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COMPRESSIBLE THICKNESS DEPTH DETERMINATION UNDER DIFFERENT CALCULATION METHODS OF THE SETTLEMENTS ACCORDING TO NATIONAL AND EUROPEAN STANDARDS

The comparison of the compressible thickness values and the settlements values according to the cone penetration test data in accordance with the current regulatory documents of the Belarus Republic and EUROCODE 7 «Geotechnical design» (part 1, 2) is presented. Two calculation methods of the foundation settlement for the limiting state of SLS and two methods for calculating of the settlements according to National standards are considered according to European norms. The ratios of the compressible thickness and the upset distances are determined using different calculation methods according to European and National standards. The proportions of the compressible thickness and the settlements values for different types of foundations are determined according to European and National standards.

***Keywords:** compressible thickness, cone penetration test, foundation settlement, method of layer by layer summing up, method of equivalent layer, Schmertmann's method.*

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ВИЗНАЧЕННЯ ГЛИБИНИ СТИСЛИВОЇ ТОВЩІ ПРИ РІЗНИХ МЕТОДАХ РОЗРАХУНКУ ОСІДАНЬ ЗА НАЦІОНАЛЬНИМИ ТА ЄВРОПЕЙСЬКИМИ НОРМАМИ

Наведено порівняння величин стисливої товщі й величин осідань за даними статичного зондування згідно з чинними нормативними документами Республіки Білорусь і EUROCODE 7 «Geotechnical design» (part 1, 2). Розглянуто відповідно до європейських норм два методи розрахунку осідань фундаменту для граничного стану SLS і два методи розрахунку осідань за національними нормами. Визначено співвідношення величини стисливої товщі й величини осідань при різних методах розрахунку за європейськими і національними нормами. Установлено співвідношення величини стисливої товщі та величини осідань для різних типів фундаментів за європейськими і національними нормами.

***Ключові слова:** стислива товща, статичне зондування, осідання фундаменту, метод пошарового підсумовування, метод еквівалентного шару, метод Шмертмана.*

Introduction. At present, the design of buildings and structures foundation is based on the foundation bases calculations under limit states. In many cases, it is sufficient to use the methods of calculation based on the simplest models of soil behavior under load: the theory of limit equilibrium - for calculations taking into consideration the bearing capacity and the theory of linear deformation – for calculations according to deformations. However, in a number of cases, such approach leads to excessive reserves when the buildings' design or, in particularly difficult cases, it is insufficient for project objectivities.

According to Vynnykov Yu. L. [13] they point out the following models of: linearly deformable surroundings, nonlinearly elastic, the theory of limit equilibrium; elastic-plastic surroundings and the plastic flow theory; and those that are based on the concept of critical state of ground coat, etc.

In models of linearly deformable surroundings [1 – 4, 13], apart from one batch of ground coat and linear dependence between stresses and deformations under load, only its general deformation is considered not specified by elastic and plastic components. The first assumption makes it possible to use the elasticity theory when stress calculations in the solid, and the second, having the known stresses, makes it possible to determine the finite deformations of the primary structure.

The question of present interest in the field of geotechnics is to determine the value of the compressible thickness of the foundation base. The depth of the compressible thickness is one of the boundary conditions on which the value of the foundation settlement depends.

The depth of the compressible thickness depends on many factors [15]:

– width of the bottom of foundation, shape, rigidity, depth of its laying;
– pressure on the bottom of foundation and its depth distribution;
– ground condition and properties;
– groundwater level;
– growth rate of excess pressure at various depths;
– values of structural strength of soil etc.

The effect of the strength characteristics of the soil on the amount of the compressible thickness will be visible under loads that exceed certain level, when the value of the compressible thickness ceases to depend on the loads acting on the foundation base. As in the National and European normative documents [1 – 4] it is envisaged to apply the theory of linear deformation wherein the average pressure under the base of the foundation should not exceed the limit when the force deformation relationship $S = f(p)$ is close to linear, so the depth of compressible thickness will not depend on the strength characteristics of the foundation base.

Konovalov P.A. [12] divides the determination various calculation methods of soil thickness into three groups. The first group includes compressible foundation thickness determination methods without considering settlement calculation the compression of those frost blanket courses where the additional vertical pressures from the loads on the foundations constitute a certain constant fraction of K from these layers natural pressure on the roof.

The second group includes the methods where the value of compressible thickness depends on the ratio of layers deformations at its boundary. The third group includes the techniques that cannot be referred to the first and the second group.

