

Consideration of soil strata heterogeneity influence on differential foundation settlements of overpasses for high-speed railways

*Sergei Kudryavtsev*¹, *Vladimir Ulitskii*², *Sergei Alekseev*², and *Stanislav Kondrat'ev*^{2,*}

¹Far Eastern State Transport University, 47 Seryshev St., Khabarovsk, 680021, Russia

²Emperor Alexander I St. Petersburg State Transport University, 9 Moskovsky Pr., Saint Petersburg, 190031, Russia

Abstract. The implementation of projects for the construction of high-speed railways actualizes the search of effective approaches to accounting the influence of soil strata heterogeneity along the course of the track on differential foundation settlements of overpasses. Russian special technical conditions prescribe sufficiently stringent regulation limits of absolute values of overpasses' foundation soil settlements (20 mm for ballastless track) and angles of break in profile (the differential foundation soil settlement), which should not exceed 1 ‰ for ballastless track. These requirements make it necessary to develop the calculation method, which is based on the criterion of deformation. To ensure compliance of design solutions to the specified regulations it is appropriate to use the method of the predefined equated soil settlements for design of shallow foundations of overpasses for high-speed railways. Several features of application of this method are presented in this article.

1 Introduction

The solutions of tasks, related to transportation process, cannot be achieved without railway infrastructure construction [1]. Analysis of the world experience of high-speed railway realizations showed a widespread use of artificial structures [2]. The leading explanation for this is connected with necessity of taking into account the heterogeneity and complexity of geotechnical conditions along the route, which in a number of cases is led to expediency of overpasses use (instead of embankments) as a result of feasibility study [3].

According to the Russian regulations requirements (the project specific standard [4]), which are related to artificial structures design for the high-speed railway "Moscow-Kazan-Ekaterinburg", the maximum allowable value of foundation soil settlement for overpasses must be less than 30 mm and 20 mm for ballast and ballastless tracks respectively. Also, the angles of break in profile (the differential foundation soil settlement), respectively, must be less than 1,5 ‰ and 1‰. Similar requirements are represented in the building codes of other countries [5, 6]. These fairly strict limitations cause the development of the calculation method, which is based on the criterion of foundation soil deformation – the

* Corresponding author: kondratev.s@yandex.ru

allowable foundation soil settlement, which is determined by design engineer. This possibility is realized in the predefined equalized soil settlements method [7, 8], based on the foundation soil settlement determination for a number of calculated foundations at the initial stage of design.

2 Theory section

Analysis of the question of foundation soil settlement determination in respect to the nonlinear stage of soil deformation has shown the applicability of two approaches, which can be broadly classified into two groups: numerical and analytical (approximate) methods. The first group includes solutions, which are based on the use of differential dependencies for soil state description (for example, plastic flow theory). The second group contains the approximate analytical (engineering) methods, which describes under given conditions the foundation soil settlement with sufficient accuracy. It is obvious that the use of first group methods allows obtaining the most accurate results; however, their application requires more time-consuming calculation procedures and obtaining additional experimental data [7]. The considered design method using the predefined equalized soil settlements relates to the second group methods and applies for calculation of the shallow foundations (using the natural bases). The main assumptions of this method are presented in the publications [7-9].

The traditional regulatory approach [10] to design of shallow foundations is to determine their size by bringing the average contact pressure under the bottom of foundations to the $0,9-0,95 \cdot R$ (R – the design resistance of a soil), i.e. it is based on the pressures equalization. That is the reason of difference in volumes of soils V , which are involved in the work ($V_1 \neq V_2$), what promotes the development of unequal foundation soil settlements S_1 and S_2 (Fig. 1). Accordingly, this approach is limitedly applicable in changeable geotechnical conditions along the railway line. This is related to the fact that under similar loads N ($N_1 \approx N_2$) on the overpasses' foundations (generally) the different soils have the unequal values R ($R_1 \neq R_2$) and cause the unequal decisions on foundations' widths b ($b_1 \neq b_2$) and their settlements S ($S_1 \neq S_2$).

