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Determination of soil deformation moduli after National Building Codes of Russia and Germany

Расчетные модули деформации грунта согласно национальным стандартам России и Германии

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Abstract. The paper analyzes the differences in carrying out compression tests in accordance with the regulatory documents of Russia and Germany and subsequent processing of the obtained data. The paper gives the reasons for significant differences in the values of compression and design deformation moduli obtained from the compression test data in accordance with Russian and German National Building Codes. Approximate differences of the above-mentioned moduli have been revealed for various types of soil. The transition coefficients have been calculated for the compression and design moduli obtained from the compression test data in accordance with Russian and German National Building Codes. The paper describes the applicability of these transition coefficients. The paper presents the research results carried out within the framework of international cooperation of two universities: Industrial University of Tyumen (Russia) and Beuth University of Applied Sciences, Berlin (Germany). The results of the research prove the correctness of the calculated transition coefficients.

Аннотация. Произведен анализ отличий проведения компрессионных испытаний в соответствии с нормативными документами России и Германии и последующей обработки данных. Описаны причины значительных различий получаемых значений компрессионных и расчетных модулей деформации, вычисляемых по данным компрессионных испытаний в соответствии с российскими и немецкими национальными стандартами. Выявлены приблизительные отличия вышеупомянутых модулей для различных видов грунта. На основе этого вычислены переходные коэффициенты для компрессионных и расчетных модулей деформации, полученных по данным компрессионных испытаний согласно российским и немецким национальным стандартам. Описаны условия применения данных коэффициентов. Представлены результаты исследований, проведенных в рамках международного сотрудничества двух университетов: Тюменского индустриального университета (Россия) и университета прикладных наук им. Бойта, Берлин (Германия). Результаты исследований подтверждают корректность применения приведенных переходных коэффициентов.

Introduction

International cooperation in various fields between Russia and Germany is a question of present interest; there is a growing interest in solving common scientific problems and executing joint industrial projects which can be implemented both in Russia and Germany. The lack of uniformity of terms, concepts, their interpretation and compliance with national technical (industrial) standards is a certain obstacle to effective joint scientific work and productive cooperation.

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Unification of the initial data for calculations, consideration of the methods for determining various characteristics and parameters and verification of the results obtained are topical issues in the sphere of construction.

Great attention is being paid to unification of the regulatory documents: National Building Codes are being updated with regard to the requirements of European (EN) and International (ISO) Standards [1–5]; various aspects of misbalance between the foreign and Russian regulatory framework are being studied [4–7], as well as the relevance of the changes introduced to the updated standards [5–8]. But in addition to the adopted International and European regulatory documents, Germany has its own Building Regulations (DIN). Available studies comparing the National Building Codes of the Russian Federation and Germany are not sufficient for possible unification of geotechnical norms.

The study focuses on the principal deformation characteristic of soil – soil deformation modulus, which is the basis for foundation analysis after the second group of ultimate limit states.

E.V. Lega [9] made a general comparative analysis of the obtained values of the main physical and mechanical characteristics of silts in accordance with the Russian and German norms including the deformation modulus. However, there is no clear and detailed description and comparison of methods for determining the deformation moduli obtained. In addition, it should be noted that the studies were carried out between 1991 and 1994 in accordance with regulatory documents irrelevant at the moment. At that time, Germany lacked a document to determine the deformation characteristics of soil in the universal regulatory. Therefore, the verification and the unification of the geotechnical norms of Russia and Germany to determine the deformation modulus cannot be considered as studied and thus, further studies are needed to take the diversity of soil types into account.

At present, a number of different methods can be used to determine the deformation modulus [5–8, 10–19]; here, the resulting values of the deformation modulus for one and the same soil can vary significantly depending on the method of its determination (several times for clay soils), as it is shown in the works of the authors [5–8, 13, 14, 19–24].

When calculating the settlements of buildings and structures, especially in complex soil and groundwater conditions, the question arises of whether the design deformation modulus is chosen correctly. Table 1 presents the methods for determining the deformation modulus and the reference standards of Russia and Germany regulating them.