There is no single method to determine the depth of the compressible thickness either in National or European normative documents [1 – 4]. In the most methods of calculation of the settlement, the depth of the compressible thickness is limited by that soil layer where the deformations are insignificant and, therefore, they can be not considered.

To calculate the foundation settlement and to determine the depth of the compressible thickness in National normative documents three methods are presented [1, 2]:
1) the method of layer by layer summing up using the computational scheme of linearly deformable half-space, limited by the conditional depth of the compressible thickness H_c;
2) the finite thickness linearly deformable layer method;
3) the equivalent layer method.

In the method of layer by layer summing up, the lower boundary of the compressible foundation's thickness is limited by the depth $z = H_c$, on the ground of the following conditions:

a) when $b \le 5$ m – $\sigma_{zp} = 0{,}2p_{zg}$;

b) when $b > 20$ m – $\sigma_{zp} = 0{,}5\, p_{zg}$;

c) when $5 < b \le 20$ m – σ_{zp} are taken according to the linear interpolation of values $0{,}2\, p_{zg}$ and $0{,}5\, p_{zg}$,

where σ_{zp} – is the additional vertical normal stress at depth $z = H_c$;

p_{zg} – is a vertical pressure of sole weight;

b – is the width of foundation bottom.

If within depth H_c, determined according to the above mentioned conditions, a layer of soil with a strain modulus $E > 100$ MPa underlays, so the thickness of the compressible layer is taken up to the top roof of this soil.

If the lower boundary of the compressible thickness is in a layer of weak soil with a strain modulus $E < 5$ MPa or such layer lies beyond of the specified boundary at depth not exceeding the width of the foundation b, the found value H_c increases up by the thickness of this layer, and the most minimum value is taken for H_c, corresponding to the weak underlying bedrock or the depth where the condition $\sigma_{zp} = 0{,}1p_{zg}$ is satisfied.

When using the calculation of settlement by the equivalent layer method, on the assumption of the triangular diagram of the pressure distribution at the foundation base, the depth of the compressible thickness is determined by the formula 5.48 [2]:

$$H = 2 \cdot h_э = 2 \cdot A\omega \cdot b \tag{1}$$

In this case, the depth of the compressible thickness does not depend on the load transferred to the foundation.

In Eurocode 7 [3, 4] there is no unified approach in determination of foundation bases settlements. General requirements and recommendations are provided to determine the ultimate operational states and limit values of foundation displacements. Appendix F describes the simple analytical methods for the calculation of the settlements [3]. In Eurocode 7 part 2 [4] four methods are given (although they are not given in Eurocode 7 part 1 [3]) to calculate the settlements, based on the results of field tests using semi-empirical calculation models (Appendix B2, C2 and D4 [4]). The use of this particular method is usually specified in National Annex to Eurocode.

The general definition of the compressible thickness is given in [3] and does not depend on the foundation settlement calculation method. Usually this depth is taken as effective vertical stresses from the foundation make up 20% of the stresses from the external load. But in many cases this depth is assigned approximately equal to one or double width of the foundation, but this depth can be reduced for lightly loaded wide foundation plates.

Analysis of recent achievements and publications. In the lectures [5 – 7], the examples of subsurface settlement calculation are given. In the work [9] the example of subsurface foundation settlement calculation is given considering consolidation on a multilayer foundation and determination of compressible thickness depth. The authors [8, 10] explain and comment on the articles of Eurocode 7 containing new approaches to design, give the examples of foundation settlements calculation according to European standards. The authors [12, 14 – 15, 17 – 19] give examples of compressible thickness determination using the different calculating of the settlement calculating methods.

Identification of the previously unsolved parts of a common problem. In spite of the increased interest of well-known scientists in the selected problems, compressible base thickness depth determination according to National and European norms continues is relevant. These issues remain undisclosed that requires their further development.

The object of the work is the following – comparison of the results of the compressible thickness values and the foundation settlement values according to cone penetration test data in accordance with National and European design standards.

The basic part. Different methods of determining of compressible base thickness value correspond to one or another technique for calculation of the final foundation settlement. This article discusses the settlement determination method according to the data of cone penetration tests in sandy soil and silty-clayed soil.

Stage 1. Determination of the compressible thickness value when calculating the subsurface foundation settlement in sandy soil.

We are going to consider the simplest case of subsurface interaction foundation with the homogeneous soil base. It is restricted by the problem of final stabilized foundation settlement definition due to the load action transmitted to the soil through the foundation base.

To calculate the foundation settlement, the results of cone penetration test within Vitebsk region, the Republic of Belarus were admitted in this work.