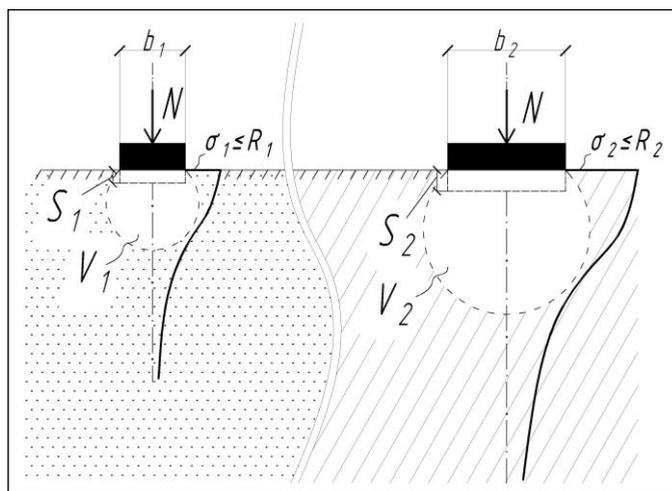


Fig. 1. The structural scheme to the calculation task.

The special feature of overpasses' foundations calculation using the predefined equalized soil settlements is the ability to select at the initial stage of design the value of the foundation soil settlement that matches the normative quantity. For determination of the

foundation width for the certain soil settlement, degree of loading and ground conditions, the following formula is used [9]:

$$S_i = \frac{\eta \cdot b^2 \cdot (N_\gamma \cdot \xi_\gamma \cdot b \cdot \gamma_I + N_q \cdot \xi_q \cdot d \cdot \gamma_I' + N_c \cdot \xi_c \cdot c_I - 1,05 \cdot P_{in.cr})}{\eta \cdot b^2 \cdot (N_\gamma \cdot \xi_\gamma \cdot b \cdot \gamma_I + N_q \cdot \xi_q \cdot d \cdot \gamma_I' + N_c \cdot \xi_c \cdot c_I) + 0,05 \cdot P_{in.cr} \cdot \eta \cdot b^2 - N_0} \cdot \frac{1,1 \cdot P_{in.cr} \cdot \omega \cdot b \cdot (1 - \mu^2)}{E_0} \cdot \frac{k \cdot (\frac{N_0}{\eta \cdot b^2} + d \cdot \gamma_{av})^n}{P_{in.cr}^n} \quad (1)$$

b – foundation width; c_I – soil cohesion; d – foundation depth; E_0 – deformation modulus; k, n – empirically determined coefficients, correspondingly equated 1,01 and 1,27 for weak soils, 0,96 and 1,04 – for moderately firm soils, 0,91 and 1 – for stiff soils; N_γ, N_q, N_c – bearing capacity coefficients; N_0 – vertical load at the edge of a foundation; $P_{in.cr}$ – initial critical pressure on a soil; γ_I – unit weight of a soil below the foundation base; γ_I' – unit weight of a soil above the foundation base; γ_{av} – average unit weight of a soil and a foundation, usually equated 22 kN/m³; η – aspect ratio of a foundation; ξ_γ, ξ_q, ξ_c – foundation form coefficients; ω – stiffness coefficient of a foundation.

It is obvious that the solution (1) in the form of polynomial equation is difficult due to the introduction of empirical coefficients, which are necessary for correct consideration of soil deformation processes in conditions of different soil densities. Therefore, the calculations according to (1) must be carried out by means of successive approximation, which is implemented in the software "BRNL-FI" [11], developed for the automation of calculations according to the proposed method.

3 Experimental section

For the experimental verification of applicability of the considered method to overpasses' foundations design and for controlling the correctness of the entered assumptions [7-9] were conducted the laboratory small-scale (tray) plate-load (stamp) tests. Tests were carried out using the dust sand with layer-by-layer compaction for different presetted soil densities. The load on the stamps was transmitted through the lever device. Their settlement was determined by the dial gauge with scale division equated 0,01 mm.

Consider the problem of determining the dimensions of 2 stamps with the same soil settlement, which is equal to, for example, $S_1=S_2=5$ mm, and the different values of vertical loads ($N_1=0,095$ kN, $N_2=0,13$ kN). Then, using the expression (1), the widths of stamps are equal to $b_1=0,09$ m and $b_2=0,067$ m. For the cylindrical tray, as a rule, round stamps are used. It is necessary to take into account the equivalent area when defining their diameters: $d_1=0,103$ m, $d_2=0,0756$ m. For the tests it is equated: $\varnothing_1=0,1$ m, $\varnothing_2=0,075$ m; the pressures under their bottoms are respectively $P_1=12,09$ kPa and $P_2=29,42$ kPa.