Table 1. Reference Standards of RF and Germany regulating determination of the deformation modulus

Methods to determine the deformation modulus	GOST	DIN
Oedometer compressibility testing	GOST 12248-2010	DIN 18135
Triaxial deformability testing	GOST 12248-2010	absent
Flat plate load tests	GOST 20276-2012	DIN 18134
Screw plate load tests	GOST 20276-2012	absent
Pressuremeter tests	GOST 20276-2012	DIN EN ISO 22476-4
Dilatometer tests	absent	DIN EN ISO 22476-5
Cone penetration testing	GOST 19912-2012	DIN EN ISO 22476-1
Dynamic testing	GOST 19912-2012	DIN EN ISO 22476-2
Borehole dynamic probing	absent	DIN 4094-2

The existing regulatory documents offer some recommendations for choosing and determining the design deformation modulus, since great varieties of the deformation moduli are obtained depending on the method used.

According to Regulation – SP 22.13330.2016 [25], a plate load test is the priority method for determining the soil deformation modulus in Russia, pressuremeter tests (in case of isotropy of the properties of the tested soils). In order to interpret the data of other methods, correlation dependencies, based on the above mentioned experiments, are used. The applicability of the complex approach to determine the deformation modulus is also confirmed by the research of Russian scientists, e.g. G.G Boldyrev [7]. For structures which fall into the limits of the Geotechnical Category 1, and in some cases 2 (if statistically based data according the regional normative regulations is available), the design deformation modulus can be calculated from the compression test data taking the multiplying transition coefficient from the oedometer modulus to the modulus from plate loading test m_{oed} [25, Table. 5.1] into account; its values are correct for the compression modulus calculated in the pressure range of

0.1–0.2 MPa and they can lie in the range from 1.2 to 3 for silty-clayed soils. According the previous version of the same regulation SP 22.13330.2011 [26] the caclulation of the design deformation modulus is performed in the same pressure range of 0.1–0.2 MPa using the transition coefficient from the compression modulus to the modulus from plate loading test m_k in the range of 2 to 6 [26, Table. 5.1]. At this point it should be noted that the deformation modulus determined using both the transition coefficient m_k and the coefficient m_{oed} has th esame value. For sandy soils, the multiplying coefficient is absent. These transition coefficients are widely used in Russia, but compression tests are compulsory and are often conducted together with cone penetration tests and less often with dynamic tests. The priority methods are rarely used due to their high labour intensity and cost, only by agreement with the client.

The design deformation modulus is also an urgent problem in Germany. There is a lack of any clear recommendations concerning the design deformation modulus in the regulatory document DIN 4019: 2015-05 [27] which regulates the settlement calculation; it can be chosen by a design engineer after comparison of the results of laboratory and in-situ tests and monitoring the settlements of structures, but some recommendations still exist. Thus, in accordance with paragraph 8.4 of the DIN standard [27], in the absence of specific soils and settlement monitoring data, the design deformation modulus E^* may be assumed to be approximately equal to the oedometer modulus E_s determined in accordance with DIN 18135: 2012-04 [28], taking into account the state of the soil formation at a corresponding pressure. It is necessary to consider that in laboratory conditions a sample of cohesionless soil of sufficiently good quality intended for accurate determination of the soil deformation characteristics can be obtained only in exceptional cases; when testing cohesive soil in laboratory conditions, reliability of the deformation modulus depends on the quality of the taken sample, its treatment and the experiments, taking the soil stressed state in the massif into account.

In order to conduct the research, the basic method for determining the deformation modulus in Russia and Germany was considered – compression tests performed in accordance with GOST 12248-2010 [29] and DIN [28].

Research objectives: to identify the principal differences in conducting compression tests and factors affecting the results; possible differences between the compression and design deformation moduli obtained in accordance with Russian and German National Building Codes; search for transition coefficients.

