A total of 18 compression tests were carried out. Graphic processing. The compression curves were processed by seven graphical methods for determining the preconsolidation stress (Table 1).

Table 1. Brief description of methods for determining preconsolidation stress and principles of their construction (Matveev, Shanina, 2022)

Method	Principle of the method
Group of semilogarithmic methods	
Casagrande	Constructions are carried out in the space of the porosity coefficient and the logarithm of stresses e — log σ. A tangent and horizontal line is drawn to the point of maximum curvature of the compression curve. Next, a bisector is drawn between them. The point of intersection of the bisector and the tangent to the final segment determines σ_p (Casagrande, 1936)
Pacheco Silva	The construction space is e — log σ. A horizontal line will be drawn through the initial porosity coefficient e_0 until it intersects with the tangent to the final section. Next, a vertical line is lowered from the intersection point until it intersects with the compression curve, after which another horizontal line is drawn, the intersection of which with the tangent to the final section determines σ_p (Pacheco Silva,1970).
Burland	Constructions are carried out in the space of the porosity index and the logarithm of stress I_V — log σ, which is equivalent to the space e — log σ. The σ_p is determined by the intersection of the tangents to the initial and final sections of the compression curve (Burland, 1990).
Boone	The construction space is e — log σ. This method uses an unloading loop. The σ_p is determined by the intersection of the tangent to the end section and a line parallel to the unloading loop passing through the overburden pressure point (Boone, 2010).
Group of bilogarithmic methods	
Butterfield, Oikawa, Sridaran, Onitsuka	Logarithmic methods have been proposed by many researchers (Butterfield, 1979; Oikawa, 1987; Onitsuka, 1995). The methods use logarithmic space for the dependence of e+1 on stress σ. The difference between the methods is in the choice of the logarithm base. The methods offer the same designs that do not depend on the scale of the axes.

Energy Methods Group	
Tavenas, Becker	The strain energy is used as a criterion for determining σ_p. The constructions are carried out in the bilinear space of the dependence of the accumulated strain energy *W* on the effective stress σ. The preconsolidation stress σ_p is determined by the simple intersection of the tangents to the start and end sections (Becker et al, 1987).
Wang and Frost	Similar to Becker's method, but uses an unloading loop during construction. To obtain the line of dissipated strain energy, the decompression line is graphically subtracted from the primary compression line (Wang, Frost, 2004).

Previously conducted studies show (Matveev, Shanina, 2021) that the most reliable data are obtained by the Boone method, because the unloading branch is used for construction, which does not affect the effects of the non-expressed inflection of the compression curve. The bend is not expressed due to the disturbance of the soil structure during sampling and the predominance of the mixed nature of structural connections over cementation ones in the studied soils.

3 Results

Characteristics of the studied soils. Soil samples were collected from various sites in Moscow: Fadeev street (55.77°N, 37.60°E) and Desenovskoe village (55.52°N, 37.38°E) at depths ranging from 7.7 to 23.8 m and belong to the Jurassic system, being marine sediments. For the selected samples, the particle size distribution, chemical and mineral composition, and physical properties were determined. The mineral composition is dominated mainly by smectites (from 38.5% to 46.5%). In accordance with the classification according to GOST 25100-2020 according to the degree of salinity D_{sal}, the studied soils are distinguished from non-saline to slightly saline (from 0.40% to 0.71%), the type of salinity is marine. Based on the relative swelling strain without load ε_{sw}, soils are classified from moderately swelling to highly swelling (from 10.6% to 38.9%). The soils under study are classified as stiff clays (I_p from 15 to 58%, I_L from 0.07 to 0.26). In general, the property indicators correspond to the literature data (STO 36554501-020-2010; Kudryashova, 2002). The compression curves were processed by seven graphical methods for determining the preconsolidation stress, the results are presented in Table 2.

