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Qualified method of layer-by-layer summation to define the settlement of foundation

Уточненный метод послойного суммирования для определения осадки фундаментов

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Ключевые слова: упругое полупространство; осадка; модуль деформации; трехосное сжатие

Abstract. The calculation of setting is the main criterion while designing shallow foundations as the complete setting. Methods of defining deformation in soil body show the calculation value of the final settlement which is several times different from the real. It is stated that the deformability of the ground coat is defined to a great extent by the degree of the horizontal intensity caused by natural pressure and by exterior additional loading. Here is offered a specified method of calculation of shallow foundations settlement based on the method of layer-by-layer summing. This method takes into account the separation of the exterior additional loading diagram into component parts which cause elastic and elastic-plastic deformations as well as changing the module of the general deformation of the layers of the earth foundation depending on the state of stress. To test the method there was conducted a comparative analysis with field testing of the ground coat of natural consistency by rigid stamps with its static loading. The calculation of setting by the method offered by the authors has a high convergence with the results of the experiments and reflects the general picture of deformations of the soil body while loading as well as unloading.

Аннотация. Расчет осадки является основным при проектировании фундаментов мелкого заложения. Зачастую методы по определение деформаций в грунтовом массиве показывают расчетное значение конечной осадки в несколько раз отличающееся от действительного. Отмечено, что деформируемость грунта во многом определяется величиной горизонтальных напряжений, возникающих от бытового давления и от внешней дополнительной нагрузки. Предложен уточненный метод расчета осадки фундаментов мелкого заложения, основанный на методе послойного суммирования. Данный метод учитывает разделение эпюры дополнительного внешнего нагружения на составляющие, которые приводят к появлению упругих и упруго-пластических деформаций, а также изменение модуля общей деформации слоев грунтового основания в зависимости от напряженного состояния. Для апробации метода проведен сопоставительный анализ с полевым испытанием грунтов естественного сложения жесткими штампами, при их статическом нагружении. Расчет осадки по методу, предложенному авторами, имеет высокую сходимость с экспериментальными результатами и адекватно отражает общую картину деформирования грунтового массива, как при нагрузке, так и при разгрузке.

Introduction

Calculation of settlement is challenging when designing shallow foundations (SF), since the absolute settlement and the resultant unevenness of settlements are the specified values directly determining serviceability of buildings and structures. Despite numerous methods which were developed by domestic and foreign authors for evaluating deformations in soil body, the calculated value of the final settlement sometimes differs several times from the actual one [1–4]. In engineering practice, in sample

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calculation of SF, the settlements exceeding the specified values may be obtained. Thus, cheaper shallow foundations are to be refused in favor of pile or pile-slab ones, but the opposite situation is possible in weak soils [5–8].

The final settlement is affected by some subjective and objective factors and primarily, the model of foundation and soil compressibility characteristics. When designing foundations, it is the engineer's responsibility to choose a geomechanics or contact model. Any model of soil bed used in the specific problem makes it possible to take into account the features of soil body deformation, but with the assumptions typical for each model [9, 10].

The elastic half-space model (EHM) has been the basic model of soil bed for a long time [11]. Application of the geomechanics model makes it possible to evaluate the stress state in unspecified external loading at any point of the soil body. Under certain conditions in initial loading, deformation of soil body predicted by EHM is a linear function and generally agrees with the experimental data [12–15].

Ignorance of nonlinear behavior of the soil bed, significant exaggeration of distribution capacity of the bed and strong forces concentrated at the edges of the foundation are the obvious drawbacks of this model. Numerous improvements and modernizations of EHM did not provide a universal tool to adequately predict the final settlement of shallow foundations different in areas and levels of loading [16, 17].

