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DETERMINATION OF THE SOIL RESISTANCE VALUE FOR THE FOUNDATION DESIGN OF RECONSTRUCTED BUILDINGS

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Abstract: The calculation of bases and foundations of reconstructed buildings on sandy and clayey soils requires taking into account the value of the design resistance of the soil R. It is known that in the process of long-term operation of buildings, soil under the footings becomes compacted due to pressure from the foundations, and their properties usually improve. Over this period, the value of R also increases, and in the following we will call it the calculated resistance of the compacted foundation soil R_{comp}. The authors have analyzed known methods of determining R_{comp}, published by Russian scientists over the past 50 years.

The purpose of this work was to refine the method for determining the value of the design resistance of the compacted soil R_{comp} for the design of foundations for reconstructed buildings. Among the considered ones, the most effective is the engineering method of determining R_{comp} based on the recommendations for calculating the value of R according to the formula (5.7) of SP 22.13330.2016, which is supplemented by coefficients that take into account changes in the physical and strength characteristics of soils. The greatest increase in the value of R to R_{comp} (by 45-60%) is observed for shallow foundations on clayey low-plastic soils, while the smallest increase occurs in cases of ground water saturation during the operation of the building (by 20-25%). However, if the additional loading p from the foundation is insignificant ($p/R \leq 0.6$-0.7), then the value of R (for uncompacted soil) decreases by 10-15% and more. The greatest compaction effect for clay soils during the building's operational life occurs when the pressure at the footings p is 80% or more of the calculated soil resistance R ($p \geq 0.8\ R$). All these factors must be considered when determining the reserve strength of the foundations of reconstructed buildings.

Keywords: design resistance of the foundation soil, shallow foundations, compaction of the base by pressure from the foundations, improvement of soil properties

ОПРЕДЕЛЕНИЕ РАСЧЕТНОГО СОПРОТИВЛЕНИЯ ГРУНТА ОСНОВАНИЯ ПРИ ПРОЕКТИРОВАНИИ ФУНДАМЕНТОВ РЕКОНСТРУИРУЕМЫХ ЗДАНИЙ

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Аннотация. Расчет оснований и фундаментов реконструируемых зданий на песчаных и глинистых грунтах в России предусматривает использование величины расчетного сопротивления грунта основания R. При этом установлено, что в процессе длительной эксплуатации зданий (сооружений) происходит уплотнение грунтов основания давлением от фундаментов, и их свойства обычно улучшаются. За этот период происходит также увеличение значения R, которое для условий реконструкции зданий принято называть расчетным сопротивлением уплотненного грунта основания $R_{уп}$. Авторами проанализированы известные методы определения $R_{уп}$, опубликованные в работах отечественных ученых за последние 50 лет (с 1971 г.). Сравнительный анализ показал, что методы расчета $R_{уп}$ в настоящее время нуждаются в дальнейшем развитии. Цель работы заключалась в уточнении метода определения расчетного сопротивления уплотненного грунта основания $R_{уп}$ для проектирования фундаментов реконструируемых зданий. Из числа рассмотренных наиболее эффективным является инженерный метод разработанный в

ТГАСУ (Томск), получивший свое развитие в период с 2007 по 2021 гг. Метод учитывает не только улучшение свойств грунтов под подошвой фундаментов за счет постепенного догружения давлением от здания, но и их ослабление (ухудшение), вызванное обводнением основания в период его эксплуатации. Рассматриваемый метод определения $R_{уп}$ базируется на рекомендациях к вычислению значения R по формуле (5.7) СП 22.13330.2016 (Россия), в которую вносятся дополнения в виде коэффициентов, учитывающих изменения физических и прочностных характеристик грунтов. Например, наибольшее повышение значения R до $R_{уп}$ (на 45-60%) наблюдается для фундаментов мелкого заложения на глинистых грунтах тугопластичных, а наименьшее – для случая обводнения этих грунтов в период эксплуатации здания (на 20-25%). Если же догружение грунта основания давлением p от фундамента незначительно ($p/R \leq 0{,}6$-$0{,}7$), то значение R (неуплотненного грунта) понижается на 10-15% и более. Следует также заметить, что наибольший эффект уплотнения глинистых грунтов основания за период эксплуатации зданий происходит в том случае, когда давление по подошве фундаментов p составляет 80% и более от расчетного сопротивления естественного гранта основания R ($p \geq 0{,}8\ R$). Все это необходимо учитывать при определении резерва прочности основания фундаментов реконструируемых зданий, в каждом конкретном случае, в зависимости от вида (разновидности) грунта, срока их эксплуатации.