The soil – is sand of medium size, medium strength. Calculation values of soil characteristics:

q_s = 6,53 MPa, E = 26,85 MPa, γ_{II} = 18,8 kn/m^3, c_{II} = 0,001 MPa, φ_{II} = 35,5^o .

Pressure on the base P=100, 150, 200 kPa (given conditionally).

1.1. The determination of compressible thickness depth and the calculation of the pad foundation settlement according to National and European standards.

Pad foundation with the dimensions in terms 3×3 m. The embedment depth is of 2 m.

For the comparative analysis of the compressible thickness determination and the settlement value, three methods for settlement calculation were chosen: the method of layer by layer summing up [3], the equivalent layer method [3], and the Schmertmann's method Appendix D.3 [4]. The final foundation settlement S using the design scheme in the form of a linearly deformable half-space with conditional restriction of the compressible thickness determined by the method of layer by layer summing up according to the formula:

$$S = \beta \cdot \sum_{i=1}^{n} \frac{\sigma_{zp,i} \cdot h_i}{E_i}, \quad (2)$$

where β – is the nondimensional coefficient, equal to 0,8;

$\sigma_{zp,i}$ – is the average value of the additional vertical stress in the i-th elementary layer of the soil, equal to half of the sum of the stresses at upper and lower boundaries of the i-th elementary layer, kPa;

h_i and E_i – are respectively, the thickness and the modulus of deformation of the i-th elementary layer of soil. The thickness of the layer h_i should not exceed 0.4 times of the foundation width;

n – is the number of layers where the compressible thickness of the soil is divided.

Table 1 – Results of the foundation settlement according to the formula (2)

Pressure on foundation kPa	100	150	200
Value of the settlement according to the formula (2), m	0,004	0,009	0,012
Value of the compressible thickness, m	3,17	4,14	4,83

The final impaction settlements (maximum final – for flexible and medium – for rigid foundations), when using the equivalent layer method, are determined using the theory of filtration consolidation on the assumption that the base is a linearly deformable body, according to the formula:

$$S = h_э \cdot m_v \cdot p_0 , \tag{3}$$

where m_V – is a coefficient of relative compressibility of the ground coat of a homogeneous base,

p_0 – is an additional pressure at the level of the bottom of foundation, MPa;

$h_э$ – is the depth of the equivalent layer, m, is determined by the formula:

$$h_э = A_\omega \cdot b , \tag{4}$$

where A_ω – is the coefficient of the equivalent layer, accepted depending on the soil type and the shape of the foundation bottom, (table 5.14 [2]);

b – is the width (diameter) of the foundation, m.

Table 2 – Results of the foundation according to the formula calculation (3)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (3), m	0,0085	0,015	0,022
Value of the compressible thickness, m	5,94	5,94	5,94

The third method to determinate the foundation settlement according to the data of cone penetration test is the use of the Schmertmann's method [4, 11] when calculation. The foundation settlement s due to the load q is determined by the formula:

$$s = C_1 \cdot C_2 \cdot \left(q - \sigma'_{v0}\right) \cdot \int_0^{z1} \frac{I_z}{C_3 \cdot E'} dz , \tag{5}$$

where $C_1 = 1 - 0,5 \cdot \left[\sigma'_{v0} / \left(q - \sigma'_{v0}\right)\right]$, $C_2 = 1.2 + 0.2 lg\, t$,

C_3 – is a correcting coefficient depending on the foundation shape (for square foundations C_3 = 1,25 for square foundations, 1,75 for spread foundations) ,

σ'_{v0} – is the initial effective vertical stress at the level of the bottom of a foundation,

t – is the time, year,

I_z – is the factor of the influence of stress,

E' – is the Young's modulus, E' = 2,5 q_c for square foundations, E' = 3,5 q_c for spread foundations

Table 3 – Results of the calculation of the foundation according to the formula (5)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (5), m	0,0048	0,011	0,0165
Value of the compressible thickness, m	6,0	6,0	6,0

1.2. The compressible thickness depth determination and the calculation of the settlement of raft foundation according to National and European standards.

The raft foundation with the dimensions in terms is of 12×12 m. The embedment depth is of 2 m.

Table 4 – The calculation foundation design results according to the formulas (2, 3, 5)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (2), m	0,009	0,021	0,031
Value of the compressible thickness according to the formula (2), m	4,23	6,43	8,32
Value of the settlement according to the formula (3), m	0,034	0,061	0,089
Value of the compressible thickness according to the formula (3), m	23,76	23,76	23,76
Value of the settlement according to the formula (5), m	0,0126	0,028	0,044
Value of the compressible thickness according to the formula (5), m	24	24	24

1.3. The compressible thickness depth determination and the calculation of the settlement of the spread foundation according to National and European standards.