Table 2. Values of preconsolidation stress of the studied Jurassic clays

Sample ID	Degree of salinity D_{sal}	Plastisity index I_p (%)	Liquidity index I_L	Void ratio *e*	Overvurden pressure, kPa	Preconsolidation stress σ_p, kPa determined by graphical method						
						Casa-grande	Pacheco Silva	Becker	Wang, Frost	Bilog.	Burland	Boone
Desenovskoe village (55.52°N, 37.38°E)												
HMC745	0.40	51	0.11	1.30	194	975	783	916	937	935	829	846
HMC746	0.43	51	0.12	1.33	206	501	330	562	538	477	352	340
HMC747	0.61	52	0.10	1.30	224	917	669	956	955	800	682	696
HMC748	0.65	56	0.09	1.31	268	1178	775	1294	1295	1011	820	846
HMC749	0.77	58	0.20	1.42	280	1276	1215	1449	1318	1031	816	714
HMC750	0.55	47	0.06	1.24	306	1258	926	1218	1305	1067	1028	1137
HMC751	0.03	54	0.11	1.34	336	873	534	1032	1026	821	621	627
HMC752	0.55	44	0.24	1.58	154	499	374	368	384	522	402	412
HMC753	0.68	45	0.17	1.57	186	722	492	676	654	652	505	493
HMC754	0.71	45	0.14	1.38	260	565	397	513	487	607	393	375
HMC755	0.16	42	0.20	1.75	280	1147	922	1117	1093	994	882	867
Fadeeva street (55.77°N, 37.60°E)												

HMC608	21	0.23	0.93	450	1521	555	1534	481	1404	1430	822
HMC609	15	0.20	0.64	460	714	388	763	368	784	647	529
HMC610	22	0.24	0.86	476	1257	696	1345	646	1276	1121	842
HMC621	24	0.23	0.77	406	936	456	1026	289	1184	940	712
HMC622	29	0.22	0.83	426	936	456	1026	343	1108	940	724
HMC623	15	0.26	0.73	446	1754	406	1902	231	1465	1662	717
HMC624	27	0.13	1.22	466	1254	573	1291	592	1135	1072	663

The grahical methods give different results, and the methods themselves have a high variation due to the inaccuracy of graphical constructions. Of particular interest is the HMC750 sample, which has an abnormally high value of the preconsolidation stress to other samples. Since this sample does not differ from neighboring samples in other properties, this is most likely due to the peculiarities of graphical constructions.

The overconsolidation parameters were also evaluated by correlation dependencies with index tests. The following formulas were used:
Stas, Kulhawy, 1984

$$\sigma'_p = p_a 10^{1,11-1,62\, IL}$$

DeGroot et al., 1999

$$\sigma'_p = 10^{2,9-0,96\, IL}$$

Kootahi, Mayne, 2016

$$\begin{cases} \log(\sigma'_p/p_a) = 0.17 + 0.86 \log(\sigma'_p/p_a) - 0.09 \log LI\,, OCR < 3 \\ \log(\sigma'_p/p_a) = 0.62 + 0.73 \log(\sigma'_p/p_a) - 0.24 \log LI\,, OCR \geq 3 \end{cases}$$

In order to avoid a sharp jump, in our study, the transition between formulas was provided by a weight sigmoid (logistic) function.

The overconsolidation parameters were also evaluated by correlation dependencies with cone penetration tests (CPT). The following formulas were used:
Mayne, 2009

$$\sigma'_c = 0,33(q_t - \sigma_{zg})^{m_{IC}}$$

$$m_{IC} = 1 - \frac{0,28}{1 + (I_c/2,65)^{25}}$$

$$I_C = \sqrt{(3,47 + \lg Q)^2 + (1,22 + \lg F)^2}$$

Ladd, Foot, 1974 (SHANSEP)

$$\left(\frac{c_u}{\sigma_0}\right)_{OC} = \left(\frac{c_u}{\sigma_0}\right)_{NC} OCR^m$$

$$c_u = \frac{(q_c - \sigma_{zg})}{N_k}$$

We believe that $\left(\frac{c_u}{\sigma_0}\right)_{NC} \approx 0,22;\ m \approx 0,8; N_k \approx 14$

Figure 1 shows the change of overburden stress and preconsolidation stress of Jurassic clays in Desenovskoe village with depth. Preconsolidation stress were determining by oedometer test with Boone interpretation method (red markers; the maximum and minimum estimates of preconsolidation stress are marked with segments, since graphical methods are subjective) and correlation dependencies with index tests: Stas, Kulhawy, 1984 (blue markers), DeGroot et al., 1999 (orange markers), Kootahi, Mayne, 2016 (green markers, left bound for NC clay, right bound for OC clay, middle point with logistic smoothing procedure).