Ключевые слова: реконструкция зданий, расчетное сопротивление грунта основания, фундаменты мелкого заложения, уплотнение основания давлением от фундаментов, улучшение свойств грунта

INTRODUCTION

In Russia, when calculating the bases and foundations of reconstructed buildings on sandy and clayey soils for the second group of limit states, the parameter of design soil resistance R is used in accordance with SP 22.13330.2016. It is known that during the long-term operation of buildings, the foundation soils become compacted under the pressure from the foundations, and their properties usually improve (P. A. Konovalov, 1986; A. I. Polishchuk et al., 1997, and others). Due to the compaction of the soil and the improvement of its properties, there is also an increase in the parameter R, which for the conditions of reconstruction of buildings is usually called the calculated resistance of the compacted soil of the foundation R_{comp}. The authors of the article have analyzed known methods for determining the parameter R_{comp}, published in the works of: B. I. Dalmatov et al. (1985–1990), V. A. Zurnadzhi & M. P. Filatova (1970), P. A. Konovalov et al. (1986–2011), A.V. Pilyagin (2005–2017), A. I. Polishchuk et al. (1997–2023), A. G. Roitman et al. (1971–1990), N. G. Smolenskaya et al. (1979), E. A. Sorochan & Yu. I. Dvorkina (1976–1986), V. M. Ulitsky et al. (1986–1993), G. I. Shvetsov & I. V. Noskov et al. (1991–2002), V. B. Shvets, V. V. Lushnikov et al. (1981–1995) and others [1, 2, 13–18]. The comparative analysis showed that the current methods for calculating R_{comp} require further development.

This work aimed to substantiate a method for evaluating the design resistance of compacted subsoil (R_{comp}) to support foundation design in building reconstruction projects. This article was prepared with the participation of T.N. Gutnik.

DESIGN METHODOLOGY AND THEORETICAL APPROACHES

Currently, existing regulatory documents contain limited information on methods for determining the design bearing capacity of compacted foundation soils (R_{comp}) for building reconstruction projects. This results in frequent use of natural soil characteristics obtained from geotechnical investigations for new construction when designing (assessing loading conditions for) shallow foundations on sandy and clayey soils. In such cases, the improvement (change) in soil properties due to long-term compaction under foundation loads is frequently neglected. Let us consider the main methods used in Russia for determining the R_{comp} parameter at the stage of justifying design solutions for foundation systems of reconstructed buildings.

When designing foundations for reconstructed buildings, parameter R [Method (5.7) of SP 22.13330.2016] is frequently used as for new construction conditions. However, at the same time, prior to the design process, during the preparation of a report on the technical condition of a reconstructed building, an engineering and geological survey is conducted at the site (either fully or partially, as a means of verification), including a survey of existing foundations and their foundations. During this stage, samples of compacted soils are collected from under the bases of foundations to determine their physical and mechanical properties. The properties of the soil thus determined allow for the calculation of the R_p parameter, which is used to assess the loading capacity of the foundations under consideration. This method can be described as experimental method. The physico-mechanical properties of foundation soils for reconstructed buildings can also be determined through alternative methods such as geophysical surveys, sounding, or penetration tests. The determination of the R_p parameter based on actual soil characteristics established experimentally during foundation investigations, readers may refer to works by P.A. Konovalov, E.A. Sorochan, Yu.I. Dvorkina, A.I. Polishchuk et al., V.M. Ulitsky et al., and A.G. Roitman et al. [1,3,5,6,10,12,14, etc.]. The experimental method for determining the R_{comp} parameter discussed above is based on current regulatory documents, has undergone verification, and has proven effective in the design practice of foundations for reconstructed buildings. However, its implementation requires a significant amount of time-consuming preparatory work related to collecting samples, soil samples taken from under the foundation base and determination of their physical, strength, and deformation characteristics under specified loading conditions.

