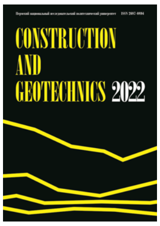
Тер-Мартиросян, А.З. Штамповые испытания. Перспективы развития / А.З. Тер-Мартиросян, К.А. Филиппов // Construction and Geotechnics. – 2024. – Т. 15, № 1. – С. 61–82. DOI: 10.15593/2224-9826/2024.1.05

Ter-Martirosjan A.Z., Filippov K.A. Plate load test. Prospects for development. *Construction and Geotechnics.* 2024. Vol. 15. No. 1. Pp. 61-82. DOI: 10.15593/2224-9826/2024.1.05

пермский
политех

CONSTRUCTION AND GEOTECHNICS
Т. 15, № 1, 2024
http://vestnik.pstu.ru/arhit/about/inf/



DOI: 10.15593/2224-9826/2024.1.05
УДК 624.131.524.3: 624.131.526: 624.131.383

PLATE LOAD TEST. PROSPECTS FOR DEVELOPMENT

A.Z. Ter-Martirosjan, K.A. Filippov

Moscow State University of Civil Engineering (National Research University),
Moscow, Russian Federation

ARTICLE INFO

Received: 01 December 2023
Approved: 22 January 2024
Accepted for publication:
05 February 2024

Keywords:
soil mechanics, field tests of soils, plate load test, deformation characteristics, strength characteristics, scale effect.

ABSTRACT

Plate load testing occupies an important place in the cycle of engineering surveys for construction. This is caused by the fact that they most closely reflect the operation of shallow foundations under natural or artificially transformed soil conditions. In addition to working in the field of conditionally linear deformations the plot of settlement versus load obtained in the course of plate tests can characterize the plastic, strength and rheological properties of the base. However, in modern Russian practice, their results are mainly used exclusively to obtain the deformation modulus. The purpose of this work is to search the prospects for the development of the Russian practice of plate load testing. The world regulatory framework for conducting plate tests and applying their results as well as comparison of various standards has been examined in this paper. Also it is emphasized the main differences and outlined the development prospects for Russian practice: the use of direct design methods, the determination of strength parameters of soils, the determination of undrained strength, the determination of the bed coefficient. The authors of the paper also consider a number of tasks which need to be solved for the implementation of the outlined prospects, as well as the ways of their solution. The main tasks, according to the analysis, are closely connected with considering the large-scale effect in the transition from the parameters obtained during plate tests to the parameters used in the calculation of foundations. In order to take into account the scale effect in determining the strength parameters it is promising to use the method based on the influence of average stresses on the value of the internal friction angle and in determining the deformation parameters – the method of Y.K. Zaretsky, used in the practice of hydraulic engineering.

© **Armen Z. Ter-Martirosyan** – Doctor of Technical Sciences, Professor, e-mail: mgroif@mail.ru.
Kiril A. Filippov – Postgraduate Student, e-mail: 4155599@gmail.com.

Тер-Мартиросян Армен Завенович – доктор технических наук, профессор, e-mail: mgroif@mail.ru.
Филиппов Кирилл Александрович – аспирант, e-mail: 4155599@gmail.com.

ШТАМПОВЫЕ ИСПЫТАНИЯ. ПЕРСПЕКТИВЫ РАЗВИТИЯ

А.З. Тер-Мартиросян, К.А. Филиппов

Национальный исследовательский Московский государственный строительный университет,
Москва, Российская Федерация

О СТАТЬЕ

Получена: 01 декабря 2023
Одобрена: 22 января 2024
Принята к публикации:
05 февраля 2024

Ключевые слова:

механика грунтов, полевые испытания грунтов, штамповые испытания, деформационные характеристики, прочностные характеристики, масштабный эффект.

АННОТАЦИЯ

Штамповые испытания занимают важное место в цикле инженерных изысканий для строительства. Это обусловлено тем, что они в наибольшей степени отражают работу фундаментов мелкого заложения при естественных или искусственно преобразованных грунтовых условиях. Получаемый в ходе штамповых испытаний график зависимости осадки от нагрузки, помимо работы в области условно линейных деформаций, может характеризовать пластические, прочностные и реологические свойства основания. Однако в современной российской практике их результаты преимущественно используются исключительно для получения модуля деформации. Целью настоящей работы является поиск перспектив развития российской практики штамповых испытаний. В работе рассматривается мировая нормативная база по проведению штамповых испытаний и применению их результатов, проводится сопоставление различных стандартов, подчеркиваются основные различия, обозначаются перспективы развития для российской практики: применение прямых методов проектирования, определение прочностных параметров грунтов, определение недренированной прочности, определение коэффициента постели. Также в работе рассматривается ряд задач, требующих решения для реализации обозначенных перспектив, а также пути их решения. Основные задачи, согласно проведенному анализу, связаны с учетом масштабного эффекта при переходе от параметров, полученных при проведении штамповых испытаний, к параметрам, используемым в расчете фундаментов. Для учета масштабного эффекта при определении прочностных параметров перспективным является применение методики, основанной на влиянии средних напряжений на величину угла внутреннего трения, а при определении деформационных – методики Ю.К. Зарецкого, используемой в практике гидротехнического строительства.

Introduction

In the Russian Federation testing of soils with a flat plate – vertical static load (hereinafter referred to as plate load test) occupies an important place in the cycle of engineering surveys for construction and, in accordance with SR 446.1325800.2019, is one of the main methods for obtaining deformation characteristics of soils. The results of plate load test are used, among other things, to obtain correction factors for the deformation modulus obtained from the results of laboratory tests of samples in a compressive stress device.

Such attitude towards plate load tests is due to the fact that they most closely reflect the operation of shallow foundations under natural or artificially transformed soil conditions. One of the test results is a graph of the dependence of settlement on load, the shape and theoretical division into phases of which are known from the works of N.M. Gersevanov [1] (Fig. 1). However, in modern testing practice in accordance with GOST 20276.1-2020 for non-subsiding soils the information obtained as a result of the test is reduced to generating deformation characteristics – deformation modules along the primary and secondary loading branches, describing the operation of the base in the linear deformation phase and in a small part of the shear deformation phase.

Thus, information about the base operation in the most part of the shear deformation phase and during the failure phase is not used. The ability to obtain information on the long-term strength and rheological properties of the tested soil is not used either. As will be shown later, this can be explained by the fact that the task of determining strength parameters from the plate load tests is associated with a number of difficulties caused by economies of scale. The purpose of this work is to determine the prospects for research related to the development of plate load test of soils. The objectives of the work include: the study of Russian and world regulatory documents governing the realization of plate load tests; analysis of research works devoted to plate load tests, obtaining strength characteristics of soils based on their results and manifestation of economies of scale; identification of the prospects for future research.

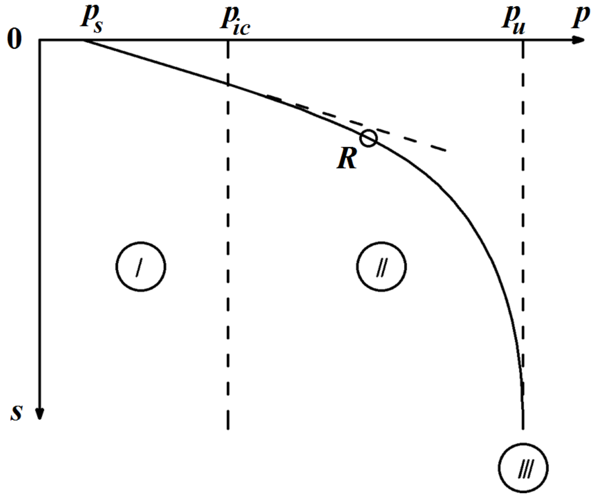


Fig. 1. Diagram of the settlement dependence of foundation on the dispersed base on the load:
I – compaction phase, *II* – phase of shear deformation development, *III* – fracture phase,
p – pressure, s – settlement, p_s – structural strength, p_{ic} – initial critical load,
p_u – ultimate critical load, R – design resistance

Рис. 1. График зависимости осадки фундамента на дисперсном основании от нагрузки:
I – фаза уплотнения, *II* – фаза развития сдвиговых деформаций, *III* – фаза разрушения,
p – давление, s – осадка, p_s – структурная прочность, p_{ic} – начальная критическая нагрузка,
p_u – предельная критическая нагрузка, R – расчетное сопротивление

Regulatory framework. Documents of the Russian Federation

In the Russian Federation plat load tests are carried out in accordance with the (State Standard) GOST 20276.1-2020, being the first separate document dedicated exclusively to this type of testing. Previously plate load tests were regulated by a number of versions of the general document on methods for field determination of strength and deformability characteristics (GOST 20276-2012, GOST 20276-99, GOST 20276-85). At the same time, the requirements set forth in GOST 20276.1-2020 differ little from the corresponding sections of GOST 20276-85; the most significant change has been the method of determining the deformation modulus by the reloading branch. Other additions are related to new capabilities of digital devices for sediment measurement, expansion of classification of organomineral soils, etc.