The calculated data are compared with the results of stamp tests, which are represented in the form of graph $S=f(P)$ (Fig. 2). Analysis of this graph for the given soil settlement $S_1=S_2=5$ mm showed that the pressure under the stamp bottom ($\varnothing_1=0,1$ m) was 13,7 kPa, for another stamp ($\varnothing_2=0,075$ m) – 27,3 kPa. It is obvious that deviations of the experimental pressure values from the calculated P_1, P_2 are minimal ($\approx 10\%$), which confirms the correctness of the introduced assumptions [7-9] and the calculations carried out by the formula (1). Thus, it is possible to preset the allowable value of the soil settlement for a number of being designed foundations and determine their dimensions. The final justification of such decisions for the considered type of structure must be made based on adequacy assessment of the reliability coefficient of the soil base strength.

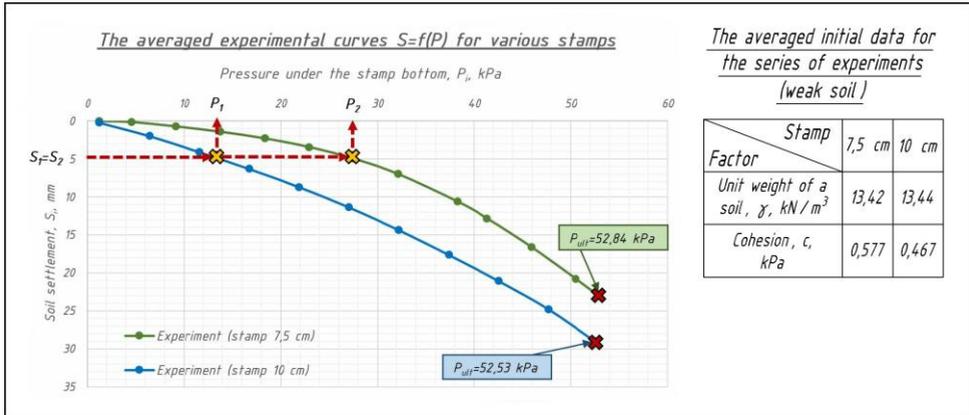


Fig. 2. The averaged experimental curves «soil settlement-pressure», obtained in laboratory tests for various stamps.

4 Calculation example

Consider the example of using the predefined equalized soil settlements method for the calculation of shallow foundations for high-speed railway overpasses. The initial data are presented in Fig. 3.

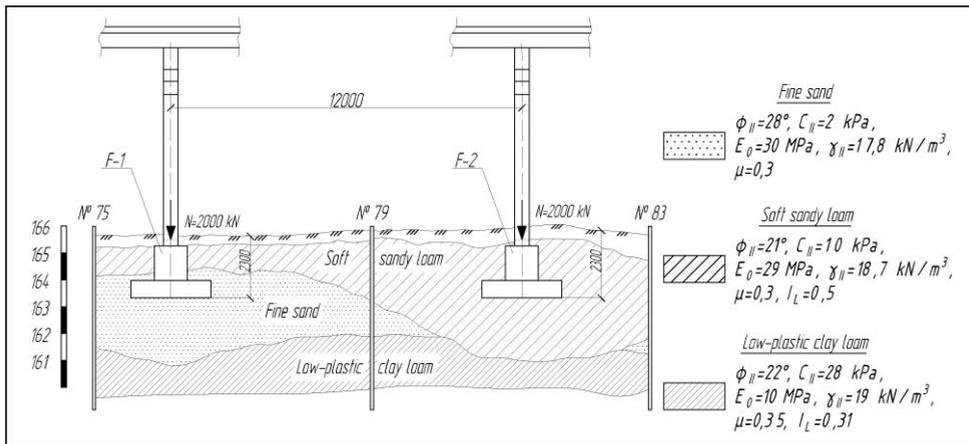


Fig. 3. The initial data for calculation example.

For the purpose of calculation results comparison using the traditional (regulatory) approach and the proposed method the widths of shallow foundations are defined (considering the vertical force N). To simplify the calculations, the horizontal forces and moments are excluded and the over-foundation structures are determined conditionally.

