

Calculating methodology of large base slabs: compressible strata capacity and foundation settlement

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Abstract. The paper focuses on determining foundation active zones and calculating foundation settlement which is the question of great scientific and practical interest. According to existing methodologies, researchers apply the theory of homogeneous isotropic linear-deformable medium to determine the deformation of soil foundations. In this study the authors propose to use the theory of soils compression seal and its one-dimensional problem solution to calculate the sediment of large base slabs. To justify this methodology, the authors specify the minimum size of foundation slabs. They analyze the Boussinesq's Formula and prove that compacting pressure is evenly distributed throughout the area of the slab bottom. The researchers delimit concepts of the active zone and the compressible strata. It is assumed that the compressible strata is a part of the active zone. The existing methods on calculating compressible strata capacity introduced by N.A. Tsytoich and K.E. Egorov (SP 22.13330.2016) are also analyzed in the paper. Besides, formulas of determining compressible strata capacity and of calculating slab foundation settlement are presented. Calculation results of this methodology and the method suggested in the existing code specification (CS) are produced and compared. The researches come to the conclusion that, according to CS, compressible strata capacity increases with the increase of foundation space under the same load. This corresponds to the theory of linear-deformable half-space. The authors believe that the size of slab foundation settlement depends only on the compacting pressure capacity (which coincides with the Winkler's hypothesis), and on the properties of foundation soils. The authors assign the application area of the spatial problem solution for calculating foundation settlement.

1 Introduction

The issues of the actual stress distribution under a foundation base were dealt with by N.A. Tsytoich, K.E. Egorov, P.A. Kononov, P.I. Dranishnikov, H.R. Hakimov, Yu.F. Tugaenko, V.N. Golubkov, V.A. Kuzmitskin, Yu.I. Dudenko [1-5].

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At the moment the determination of compressible strata capacity and foundation settlement is carried out by the method SP 22.1330.2016. The following hypothesis of the elastic theory is the basis for these calculations: the zone of distribution of tension from the loading attached to the surface of the massif of a soil on depth of the massif is not limited and tends to infinity. However, at a particular depth the tension from the base weight begins to exceed secondary tension from the weight of a construction. Therefore, without a big share of an error there is an assumption that a slight increase in tension at this depth practically does not cause consolidation of the soil. In this regard, the depth of the compressed thickness of the massif of the soil under the base is limited to that layer in which deformations of the soil are slight and therefore can be neglected.

By results of the recent researches conducted by P.A Konovalov, Yu.F. Tugayenko, Yu.I. Dudenko, the conclusion is drawn that the criterion of establishment of power of the compressed thickness is accepted conditionally and does not reflect the actual distribution of deformation in the ground massif. As a result, when calculating, they receive the overestimated depths of the compressible strata, while absolute values of measured movements of the soil appear smaller than calculated.

The authors of the article share the same viewpoint, alternatively offering an original method of power rating of the compressible strata and calculation of foundation settlement which suggests the application of a one-dimensional problem of compressible strata.

2 Materials and methods

To apply the one-dimensional problem of compressible strata it is to prove that base slabs function is subject to the following conditions:

- 1) The load on the soil surface has continuous distribution into all directions, i. e. this can be called "slab foundation".
- 2) The compacting pressure is evenly distributed on the area of a slab base.
- 3) The power of the compressible strata is sufficient for the application of the problem solution.
- 4) The tension is evenly distributed on the compressible strata.

To prove the first point we will refer to works of N.A. Tsytovich [5] who considered that the foundations with an area more than 50 sq.m belong to 'slab foundations'. In turn, K.E. Egorov considers as slab ones only foundations of more than 10 m width [1, 4]. According to the SP 22.13330.2016 slab foundations are only those of more than 20 m width [6, 7]. According to authors of the article the minimum size of the slab foundation side is equal to 14 m as the sum of two flights of stairs (6 m each) and ledges of external axes of the building (1 m each). It should be pointed out that nowadays for 9 floor buildings and higher it is sensible to use a continuous slab under all the building (or section).

For the proof of the second point we will give a formula of determination of contact pressure under a sole of a rigid stamp [4]:

$$P_0 = \frac{P}{2 \cdot \sqrt{1 - \left(\frac{r}{R}\right)^2}}, \quad (1)$$

where P – middle pressure per area unit of the foundation base, kPa;

R – width/length of the rectangular foundation, m;

r – "floating" coordinate, m.

Let us designate boundary conditions:

$$\text{with } r=0, \quad P_0 = \frac{P}{2}; \quad \text{with } R=\infty, \quad P_0 = \frac{P}{2}. \quad (2)$$

Thus, with a very big area of a foundation slab compacting pressure is evenly distributed under its base.