The spread foundation with the dimensions in terms 3×30 m. The embedment depth is of 2 m.

Table 5 – Results of the foundation calculation according to the formulas (2, 3, 5)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (2), m	0,006	0,014	0,021
Value of the compressible thickness according to the formula (2), m	4,5	6,44	7,84
Value of the settlement according to the formula (3), m	0,02	0,037	0,053
Value of the compressible thickness according to the formula (3), m	14,28	14,28	14,28
Value of the settlement according to the formula (5), m	0,0043	0,0097	0,0153
Value of the compressible thickness according to the formula (5), m	12	12	12

Stage 2. Determination of the compressible thickness when the calculation of the subsurface foundation settlements in silty-clayed soil.

The soil – is the stained low-plasticity sand clay having the average strength,. Calculated values of ground coat characteristics: q_s = 1,78 MPa, E = 6 MPa, γ_{II} = 21,4 kH/m^3, W_L = 23,02%.

Pressure on foundation P = 100, 150, 200 kPa (given conditionally).

2.1. The determination of the compressible thickness depth and the calculation of the pad foundation settlement according to National and European standards.

The pad foundation with the dimensions in terms 3×3 m. The embedment depth is of 2 m.

The foundation settlements can be determined according to European standards using different formulas. In this case, the characteristics of the soil were obtained with the help of cone penetration test and in [5] it is said «both semi-empirical and analytical methods of calculation should be used».

The total settlement of the subsurface foundation in silty-clayed soil

$$S_d = S_e + S_c. \tag{6}$$

where S_e – is the immediate settlement according to the formula (7),

S_c – is the soil consolidation settlement according to the formula (8).

For calculation it is applied the formula of the immediate settlement Annex F [4].

$$S = \frac{P \cdot b \cdot f}{E_m} \tag{7}$$

where P – is the pressure imposed to the soil;

E_m – is the design value of the Young's modulus of elasticity. The ratio between the odometer module and the cone resistance is shown in the table D2 [4];

b – is the width of the foundation bottom;

f – is the coefficient of the settlement:

The formulas for the consolidation settlements of the subsurface foundations calculation according to the data of CPT for silty-clayed soil are not available in [3, 4], however, it is suggested to use the formula given in [16]:

$$\Delta H = \sum_{1}^{n} H_1 \left(\frac{C_c}{1+e_1} \right) \cdot \log_{10} \left(\frac{P_1^{/} + \Delta \bar{P}_{1-2}}{P_1^{/}} \right) \tag{8}$$

where C_c – compression index;

n – no. of compressible sublayers used;

e_1 – is the initial void ratio;

$P^{/}_1$ – is the initial vertical effective stress (fig.1.);

$\Delta \bar{P}_{1-2}$ – is the expected increase in stress (fig.1);

H_1 – is the initial thickness (fig.1).

The pressures distribution method under the bottom of foundation «2:1» is compared fairly well with the theoretical Boussinesq method at depth of the compressible thickness from B to 4B, but it cannot be applied at depth of the compressible thickness from 0 to B [18].

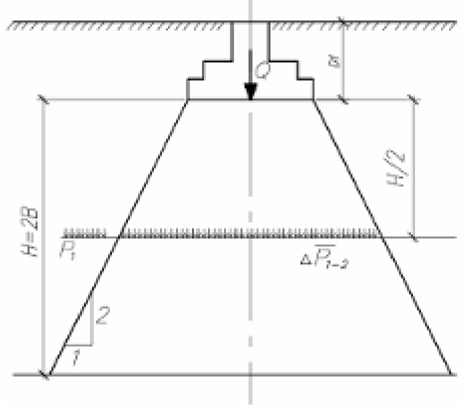

Figure 1 – Distribution of pressures in soil body using the method 2:1

As the depth of the compressible thickness is not regulated in this settlement calculation, so according to [3] it is taken the value of the compressible thickness equal to double width of the basement.

Table 6 – Results of foundation calculations according to the formulas (2, 3, 6)

Pressure on foundation, kPa	100	150	200
Value of the settlement according to the formula (2), m	0,016	0,034	0,054
Value of the compressible thickness according to the formula (2), m	2,86	3,85	4,54
Value of the settlement according to the formula (3), m	0,031	0,058	0,085
Value of the compressible thickness according to the formula (3), m	5,64	5,64	5,64
Value of the settlement according to the formula (6), m	0,092	0,133	0,171
Value of the compressible thickness according to the formula (6), m	6	6	6

2.2. The compressible thickness depth determination and the calculation of the foundation slab settlement according to National and European norms.