According to [18–20], the value of deformation modulus is of great importance for valid description of the deformability of soil body. At present, there exist some procedures to calculate the value; in here, the results can differ by several times. For historical reasons, the deformation modulus evaluated with the stamp, 5000 cm^2 in area, is considered to be the reference in Russia. Due to complexity of the stamp tests, their application in everyday engineering practice is quite difficult. However, as seen from the in-situ tests, the stamp modulus does not guarantee the adequate description of layer-by-layer deformations in depth, particularly when the foundation size significantly exceeds the stamp. Laboratory methods evaluating soil deformability characteristics are widespread, but a designer can obtain different results due to different representations. For instance, the in-situ tests showed that in transition from the constrained modulus to stamp deformation one, the multiplying coefficient m_k does not always correctly illustrate the resulting settlement and all the more, the actual deformation of soil bed in depth [19].

Despite evident values of the deformation moduli obtained by different methods and above all, by the stress state generated during the tests, design models usually include a constant that determines deformability of the layer in the entire area of loading. Given the in-situ test data which show that total compression mainly occurs within a sufficiently thin layer under the foundation while the rest is distributed to a greater depth, some authors propose to divide these zones into the elastic-plastic (large) and elastic (small) deformations. In [17] it is made by taking into account the structural strength of soil p_{str} and bilinear model where deformability in vertical stresses does not exceed p_{str} and is determined by the modulus of elasticity E_e;; in greater stresses – by the modulus of elastoplasticity E_{pl}.

According to [21, 22], the deformability of soil is strongly affected by the stress state of soil body. In their books on testing silty clays and sandy soils in stabilometers G.G. Boldyrev [18] and I.K. Aimbetov [23] show that the soil deformation modulus depends linearly upon the lateral (horizontal) stresses. Thus, E increased 2 times in semisolid sandy loam with the increase of horizontal stresses from 100 to 300 kPa and 3 times – in fine sand.

Thus, the "braking" effect of soil's own weight onto deformation of soil bed can be explained as opposed to the weightless half-space, especially when OCR increases. Thus, deformability of soil is largely dependent upon horizontal stresses being the sum of the horizontal overburden pressure σ_{xg} and horizontal normal component of the stress state σ_{xp} arising from the external load. Therefore, the deformation modulus at each point of the soil bed is an integral parameter of soil properties and its stress state and, consequently, it cannot be constant even in one geotechnical element. If the external pressure increases, the modulus will change under changing stress state and, above all, under the values of lateral pressure.

Methods

Proposed is the qualified method to calculate settlements in shallow foundations, and principally slab foundations, based on the convenient method of layer-by-layer summation adopted in Russian Building Regulation SP 22.13330.2011 [24] and DIN 4019. The proposed method takes into account the elastic-plastic deformation of soils and possesses the following features [25]:

- Separation of the diagram σ_{zp} (Fig. 1) into components: σ^{*}_{zp} – results in elastic and σ^{**}_{zp} – elastic-plastic deformations. The component σ^{*}_{zp} corresponds to the initial stress state in soil bed and may be equal to the dead weight pressure at a given depth $\sigma^{*}_{zp} = \sigma_{zg}$ or part of it $\sigma^{*}_{zp} = k\sigma_{zg}$ or structural strength of soil p_{str}, in turn, their values may be corrected with *OCR.*

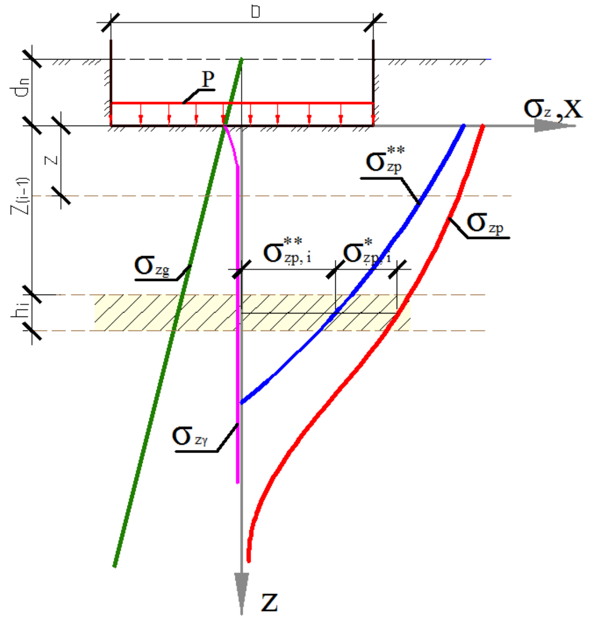

Figure 1. Design diagram of the bed to calculate settlement in a shallow foundation after the proposed method (SP*)

- Consideration of the changed total deformation modulus *E* of soil bed layers due to the increase of load and stress state.