Let us briefly outline the essence of the regulated methodology and its features. Plat load tests (Fig. 2, *a*) can be carried out in shallow mine workings (clearings, pits, pits with a minimum plan size of 1.5 × 1.5 m) or in boreholes with a diameter of 325 mm. In the process of conducting tests in wells, in order to preserve the structure and SSS of the soil, drilling methods are regulated (starting from the mark 1 m above the test site it is allowed only rotational drilling); the fall of the groundwater level in the well is not admitted. The minimum thickness of the homogeneous layer of the tested soil should be at least two diameters of the plate. Plates with an area of 5000, 2500, 1000 cm^2 are used for testing in a pit, hole or pipe, and 600 cm^2 – in the well bottom.

The tests are carried out by applying pressure in stages in the range of 0.01–0.1 MPa, depending on the type of soil (classification indicators). The load is maintained to the point of conditional stabilization of the settlement, the criterion of which is the settlement rate of less than 0.1 mm in a given time (also depends on the type of soil and varies from 0.5 hours to 4 hours). Settlement is measured with an error of no more than 0.1 mm, the load is measured with an error of no more than 5 % of the pressure stage. Maximum pressure on the plate p_n should be defined taking into account the expected pressure at the base of the foundation. In order to determine the deformation modulus along the reloading branch, soil can be unloaded and then reloaded.

Processing of the results consists in plotting (Fig. 2, *b*) the dependence of the plate settlement on pressure and calculating the modulus of deformation in the pressure range from p_0 (initial pressure – from the self-weight of the soil) to $p_п$. The deformation modulus is found by Schleicher's supplemented formula:

$$E = \left(1 - v^2\right) K_1 K_p D \frac{\Delta p}{\Delta s}, \tag{1}$$

where v – poisson's ratio; K_1 – shape coefficient (equal to 0.79 for a round rigid plate); K_p – coefficient which takes into account the depth of the plate and is accepted according to the GOST 20276.1-2020 table; D – plate diameter; Δp – pressure increment; Δs – settlement increment.

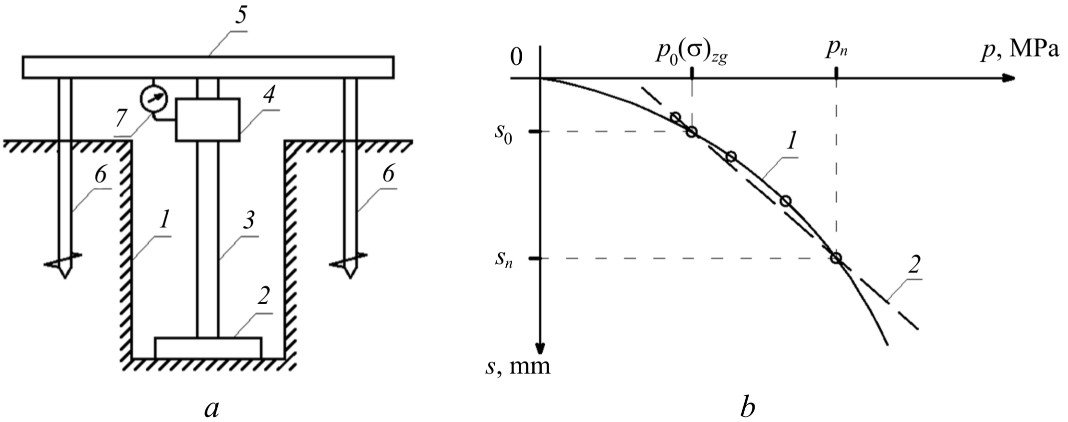


Fig. 2. Plate load tests: *a* – field test scheme [2]: *1* – pit, *2* – plate, *3* – rack, *4* – jack, *5* – thrust beam, *6* – anchor piles, *7* – deformation meter; *b* – field test results: *1* – "settlement-load" experimental curve; *2* – linear approximation

Рис. 2. Штамповые испытания: *а* – схема полевых испытаний [2]: *1* – шурф, *2* – штамп, *3* – стойка, *4* – домкрат, *5* –упорная балка, *6* – анкерные сваи, 7 – измеритель деформаций; *b* – результаты полевых испытаний: *1* – экспериментальная кривая «осадка – нагрузка»; *2* – линейная аппроксимация

The modulus obtained is used for calculation of settlement according to SR 22.13330.2016.

At present data on deformation of the test soil in time during plate load testing are not used to obtain parameters of primary and secondary consolidation. To determine them, the regulatory procedure provides for compression tests (GOST 12248.4-2020 – appendix B). For further calculation of structures with regard to creep the regulatory procedure is described in «Rules and regulations in the nuclear power industryPiNAE-5.10-87 “Foundations of reactor compartments of nuclear power plants”» (1989).

It should be noted that the above mentioned recommendation for determining the maximum test pressure during plate load testing leads to the fact that the absolute majority of tests are carried out at a very insignificant level of plastic deformations and at pressure far from the critical limit. It makes possible to use more economical designs of anchor systems, but practically eliminates the use of the obtained data for analyzing the bearing capacity of the base.

All these facts cause difficulties in conducting research related to the expansion of the plate load testing capabilities using the data available to survey organizations.

Further let’s turn to the foreign practice of plate load testing.

Regulatory framework. Foreign documents

U.S. Documents

In the USA project practice is regulated by documents in force in a particular state, which, as a rule, are created on the basis of common standards [3]. At the same time, geotechnical practice is much less “codified” than, for example, the design of reinforced concrete structures.

The most commonly used are 2 general design standards, which include geotechnical sections: AASHTO (American Association of State Highway and Transportation Officials) LRFD (load-and-resistance factor design) Bridge Design Specifications – standard governing the design of bridges and IBC (International Building Code) – a common standard which ensures the safety of buildings and structures. Recommendations for the design of foundations are also contained in the standard for the design of reinforced concrete structures (ACI 318).

Neither IBC nor ACI 318 contain descriptions of specific methods for calculating settlement and load-bearing capacity which leaves the designer the right to choose the methods independently. AASHTO to a greater extent regulates the methods of geotechnical design. It provides specific instructions for the design of foundations for “Strength Limit States” (analogue of the first limit state), including load-bearing capacity and “Service Limit States” (analogue of the second limit state), including settlement.

In the section AASHTO, devoted to the load-bearing capacity, resistance coefficients are given (“Resistance Factor”) (are analogues of safety coefficients and show what fraction of the resistance calculated according to a particular method should be taken into account in limit state tests), including load-bearing capacity based on the results of plate load test (PLT).

As can be seen from the table, the load-bearing capacity of PLT results is considered to be more accurate than other methods that include theoretical (using the theory of ultimate equilibrium).

The document contains clarifications that when using the bearing capacity determined by the plate, the following factors should be taken into account:

– discrepancy between the consolidation processes for the plate and the real foundation due to the different depth of the compressible layer;

– the influence of the scale effect on the calculations for two groups of limit states, including those requiring consideration of the stratification of the base, the thickness of the layers, the inhomogeneity of soil properties within the compressible strata, etc.

– the possibility of applying the test results exclusively within the survey site (in similar engineering and geological conditions, in soils of the same genesis with similar characteristics).

Resistance coefficients according to AASHTO LRFD Bridge Design Specifications

Коэффициенты сопротивления по AASHTO LRFD Bridge Design Specifications

Method/soil/conditions		Resistance coefficients
Ultimate Pressure	Theoretical method, clay	0.50
	Theoretical method, sand, characteristics by the CPT results (static probing)	0.50
	Theoretical method, sand, characteristics by the SPT results (Dynamic Hollow Probe Sensing)	0.45
	The semi-empirical method (Meyerhoff, 1957), all soils' types soilsoilsвсе виды грунтов	0.45
	Rock	0.45
	Plate load tests	0.55

Tests for determining the load-bearing capacity are regulated by the standard ASTM D1194-94 – "Standard test method for bearing capacity of soil for static load and spread footings". It should be mentioned that in 2003 ASTM D1194-94 was recalled by the American Society for Testing Materials. This may indicate both the imperfection of the document and the imperfection of the methodology for determining the carrying capacity from PLT results in American practice as a whole. In favor of the latter, it says that a new version of the standard has not been prepared for 20 years. Also, ASTM documents do not contain standards for determining the deformation modulus based on the results of plate load tests. Let's consider the peculiarities of ASTM D1194-94:

- the jack used to load the plate is selected for the specific ground conditions, but it must provide a load of at least 50 tf;
- at least one measuring instrument shall record the load value with an error of not more than 2 % of the applied load increment; the settlement shall be measured with an accuracy of at least 0.01 inch (0.25 mm);
- three round steel support plates of at least 1 inch (25 mm) thickness having different diameters ranging from 12 to 30 inches (305 to 762 mm) are used in the tests;
- tests are carried out at the level of the assumed foundation base (under the same soil conditions), while the tested soil should have a thickness of at least 2 plate diameters (similar to the requirement of GOST 20276.1-2020);
- plates must have such relative burial depth (ratio of laying depth to diameter) as the foundation being designed, otherwise processing of results using the theory of limit equilibrium is required;
- at least three bore holes are required during the tests; the distance between them must be at least five diameters of the largest plate;
- load is applied in stages of not more than 1.0 t/ft2 (95 kPa) or not more than one tenth of the specified bearing capacity (hence we can understand that before the tests it must be known the parameters of the tested soil, according to which a preliminary assessment of the bearing capacity was carried out);
- each load stage should be withheld for at least 15 minutes. The load should be withheld until the settlement stabilizes or until its constant speed is established (stabilization criteria are not given in the standard). The holding time should be taken equal for each stage of each test (in case of an increase in the holding time, further intervals of not less than the duration should be taken);
- test of each plate is continued until the peak value of the load or until a constant minimum is reached by the ratio of the load increment to the settlement increment. If possible, the

test shall be continued until a settlement of 10 % of the plate diameter is reached or until the destructive load is reached;

– after the completion of the test the load is removed in three approximately equal steps, continuing to record the results.