Methods

The principal differences in carrying out compression tests in accordance with GOST [29] and DIN [28] are expressed in the duration of the increment load. To consider unsaturated soil, according to GOST [29], the increment load is maintained until the conditional stabilization of the soil sample deformation occurs. Incremental portion is taken as a criterion of conditional stabilization of deformation, which does not exceed 0.05% for the time indicated in [29, Table. 5.3] and depends on the type of soil. With water-saturated clay, organic or organic-mineral soil, the end of compaction at this increment load is determined as the end of 100% filtration consolidation. In accordance with DIN [28], each portion of increment load must be maintained at the same time interval, at least until the completion of 100 % primary consolidation. In here, these differences do not affect the results, since in both cases the increment load is maintained up to a certain stabilized state of the soil. The done research also proves this [30].

Processing of the experimental data greatly affects the value of the deformation modulus calculated from the compression test data. According to DIN [28], an oedometer deformation modulus is obtained as a result of compression tests. It is evaluated by the formula:

$$E_s = \frac{\Delta\sigma'}{\frac{\Delta s}{h_i}} = \frac{\Delta\sigma'}{\Delta s'}(1 - s'), \tag{1}$$

where $\Delta\sigma'$ – interval of axial stress variation in which the deformation modulus is determined;

Δs – change of *compressive deformation* of the sample in dependence of the variation in axial stress $\Delta\sigma'$;

h_i – height of the sample which agrees with the mean axial stress of the considered interval:

$$h_i = h_0 - s_i = h_0 - h_0 s' = h_0(1 - s'), \tag{2}$$

h_0– initial height of the sample;

s – *compressive deformation* of the sample which refers to the mean axial stress of the considered interval;

s' – *relative compressive deformation* of the sample which refers to the mean axial stress of the considered interval:

$$s' = \frac{s}{h_0}, \tag{3}$$

$\Delta s'$ – change of *relative compressive deformation* of the sample in dependence of the variation in axial stress $\Delta\sigma'$:

$$\Delta s' = \frac{\Delta s}{h_0}, \tag{4}$$

In accordance with the Russian State Standard GOST [29], the oedometer and compression deformation moduli can be obtained from the data of compression tests. The oedometer deformation modulus is evaluated by the formula (5), compression one – by the formula (6):

$$E_{oed} = \frac{\Delta p}{\Delta \varepsilon}, \tag{5}$$

$$E_k = E_{oed}\beta, \tag{6}$$

where Δp – pressure interval at which the deformation modulus is determined;

$\Delta\varepsilon$ – variations in the relative deformation which agree with Δp:

$$\Delta\varepsilon = \frac{\Delta h}{h}, \tag{7}$$

h – initial height of the sample;

β – coefficient that takes the absence of lateral expansion of soil in the compression equipment into account:

$$\beta = 1 - \frac{2\nu^2}{1-\nu}, \tag{4}$$

ν – Poisson's ratio.

In real values of Poisson's ratio within 0.1–0.45 for soils (the smallest value corresponds to coarse soil, the largest one – to clay soil), β takes the values within 0.26–0.98 (the smallest value corresponds to clay soil, the largest one – to coarse soil). In the absence of experimental data in engineering calculations, the value of Poisson's ratio can be taken within 0.27–0.45 depending on the type of soil in accordance with the Russian regulatory document [25, Table. 5.10]; in here, β is of values of 0.26–0.8.

In order to determine the compression modulus, β can be chosen according to [29, paragraph 5.4.6.4] equal to 0.8 for sands, 0.7 – for clayey sands, 0.6 – for silts and 0.4 – for clays.