Calculation of the settlement applying the qualified method (SP*) in a construction pit less than 5m in depth is evaluated by the formula:

$$s = \sum_{i=1}^{n} \frac{(\sigma^{**}_{zp,i} - \sigma_{z\gamma,i}) \cdot h_i}{E_i} + \sum_{i=1}^{n} \frac{\sigma^{*}_{zp,i} \cdot h_i}{E_{e,i}}, \qquad (1)$$

where $\sigma^{**}_{zp,i}$ – vertical stress component resulting in elastic-plastic deformation of soil in the *i*-layer due to the average pressure across the foundation footing;

$\sigma^{*}_{zp,i}$ – vertical stress component resulting in elastic deformation of soil in the *i*-layer due to the average pressure across the foundation footing;

h_i – height of the *i*-layer;

E_i – deformation modulus of the *i*-layer of soil across the branch of primary loading;

$E_{e,i}$ – deformation modulus of the *i*-layer of soil across the branch of secondary loading;

It is needed to calculate the total deformation modulus *E* of every given engineering-geological element by means of stabilometers [26]; this makes it possible to consider stress-strain state of the samples in different values of the lateral pressure, when unloading and constructing the function $E = f(\sigma_{xp} + \sigma_{xg})$ (Fig. 2). The approach is advantageous since Poisson's ratio μ, being controversial for soils but influential for their compressibility, is not necessary to be taken into account directly in the formula when calculating the settlement through the non-dimensional coefficient *β*.

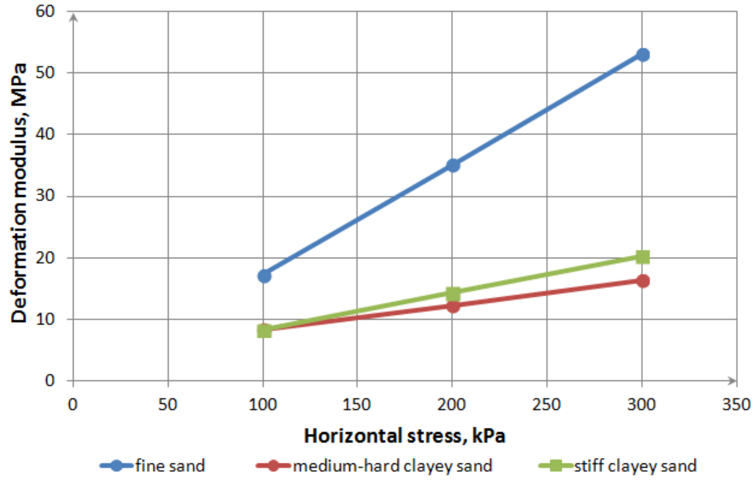

Figure 2. G.G. Boldyrev's dependency diagram $E = f(\sigma_x)$ **obtained after stabilometer tests [17]**

The method aims at calculating the lateral pressures σ_{xg} and σ_{xp} which directly affect the total deformation modulus *E*. In lack of the reliable values of *OCR*, the value σ_{xg} is taken in accordance with geo- or hydrostatics, i.e. $\sigma_{xg} = \sigma_{zg} \dfrac{\mu}{1-\mu}$ (2) and $\sigma_{xg} = \sigma_{zg}$ (3) correspondingly. Hydrostatics is used more frequently, but there is not any consensus here [27]. The value σ_{xp} may be obtained from solutions of the EHM theory. It is necessary to consider that Poisson's ratio μ=0.5, in its classical formulation for elastic half-space, may considerably differ for real soils. Thus, to calculate σ_{xp} after the given dependencies seems to be the most appropriate for soil beds loaded with flat footings.