The experience of increasing loads on building structures, including foundations, due to the addition of extra floors has shown that the soils supporting the foundations often have a reserve of strength. These issues were first addressed in scientific publications as early as the 1930s [1, 9, 12, 16, 17]. However, these publications provided only general recommendations regarding potential additional loading of existing foundations and subsoils without specific quantitative guidelines. For example, Professor P. A. Konovalov (1980) suggested that increased ground pressure during building reconstruction should be determined based on the allowable pressure R (used for new building design) with enhancement factors ranging from 1.1 to 1.5 depending on soil type [1]. In the 1941 building regulations, which were developed for construction under military conditions, it was recommended that the R - value be increased by 40% during reconstruction, provided that there were no cracks were observed in walls or other structural elements due to differential foundation settlement. In subsequent regulatory documents, the pressure on the foundations varies from 20% to 25% depending on the duration of their operation and the absence of defects, provided that they are at least 20 years old. The 1974 (SNIP P-15-74) and 1983 (SNIP 2.02.01-83*) documents on the design of foundations for buildings and structures no longer contain any recommendations regarding potential increases in R for soils beneath existing buildings [11].

In 1970, V.A. Zurnadzhi and M.P. Filatova proposed a method for determining the increased allowable ground pressure $R^{и}$, in their work [4]. According to the authors, their method should be considered as preliminary, and the following formula was provided:

$$R^{и} = K_з \cdot \sigma_p, \quad (1)$$

where: σ_p – design soil pressure beneath an existing building, kPa;

$K_з$ – the increasing coefficient is determined depending on the type of soil, its humidity, the calculated pressure at the base of the foundation σ_p and the operating time of the building.

According to the tabular data [4] for loess–like loams with a humidity from 5 to 20%, a design pressure of σp from 100 to 300 kPa, and building service life of 5-25 years, the enhancement factor values ($K_з$) vary within

1.0-1.4. If the base contains sands of various sizes and densities, regardless of their humidity, at σp from 100 to 400 kPa and the service life of the building from 5 to 25 years or more, the k_s values range from 1.1 to 1.5.

For cases where data on the actual soil characteristics in the compacted area under the foundation base is unavailable, P. A. Konovalov and A. G. Roitman, (1970-1972) and later E. V. Polyakov and V. K. Sokolov (1972) developed a method for determining parameter *R'*, which takes into account the compression (pre-consolidation) effect of foundation soils during construction maintenance. The equation developed by P. A. Konovalov and A. G. Roitman is as follows:

$$R' = R \cdot m \cdot k_s, \quad (2)$$

where: *R'* - calculated ground resistance of the base, taking into account the effect of compression (compaction) of the base by pressure from the foundation of the reconstructed building, kPa;

R – the calculated resistance of the soil of the base during its natural occurrence (unconsolidated state), determined by SP 22.13330.2016, kPa;

m – the coefficient that takes into account the change in the physico–mechanical properties of the soils (the degree of compression of the soils) of the foundation under the foundation during the period of operation of the building;

k_s – a coefficient that takes into account the degree of realization (using) of the maximum precipitation of the foundation during the period of operation of the building (determined by the ratio of the calculated precipitation at a pressure equal to the calculated to the maximum allowable precipitation). The values of the *k* coefficient for different types (varieties) of soils are determined according to the tables (P. A. Konovalov, 2011).

