

General Calculation Principles of Structurally-Unstable Soils Deformation

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Abstract— A building or a construction is erected on the soil foundation. Its stability, reliability and operation are determined not only by design solutions, but also by soil properties.

The main reason for load-bearing structures' deformation is the uneven or excess foundations slumping. So, the primary problem of foundations design is fulfillment of condition, according to which the calculated deformations must not exceed the permitted values, limited with SP 22.13330.2011 specifications. The foundation slumping can be relatively determined only with the direct proportionality between stresses and deformations of soils, i.e. in non-subsiding soils. In subsiding soils the dependence between the working stress and deformation is of nonlinear character. To eliminate the subsiding properties of loess soil foundation, the presoaking method is used. The authors of the paper present the calculation procedure, which ensures the efficiency of presoaking, based on the approximate calculation scheme. In the case under consideration the method includes calculating additional slumping within the limits of the upper unconsolidated layer of the soaked foundation. The foundation is taken as a two-layer soil: the upper layer is unconsolidated subsiding soil and the lower base layer is consolidated non-subsiding soil, assuming that the vertical normal stress distribution in the presoaked foundation is linear.

Keywords—deformations, slumping, stress, structurally-unstable soils.

I. INTRODUCTION

In the South of Russia and Ukraine, there are widespread weakly sagged ($S_{rbw} = 15$ cm) and moderately sagged ($15 < S_{rbw} < 50$ cm) soils loess strata. These soils are characterized by the development of significant subsidence in the core from the loads of structures (Fig. 1), the micro- and macrostructure of which is shown in Fig. 2, 3.

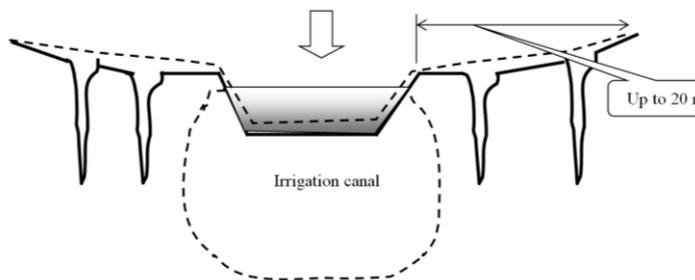


Fig. 1. Characteristic scheme of the subsidence phenomenon of loess soil

The degree of change in strength when moistening subsiding soils through their direct strength characteristics should be evaluated by the coefficient K_c , which is a product of the relationship of adhesion and the angle of internal friction at natural humidity and in the water-saturated state. K_c can also serve as a quantitative characteristic of strength. For fig. 4 its dependence on the relative subsidence, which can be assumed to be linear, is given.

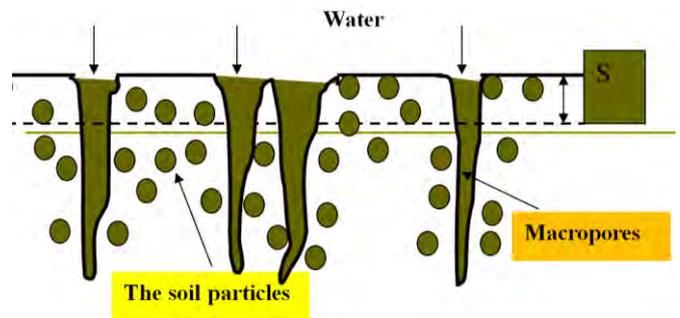


Fig. 2. The scheme of the loess soil macrostructure and the possibility of subsidence in contact with water

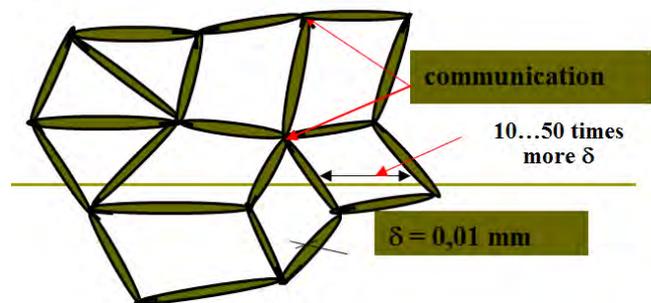


Fig. 3. Microstructure of loess soil

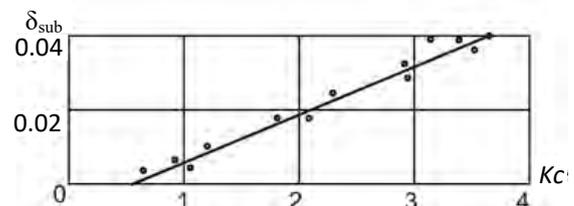


Fig. 4. Dependence of relative subsidence δ_{sub} the degree of reduction of the strength of loess-like loams K_c

Nowadays foundation slumping can be easily determined only with direct proportionality between soil stresses and deformations. In non-subsiding soils this condition is fulfilled if stress intensity along foundation bottom does not exceed active earth pressure. In subsiding soils the dependence between active soil pressure and deformation is non-linear. That is why studying stress state of loess soil foundation with the theory of linear solid (elasticity theory), while determining its deformation, is not accurate [1...6].