The document regulates another variant of the test: the load is applied to the soil in steps corresponding to the specified settlement with a step of approximately 0.5 % of the plate diameter. After each settlement step is applied, the load is measured at the selected time interval (30 s, 1 min, 2 min, 4 min, 8 min, 15 min) until the load change stops or the load-logarithm time plot becomes linear.

It should be noted that ASTM D1194-94 does not contain specific requirements for the selection of a load-bearing capacity value.

In American practice, ASTM D1195-93 and ASTM D1196-93 standards are also applied for plate load testing of pavement soils and pavement materials. ASTM D1195-93 regulates the same repetitive load test to determine the strength of pavement structure, and ASTM D1196-93 regulates step load tests to determine the strength of the pavement structure and the stiffness of the underlying layer. In this review, these documents are discussed in detail.

As it was mentioned above, the main regulatory documents do not contain specific methods for calculating settlement. This makes possible to consider the application of the results of plate load tests for determination of the foundation settlement according to the method described in the fundamental work of K. Terzaga and R. Peck [4]. In the last (third) edition of this work the settlement of the designed foundation, depending on the settlement of the plate with a diameter of 1 foot, is determined by the formula:

$$S = S_1\left(\frac{2B}{B+1}\right), \tag{2}$$

where S_1 – settlement of the plate, foot; B – foundation geometry (diameter or width), foot.

The third edition of the paper contains a reference to the conclusion of Bjerum and Egstad about the unreliability of the formula [5].

Another way to use PLT results is to obtain undrained shear resistance s_u according to the given in the paper [4] the well-known formula for the load-bearing capacity of the foundation on the base with a zero angle of internal friction q_d:

$$q_d = (2+\pi)s_u = 5{,}14s_u \tag{3}$$

Documents of the European Union

EN 1997-1: Eurocode 7 – the first part of the main geotechnical document of the European Union contains general requirements for geotechnical design and requirements for the design of shallow foundations (“Spread foundations”). Here the design principles are established, for the simplified understanding of which it is possible to draw an analogy with limit states from the Russian practice. “Ultimate limit states” (Absolute Limit States) – is the analogue of the first limit state, “Service-ability limit states” (Usability Conditions) – is the analogue of the second limit state. In this case the choice of the method of calculating the settlement and permissible values is left to the discretion of the designer or the national rule-making body [6].

As an example for determining the load-bearing capacity using the semi-empirical method, the first part of the document provides a calculation based on the results of pressiometric tests.

The second part of the document (EN 1997-2: Eurocode 7) provides the guidance on engineering surveys, in particular plate load tests. The relevant section contains the following applications of the test results:

1) Using the obtained geotechnical parameters in indirect design methods. Judging by the document items and the examples given in the appendices, it is generally accepted to use the results in determining the undrained shear resistance, deformation modulus and bed coefficient.

2) Use of test results in direct design methods when one of the conditions is met:

– the size of the plate was chosen taking into account the size of the designed foundation (author’s note: apparently, it means that the dimensions of the plate and foundation are equal), in this case, no other geotechnical parameters are required during the design;

– under the base of the plate there is a homogeneous layer with a thickness of more than 2 plate diameters; the results obtained for the plate are transformed taking into account the difference in the size of the plate and the designed foundation.

For undrained shear resistance c_u it is given the formula:

$$c_u = \frac{p_u - \gamma z}{N_c}, \tag{4}$$

where p_u – bearing capacity according to PLT results, $p_u - \gamma z$ – full stresses for the case when the test is carried out in a well with a diameter of less than 3 plate diameters; N_c – bearing capacity factor for round plate ($N_c = 6$ – for pit test, $N_c = 9$ – for testing in a well with a depth of more than 4 plate diameters).

The Schleicher formula is used to determine the modulus of deformation, as well as in Russian norms. The difference lies in the choice of the burial impact factor C_z : graphs are provided for it and they take into account the dependence of the coefficient on the relative depth and the Poisson’s ratio (Fig. 3).

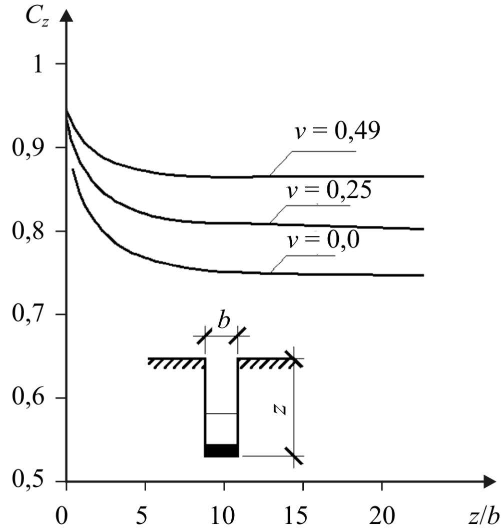


Fig. 3. Depth impact factor graphs C_z (EN 1997-2: Eurocode 7)

Рис. 3. Графики коэффициента влияния заглубления C_z (EN 1997-2: Eurocode 7)

To calculate the bed factor, the formula is given:

$$k_s = \frac{\Delta p}{\Delta s}, \qquad (5)$$

where Δp – selected pressure range, Δs – increment of settlement when pressure is applied Δp.

The recalculation of parameters for the case of the direct design method is regulated for unconnected soils – the value of foundation settlement should be taken according to the schedules depending on the plate settlement (Fig. 4).

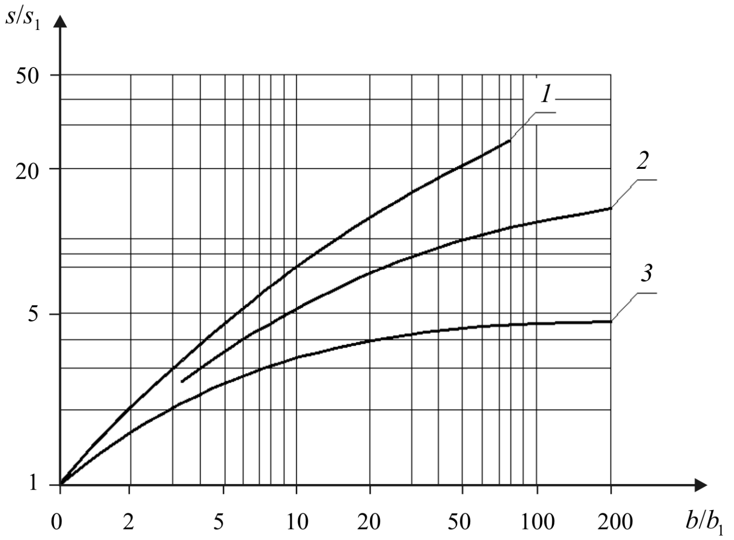


Fig. 4. Graphs for stamp settlement recalculation S_1 into the foundation settlement S depending on plate size ratio b_1 and the size of the foundation b (EN 1997-2: Eurocode 7):
1 – loose sand, *2* – medium-density sand, *3* – dense sand

Рис. 4. Графики для пересчета осадки штампа S_1 в осадку фундамента S в зависимости от соотношения размера штампа b_1 и размера фундамента b (EN 1997-2: Eurocode 7):
1 – рыхлый песок, *2* – песок средней плотности, *3* – плотный песок

The document establishing the requirements for testing is EN ISO 22476-13. Also there are some national standards, such as BS-1377 part9-90 and DIN18134-2012.

DIN18134-2012 contains instructions for conducting tests to obtain deformation modulus and bed coefficient. The regulated test procedure does not imply a guaranteed production of bearing capacity parameters: for a plate with a diameter of 300 mm it is recommended to carry out the test either to a maximum test pressure of 0.5 MPa or to a settlement of 5 mm, for a plate with a diameter of 600 mm – 0.25 MPa or 8 mm, for a plate with a diameter of 762 mm – 0.2 MPa or 13 mm.

BS-1377 prescribes to perform the test until the settlement reaches at least 15 % of the plate diameter, which in turn is more likely to bring the plate base to the limit state.