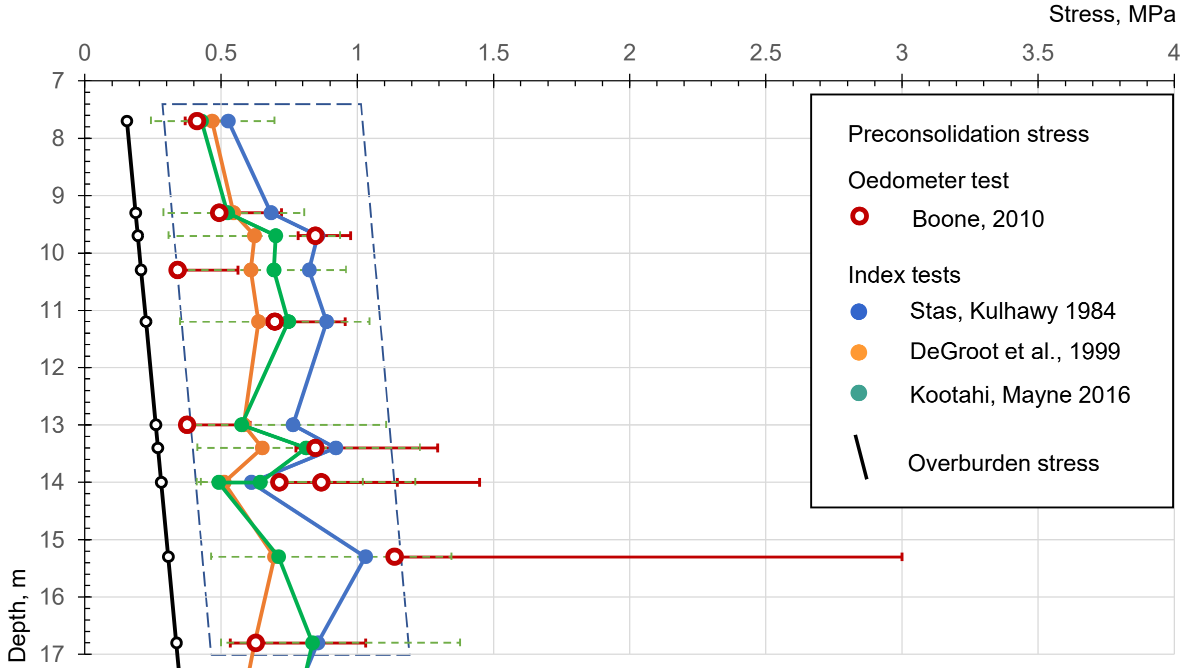

Figure 1. Variation with depth of overburden stress and preconsolidation stress of Jurassic clays, determining by oedometer and index tests in Desenovskoe village.

It is easy to see that the data obtained from various empirical formulas and experimental values generally correspond to each other, forming a 700 kPa wide band along the overburden pressure line. The preoverburden stress *POP* ranged from 115 to 831 kPa, average value 650 kPa

Figure 2 shows the change of overburden stress and preconsolidation stress of Jurassic clays in Desenovskoe village with depth. Preconsolidation stress were determining by oedometer test with Boone interpretation method and correlation dependencies with cone penetration test (CPT): Mayne, 2009 and SHANSEP.