When comparing formulas (1) and (5), it is obvious that the oedometer modulus E_s of DIN [28] is approximately equal to the oedometer modulus of GOST [29] E_{oed}. This is because the only difference is the factor *(1-s')* in the formula (1), which is close to U, since the relative compressive deformation of the sample – s' is very small. Thus, the coefficient β can be used as a transition coefficient from the oedometer deformation modulus obtained by DIN [28] E_s to the compression modulus obtained by GOST [29] E_k. In here, it is necessary to take into account that the types of soil do not always match together in Russian and German classifications (for example, very soft silt in Russian classification can be weakly low plasticity clay in German classification; this is proved by the studies [31]). However, in most cases β values as transition values are acceptable. Thus, it is possible to calculate the transition coefficients from the compression modulus obtained by GOST [29] E_k to the oedometer deformation modulus obtained by DIN [28] E_s, which can be applied regardless of matching of the soil types in German and Russian classifications: 2.5 for clays; 1.67 for silts, 1.43 for clayey sands and 1.25 for sands.

Based on the assumption that the oedometer deformation moduli obtained by GOST [29] and DIN [28] are equal and taking into account the multiplying coefficient m_{oed} ($m_{oed} = \beta \cdot m_k$), it is possible to determine the approximate transition coefficients from the design deformation modulus taken in accordance with SP [25,26], i.e. $E = m_{oed} \cdot E_{oed}$ or $E = m_k \cdot E_k$, to the design deformation modulus taken in accordance with DIN [27], i.e. $E^* \approx E_s$, (Table 2). The coefficient m_{oed} can be used as the transition coefficient from $E^* \approx E_s$ after DIN [27] to $E = m_{oed} \cdot E_{oed}$ after SP [25] or $E = m_k \cdot E_k$ after SP [26] (Table 3).

Table 2. Transition coefficients from $E = m_{oed} \cdot E_{oed}$ after Building Regulations (SP) [25] to $E^* \approx E_s$ after DIN [27]

Soil type	**Voids ratio, e**					
	0.45–0.55	0.65	0.75	0.85	0.95	1.05
Clayey sands	0.36	0.40	0.48	0.71	-	-
Silts	0.33	0.37	0.42	0.56	0.67	0.83
Clays	-	0.42	0.42	0.45	0.50	0.56

Table 3. Transition coefficients from $E^* \approx E_s$ after DIN [27] to $E = m_{oed} \cdot E_{oed}$ after Building Regulations (SP) [25]

Soil type	**Voids ratio, e**					
	0.45–0.55	0.65	0.75	0.85	0.95	1.05
Silts	3.0	2.7	2.4	1.8	1.5	1.2
Clays	-	2.4	2.4	2.2	2	1.8

The values given in Tables 2 and 3 are determined by interpolation for intermediate values of the void ratio *e*.

To confirm the theoretical prerequisites in the framework of international cooperation of two universities: the Beuth University of Applied Sciences, Berlin (Germany) and the Industrial University of Tyumen (Russia), a number of experiments were carried out on various types of soils. The investigated soils and their basic physical characteristics are presented in Table 4 in accordance with Russian Building Regulation / German Standards. The physical characteristics of the soils have been determined in accordance with the Russian document GOST 5180-2015 [32] and the regulatory framework of Germany: DIN EN ISO 17892-1: 2015-03 [33], DIN EN ISO 17892-2: 2015-03 [34], DIN 18122-1: 1997-07 [35]. Classification of the soil is presented in accordance with GOST 25100-2011 [36] and DIN 18196: 2011-05 [37], DIN EN ISO 14688-1: 2013-12 [38], DIN EN ISO 14688-2: 2013-12 [39].