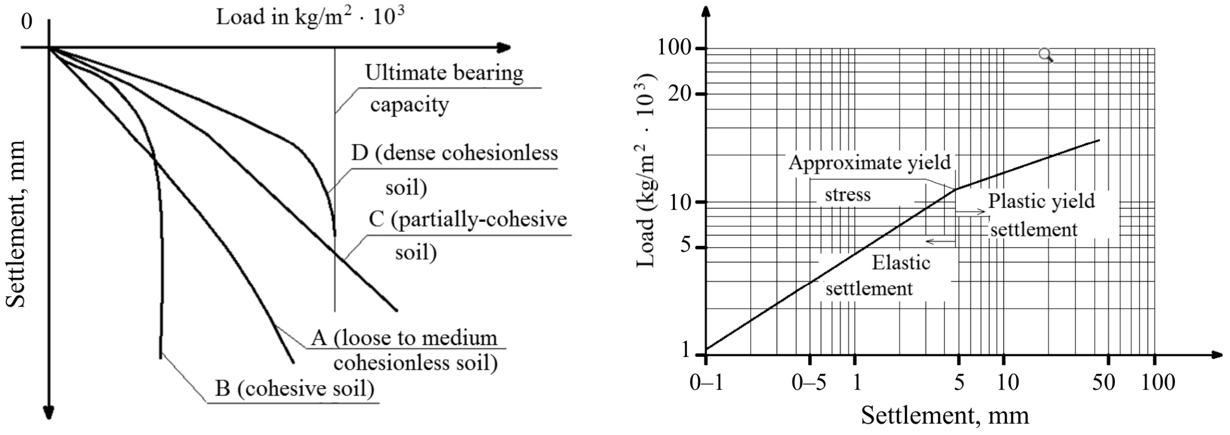
Documents of India

The consideration of the Indian standard IS 1888 is of interest. In the process of designing a foundation on a homogeneous soil base it allows you to determine the bearing capacity, settlement and bed factor.

One of the points of the standard is devoted to the “scale effect”, it states that for clay soils the ultimate critical pressure differs slightly for the plate and the large foundation, while for sandy soil it increases with the size of the load area. Thus, the standard takes into account only the influence of the size of the foundation, which directly follows from the theory of ultimate equilibrium (Fig. 5, *a*).

In testing, it is used plates of 300–750 mm size, with thickness of not less than 25 mm. For tests of sandy soil tests are carried out with three plates of different diameter, and for clay ones – with one plate 450 mm. Accuracy of settlement registration is 0.01 mm. The load is applied in increments of 10 tf/m^2 or 1/6 of the expected carrying capacity.

In the case of clay soils, a "settling time" curve should be plotted for each load step, each subsequent load step should be applied only when the curve shows that the settlement has exceeded 70 to 80 % of the probable stabilized settlement at that stage (the document does not provide guidance on how to determine it) or at the end of the 24-hour period. For non-cohesive soils, each load increment should be maintained for at least one hour or until the subsidence rate decreases (to a value of 0.02 mm/min).



a *b*

Fig. 5. Tests according to IS 1888 standard: *a* – graph forms for different soil conditions;
b – method of graphical determination of bearing capacity according to the "settlement – load" graph on a logarithmic scale
Рис. 5. Испытания по стандарту IS 1888: *a* – формы графиков для различных грунтовых условий;
b – способ графического определения несущей способности по графику «осадка – нагрузка» в логарифмическом масштабе

The test shall continue until the settlement is 25 mm under normal conditions or 50 mm under "special" ground conditions such as dense gravel soil or until breakage, whichever comes first. Alternatively, if the settlement does not reach 25 mm, the test should be continued to a pressure at least twice the design pressure (author's note: this probably refers to the pressure under the base of the designed foundation). If necessary, the data of the unloading test shall be recorded. It is emphasized that the "settlement-load" curves are constructed on the arithmetic scale.

The standard provides typical forms of graphs for different soil conditions and it is noted that the load-bearing capacity in cases *B*, *D* is not difficult, and for cases *A*, *C* the graph should be reconstructed on a logarithmic scale, and then the breaking point on the graph should be taken as the load-bearing capacity (Fig. 5, *b*).

In this case, the permissible pressure under the foundation base ("Safe bearing pressure") is determined depending on the permissible settlement. Settlement of the designed foundation S_t is determined by the formula:

$$S_t = S_p\left[\frac{B\left(B_p+0,3\right)}{B_p\left(B+0,3\right)}\right], \tag{6}$$

where S_p – plate settlement, m; B – size of foundation, m; B_p – size of plate, m.

This formula is a variant of the previously indicated formula from the work of K. Terzagi and R. Peck, which allows to extend to her the conclusions of Bjerum and Egstad, indicated above.

Documents of China

China standards do not differ from the American ASTM standard in terms of requirements for the number of test points, prospect hole sizes, load application systems and movement registration. There are differences in plate sizes, settlement stabilization criteria and test completion criteria [7]:

– For weak clay soils, according to Chinese standards, the diameter should be at least 80 cm, there is no such requirement in ASTM, which allows using a minimum plate diameter (30 cm) for them.

– Chinese regulations provide stabilization criteria for each load application step (if the settlement does not exceed 0.1 mm/h for 2 hours, it is considered to have stabilized); ASTM specifies only the interval between load stages.

– The Chinese Code specifies the criteria for the completion of the test, one of the conditions should be met:

1. The soil around the plate shows obvious lateral extrusion, the load in the system gradually decreases.
2. The settlement at this load level is 5 times more than the settlement at the previous load level, and the load-settlement curve shows an obvious steep decline.
3. After the next stage of load settlement is not stabilized within 24 hours. Total settlement is more or equal to 6 % of width or diameter of low-depth plate, or total settlement exceeds or equals 150 mm; the ratio of the total settlement to the diameter of the plate in the process of testing for the load of the buried plate exceeds or equals 0.04.
4. The maximum test load has been reached (twice as much as designed)

Chinese standards regulate the methods for determining the deformation modulus and bed coefficient based on test results.

Results of regulatory documents review

The review showed that the regulatory frameworks of the countries selected for consideration contain some methods that allow the use of the results of plate load tests for the design of foundations, taking into account the strength parameters of the foundation. It should be noted, however, that although the methodologies mention the need to account for large-scale effects the standards under consideration do not provide specific practical guidance for such accounting, other than the recommendation to “use the ultimate equilibrium theory”. However, it is known from practice and studies conducted to date that the impact of the scale effect is not only related to the results which directly follow from the known solutions of the ultimate equilibrium theory. The influence of the scale effect on the settlement is also not limited to the positions obtained in the analysis of the solutions of the elasticity theory.

Next, it will be considered the studies devoted to the influence of the scale effect on the fracture and deformation of plates and foundations of various sizes.

Strength parameters. Factors influencing load-bearing capacity

The theoretical foundations for calculations allowing to obtain the effect of the loading area on the bearing capacity coefficients were laid down in the work on the theory of marginal soil equilibrium, taking into account the nonlinearity of the shear graph (envelope of Mor circles) at significant stresses, in particular, in the work of V.V. Sokolovsky [8].

One of the first works in which, on the basis of experimental studies, the influence of the loading area on the bearing capacity coefficients was recorded was the work of De Beer in 1965 [9]. His research showed that the bearing capacity coefficients N_γ from Terzaghi's formula (7), calculated according to various methods by recalculating from the actually obtained bearing capacity (critical load on the soil) Q_d decrease as the size of the foundation increases (Fig. 6).

$$Q_d = Q_c + Q_q + Q_\gamma = 2B\left(cN_c + \gamma D_f N_q + \gamma B N_\gamma\right), \tag{7}$$

where Q_c – critical load on weightless soil without surcharging, Q_q – critical load on weightless soil without adhesion, but with surcharging, Q_γ – critical load on soil with non-zero specific gravity without surcharging and adhesion, B – half-width of foundation, D_f – foundation embedment, γ – specific gravity of base soil, N_c, N_q, N_γ – dimensionless bearing capacity coefficients.

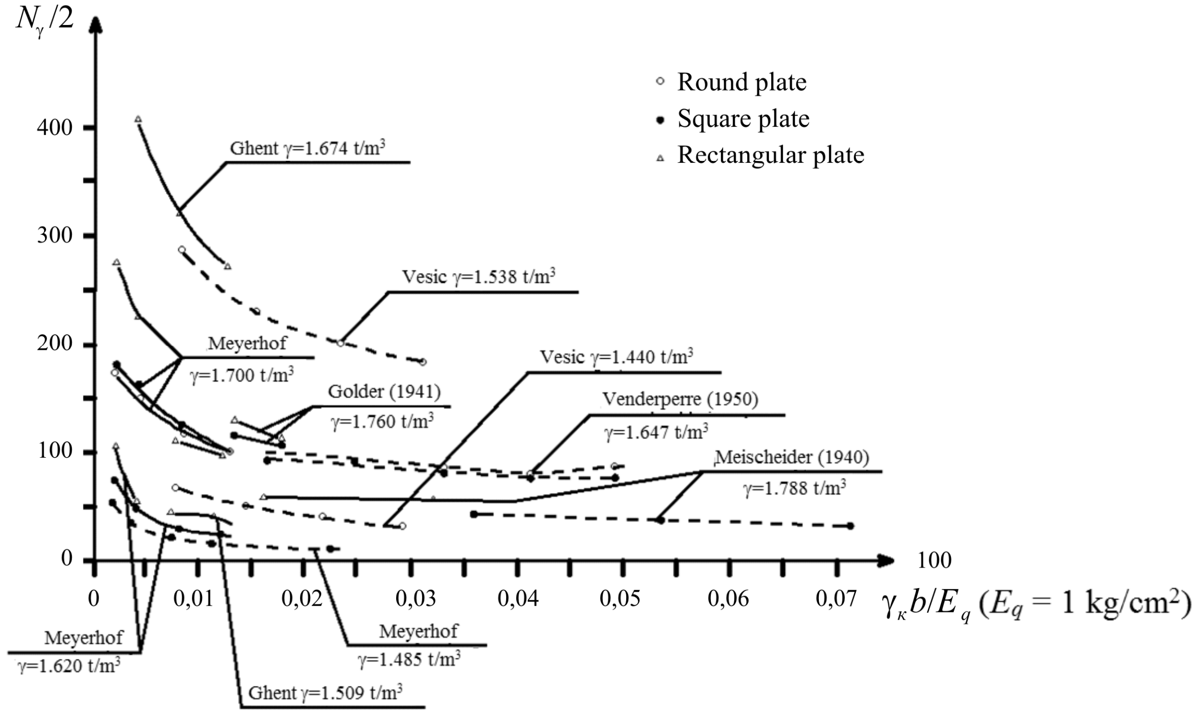


Fig. 6. Influence of Loading Area on Bearing Capacity Factor N_γ [9]
Рис. 6. Влияние площади загружения на величину коэффициента несущей способности N_γ [9]