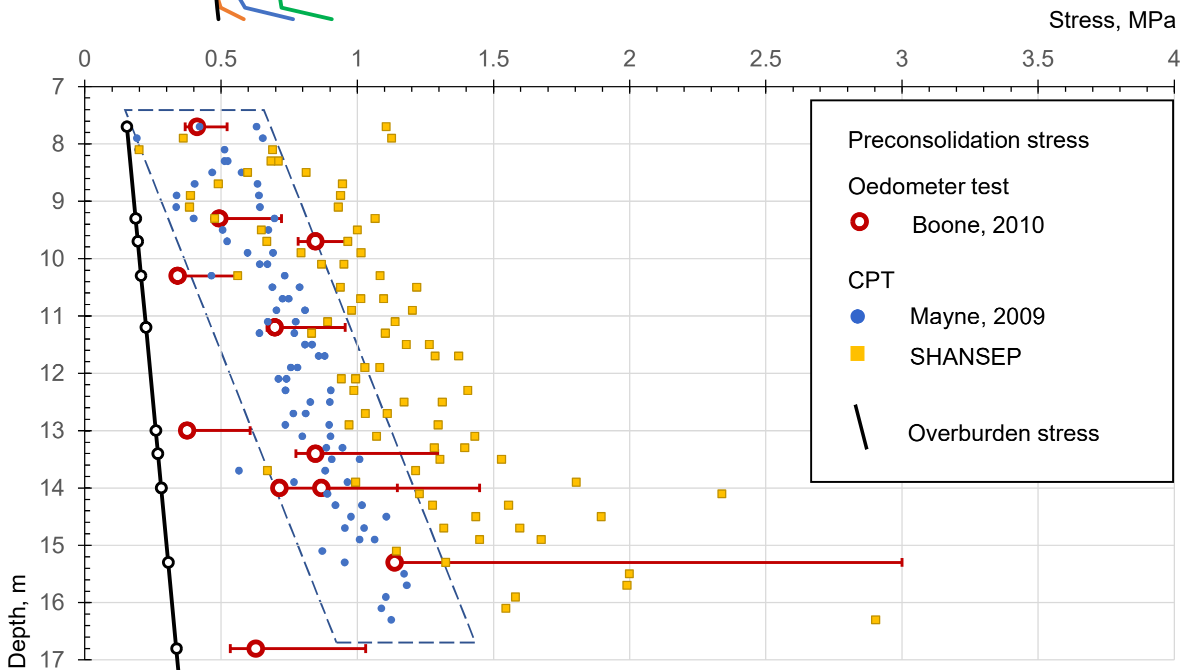

Figure 2. Variation with depth of overburden stress and preconsolidation stress of Jurassic clays, determining by oedometer and CPT tests in Desenovskoe village.

The Mayne method matches the experimental data better than SHANSEP. At the same time, there is an increase in *POP* with a depth of 300 to 900 kPa, while the *OCR* equal 4 remains almost constant. This is probably due to the peculiarity of the interpretation of CPT data.

Figure 3 and 4 shows the change of overburden stress and preconsolidation stress of Jurassic clays in Fadeev street with depth. The data obtained from various empirical formulas and experimental values generally correspond to each other, forming a 500 kPa wide band along the overburden pressure line. The preoverburden stress *POP* ranged from 69 to 372 kPa, average value 250 kPa.

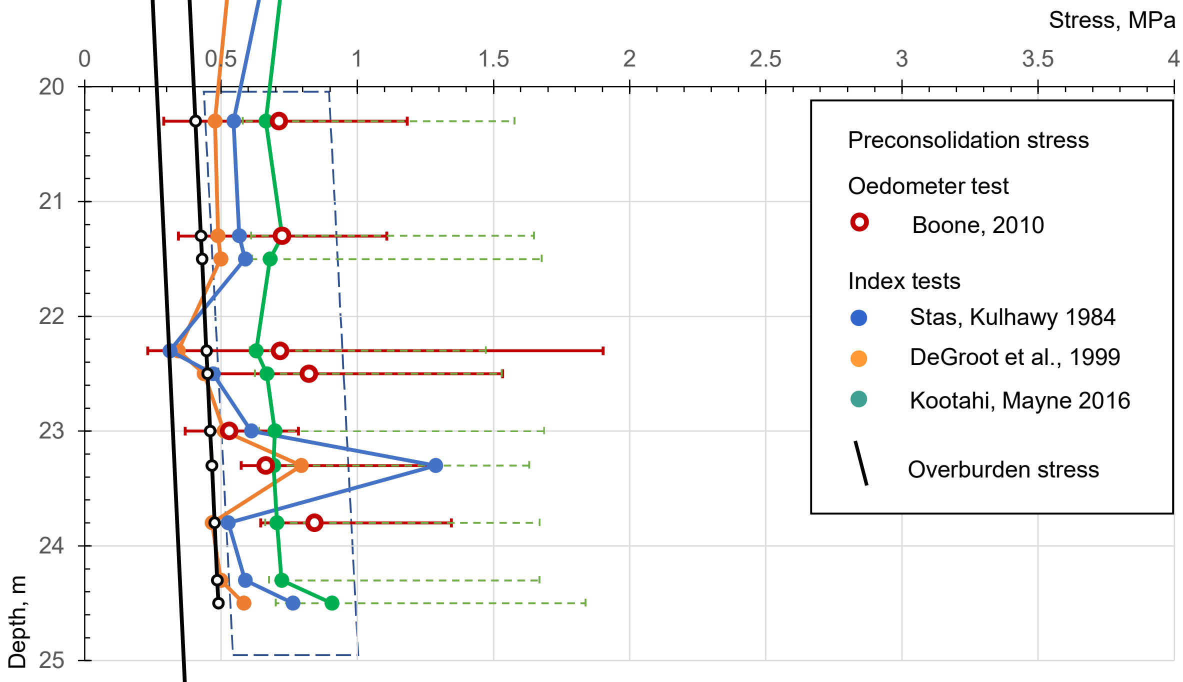

Figure 3. Variation with depth of overburden stress and preconsolidation stress of Jurassic clays, determining by oedometer and index tests in Fadeev street.