The foundation slab with the dimensions in terms 12×12 m. The embedment depth is of 2 m.

Table 7 – Results of foundation calculations according to the formulas (2, 3, 6)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (2), m	0,027	0,077	0,138
Value of the compressible thickness according to the formula (2), m	3,46	5,97	7,96
Value of the settlement according to the formula (3), m	0,124	0,232	0,34
Value of the compressible thickness according to the formula (3), m	22,56	22,56	22,56
Value of the settlement according to the formula (6), m	0,371	0,531	0,69
Value of the compressible thickness according to the formula (6), m	24	24	24

2.3. The compressible thickness depth determination and the calculation of the spread foundation settlement according to National and European norms.

The spread foundation with the dimensions in terms 3×30 m. The embedment depth is of 2 m.

Table 8 – Results of foundation calculations according to the formulas (2, 3, 6)

Pressure on base of foundation, kPa	100	150	200
Value of the settlement according to the formula (2), m	0,023	0,051	0,084
Value of the compressible thickness according to the formula (2), m	3,96	5,86	7,31
Value of the settlement according to the formula (3), m	0,074	0,139	0,205
Value of the compressible thickness according to the formula (3), m	13,56	13,56	13,56
Value of the settlement according to the formula (6), m	0,174	0,248	0,32
Value of the compressible thickness according to the formula (6), m	6	6	6

Results of the performed researches.

Table 9 – The compressible thickness value ratio according to National and European norms

Foundation type, calculation method	Pressure, kPa		
	100	150	200
Sandy soil			
Pad foundation, formula 2+5	0,53	0,69	0,805
Pad foundation, formula 3+5	0,99	0,99	0,99
Spread foundation, formula 2+5	0,375	0,537	0,653
Spread foundation, formula 3+5	1,19	1,19	1,19
Raft foundation, formula 2+5	0,176	0,268	0,347
Raft foundation, formula 3+5	0,99	0,99	0,99
Clay soil			
Pad foundation, formula 2+6	0,477	0,642	0,757
Pad foundation, formula 3+6	0,94	0,94	0,94
Spread foundation, formula 2+6	0,66	0,977	1,218
Spread foundation, formula 3+6	2,26	2,26	2,26
Raft foundation, formula 2+6	0,144	0,248	0,332
Raft foundation, formula 3+6	0,94	0,94	0,94

Table 11 – The settlement value ratio according to National and European norms

Foundation type, calculation method	Pressure, kPa		
	100	150	200
Sandy soil			
Pad foundation, formula 2+5	0,833	0,818	0,727
Pad foundation, formula 3+5	0,177	1,36	1,33
Spread foundation, formula 2+5	1,39	1,443	1,37
Spread foundation, formula 3+5	4,65	3,81	3,46
Raft foundation, formula 2+5	0,714	0,75	0,704
Raft foundation, formula 3+5	2,69	2,17	2,02
Clay soil			
Pad foundation, formula 2+6	0,174	0,256	0,316
Pad foundation, formula 3+6	0,337	0,436	0,497
Spread foundation, formula 2+6	0,132	0,206	0,262
Spread foundation, formula 3+6	0,425	0,56	0,64
Raft foundation, formula 2+6	0,072	0,145	0,2
Raft foundation, formula 3+6	0,334	0,437	0,493

Conclusions:

1. For spread foundations and raft foundations on a sandy base the value of the compressible thickness by the equivalent layer method [2] and by the Schmertmann's method [4, 11] is slightly different, however, in this case the value of the settlement increases more than 2 times for raft foundation, and 3.5 - 4 times spread foundation. Therefore, it is advisable to develop National tables to determine the coefficient that will depend on the value of the compressible thickness and the dimensions of the foundation in the terms.

2. There is no universal approach for determination of the compressible thickness value in European normative documents. Therefore, the designer should choose the value of the compressible thickness considering the recommendations given in the normative documents [3, 4] and in the literature sources given after each section in [3, 4].

3. Using the Schmertmann's method to determinate the settlement for silty-clayed soil [4, 16] it is required to accept the bulk of the compressible thickness for spread foundations and raft foundations within 1 – 1,5 of the width of the foundation base, then there will not be such divergence in the value of settlements according to National and European standards

4. It should be noted that in this article the compressible thickness value and the settlement values determination method according to data of the cone penetration test were considered and, accordingly, when calculation of the settlement by other methods, the compressible thickness values ratio and the settlements values will differ from the above mentioned values.

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