Results and Discussion

In order to evaluate the proposed method, a comparative analysis was conducted; in here, the in-situ tests were conducted for soils being loaded statically and tested with rigid round stamps, 1200 mm in diameter.

The soil bed of the experimental site was composed of naturally occurred silty clays. Their physical and mechanical characteristics are given in Table 1.

Table 1. Physical and mechanical characteristics of soils at the experimental site

Engineering-Geological Element (EGE)	Depth of layer, m		Soil density, gr/cm²	Solid particles density, gr/cm²	Dry soil density, gr/cm²	Water content, %	Void ratio e, f. u.	Degree of saturation, f. u.	Liquidity index I_L, f. u.	Specific gravity γ, Kn/m³	Angle of internal friction φ, degrees	Cohesion C, kPa	Compressive deformation modulus E_c, MPa	Coefficient m_k, Russian Building Regulations	Calculated deformation modulus E, MPa	Soil
	from	to														
1	0.0	1.0	1.74	2.75	1.54	13	0.79	0.46	<0.0	17.4	15	31	3.3	5.7	19	clay
2	1.0	6.0	1.85	2.7	1.5	23	0.80	0.79	0.62	18.5	15	17	2.7	3.0	8	loam
3	6.0	6.6	19.1	2.65	1.57	22	0.69	0.84	average area	19.1	31	2	25	–	25	sand

Initially, deep marks were installed in the central and edge zones of the soil body at a distance from 0.25 D to 2.00 D (Fig. 3) to record layer-by-layer deformation of soil layers. The stamp surface was loaded through the distribution system across four points. The thruster with a pre-calibrated pressure gauge was used to create pressure in the system (Fig. 4).

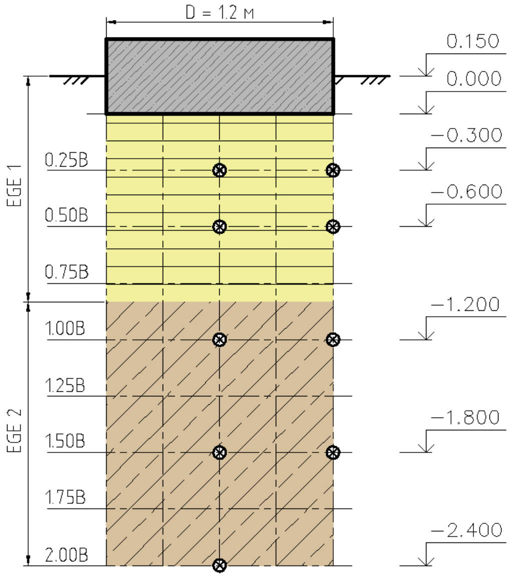

Figure 3. Location of deep marks in soil body

Figure 4. System of load transmission on the stamp surface

To study the effect of lateral squeeze on deformability of soils which occurs in the active zone, the stabilometer tests were conducted in the type A chamber. To obtain the dependencies of the changed deformation modulus upon horizontal squeezing of soil, the samples were tested in confining pressures – 50 kPa, 100 kPa and 200 kPa (Fig.6). The tests resulted in the values of the deformation modulus obtained for additional pressure in different ranges (Formula 1).