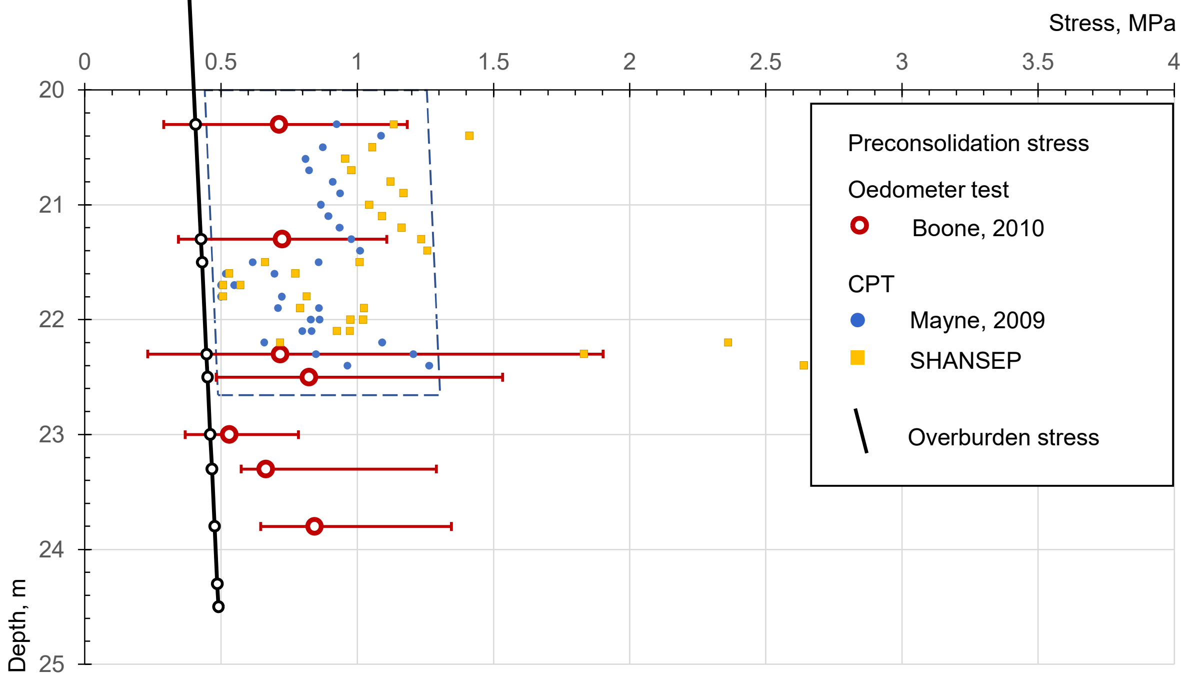

Figure 4. Variation with depth of overburden stress and preconsolidation stress of Jurassic clays, determining by oedometer and CPT tests in Fadeev street.

The CPT data form a wide band, which nevertheless corresponds to the experimental data. Average value of *POP* and *OCR*, obtained by CPT, equal 400 kPa and 1.8.

The *OCR* and *POP* of the samples taken in Desenovsky are higher than those on Fadeev Street. This is probably due to the proximity to the Desna River (less than 0.5 km), and as a result, the greater thickness of the eroded soils. On Fadeev Street, the distance to the nearest Moscow River is at least 3 km, and *OCR* is 1.2-1.9.

4 Conclusion

Overconsolidation ratio *OCR* for Jurassic clays at Desenovskoye ranged from 2.1 to 8.1, which corresponds to overconsolidated and highly overconsolidated soils, and in st. Fadeev from 1.2 to 1.9, that is, normally consolidation soils according to the GOST 25100-2020 classification. The preoverburden stress *POP* ranged from 115 to 831 kPa and from 69 to 372 kPa, respectively. Thus, the data obtained indicate that historical stresses exceeded modern ones and large thickness of the eroded soils is due to the proximity to the river.

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