At present in the research papers it is generally identified [10, 11] three main factors which determine the change in the bearing capacity coefficient N_γ (decrease with increasing width of foundations):

1) Decrease of internal friction angle with the increase of the average tension [11–15].

2) Progressive destruction [16, 17]. It occurs due to the fact that the shear stresses acting on the sliding surface are not evenly distributed. This leads to a decrease in strength characteristics at

places of stress concentration when overcoming peak strength. At the same time, different values are mobilized on the sliding surface φ.

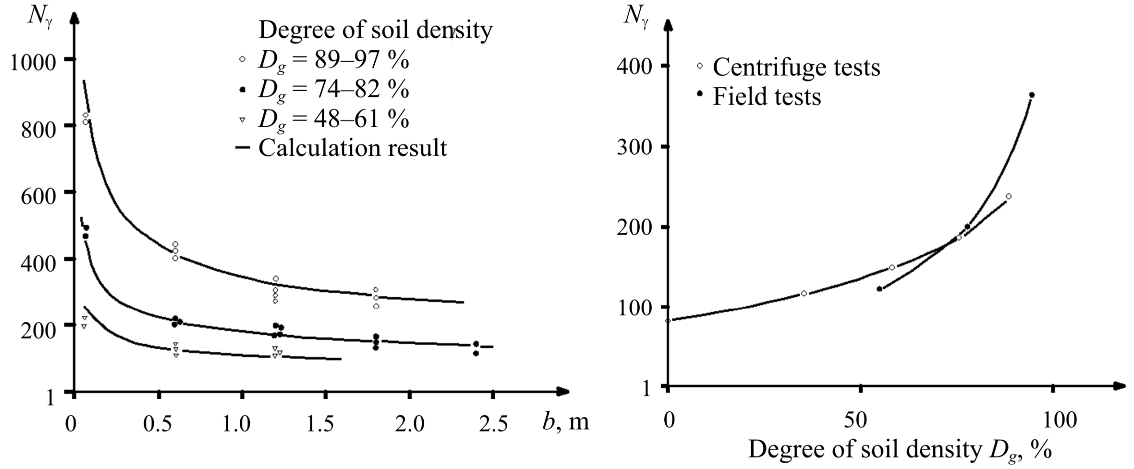
3) Influence of particle size/foundation size ratio [16, 18, 19].

The study of Pierre Habib (1974) [19] is devoted to the influence of particle size (the number of particles under the foundation) on the scale effect. Based on the obtained data, he developed an empirical formula for obtaining an adjusted bearing capacity coefficient N_γ^*:

$$N_\gamma^* = N_\gamma + \frac{400}{n}, \tag{8}$$

where N_γ – theoretical value of bearing capacity coefficient; $n = \frac{B}{\delta}$ – number of particles under foundation base; B – foundation width; δ – average size of particles under foundation base.

However, according to Hettler and Gudehus, as well as the conclusions of other researchers [12, 20–23], the particle size effect can be neglected. The ratio of foundation size to d50 (the diameter of particles less than which the soil contains 50 % of particles by mass, respectively) for full-scale tests is generally greater than 50–100 [24], which leads to a minimal influence of this factor. At the same time, the degree of soil density has an impact on the severity of the effect [12, 22, 23] (Fig. 7).



a *b*

Fig. 7. Influence of density level on the scale effect: *a* – when tested in a centrifuge by the example of the graph of the dependence of load-bearing factor N_γ on the plate width *b* [23], *b* – the same, added by the results of field tests [12]

Рис. 7. Влияние степени плотности на проявление масштабного эффекта: *а* – при испытаниях в центрифуге на примере графика зависимости коэффициента несущей способности N_γ от ширины штампа *b* [23], *b* – то же, дополненное результатами полевых испытаний [12]

The effect of progressive collapse manifests itself mainly after the “peak” in the “settlement-load” graph. The authors [12] single out the influence of medium stresses as the most significant factor. They propose the following methodology, based on Meyerhoff’s proposal, to account for the scale effect for a non-cohesive soil:

1) Based on the results of plate test it is determined the load-bearing capacity p_0, load-bearing capacity factor N_γ is found by the well-known formula of Tertsagi (7) by reverse recalculation. It is easy to do this for cases when the depth of laying *d* can be equated to zero (the test is carried out at a very shallow depth).

2) From the value N_γ it is determined the angle of internal friction φ_0 by reverse recalculation according one of the corresponding formulas of the theory of the ultimate equilibrium of the soil. The angle of internal friction is recalculated taking into account the acting average stresses according to the formula:

$$\varphi = \arcsin\left(\frac{\sin\varphi_0}{\left(\frac{\sigma_2}{\sigma_{2.0}}\right)^{\beta} + \sin\varphi_0 \cdot \left[1 - \left(\frac{\sigma_2}{\sigma_{2.0}}\right)^{\beta}\right]}\right). \tag{9}$$

Here the ratio $\frac{\sigma_2}{\sigma_{20}}$ for the sake of simplicity, is proposed to take equal to $\frac{b}{b_0}$; empirical coefficient $\beta \approx 0{,}1$ [12].

3) The new value of the internal friction angle is used to determine N_γ, N_q for the designed foundation, then the load-bearing capacity p is determined.

It is also worth noting the work of S. Shiraisi [25], in which expressions are given to adjust the carrier ratios N_γ и N_q based on model tests of dense sandy soil from internal friction angles 41,5–43 $d_{60} = 0.86$ mm. Expression for N_γ foundation of B width from the given work in general form can be written as follows:

$$N_\gamma = N_\gamma^* \left(\frac{B}{B^*}\right)^{-\beta}, \tag{10}$$

where N_γ^* – bearing capacity reference factor (in Shiraisi's work is defined for the foundation reference size $B^* = 1{,}4$ m); $\beta = 0{,}2$ – empirical factor.

A number of works directly use the dependence of the angle of internal friction on the effective average stresses when calculating by the finite difference method (according to the Sokolovsky method) [14] and the finite element method [26]. The solution of the continually heterogeneous problem of the theory of marginal equilibrium of soils today is one of the most promising ways to account for the large-scale effect.

Thus, today in the world geotechnical practice there is an idea of the reasons for the manifestation of a large-scale effect for the bearing capacity of foundations on sandy soil, as well as a number of methods for taking it into account.

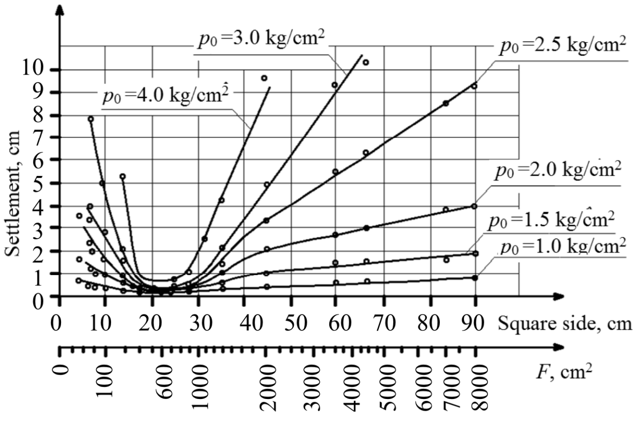
Deformability parameters. Impact of the Scale Effect

It is known from geotechnical practice that the size of the foundation (or plate) affects the degree of deviation of the actual (experimentally obtained) values of settlement and bearing capacity from the results of analytical calculations.

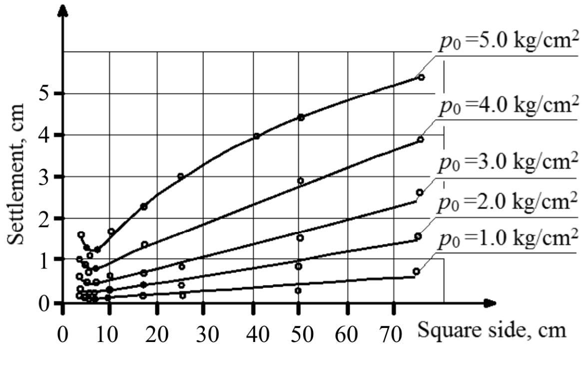
In the work of N.A. Tsytovich [27] there are graphs reflecting the influence of the size of a square plate on its settlement at the same pressure on the base (Fig. 8).