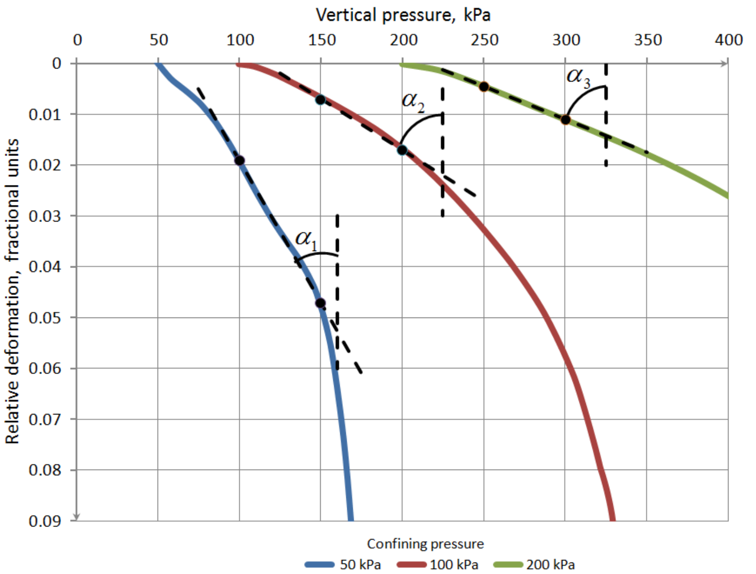

Figure 6. The results of stabilometer tests for EGE №2 – high-plastic loam

$$\boldsymbol{E_1 = tg\alpha_1}, \quad \boldsymbol{E_2 = tg\alpha_2}, \quad \boldsymbol{E_3 = tg\alpha_3} \qquad (1)$$

Dependency of the deformation modulus upon the value of horizontal stresses is of linear character (Fig.7); in here, soil rigidity is increased proportionally due to horizontal pressure. It is necessary to underline that the deformation modulus of high-plastic loams increases 1.5 times faster than that of solid clays. Obviously, this happens due to the structure of soil skeleton.

Rachkov D.V., Pronozin Ya.A., Chikishev V.M. Qualified method of layer-by-layer summation to define the settlement of foundation. *Magazine of Civil Engineering*. 2017. No. 4. Pp. 36–45. doi: 10.18720/MCE.72.5.

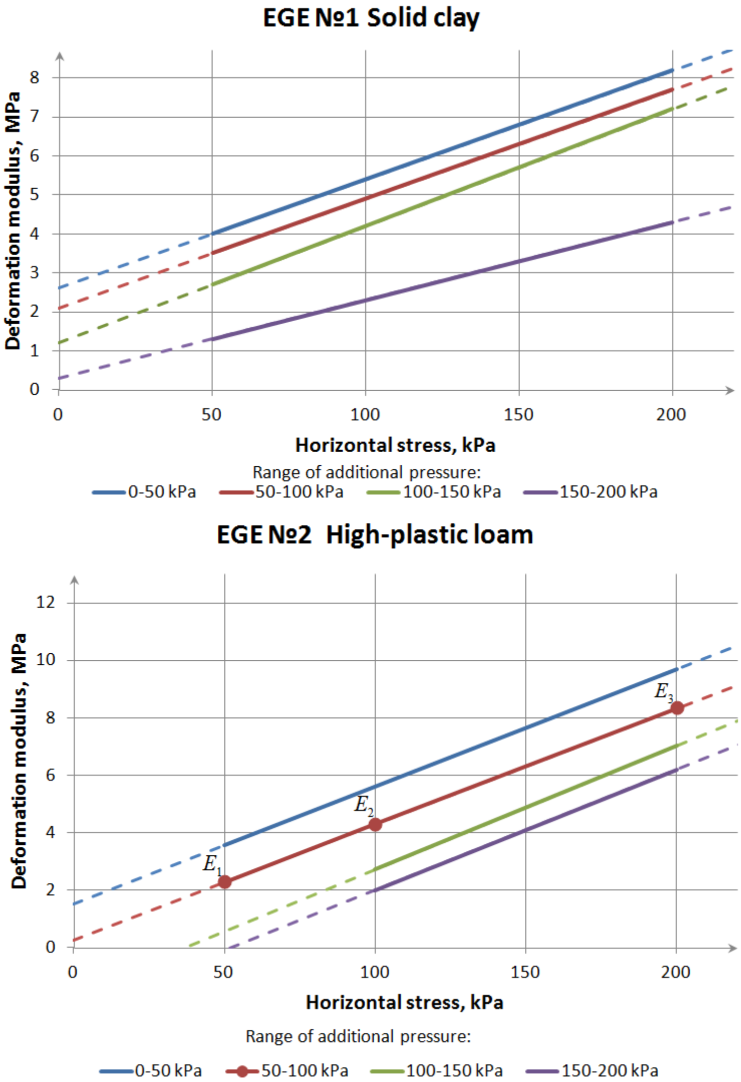

Figure 7. Dependency diagrams of the deformation modulus and the value of horizontal squeezing