The solvation provided above confirms Vinkler hypothesis [4-6] according to which the local resilient settling in the point is directly proportional to an applied load, i.e.:

$$Z = \frac{P}{C_z}, \quad (3)$$

where C_z – elastic coefficient of the basis, kPa/m;

Z – resilient settling, m;

P – resilient pressure, kPa.

To prove the third point we need to define the terms “compressible strata” and “active zone” (strata).

Active zone H_a is the depth to which tension in the ground massif from a foundation base extends. As the soil tensions are determined by a formula of the elastic theory according to which they continuously fade, the active zone tends to infinity.

Compressible strata H_c is a part of the active zone and it forms the foundation settling. Finding the compressible strata capacity is the major question in mechanics of soils.

According to a primal problem of compression consolidation of soils, the compressible strata capacity is defined as the distance from a foundation base to a surface of “an incompressible layer”. It is a layer, which does not have any settling, or a conditional horizon under which there is a foundation base soil with the infinitesimal size of deformations (they may not be taken into account).

The following are some of the familiar cases of the appointment of compressible strata capacity.

According to N.A. Tsytoovich [5] the compressible strata is called “equivalent layer”, which is equal to:

$$h_y = A \cdot \omega \cdot b, \quad (4)$$

where A – coefficient that takes account of the lateral extension of the soil;

ω – coefficient that takes into account the shape and rigidity of the foundation;

b – width of foundation base, m.

The active zone is defined as the distance from the surface of the load application to the horizon, where the tension is zero:

$$\dot{I}_a = 2 \cdot h_y. \quad (5)$$

According to K. E. Egorov [1, 4, 7] (the method of linear-deformable half-space), the active area is equal to infinity, and the compressible strata is calculated by the formula:

$$\dot{I}_{\bar{n}} = (\dot{I}_0 + \psi \cdot b) \cdot K_p, \quad (6)$$

where H_0 и ψ - accepted respectively equal for bases, consisting of silt-clay soils

9 m and 0.15; Sandy soils – 6 m and 0.10;

b – foundation base width, m;

K_p – coefficient taken equal to 0.8 at an average pressure under the foundation base of 100 kPa, and equal to 1.2 – if 500 kPa.

In accordance with the provisions of SP 22.13330.2016 [7] the compressible strata under the base of slab foundations is a part of the active zone and is defined as the distance from the surface of the load application to the horizon, where the sealing pressure is no more than 50% of natural pressure ($\sigma_{zp} \leq 0,5 \sigma_{zg}$).

According to the authors of the article, the active area is a distance from the surface of the load application to the horizon, where the equality is:

$$P = \gamma \cdot H_a, \tag{7}$$

where γ - specific gravity, kN/m^3 ;

H_a – power of an active zone, m;

P – pressure from the weight of buildings, kPa.

On the fourth point we cite Prof. N.A. Tsytoich [5], who points out that the capacity of compressible strata, being less than $b/2$ without a substantial error, is enough for application the one-dimensional problem solution of soils compression seal to calculate the sediment of large base slabs.

To demonstrate that compacting pressure is evenly distributed throughout the area of the slab bottom you are to examine two figures from the book by N.A. Tsytoich [5]. As you can see from Figure 1 and Figure 2, according to N.A. Tsytoich [5], vertical compressible pressure under the foundation base is distributed more evenly as it approaches the uncompressible layer.

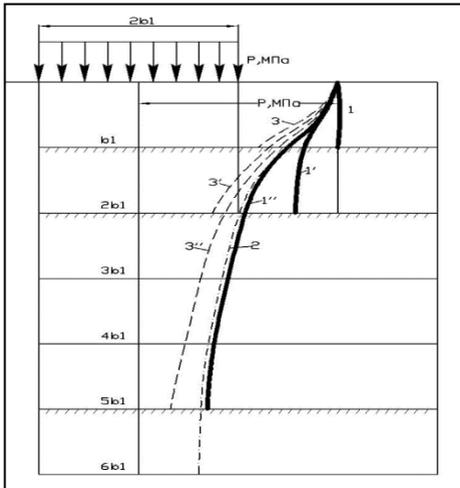


Fig.1. Plots of distribution of maximum compressive stresses under the center of a flexible uniformly loaded strip in the soil layer of bounded thickness b_1 , $2b_1$, and $5b_1$. 1-in the presence of underlying incompressible rock; 2- for a homogeneous half-space; 3- for an inhomogeneous layer with increasing soil compressibility in depth.