The observed dependence may indicate the manifestation of the influence of particle size, which causes plastic deformations at small plate sizes (for loam, a sharp increase in settlement is observed at smaller plate sizes than for sand).

With an increase in the size of the plates for a number of pressures, the dependence of the settlement on the size of the plate begins to deviate from the linear one, which indicates a different manifestation of the scale effect.



a



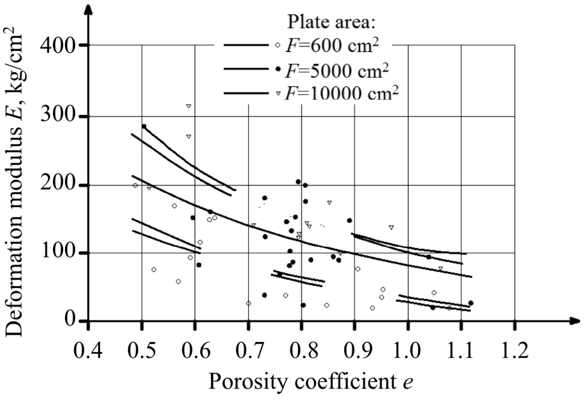
b

Fig. 8. Dependence of settlement on the size of cargo area:

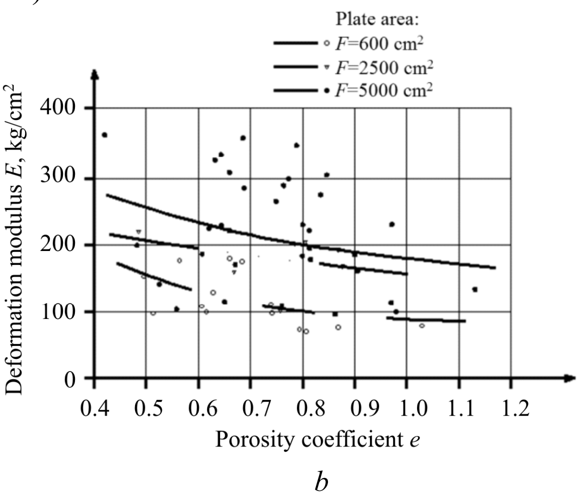
a – for sand with specific gravity $\gamma = 1.52\frac{\text{тс}}{\text{м}^2}$, $n = 42\ \%$, *b* – for loam with 46 % of sand [27]

Рис. 8. Зависимость осадки от размера грузовой площади: *а* – для песка с удельным весом $\gamma = 1{,}52\frac{\text{тс}}{\text{м}^2}$, $n = 42\ \%$, *b* – для суглинка с 46% песка [27]

In the work of V.M. Chizhevsky [28], devoted to the deformability of clay soils of the Urals, the influence of the plate diameter on the resulting modulus of soil deformation is also noted. A visual illustration is the graphs of the dependence of the deformation modulus on the porosity coefficient, built for different plate diameters (Fig. 9).



a



b

Fig. 9. Relationship between deformation modulus *E* and porosity coefficient *e* of clay alluvial (*a*) and deluvial (*b*) soils

Рис. 9. Зависимость между модулем деформации *E* и коэффициентом пористости *e* глинистых аллювиальных (*a*) и делювиальных (*b*) грунтов

Also of interest are the studies of Y.K. Zaretsky [29] devoted to the influence of the load case area on the value of the deformation modulus, which must be taken into account when calculating by the layer-by-layer summation method for large-sized structures. The method is based on the concept of G.K. Klein [30], who proposed to consider the soil base as a linear-deformable half-space with a continuously changing modulus of deformation (according to the power law).

The solutions obtained within the framework of this concept lead to the conclusion that as the load area increases, the settlement changes nonlinearly, even in using a linear deformation model for the ground.

In the modern edition of SR 23.13330.2018 “Foundations of Hydraulic Structures”, the formula for taking this phenomenon into account is:

$$E_i = E_i' \beta_i m_{ci}, \tag{11}$$

where E_i' – modulus of deformation without adjustment;

$$\beta_i = 1 - \frac{2v_i^2}{1 - v_i}, \tag{12}$$

where v_i – coefficient of transverse expansion; m_{ci} – coefficient of working conditions determined by the formulas:

$$m_{ci} = \left(\frac{A}{A_0}\right)^{\frac{n_i}{2}} \text{ at } A \geq 675 \text{ m}^2. \tag{13}$$

$$m_{ci} = 1 \text{ at } A < 300 \text{ m}^2 \text{ .} \tag{14}$$

at $300 \text{ m}^2 < A < 675 \text{ m}^2$ – by linear interpolation,

where A – foundation area; A_0 – area equal to 1 m^2; n_i – parameter determined by the results of soil tests with platess of different areas A_1 and A_2 under the same load according to the formula:

$$n_i = 1 - \frac{2\lg\left(\frac{\Delta\varepsilon_{1,i}}{\Delta\varepsilon_{2,i}}\right)}{\lg\left(\frac{A_1}{A_2}\right)}, \tag{15}$$

where $\Delta\varepsilon_{1,i}$, $\Delta\varepsilon_{2,i}$ – increment of plate settlement from additional pressure based on the results of plate tests.

In the absence of tests, it is permissible to assume values of n_i for dusty-clayey glacial soils – 0.1–0.2, for other dusty-clayey soils – 0.15–0.3, for sandy soils – 0.25–0.5.

It should also be noted that the effect of the loading area is taken into account in the method of linearly deformable layer (Egorov method) described earlier. Coefficients k_c, k_m, depending on the size of the foundation and the depth of the compressible thickness are obtained empirically, which is an additional confirmation of the effect of the loading area on the stiffness of the base.

Thus, in Russian practice, there are a number of studies for the large-scale effect in deformation calculations, as well as the methodology for its accounting, which is reflected in regulatory documents.

Analysis of the results and prospects of further reseach

1) The standards of many countries (USA, Germany, Great Britain, India, China, etc.) devoted to the execution of plate load tests and their use in calculations contain methods which allow using directly or indirectly information on the strength of base soils. The norms of the Russian Federation, in turn, do not contain any guidance on this issue. Research in this direction can make it possible to obtain additional parameters both for verifying the results of laboratory tests and for direct use in base calculations without significantly increasing the cost of testing. One of the advantages of this way is the ability to speed up the acquisition of preliminary data for foundation calculations, especially for objects located at a considerable distance from laboratories.

2) In the standards of most of the countries considered, there is a similarity of approaches to design with Russian practice – analogues of the theory of limit states are also used. However, there is a discrepancy in the issue of settlement calculation: the Russian system of regulatory and technical documentation does not provide for the possibility of calculating settlement without using the deformation modulus (direct design method).

3) Existing methods whic allow taking into account the strength characteristics of soils at interpreting the results of plat load tests (normative and proposed in studies) do not practically consider clay soils (with the exception of methods for determining undrained strength). This may be due to the inability to withstand the load in the field for a sufficient time to obtain the result in effective strength parameters. It should be noted that research in this direction can be carried out to obtain results at full voltages.

4) In order to apply all the proposed methods for consideration in research and construction practice, the soil under study must be a homogeneous layer of sufficient thickness so that the expected area of plastic deformations and fractures is located within its boundaries for both the plate and the designed foundation. In order to obtain strength characteristics, a load sufficient to bring it to the limiting state must be applied to the base (the criteria for its occurrence can be taken as the absence of stabilization of the settlement, the achievement of a settlement of at least 15 % of the diameter of the plate (according to BS-1377).

5) Of the methods considered, the most universal direct design method is the use of a plate settlement schedule for determining the settlement of the designed foundation. Its use for a rare case of coincidence of the dimensions of the plate and foundation is not difficult. For the case when the dimensions of the designed foundation differ significantly from the dimensions of the plate, world practice recommends taking into account the scale effect. However, the ways of accounting for it today are the subject of discussion.

From the analysis of the reviewed research papers it can be concluded that the scale effect for the load-bearing capacity is a decrease in the load-bearing capacity coefficients with an increase in the size of the load case area, and for deformations - in an increase in the modulus of deformations with an increase in the load case area. It can be concluded form this fact that when using the direct design method to calculate the settlement of the foundation with dimensions exceeding the dimensions of the plate it is necessary to adjust the settlement taking into account its nonlinear dependence on the dimensions of the load case area (for this purpose, the method of Y.K. Zaretsky can be used).

For the practice of calculating foundations on weak bases it may be useful to apply the results of plate load tests to assess undrained shear resistance using formulas from the the paper of Terzaghi and Peck, from EN 1997-2: Eurocode 7 or using the theory of instantaneous strength of Yu.I. Solovyov [31].

6) For the design of flexible foundations (slab and strip), it is useful to interpret the plate load test results to obtain the bed coefficient. It is also possible to adjust the value of the coefficient by applying the method of Y.K. Zaretsky.