Loess soil stress state during calculation of their slumping deformations must be determined by the theory of non-linear deformable solids. As other calculation principles of soil models are underdeveloped, we should take into account a soil linear strain model, that is, follow this condition when determining loess soils stress state judging by the theory of uniform linear solid.

The main problem of loess foundation calculation is meeting the requirement that deformations (slumping, subsidence and sagging), determined by calculation, should not exceed upper limits, restricted by norms (Construction Rules and Regulations 2.02.01-83, Construction Rules 22.13330.2011).

II. RESULTS AND DISCUSSION

It has been determined that introducing equivalent load loess foundation deformation calculation can be done by

calculating common soils slumping. Here, the load along the foundation bottom according to the value of the expected slumping and additional sagging will be overstated [6...13].

Let us study, according to this principle, possible ways of calculating loess foundation. Let slumping values and additional sagging of loess foundation, calculated preliminarily by formulas (1) and (2) according to the dependence (3), correspond to the equivalent loads $P_{eq}^{S_1}$ and $P_{eq}^{S_2}$.

$$S_1 = \frac{\beta \rho_0^m}{1+m} H^{1+m}; \quad (1)$$

$$S_2 = \frac{\beta m h_0 (P_0 - P_s)}{(1+m)(1-\alpha_{h_0})} \left[1 - \left(1 - \frac{1-\alpha_{h_0}}{h_0} h_s \right)^{1+m} \right] \quad (2)$$

$$P_{eq} = \frac{1,65^E (1-\nu) Sa}{(3-4\nu)(1+\nu)}. \quad (3)$$

Determining corresponding values of the equivalent loads, we can use Shleifer-Tsitovich formula:

$$P_{eq} = \frac{ES}{\omega b(1-\nu^2)}, \quad (4)$$

where ω is a coefficient depending on the foundation shape and rigidity whose values are given in [2];

TABLE I. RECOMMENDED VALUES OF SPECIFIC ADHESION, MPA, AND INTERNAL FRICTION ANGLE, DEG. THE LOESS SOIL WITH SR=0.8 AND THE SEISMIC EXCITATION INTENSITY OF J=7-8 POINTS

| W_p | Indicators | Characteristics of soil with void ratio e | | | | |
|-------|------------|---|--------|--------|--------|--------|
| | | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 |
| 0.15 | C_w | 0.016 | 0.013 | 0.011 | 0.009 | 0.007 |
| | ϕ_w | 24°30' | 22°20' | 21°30' | 20°30' | 20°10' |
| 0.17 | C_w | 0.030 | 0.024 | 0.02 | 0.016 | 0.014 |
| | ϕ_w | 21°40' | 21°30' | 20°30' | 20°10' | 19°10' |
| 0.19 | C_w | 0.034 | 0.031 | 0.027 | 0.023 | 0.018 |
| | ϕ_w | 20°40' | 20°10' | 19°40' | 18°50' | 18°15' |
| 0.21 | C_w | | 0.036 | 0.032 | 0.030 | 0.026 |
| | ϕ_w | | 19°20' | 18°40' | 18°30' | 17°40' |
| 0.23 | C_w | | | | 0.035 | 0.031 |
| | ϕ_w | | | | 17°40' | 17°15' |

TABLE II. RECOMMENDED VALUES OF SPECIFIC ADHESION, MPA, AND INTERNAL FRICTION ANGLE, DEG. LOESS WITH SR 0.8 (STABLE SHEAR WITH PRE-COMPRESSION OF SAMPLES)