The diagrams indicating dependency of the stamp settlement upon vertical pressure were obtained after the in-situ tests (Fig. 8). First, the experimental value of initial critical pressure upon soil was evaluated as if for a flat round foundation after the formula of K.E. Egorov and T.I. Finaeva (*p* = 100 kPa*). The design resistance of soil evaluated by the formula given in Russian Building Regulations SP 22.13330.2011 was *R = 140 kPa*.

As seen from the diagrams, calculation of settlement possesses 40% of allowance across the whole range of loading without reference to the time factor (in *t≈0*) in accordance with the proposed method which applies the dependencies obtained after the stabilometer tests. The normative technique, i.e. the compressive deformation modulus and coefficient $m_{k,}$ resulted in significantly underestimated value of the final settlement as compared to the experimental results. Calculation of settlement by means of DIN 4019 using the results of compressive tests and ignoring the transition coefficients exceeds the experimental values in 90–110 %. In accordance with the investigations [28] carried out on weak water-saturated soils, the settlements continue to increase with time (t → ∞) after normal loading of the soil body and exceed, on average in 20–30 %, the initial settlements which are recorded when loading is stopped. Therefore, the settlements tend to approach the ones calculated after SP* with disagreements to be 5–15 % in the limits of the calculated design resistance *R*.

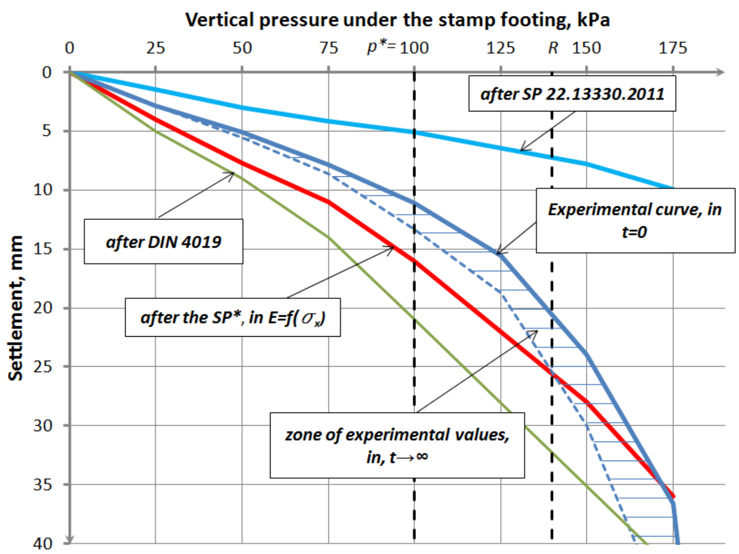

Figure 8. Dependency diagrams of the stamp settlement and vertical pressure

Calculations made after Russian Building Regulations SP 22.13330.2011 revealed considerably underestimated values of final settlements in the foundation model in gradual stepwise loading. Disagreements with the experimental results in the whole range of loading was nearly 100 %; if taking into account the factor of settlements which increases with time, then the results will differ in 2.5–3 times. These scattered results appear due to large values of the deformation modulus which was calculated after the compressive tests and resulted in the stamp modulus with the multiplying coefficient m_k.

The in-situ tests and the proposed technique revealed similar performance of the soil body when evaluating layer-by-layer deformation of soil (Figs. 9, 10). Nearly 70 % of settlement is generated in the surface zone, up to 0.8 D and within the depth of compressible thickness to be 2.0 D, determined in accordance with Russian Building Regulations SP 22.13330.2011. The diagrams of relative and absolute settlements plotted after the qualified method and experimental data obtained from the deep marks disagree in nearly 20 % across the overall thickness of the active zone. It is necessary to point out that weakening of deformations across the depth occurs much earlier than it is given in the solution after EHM theory, i.e. it agrees with the experimental data [29–31]. Calculation diagram of the settlements of soil layers and relative vertical settlement across the overall depth of compressible thickness shows the actual deformation. Difference in 7 mm in settlements on the soil bed surface can be explained by cutting the soil with stamp edges in the process of loading, as given in [17, 21]. This fact can be optionally considered when designing shallow foundations.