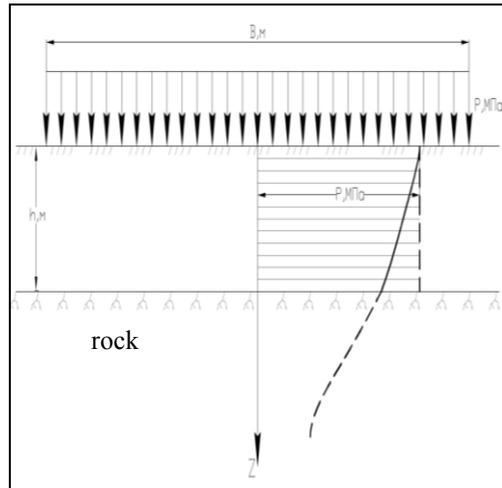


Fig.2. Scheme of application of the one-dimensional compaction problem for structures that occupy a large area in the plan and are built on a layer of compressible soils, underlying rock, with little power of the soil layer (at a thickness of $h \leq b / 4$ and with a known approximation $h < b/2$).

Using the previously described motivation about the possibility of applying the problem solution of soils compression seal to calculate the sediment of large base slabs. We are showing below a comparison of the above parameters, calculated in accordance with SP 22.13330.2016 [7] and according to the method proposed by the authors.

3 Results

To calculate the sediment of the foundation the following formulas were used:

1) according to [7]:

$$S = \beta \cdot \sum_i^n \frac{G_z \cdot h_i}{E_{0i}} \tag{8}$$

2) according to the authors of the article:

$$S = P \cdot H_c \cdot \frac{\beta}{E_{0i}} \tag{9}$$

In depth calculations for all foundation slabs it was taken equal to 3 m. The base included three geotechnical item indicators of physical and mechanical properties of soils, which are presented in Table 1.

Table 1. Initial data for definition of raft Foundation and the value compressible column.

Properties	GTI 1	GTI 2	GTI 3
Layer capacity, m	5.00	4.00	20.00
Specific gravity, kH/m ³	17.60	18.20	19.40
Humidity, of piece	0.18	0.21	0.25
Yield point, of piece	0.33	0.34	0.42
Plastic limit, of piece	0.19	0.18	0.21
Plasticity number, of piece	0.14	0.16	0.21
Flow index, of piece	<0	0.31	0.19
Corner of inner friction, degree	18.00	19.00	17.00
Specific coupling, kPa	18.00	20.00	24.00
Module of deformation, MPa	10.20	11.00	12.50
Soil name	solid loam	low-plastic loam	semisolid clay

For foundation soils within the compressible strata the averaged values of the specific gravity and the module of the overall deformation were calculated:

$$\gamma = \frac{\gamma_1 \cdot h_1 + \gamma_2 \cdot h_2 + \gamma_3 \cdot h_3}{h_1 + h_2 + h_3}, \quad E = \frac{E_1 \cdot h_1 + E_2 \cdot h_2 + E_3 \cdot h_3}{h_1 + h_2 + h_3} \tag{10}$$

where h_i – height of i layer, m;
 γ_i – specific gravity of i layer, kH/m³;
 E_i – deformation module of i layer, MPa.

The compressible strata capacity was defined:

1) According to the method SP 22.13330.2016 [7] - as far as the boundary layer, where there was a natural ratio of runs and additional pressures:

$$\sigma_{zpi} = 0,5 \sigma_{zgi} \tag{11}$$

2) According to the method of the authors of the article - where the boundary is the horizon, with the running condition (7) : $P = \gamma \cdot H_a$.

From where it follows that the compressible strata:

$$H_c = \frac{P}{\gamma} - d \tag{12}$$

where d – the depth of the underlay of the foundation slab, m.

The definition of raft foundation and the value compressible column according to CII 22.13330.2016 [7] and the method of the article’s authors are represented in Table 2.

Table 2. Definition of raft Foundation and the value compressible column.