Table 4. Physical characteristics of tested soils

Soil type	**ρ, g/cm^3**	**ρ_s, g/cm^3**	**ρ_d, g/cm^3**	***n*, %**	***e*, unit fraction**	***W*, %**	**W_P, %**	**W_L, %**	**I_p, unit fraction**	**I_L, unit fraction**
Dense sand of medium size / Even-graded sand of medium size coarse sandy, fine sandy, fine gravelley	1.89	2.67	1.83	0.31	0.46	3	-	-	-	-
Firm silt of undisturbed structure / intermediate plasticity clay firm of undisturbed structure	1.92	2.71	1.48	0.46	0.83	30	22.0	$\frac{34.4}{43.0}$	$\frac{0.12}{0.21}$	$\frac{0.65}{0.38}$
Stiff clay of undisturbed structure / high plasticity clay stiff of undisturbed structure	1.96	2.77	1.50	0.46	0.85	31.1	22.8	$\frac{51.0}{66.7}$	$\frac{0.28}{0.44}$	$\frac{0.29}{0.19}$
Very stiff clay of undisturbed structure / high plasticity clay stiff of undisturbed structure	2.10	2.97	1.63	0.45	0.82	28.9	25.1	$\frac{50.2}{66.4}$	$\frac{0.25}{0.41}$	$\frac{0.15}{0.09}$
Firm silt of disturbed structure / low plasticity clay soft of disturbed structure	2.0	2.71	1.64	0.40	0.65	22.0	15.0	$\frac{28.0}{33.7}$	$\frac{0.13}{0.19}$	$\frac{0.54}{0.37}$

Note to the Table: the values of W_L, I_p, I_L given above the line are obtained after Russian Building Regulations, under the line - after German Standards.

The soil types given below are referred only to the Russian classification in accordance with GOST [36].

In order to obtain statistical data for each type of soil, several compression tests were performed in accordance with the GOST [29] and DIN [28] methods. Sand of medium size, firm silt undisturbed structure and stiff clay of undisturbed structure with medium consistency were tested in the geotechnical laboratory of the Beuth University (Germany) in a mechanical compression device with an internal diameter of the ring of 100 mm and a height of 30 mm, clay with undisturbed structure and very stiff consistency – in the laboratory of the Geotechnical Department of TIU (Russia) in an automated compression device ASIS with an internal diameter of the operating ring of 87 mm and a height of 25 mm. In the laboratory of the TIU samples of the same homogeneous soil (silt of disturbed structure with firm consistency) were also prepared and tested to avoid errors by comparing the results obtained with the GOST [29] and DIN [28] methods, caused by the inherent heterogeneity of a soil from natural deposition.

Results and Discussion

As a result of testing the twin samples, the compression curves almost completely coincided. According to the experiments with the other soils, the compression curves of the same soil type have permissible deviations. The obtained statistical average compression curves of the tested soils are shown in Fig. 1.