The coefficient *m* in formula (2) depends on the ratio of the foundation pressure before vertical extension p_0 to the design soil resistance *R*.

At $p_0/R \geq 0.8$ (more than 80%), the coefficient $m = 1.3$, at $p_0/R = 0.7$-0.8 (equal to 70-80%), the coefficient $m = 1.15$, at $p_0/R \leq 0.7$ (less than 70%), the coefficient $m = 1$.

The ratio p_0/R equaling 1 signifies the complete utilization of the calculated soil resistance in the foundation for calculations pertaining to the second group of limiting states [1, 14].

The formula of E.V. Polyakov and V.K. Sokolov for determining *R'* has the following form:

$$R' = kR, \quad (3)$$

where: R', R – the same as in formula (2);

k – the coefficient of increase in the resistance of the base soil, depending on the ratio p_0/R (here p_0 is the actual pressure on the base soils up to the superstructure, kPa); The values of the coefficient *k* vary from 1.0 to 1.5 and are taken according to the tables (P.A. Konovalov, 1980).

Formula (3) may be applied when the building being vertically extended has been in service for at least 3 years for sandy soils, 5 years for sandy loams, and 8 years for clayey soils. In contrast to the method of P. A. Konovalov and A.G. Roitman, formula (3) includes only a single coefficient *k*, which accounts for the amount of load/magnitude of pressure transmitted to the soil by the foundation. The difference between the two methods also lies in the absence of a parameter in formula (3) to account for changes in foundation settlement during the operation of the structure. The values for the *k* coefficient are derived from tables (P. A. Konovalov, 1980).

In AO TSNII Promzdaniy (Moscow), research was conducted (1965) into the strength characteristics of sand soils at the bases of existing buildings (operating period from 20 to 120 years). Based on the research findings, a linear correlation was identified between the strength properties of soil and the duration of its loading, followed by the development of empirical formulas for determining the angle of internal friction and specific cohesion of

sands at given time intervals after initial loading [5-7]. The considered methodology allowed:

- to determine design bearing capacity values of foundation soils accounting for their time-dependent consolidation;
- to address the issue of necessity for strengthening foundations and bases for the reconstruction of buildings, considering changes in strength properties of the soil.

Based on the data obtained by Yu.I. Dvorkin and E.A. Sorochan from AO TSNII Promzdaniy (1972), a method has been developed for calculating the calculated resistance of compacted soil in the foundation base for sandy soils. The proposed method takes into account the time-dependent improvement in the building properties of sandy soils and is determined using the following formula for foundation design:

$$R_{comp} = R \cdot K_E, \quad (4)$$

where: R – the calculated resistance of the soil of the base during its natural occurrence (unconsolidated state), determined by SP 22.13330.2016, kPa;

K_E – a coefficient accounting for the improvement of soil engineering properties, adopted from tabulated data (E. A. Sorochan, 1986).

In TSASU (Tomsk), researches were conducted (1997-2000) to evaluate the load on the clay foundation of reconstructed (long-operating), buildings led to the development of a method for determining the compacted soil resistance parameter R_{comp} (by author A.I. Polishchuk), considering its compressibility [8,9]. The method is based on formula (5.7) for calculating the designed resistance of natural soil base R, as per SP 22.13330.2016. Coefficients K_γ, K_c, K_φ, K_s are included in formula (5.7), taking into account changes in soil strength characteristics during compaction and wetting (soaking) during building operation. The formula, considering the accepted coefficients, takes the following form:

$$R_{comp} = \frac{\gamma_{c1}\gamma_{c2}}{k}\left[M_\gamma k_z b \gamma_{II} K_\gamma + M_q d_1 \gamma'_{II} + \left(M_q - 1\right) d_b \gamma'_{II} + M_c c_{II} \cdot K_c\right] \cdot K_{s,} \quad (5)$$

where: K_γ, K_c – coefficients that take into account the change in the characteristics of density p (specific gravity) and specific adhesion to the soil of the foundation under the foundation during the period of operation of the building (Table 1);