According to the requirements (the project specific standard [4]), the foundation soil settlement of the overpass shall be less than to 20 mm (the ballastless variant of track is accepted), the maximum allowable angle of break in profile – 1‰. The results of the calculations are presented in the Table 1. Thus, the calculation with traditional (regulatory) method, using the elementary layer-by-layer summation of soil settlements, showed the excess of the absolute foundation soil settlement values ($S=3,79$ cm; 2,44 cm) and their irregularity values ($dS/l=1,13\%$) relative to the maximum allowable quantities for overpasses of high-speed railways.

Table 1. The results of the calculation example.

Calculation method	№	P_i , kPa	P_{ult} , kPa	S , cm	dS/l , ‰	b , m	K_r
Traditional (regulatory) [10]	F-1	459	1375	3,79	1,13	2,2	2,7
	F-2	268	726	2,44		3	2,4
Proposed method [11]	F-1	244	1449	2	0	3,2	5,3
	F-2	234	733	2		3,3	2,8

The use of the predefined equalized soil settlements is allowed obtaining the satisfactory solution ($S=2$ cm; $dS/l=0$) regarding requirements [4], however, with large widths of the foundations bases b and with increasing the reliability factor of foundation soil (base) strength K_r . This circumstance is connected with the consideration of the range of design pressures: according to the requirements [10] – it is the $P_i \leq R$; according to the proposed method – $1,1 \cdot P_{in.cr} \leq P_i < P_{ult}$, which makes it possible to use the nonlinear stage of soil deformation. It should be noted that all calculation decisions are satisfactory in respect to the soil bearing capacity ($P_i < P_{ult}$) and have sufficient reliability, which significantly exceeds the requirements [10] ($K_r=1,2$) for buildings of III geotechnical category.

5 Conclusions

1. Use of the predefined equated soil settlements method for design of shallow foundations of overpasses for high-speed railways allows ensuring compliance with sufficiently stringent regulatory requirements related to the absolute values of foundation soil settlements and their irregularity values.
2. Proposed design method takes into account the nonlinear stage of soil deformation, which provides greater range of possible values of presetted foundation soil settlements in comparison with the traditional (regulatory) approach.
3. Consideration of the nonlinear stage of soil deformation suggests the qualitative change in the design method of shallow foundations (using the natural bases) due to the more economical foundation design solutions, which promotes reducing the material and time consumption.
4. Accepting the final decision after the trial design stage in respect to the construction of shallow foundation using proposed method must be made based on adequacy assessment of the reliability coefficient of the soil base strength for the considered type of building.

References

1. Yu.I. Efimenko, V.I. Kovalev, S.I. Loginov, *Railways. The basic course* (UMC-GDT Publishing, Moscow, 2013)
2. V.N. Smirnov, Bridge crossings on the high-speed railways (HSR), *Proceedings “125 years in bridge construction”*, 103-112 (2008)
3. V.M. Ulitskii, A.G. Shashkin, Successful construction of high-speed motorways: the geotechnical constituent, *Transport of the Russian Federation* **2-3(63-64)**, 36-39 (2016)
4. *Technical specifications: Artificial structures on Moscow–Kazan section of Moscow–Kazan–Ekaterinburg high-speed railway mainline. Design and construction norms and requirements* (PGUPS Publishing, St. Petersburg, 2016)
5. *Professional standard of the People’s Republic of China: Code for Design of High-speed Railway (Trial)* (China Railway Publishing House, Beijing (2010)
6. *California High-Speed Train Project: Design Criteria*, California High-Speed Rail Authority (Sacramento, 2012)

7. S.I. Alekseev, *The automated method for foundations calculating considering the two limit states* (SPbPU Publishing, St. Petersburg, 1996)
8. S.I. Alekseev, *Design of foundations using the method of the predefined equated foundation soil settlements* (“OOF “CKS” Publishing, St. Petersburg, 2015)
9. S.I. Alekseev, S.O. Kondrat’ev, *Procedia Engineering* **189**, 126-132 (2017)
10. Building code: SP 22.13330.2016
11. S.I. Alekseev, S.O. Kondrat’ev, BRNL-FT - Design of eccentrically loaded foundations using the predefined equalized soil settlements method, RF Certificate of State Registration of Software No 2017613015 (2017)