Pressure, kPa	Calculation parameters	Method									
		SP	Authors	SP	Authors	SP	Authors	SP	Authors	SP	Authors
Slab size, m		14×14		18×18		22×22		26×26		30×30	
80	capacity, m	11.2	6.8	11.7	6.8	12.4	6.8	13.5	6.8	14.4	6.8
	settlement, cm	9.4	5.4	10.5	5.4	11.5	5.4	12.7	5.4	13.6	5.4
100	capacity, m	12.0	7.9	12.6	7.9	13.4	7.9	14.7	7.9	15.8	7.9
	settlement, cm	11.1	7.0	12.5	7.0	18.8	7.0	15.2	7.0	16.5	7.0
120	capacity, m	12.7	9.0	13.5	9.0	14.4	9.0	15.7	9.0	17.0	9.0
	settlement, cm	12.8	8.8	14.6	8.8	16.1	8.8	17.8	8.8	19.5	8.8
140	capacity, m	13.4	10.0	14.2	10.0	15.3	10.0	16.8	10.0	18.0	10.0
	settlement, cm	14.5	10.7	16.6	10.7	18.5	10.7	20.6	10.7	22.4	10.7
160	capacity, m	13.9	11.1	14.8	11.1	16.1	11.1	17.7	11.1	19.1	11.1
	settlement, cm	16.2	12.8	18.6	12.8	20.9	12.8	23.3	12.8	22.5	12.8
180	capacity, m	14.5	12.2	15.5	12.2	16.8	12.2	18.5	12.2	20.1	12.2
	settlement, cm	17.9	15.2	20.7	15.2	23.3	15.2	26.1	15.2	28.7	15.2
200	capacity, m	15.0	13.3	16.2	13.3	17.4	13.3	19.3	13.3	21.0	13.3
	settlement, cm	19.7	17.7	22.9	17.7	25.7	17.7	28.9	17.7	21.8	17.7
220	capacity, m	15.5	14.4	16.7	14.4	18.1	14.4	20.0	14.4	21.8	14.4
	settlement, cm	21.4	20.5	24.9	20.5	28.2	20.5	31.7	20.5	35.0	20.5
240	capacity, m	16.0	15.5	17.2	15.5	18.8	15.5	20.7	15.5	22.5	15.5
	settlement, cm	23.2	23.4	27.1	23.4	30.8	23.4	34.5	23.4	38.1	23.4
260	capacity, m	16.4	16.6	17.7	16.6	19.4	16.6	21.3	16.6	23.2	16.6
	settlement, cm	24.9	26.6	29.2	26.6	33.3	26.6	37.4	26.6	41.3	26.6

4 Discussion

The analysis of the results (Table 2) of definition of raft foundation and the value compressible column показал следующее:

- according to the calculations of SP 22.13330.2016 [7] compressible strata capacity increases with the increase of foundation space under the same load. This corresponds to the theory of linear-deformable half-space;
- according to the authors' method the size of slab foundation settlement depends only on the compacting pressure capacity (which coincides with the Winkler's hypothesis).

Compressible strata capacity depends on the compacting pressure capacity and the properties of foundation soils. To prove the independence of compressible strata capacity and the slab foundation settlement on their area we are to analyse the dependence received by N.A. Tsytoich [5] and given below (Figure 3). It follows from Figure 3, in case of exceeding the foundation base area equal to 50 m² the graph tends to take a horizontal direction. As a result, with $b > 7$ m the foundation settlement is no longer dependent on the foundation base area but it does depend on the compacting pressure. P.A. Kononov [2] in his works compares results of determining the depth of compressible strata, calculated by different methods. Analyzing the graphs in Figure 4, the following may be noted:

- 1) The research is conducted by the authors in the context of spatial tasks with foundations, having the base of no more than 5 m width.
 - 2) The curve constructed according to Construction Norms and Regulations 2.02.01-83* tends to develop in the horizontal direction for the base of more than 5 m width. It proves that for larger in respect of the bases the compressible strata directly depend neither on the form, nor on the area of the base.
- The argument given above allows to calculate more objectively the compressible strata under the foundation and to simplify calculations.

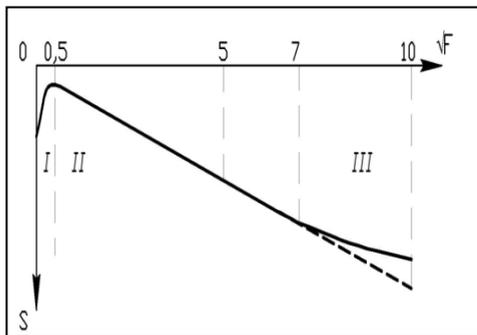


Fig.3. The dependence of precipitation natural soil from the Foundation bred N.A.Tsytovich: I- the area of the small squares of the load up to 0,25 m², II – region of the occupancy of 0,25-0,5 m² up to 25,0-50,0 m², III – more than 25,0-50,0 m².