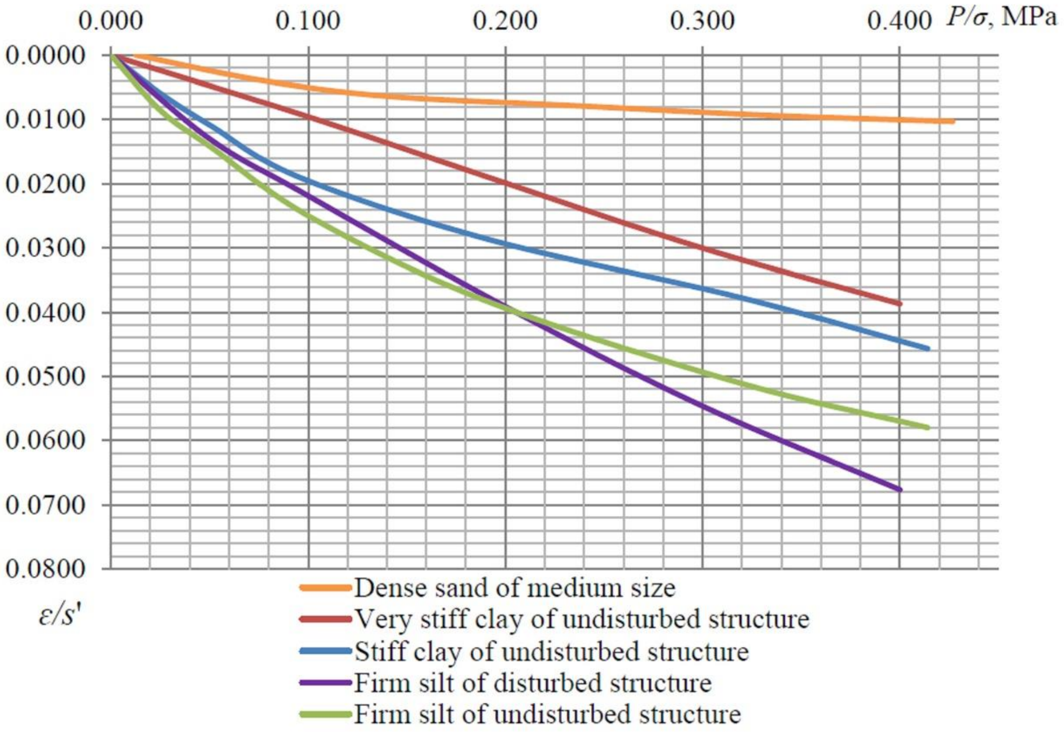

Figure 1. Plot of the relative deformation versus pressure / axial stress after compression tests according to GOST [29] / DIN [28] under primary loading

The tests resulted in determining the deformation moduli in the pressure range of 0.1–0.2 MPa (Table 5).

Table 5. Moduli of deformation of tested soils

Soil type in Russian/ German classification	Oedometer modulus E_{oed}, GOST [29], MPa	Compression modulus E_k, GOST [29], MPa	Oedometer modulus E_s, DIN [28], taken as design modulus E^*, DIN [27], MPa	Differences between E_{oed} and E_s/ E_k and E_s %	Multiplying coefficient m_k/m_{oed}, Building Regulations (SP) [26,25]	Design modulus of deformation $E = m_k \cdot E_k$, $E = m_{oed} \cdot E_{oed}$, Building Regulations (SP) [26,25]	Differences in design moduli of deformation by SP [25,26] and DIN [27], %
Medium sand	50.00	40.00	49.6	0.8 24	-	40.00	-24
Very stiff clay of undisturbed structure	9.67	3.87	9.53	1.5 146	5.65 2.26	21.87	+129
Stiff clay of undisturbed structure	9.88	3.95	9.74	1.4 147	5.5 2.2	21.73	+123
Firm silt of undisturbed structure	6.86	4.12	6.63	3.5 61	3.2 1.92	13.18	+99
Firm silt of disturbed structure	6.14	3.68	5.90	4.1 60	4.5 2.7	16.61	+182

As expected, the differences between the oedometer deformation moduli obtained by DIN [28] and GOST [29] are insignificant (1–4 %) and depend on the value of the deformation modulus itself. If the difference is smaller, the disagreement is greater, since relative settlement *s'* is also of greater importance for a weaker soil.

As expected, the least difference between the compression modulus obtained by GOST [29], oedometer modulus obtained by DIN [28] and design deformation modulus taken by the recommendations of SP [25, 26] and DIN [27] is observed for sand, the greatest – for clays.

Thus, the oedometer deformation modulus of sand determined by DIN [28] exceeds the compression modulus determined by GOST [29] by 24 %, silt – 1.6 times and clay – 2.5 times.

According to the results of sand testing, the design deformation modulus $E^* \approx E_s$ – DIN [27] exceeds the design deformation modulus $E = m_{oed} \cdot E_{oed}$ – [25] or $E = m_k \cdot E_k$ – SP [26] by 24%; for clay soil the design deformation modulus $E^* \approx E_s$ – DIN [27] is much lower than that of $E = m_{oed} \cdot E_{oed}$ – SP [25] or $E = m_k \cdot E_k$ – SP [26], namely: nearly 2.2-2.3 times – for clays, 2 times – for silts of the undisturbed structure and 2.8 times – for silts of the disturbed structure. Such a significant excess of the design deformation modulus in clays $E = m_{oed} \cdot E_{oed}$ – SP [25] or $E = m_k \cdot E_k$ – SP [26] is due to the multiplying coefficient m_k/m_{oed} which depends not only on the soil type, but also on its state.