M_q, M_γ, M_c – coefficients accepted according to SP 22.13330.2016, depending on the characteristics of the angle of internal friction ($\bar{\varphi}_{II}$) of the foundation compacted by pressure from the operated building:

$$\bar{\varphi}_{II} = \varphi_{II} \cdot K_\varphi, \quad (6)$$

where: φ_{II} – the angle of internal friction of the natural (uncompacted) soil of the base, deg;

K_φ – the coefficient that takes into account the change in the characteristic of the angle of internal friction φII over the period of operation of the building (Table 1);

K_S – a coefficient that takes into account the degree of realization (use) of the maximum precipitation of the foundation during the period of operation of the building (Table 2).

The remaining designations in equation (5) are the same as in SP 22.13330.2016.

The values of the coefficients K_y, K_φ, K_c should be selected depending/based on the ratio of the average pressure along the sole of the exploited foundation p to the calculated resistance of the natural (unconsolidated) soil of the base R, which was assumed during the initial design of the facility (they were obtained experimentally for clay soils).At the same time, the coefficients K_y, K_φ, K_c were established as the ratio of the characteristics of compacted (pressure foundations) and natural soils with a building life of more than 15 years [9].

Table 1. Values of coefficients K_y, K_φ, K_c for determining the design resistance of the compacted soil of the R_{comp} base (data by A.I. Polishchuk)

№ п/п	The foundation soils of the reconstructed building	Parameter *p/R*	Coefficients		
			K_γ,	K_φ	K_c
1	Clayey soils with index $I_L \leq 0.5$ and building service life exceeding more 15 years	more 0,8 0,5-0,8 less than 0,5	1,07-1,17 1,03-1,05 1,0	1,10 1,05 1,0	1,6 1,32 1,05
2	Clayey soils with index $I_L > 0,5$ and building service life exceeding more 15 years	more 0,8 0,5-0,8 less than 0,5	1,05-1,15 1,0-1,05 1,0	1,08 1,04 1,0	1,45 1,25 1,05
3	Clayey soils with groundwater present at foundation level and building service life exceeding more 15 years	more 0,8 0,5-0,8 less than 0,5	1,03 1,03 1,0	0,97 0,88 0,8	1,3 1,06 0,85

Note. The use of coefficients K_y, K_φ, K_c is provided for soils that do not have specific unfavorable properties (subsidence, swelling, etc.); p is the average pressure along the sole of the foundation under consideration before the reconstruction of the building; R is the calculated resistance of the natural (uncompacted) soil of the base.

Table 2. Values of coefficient Ks for determining the design resistance of compacted foundation soil

№ п/п	Foundation soils regardless of density and moisture content	coefficient K_s when S/S_u	
		0,2	0,7
1	Coarse and medium sands	1,4	1,0
2	Fine sands	1,2	1,0
3	Silty sands	1,1	1,0
4	Cohesive (clayey) soils with index $I_L \leq 0$	1,2	1,0
5	Cohesive (clayey) soils with index $I_L \leq 0.5$ and building service life exceeding more 15 years	1,1	1,0
6	Cohesive (clayey) soils with index $I_L > 0,5$ and building service life exceeding more 15 years	1,07	1,0
7	Clayey soils with groundwater present at foundation level and building service life exceeding more 15 years	1,05	1,0

Note. 1. In Table 2, the following designations are used: S – is the settlement of the foundation under a pressure p at the sole, corresponding to the estimated resistance of the natural ground at the base (p=R); S_u – is the maximum permissible settlement for the type of structure under consideration. For medium-rise buildings, the K_z factor is estimated by interpolation based on the S/S_u ratio.
2. In Table 2, figures 1-5 present data on coefficients obtained by NIIOSP experts in collaboration with Moszhilniiproekt (P. A. Konovalov, A. G. Roitman, et al., [11], [14]). The values of K_s numbered 6 and 7 were proposed by A.I. Polishchuk.