7) For sandy soil a promising research task is the determination of the internal friction angle based on the results of plate load tests. As mentioned above, the use of the technique described in the work of Hettler and Gudehus makes it possible to obtain the value of the angle of internal friction taking into account the scale effect. The most accurate and promising way to take into account the scale effect is to solve the continuum-inhomogeneous problem of the theory of ultimate equilibrium of soil.

For clay soil this task is also relevant, but it will require additional studies related to the separation of soil resistance caused by the presence of adhesion.

It should be noted that in the case of plate load testing the SSS of the soil differs from the simple one which is tried to be achieved during traditional tests to determine strength characteristics. However, it is known from practice that the values of the angle of internal friction for the same soil tested in a single-plane shear devic and in a triaxial compression device in the vertical pressure increase mode and in the horizontal pressure increase mode will differ. On the basis of this fact, the proposal [32] to use different values of the angle of internal friction for different sections of the sliding curves is constructed. The use of the values of the internal friction angle obtained during plate load tests has the prospect of solving this problem in a different way for the case of calculating the load-bearing capacity of the foundation, since the SSS of the soil during the test will be the closest to the SSS of the calculated foundation.

8) In order to obtain the rheological parameters of soils during plate load tests it is possible to use graphs of the change in settlement over time for each load step (e.g. constructed in accordance with IS 1888). For the processing of such graphs and their reverse analysis, systems of equations compiled for the problem of the long-term strength of the foundation of a given shape under the action of a given load [33, 34], as well as modifications of the standard procedure for compression tests can be used. It should be noted, however, that when processing the graphs it will be necessary to separate the contribution of rheological parameters from the effect of primary (filtration) consolidation.

9) The most global task could be the development of a comprehensive methodology which makes possible to obtain all the necessary parameters by reverse analysis of plate load test schedules (supplemented by a number of laboratory studies). Such a description is possible both by means of numerical simulation by the finite elements method and by the use of numerically analytical solutions [35, 36].

Финансирование. *Исследование не имело спонсорской поддержки.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

References

1. Gersevanov N.M. Sobraniye sochineniy [Collected works]. Stroivoenmorizdat, 1948.
2. Ter-Martirosyan Z.G., Ter-Martirosyan A.Z. Mekhanika gruntov v vysotnom stroitel'stve s razvitoy podzemnoy chast'yu [Soil mechanics in high-rise construction with developed underground part]. Moscow, ASV, 2020, 946 p.
3. Coduto D.P. Foundation design. Pomona, California State Polytechnic University, 2001.

4. Terzaghi K., Peck R.B. Soil Mechanics in Engineering Practice. John Wiley, New York, 1948.

5. Bjerrum L., Eggestad, A. Interpretation of loading tests on sand. *Proceedings European Conference SMFE*, Wiesbaden, 1963, vol. 1.

6. Il'ichev V.A., Fadeyev A.V. Opisaniye yevropeyskikh pravil geotekhnicheskogo proyektirovaniya: osnovnyye polozheniya i kommentarii [Description of European rules of geotechnical design: basic provisions and comments]. *Rekonstruktsiya gorodov i geotekhnicheskoye stroitel'stvo*, 2003, no. 5, pp. 5-20.

7. Junqing L.O.U. [et al]. Comparison of plate loading test standards in China and USA // 工程地质学报, 2014, vol. 22, no. 6, pp. 1058-1065.

8. Sokolovskiy V.V. Statika sypuchey sredy [Statics of granular media]. 4th ed. Moscow, Nauka, 1990, 270 p.

9. De Beer E.E. Bearing capacity and settlement of shallow foundations on sand. *Proc. Symp. Bearing capacity and settlement of foundations*. Duke University, 1965, pp. 15-34.

10. Oh W.T., Vanapalli S.K. Scale effect of plate load tests in unsaturated soils. *GEOMATE Journal*, 2013, vol. 4, no. 8, pp. 585-594.

11. De Beer E.E. The scale effect on the phenomenon of progressive rupture in cohesionless soils. *Soil Mech. & Fdn. Eng. Conf. Proc.* Canada, 1965.

12. Hettler A., Gudehus G. Influence of the foundation width on the bearing capacity factor. *Soils and Foundations*, 1988, vol. 28, no. 4, pp. 81-92.

13. Bolton M.D., Lau C.K. Scale effects in the bearing capacity of granular soils. *Congrès international de mécanique des sols et des travaux de fondations*. 12, 1989, pp. 895-898.

14. Ueno K. [et al]. Reappraisal of size effect of bearing capacity from plastic solution. *Journal of Geotechnical and Geoenvironmental Engineering*, 2001, vol. 127, no. 3, pp. 275-281.

15. Meyerhof G.G. The bearing capacity of sand. PhD thesis. University of London, London, 1950.

16. Tatsuoka F., Okahara M., Tanaka T., Tani K., Morimoto T., Siddiquee M.S.A. Progressive failure and particle size effect in bearing capacity of a footing on sand. *ASCE GSP27*, 1991, vol. 2, pp. 788-802.

17. Yamaguchi H., Kimura T., Fuji N. On the influence of progressive failure on the bearing capacity of shallow foundations in dense sand. *Soils and Foundations*, 1976, vol. 16, no. 4, pp. 11-22.

18. Steenfelt J.S. Scale effect on bearing capacity factor Nγ. *Proc. 9th Int. Conf. of Soil Mechanics and Foundations Engineering*, 1977, vol. 1, pp. 749–752.

19. Habib P.A. Scale effect for shallow footings on dense sand. *Journal of the Geotechnical Engineering Division*, 1974, vol. 100, no. 1, pp. 95-99.

20. Görner E. Über den Einfluß der Flächengröße auf die Einsenkung von Gründungskörpern: Experimentelle Untersuchungen aus dem Erdbaulaboratorium der Bergakademie Freiberg, 1932.

21. Hettler A., Gudehus G. A pressure-dependent correction for displacement results from 1 g model tests with sand. *Géotechnique*, 1985, vol. 35, no. 4, pp. 497-510.

22. Cerato A.B., Lutenegger A.J. Scale effects of shallow foundation bearing capacity on granular material. *Journal of geotechnical and geoenvironmental engineering*, 2007, vol. 133, no. 10, pp. 1192-1202.

23. Kimura T., Kusakabe O., Saitoh K. Geotechnical model tests of bearing capacity problems in a centrifuge. *Géotechnique*, 1985, vol. 35, no. 1, pp. 33-45.

24. Kusakabe O. Foundations. *Geotechnical centrifuge technology*, ed. R.N. Taylor. Blackie Academic & Professional, London, 1995, pp. 118–167.

25. Shiraishi S. Variation in bearing capacity factors of dense sand assessed by model loading tests. *Soils and Foundations,* 1990, vol. 30, no. 1, pp. 17–26.

26. Chakraborty D., Kumar J. Dependency of Nγ on footing diameter for circular footings. *Soils and Foundations*, 2013, vol. 53, no. 1, pp. 173-180.

27. Tsytovich N.A. Osnovy mekhaniki gruntov [Fundamentals of soil mechanics]. Leningrad, Moscow, Glavnaya redaktsiya stroitel'noy literatury, ONTI, 1984.

28. Chizhevskiy V.M. Issledovaniye deformiruyemosti glinistykh gruntov Urala [Study of deformability of clayey soils in the Urals region]. Sverdlovsk, 1972, 150 p.

29. Zaretskiy YU.K., Garitselov M.YU. Glubinnoye uplotneniye gruntov udarnymi nagruzkami [Deep compaction of soils using shock loads]. Moscow, Energoatomizdat, 1989, 190 p.

30. Kleyn G.K. Raschet balok na sploshnom osnovanii, nepreryvno neodnorodnom po glubine [Calculation of beams on a solid base, continuously heterogeneous in depth]. *Sb. trudov MIIGS Mosgorispolkoma*, 1954, vol. 3, 120 p.

31. Solov'yev YU.I. Zhestko- i uprugoplasticheskiy analiz ustoychivosti i napryazhenno-deformirovannogo sostoyaniya gruntov [Rigid and elastic-plastic analysis of stability and stress-strain state of soils]. Abstract of Doctor's degree dissertation. Moscow, 1989, 42 p.

32. Boldyrev G.G., Mel'nikov A.V., Novichkov G.A. Interpretatsiya rezul'tatov laboratornykh ispytaniy s tsel'yu opredeleniya deformatsionnykh kharakteristik gruntov [Interpretation of laboratory test results to determine the deformation characteristics of soils]. *Inzhenernyye izyskaniya*, 2014, no. 5-6, 98 p.

33. Ter-Martirosyan Z.G., Ter-Martirosyan A.Z., Vanina YU.V. Dlitel'naya osadka i nesushchaya sposobnost' osnovaniy i fundamentov vblizi vertikal'noy vyyemki pri raznykh parametrakh vyazkosti grunta [Long-term settlement and bearing capacity of foundations adjacent to vertical excavation at various parameters of soil viscosity]. *Vestnik MGSU*, 2022, vol. 17, iss. 12, pp. 1664–1676. DOI: 10.22227/1997-0935.2022.12.1664-1676.