The results obtained prove the applicability of the transition coefficients presented in Tables 2 and 3, but in transition from the design deformation modulus $E^* \approx E_s$, taken by DIN [27] to the design deformation modulus $E = m_{oed} \cdot E_{oed}$, taken by SP [25], or $E = m_k \cdot E_k$, taken by SP [26], the transition coefficients are relevant only in cases when the soil types match together by GOST [36] and DIN [37–39].

It is necessary to note that the values of the coefficient m_k or m_{oed},obtained by direct tests can significantly differ from those recommended by SP [25, 26], as seen from various studies including [19, 23]. There is a viewpoint that the values of m_k and also of m_{oed}, must be calculated taking into account the regional soil features, e.g. as in [40]. A.V. Pilyagin considers that it is generally incorrect to set the transition coefficients from the compression modulus to the plate one (m_k) due to the difference in the types of stress state of soils during compression and plate load tests [24]. Moreover, there are doubts about the applicability of the compression modulus obtained by GOST [29]. In world practice and in Germany, it is the oedometer deformation modulus that is obtained after the compression test data. In addition, in the current version of the SP [25] the increasing coefficients for the design deformation modulus are presented for the oedometer modulus which is indirectly applied in various geotechnical programs (for example, PLAXIS). The authors agree with G.G. Boldyrev that the oedometer deformation modulus is more accurate, since it is determined in direct measurements regardless of lateral expansion of soil and that it is easier to use it as a reference for finding various correlation dependences [7]. When using the oedometer deformation modulus instead of the compression modulus, it is easier to adapt Russian Building Regulations compared to the foreign regulations.

Conclusions

1. It has been stated that the principal differences in carrying out compression tests in accordance with GOST 12248 and DIN 18135 are expressed in the duration of the increment load, which do not affect the results of the experiments. In turn, processing of the experimental data significantly influences the value of the deformation modulus resulting from the compression tests. This is due to the presence of the coefficient β in the formula for the compression modulus E_k (GOST). The coefficient considers the absence of lateral deformations of the soil in the compression equipment, which underestimates the value of the compression modulus as compared to the oedometer deformation modulus E_s (DIN).

2. The oedometer modulus E_s (DIN) is approximately equal to the one E_{oed} (GOST). The difference lies in the presence of the factor *(1-s')* in the formula for determining E_s, which is close to U, since the relative compressive deformation of the sample – *s'* is very small. Therefore, the deviations depend on soil deformability, i.e. weaker soil will have a higher value of *s'* in comparison to harder soil. The difference between the values of oedometer moduli obtained by DIN and GOST will be greater in weak soil testing. The test results showed small deviations – from 1 to 4%.

3. The compression tests have resulted in the values of the oedometer deformation modulus E_s (DIN), compression modulus $E_к$ (GOST) and design deformation modulus $E = m_k \cdot E_к = m_{oed} \cdot E_{oed}$ (SP 22.13330) and $E^* \approx E_s$ (DIN 4019) which significantly differ depending upon the soil type. The smallest difference is characteristic for sands, the largest one – for clays. The following dependencies have been revealed: $E^{(SP)} > E^{*(DIN)} \approx E_s \approx E_{oed} > E_k$ – silty-clayey soils, $E^{(SP)} = E_k < E^{*(DIN)} \approx E_s \approx E_{oed}$. – for sands.

4. Based on the assumption that the oedometer deformation moduli E_{eod} (GOST) and E_s (DIN) are equal and taking into account the available dependencies of oedometer E_{eod} and compression E_k moduli (coefficient β), compression E_k and design E deformation moduli (coefficient m_k), oedometer E_{oed} and the calculated E deformation moduli (coefficient m_{oed}), the approximate transition coefficients have been determined from the design deformation modulus taken in accordance with SP $E = m_k \cdot E_к = m_{oed} \cdot E_{oed}$, to the design deformation modulus taken in accordance with DIN $E^* \approx E_s$ and vice versa, and from the compression modulus E_k (GOST) to the oedometer deformation modulus E_s (DIN) and vice versa.

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