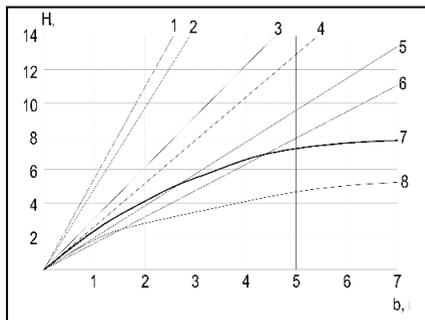


Fig.4. Dependence of capacity of compressible strata of the soil from the size of a square Foundation defined via methods: 1-V.A.Florin; 2-Plageman-Langer; 3-N.A.Tsytovich; 4-Rosenfeld; American method; 6-E.F.Vinokurova; 7- SNiP 2.02.01-83*; 8-SNiP II-16-76.

We will bring some reasonings why the area of the base influences the compressible strata capacity. Let us imagine two foundations of small sizes, for example, of $b=1$ m width, located at the considerable distance from each other and transferring the identical pressure of p (Fig.5) to the basis. Under each foundation, due to loading, the compressible strata were created and they received identical settlements. Further, we will bring these foundations to each other.

There is a question: whether there will be an increase in the compressible strata and settling under a new foundation of $b=2$ m width? Answer: the settling of the common base of $b=2$ width will be equal to the settling of each small foundation. It is explained in the following way: with the increase in the loading area of the identical pressure p an additional volume of soil appears underneath which will perceive this additional loading.

In conclusion, we will consider the dependence of the relative capacity of the compressible strata H_c/b on the width of a foundation slab b for one type of the soil and the middle pressure under a foundation base.

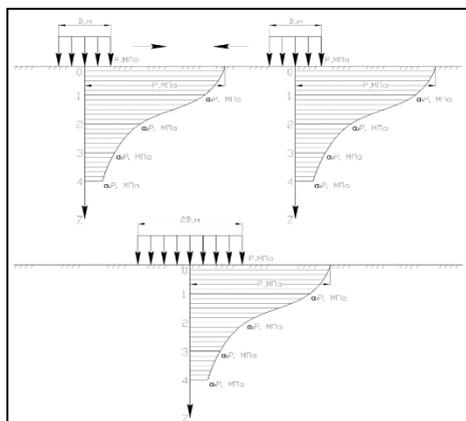
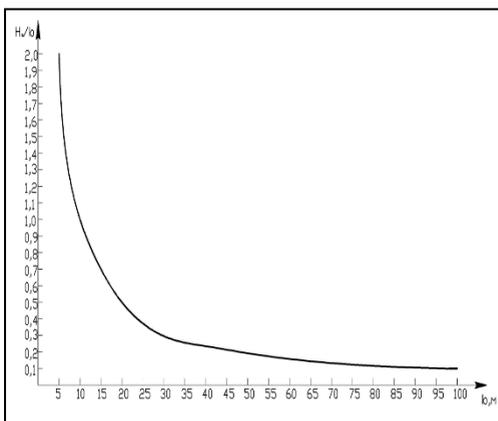
Input data for calculation: $\gamma=20$ kN/m³; $p=200$ kPa; $H_c=P/\gamma=10$ m.

Results of determination of the relative capacity of the compressible strata H_c/b from the base width b are presented in Tab. 3 and in Figure 6.

The analysis of the received results showed that with a slab base width $b \leq 10$ m the compressible strata is a part of the active zone, and with the width of $b > 10$ m – the compressible strata and the active zone are identical. Therefore the border between the application area of the spatial problem and the one-dimensional problem can be considered the base width of $b=10$ m.

Table 3. The results of determining the relative value of the compressible strata.

Foundation width, b , m	5	10	15	20	30	40	50	100
Compressible strata, H_c , m	10	10	10	10	10	10	10	10
Ratio of compressible strata and foundation width H_c/b	2	1	0,7	0,5	0,3	0,25	0,2	0,1

**Fig.5.** The plot of distribution of compressive vertical pressures in the case of increasing the size of the sole of the Foundation without changing the compacting pressure.**Fig.6.** Dependence of the ratio of compressible thickness and size of the Foundation

5 Conclusions

The theoretical researches allow to draw a conclusion on an opportunity of application of the method of the compressible strata depth and the foundation settling offered by authors. The authors proved that the compacting pressure is evenly distributed throughout the area of the slab bottom. The notions “active zone” and “compressible strata” are differentiated.

The authors suggested the method of definition of compressible strata capacity and calculation of slab foundation settling. It is found out that according to the authors’ method the size of slab foundation settlement depends only on the compacting pressure capacity and soil properties of the foundation. The authors assign the application area of the spatial problem solution for calculating foundation settlement. Further, the experimental confirmation of the theoretical research on the test stand is planned.

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