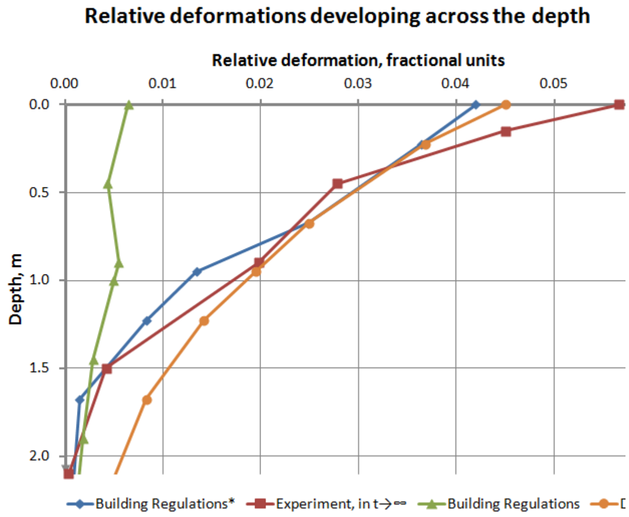

Figure 9. Diagram of relative settlements developing across the depth in p=175 kPa

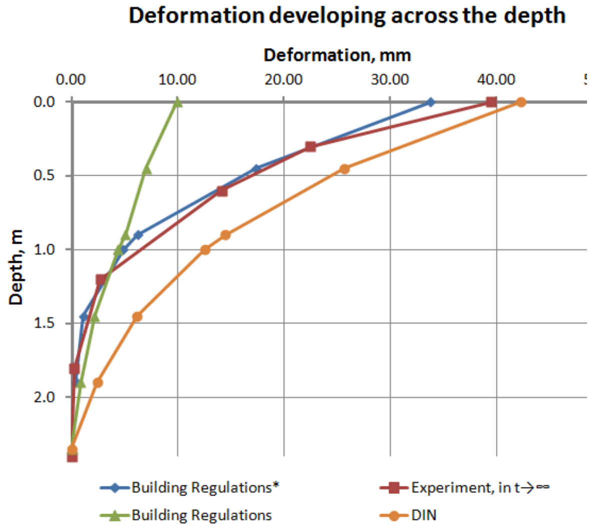

Figure 10. Diagram of settlements developing across the depth in p=175 kPa

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During the in-situ tests, the soil bed loaded statically was gradually unloaded in order to calculate elastic deformations in soil. The value of elastic deformation obtained experimentally was 8 mm, i.e. 18 % from the overall settlement of the stamp. This value almost agrees with the calculated one, i.e. 15 % (6 mm) and thus, “physicality” of the proposed method is proved.

This method does not intend to be used for settlement computation of problematic soil bed and in specific condition. The computation in specific soil coditions needs to further experimental and theoretical research.

Conclusions

The qualified method used to calculate settlements makes it possible to:

- take into account the diagram separated into components due to additional external load acting on the soil bed; this results in elastic and elastic-plastic deformations;
- use the characteristics of deformation obtained after triaxial compression indicators (stabilometers), i.e. the effect of the changed deformation modulus *E* as the horizontal stress function is taken into account; this allows considering the values adapted to specific conditions, e.g. after the value of over-consolidation ratio (OCR), structural strength $p_{str.}$ and specific soil properties;
- ignore the controversial coefficient *β* given in Russian Building Regulations SP 22.13330.2011, since it can result in significant errors when calculating the settlement;
- take into account the elastic-plastic nature of soil; in here, the calculated diagram of absolute and relative settlements of layers across the overall depth of the compressible thickness illustrates the real deformation of soil bed, i.e. "physicality" of the method is shown.

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