RESULTS AND DISCUSSION

Analyzing the methods discussed above for determining the design resistance of compacted foundation soil at the R_{comp} reveals that all are applicable only to specific soil types (or varieties.

The method proposed by Yu. I. Dvorkin and E. A. Sorochan (1976–1982, 1986) is applicable only to sandy soils with different granulometric compositions and humidity.

The method by P.A. Konovalov and A.G. Roitman (1972-1980), as well as the method by E.V. Polyakov and V.K. Sokolov (1972), are applicable not only to sandy soils but also to cohesive (clayey) soils with a liquidity index $J_L \leq 0.5$ and building service life of at least 15 years.

According to the authors themselves, the method proposed by V. A. Zurnadzhi and M. P. Filatova (1970) should be considered only as preliminary.

The method developed at TGASU (1997-2000), unlike the previously described methods by P. A. Konovalov et al. (1972-1980), E. P. Polyakov et al. (1972), and V. A. Zurnadzhi et al. (1970), has a broader application range and is applicable to clayey soils ranging from hard to soft-plastic (plastic) consistency.

It should be noted that the method developed at TSASU 1997 - 2000 takes into account not only the improvement of soil properties beneath the foundations of reconstructed buildings as a result of compaction, but also the weakening caused by flooding during the operation of these buildings. For instance, the largest increase in R to R_p is seen for shallow foundations on clay soils with an $J_L \leq 0.5$, which is 45-60%, and the smallest increase is for the case where these soils are flooded during the operation, which is 20-25%. If the compression of foundation soil due to pressure from the foundation is negligible ($p/R \leq 0.6$-0.7), the value of R for unconsolidated soils decreases by 10-15% or more [2, 9].

It is also important to note that, in some cases, the actual pressure exerted at the base of the foundations of reconstructed buildings may be 20-30% of the calculated bearing capacity of the natural, unconsolidated soil. In such instances, the effect of the compressive load from the foundations on the base is negligible. The greatest impact of compression on the foundation soil during the operational life of the structure occurs when the pressure applied to the base of the foundation is equal to 80% or greater than 80% of the bearing capacity of the unconsolidated soil ($p \geq 0.8$ R).

All these factors must be considered when determining the required strength reserve for the foundations of reconstructed structures, taking into account the specific characteristics of the soil and the anticipated service life of the building [19-25].

CONCLUSION

1. It has been determined that for the design of foundations and shallow foundations (ribbon, isolated, dense) for reconstructed buildings, it is essential to determine the parameter of calculated resistance of compacted soil at the base of the structure. Engineering methods for calculating the R_p are based on recommendations from regulatory documents for calculating R for natural (uncompacted) foundations (in accordance with SP 22.13330.2016) that have been supplemented to account for changes in soil properties beneath foundations due to compaction during building operation.

2. A review of experimental and theoretical studies suggests that the methods currently used for determining R_{comp} are applicable to certain soil types (sands, clays, loams, and sandy loams) and have limited applicability. Of the domestic methods considered for determining R_{comp}, the most effective is the engineering approach proposed at TSASU, which considers not only the improvement of soil properties under foundations due to compaction, but also the weakening (deterioration) caused by soil flooding during building operation [8, 9]. This method has broader applicability, covering clays, loams, and sandy loams from hard to soft-plastic (plastic) consistency states.

3. For the design foundations of reconstructed buildings on clay soils, it is necessary to further develop methods for determining the R_{comp}. In particular, this requires the development of a method for calculating the resistance of compacted soil R_{comp} for foundations with various shapes of the base in plan (e.g., T-shaped, trapezoidal, etc.), as well as foundations with a partially deepened slab along the perimeter.

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