34. Ter-Martirosyan Z.G., Ter-Martirosyan A.Z., Ermoshina L. Ju. Osadka i dlitel'naja nesushhaja sposobnost' svai s uchetom reologicheskih svojstv gruntov [Settlement and long-term bearing capacity of the pile taking into account the rheological properties of soils]. *Construction and Geotechnics*, 2022, vol. 13, iss. 1. pp. 5-15. DOI: 10.15593/2224-9826/2022.1.01.

35. Ter-Martirosyan Z.G., Ter-Martirosyan A.Z., Filippov K.A. Osadka i nesushchaya sposobnost' kruglogo shtampa na uprugoplasticheskom osnovanii [Settlement and bearing capacity of a round stamp on an elastic-plastic base]. *Zhilishchnoye stroitel'stvo*, 2022, no 12, pp. 3–7, DOI: 10.31659/0044-4472-2022-12-3-7.

36. Ter-Martirosyan A.Z., Ter-Martirosyan Z.G., Luzin I.N. Naprjazhenno-deformirovannoe sostojanie, osnovannoe na fundamentah glubokogo zalozhenija [Stress-strain condition of base of deep foundations]. *Construction and Geotechnics*, 2017, vol. 8, iss. 2, pp. 96-103. DOI: 10.15593/2224-9826/2017.2.09.

Библиографический список

1. Герсеванов, Н.М. Собрание сочинений / Н.М. Герсеванов. – М.: Стройвоенмориздат, 1948.

2. Тер-Мартиросян, З.Г. Механика грунтов в высотном строительстве с развитой подземной частью: учеб. пособие / З.Г. Тер-Мартиросян, А.З. Тер-Мартиросян. – М.: Издательство АСВ, 2020. – 946 с.

3. Coduto, D.P. Foundation design / D.P. Coduto. – Pomona, California State Polytechnic University, 2001.

4. Terzaghi, K. Soil Mechanics in Engineering Practice / K. Terzaghi, R.B. Peck. – New York: John Wiley, 1948.

5. Bjerrum, L. Interpretation of Loading Tests on Sand / L. Bjerrum, A. Eggestad // Proceedings European Conference SMFE, Wiesbaden. – 1963. – Vol. 1.

6. Ильичев, В.А. Описание европейских правил геотехнического проектирования: основные положения и комментарии / В.А. Ильичев, А.В. Фадеев // Реконструкция городов и геотехническое строительство. – 2003. – № 5. – С. 5–20.

7. Comparison of plate loading test standards in China and USA / L.O.U. Junqing [et al.] // 工程地质学报. – 2014. – Vol. 22, № 6. – P. 1058–1065.

8. Соколовский, В.В. Статика сыпучей среды / В.В. Соколовский. – 4-е изд. – М.: Наука, 1990. – 270 с.

9. Beer, E.E. de. Bearing capacity and settlement of shallow foundations on sand / E.E. de Beer // Proc. Symp. Bearing capacity and settlement of foundations. – Duke University, 1965. – P. 15–34.

10. Oh, W.T. Scale effect of plate load tests in unsaturated soils / W.T. Oh, S.K. Vanapalli // Geomate Journal. – 2013. – T. 4, № 8. – P. 585–594.

11. Beer, E.E. de. The scale effect on the phenomenon of progressive rupture in cohesionless soils / E.E. de Beer // Soil Mech. & Fdn. Eng. Conf. Proc. – Canada, 1965.

12. Hettler, A. Influence of the foundation width on the bearing capacity factor / A. Hettler, G. Gudehus // Soils and Foundations. – 1988. – Vol. 28, № 4. – P. 81–92.

13. Bolton, M.D. Scale effects in the bearing capacity of granular soils / M.D. Bolton, C.K. Lau // Congrès international de mécanique des sols et des travaux de fondations. – 1989. – № 12. – P. 895–898.

14. Reappraisal of size effect of bearing capacity from plastic solution / K. Ueno [et al.] // Journal of Geotechnical and Geoenvironmental Engineering. – 2001. – Vol. 127, № 3. – P. 275–281.

15. Meyerhof, G.G. The bearing capacity of sand. PhD thesis / G.G. Meyerhof // University of London. – London, 1950.

16. Progressive failure and particle size effect in bearing capacity of a footing on sand / F. Tatsuoka, M. Okahara, T. Tanaka, K. Tani, T. Morimoto, M.S.A. Siddiquee // ASCE GSP27. – 1991. – Vol. 2. – P. 788–802.

17. Yamaguchi, H. On the influence of progressive failure on the bearing capacity of shallow foundations in dense sand / H. Yamaguchi, T. Kimura, N. Fuji // Soils and Foundations. – 1976. – Vol. 16, no. 4. – P. 11–22.

18. Steenfelt, J.S. Scale effect on bearing capacity factor N_γ / J.S. Steenfelt // Proc. 9th Int. Conf. of Soil Mechanics and Foundations Engineering. – 1977. – Vol. 1. – P. 749–752.

19. Habib, P.A. Scale effect for shallow footings on dense sand / P.A. Habib // Journal of the Geotechnical Engineering Division. – 1974. – Vol. 100, № 1. – P. 95–99.

20. Görner, E. Über den Einfluß der Flächengröße auf die Einsenkung von Gründungskörpern: Experimentelle Untersuchungen aus dem Erdbaulaboratorium der Bergakademie Freiberg / E. Görner. – 1932.

21. Hettler, A. A pressure-dependent correction for displacement results from 1 g model tests with sand / A. Hettler, G. Gudehus // Géotechnique. – 1985. – Vol. 35, № 4. – P. 497–510.

22. Cerato, A.B. Scale effects of shallow foundation bearing capacity on granular material / A.B. Cerato, A.J. Lutenegger // Journal of Geotechnical and Geoenvironmental engineering. – 2007. – Vol. 133, № 10. – P. 1192–1202.

23. Kimura, T. Geotechnical model tests of bearing capacity problems in a centrifuge / T. Kimura, O. Kusakabe, K. Saitoh // Géotechnique. – 1985. – Vol. 35, № 1. – P. 33–45.

24. Kusakabe, O. Foundations. in Geotechnical centrifuge technology / O. Kusakabe; ed. R.N. Taylor: Blackie Academic & Professional, London, 1995. – P. 118–167.

25. Shiraishi, S. Variation in bearing capacity factors of dense sand assessed by model loading tests / S. Shiraishi // Soils and Foundations. – 1990. – Vol. 30, № 1. – P. 17–26.

26. Chakraborty, D. Dependency of N_γ on footing diameter for circular footings / D. Chakraborty, J. Kumar // Soils and Foundations. – 2013. – Vol. 53, № 1. – P. 173–180.

27. Цытович, Н.А. Основы механики грунтов / Н.А. Цытович. – Л., М.: Главная редакция строительной литературы, ОНТИ, 1984.

28. Чижевский, В.М. Исследование деформируемости глинистых грунтов Урала / В.М. Чижевский. – Свердловск, 1972. – 150 с.

29. Зарецкий, Ю.К. Глубинное уплотнение грунтов ударными нагрузками / Ю.К. Зарецкий, М.Ю. Гарицелов. – М.: Энергоатомиздат, 1989. – 190 с.

30. Клейн, Г.К. Расчет балок на сплошном основании, непрерывно неоднородном по глубине / Г.К. Клейн // Сб. трудов МИИГС Мосгорисполкома. – 1954. – Т. 3. – С. 120.

31. Соловьев, Ю.И. Жестко- и упругопластический анализ устойчивости и напряженно-деформированного состояния грунтов: автореф. дис. … д-ра техн. наук / Ю.И. Соловьев. – М., 1989. – 42 с.

32. Болдырев, Г.Г. Интерпретация результатов лабораторных испытаний с целью определения деформационных характеристик грунтов / Г.Г. Болдырев, А.В. Мельников, Г.А. Новичков // Инженерные изыскания. – 2014. – № 5–6. – С. 98.

33. Тер-Мартиросян, З.Г. Длительная осадка и несущая способность оснований и фундаментов вблизи вертикальной выемки при разных параметрах вязкости грунта / З.Г. Тер-Мартиросян, А.З. Тер-Мартиросян, Ю.В. Ванина // Вестник МГСУ. – 2022. – Т. 17, вып. 12. – С. 1664–1676. DOI: 10.22227/1997-0935.2022.12.1664-1676

34. Тер-Мартиросян, З.Г. Осадка и длительная несущая способность сваи с учетом реологических свойств грунтов / З.Г. Тер-Мартиросян, А.З. Тер-Мартиросян, Л.Ю. Ермошина // Construction and Geotechnics. – 2022. – Т. 13, № 1. – С. 5–15. DOI: 10.15593/2224-9826/2022.1.01

35. Тер-Мартиросян, З.Г. Осадка и несущая способность круглого штампа на упругопластическом основании / З.Г. Тер-Мартиросян, А.З. Тер-Мартиросян, К.А. Филиппов // Жилищное строительство. – 2022. – No 12. – С. 3–7. DOI: 10.31659/0044-4472-2022-12-3-7

36. Тер-Мартиросян, А.З. Напряженно-деформированное состояние оснований фундаментов глубокого заложения / А.З. Тер-Мартиросян, З.Г. Тер-Мартиросян, И.Н. Лузин // Construction and Geotechnics. – 2017. – Т. 8, № 2. – С. 96–103. DOI: 10.15593/2224-9826/2017.2.09