| W_p | Indicators | Characteristics of soil with void ratio e | | | | | | |
|-------|------------|---|--------|--------|--------|--------|--------|--------|
| | | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 |
| 0.13 | C_w | 0.014 | 0.011 | 0.008 | 0.007 | 0.06 | 0.05 | 0.04 |
| | ϕ_w | 24°50' | 24°25' | 24° | 23°10' | 22°35' | 22° | 21°20' |
| 0.15 | C_w | 0.027 | 0.021 | 0.016 | 0.013 | 0.012 | 0.01 | 0.008 |
| | ϕ_w | 23°40' | 23°25' | 22°50' | 22°25' | 21°50' | 21°20' | 21° |
| 0.17 | C_w | 0.036 | 0.033 | 0.029 | 0.024 | 0.02 | 0.017 | 0.015 |
| | ϕ_w | 22°45' | 22°15' | 21°45' | 21°20' | 20°45' | 20°20' | 19°40' |
| 0.19 | C_w | | 0.037 | 0.034 | 0.031 | 0.028 | 0.024 | 0.02 |
| | ϕ_w | | 22°10' | 21°35' | 20°15' | 19°45' | 19°20' | 18°50' |
| 0.21 | C_w | | | | 0.036 | 0.032 | 0.03 | 0.027 |
| | ϕ_w | | | | 19°15' | 18°40' | 18°30' | 18° |
| 0.23 | C_w | | | | | | 0.034 | 0.031 |
| | ϕ_w | | | | | | 17°40' | 17°25' |

TABLE III. RECOMMENDED VALUES OF SPECIFIC ADHESION, MPA, AND INTERNAL FRICTION ANGLE, DEG. LOESS SOILS IN $S_r \geq 0,8$ (RAPID SHEAR WITHOUT PRE-COMPRESSION SAMPLES)

| W_p | Indicators | Characteristics of soil with void ratio e | | | | | | |
|-------|-------------|---|--------|--------|--------|--------|--------|--------|
| | | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 |
| 0.13 | C_w | 0.016 | 0.013 | 0.01 | 0.009 | 0.007 | 0,006 | 0,005 |
| | φ_w | 23°40' | 23°20' | 23° | 22°40' | 22°10' | 21°50' | 21°30' |
| 0.15 | C_w | 0.03 | 0.024 | 0.019 | 0.016 | 0.014 | 0,012 | 0,01 |
| | φ_w | 22°40' | 22°15' | 21°40' | 21°15' | 20°50' | 20°20' | 20°00' |
| 0.17 | C_w | 0.041 | 0.037 | 0.033 | 0.028 | 0.024 | 0,021 | 0,018 |
| | φ_w | 21°15' | 20°45' | 20°15' | 20°00' | 19°25' | 19°00' | 18°30' |
| 0.19 | C_w | | 0.043 | 0.039 | 0.036 | 0.033 | 0,028 | 0,024 |
| | φ_w | | 20°30' | 20°00' | 18°45' | 18°15' | 18°00' | 17°30' |
| 0.21 | C_w | | | | 0.042 | 0.037 | 0,035 | 0,032 |
| | φ_w | | | | 17°40' | 17°25' | 17°15' | 17°00' |
| 0.23 | C_w | | | | | | 0,042 | 0,038 |
| | φ_w | | | | | | 16°40' | 16°30' |
| W_p | Indicators | Characteristics of soil with void ratio e | | | | | | |
| | | 0.8 | 0.85 | 0.9 | 0.95 | 1.0 | | |
| 0.15 | C_w | 0.009 | 0.008 | 0.006 | 0.005 | 0.004 | | |
| | φ_w | 19°25' | 18°55' | 18°35' | 18°00' | 17°45' | | |
| 0.17 | C_w | 0.017 | 0.016 | 0.013 | 0.012 | 0.011 | | |
| | φ_w | 18°00' | 17°45' | 17°20' | 17°00' | 16°40' | | |
| 0.19 | C_w | 0.021 | 0.019 | 0.018 | 0.016 | 0.014 | | |
| | φ_w | 17°10' | 16°50' | 16°40' | 16°30' | 16°00' | | |
| 0.21 | C_w | 0.028 | 0.024 | 0.022 | 0.019 | 0.017 | | |
| | φ_w | 16°40' | 16°35' | 16°10' | 15°40' | 15°00' | | |
| 0.23 | C_w | 0.035 | 0.031 | 0.028 | 0.023 | 0.021 | | |
| | φ_w | 16°10' | 15°20' | 15°00' | 14°20' | 13°50' | | |

Foundation width.

Formula (4) to determine the values of the equivalent loads is reasonable when calculating footing of rectangular and flexible foundations, as the formula of the equivalent load corresponds to the case of flat deformation of the rigid continuous foundation.

Average pressure along foundation footing is determined by value:

$$P_o = P - \gamma h_{av}.$$

Calculated pressure on the loess footing, according Construction Rules and Regulations 2.02.01-83, is determined by formula:

$$R = \frac{\gamma_{c1}\gamma_{c2}}{K} [M_y K_z b \gamma_P + M_q d_1 \gamma_P^1 + (M_q - 1) d_b \gamma_P^1 + M_c C_P],$$

where γ_{c1} and γ_{c2} are coefficients of the work conditions; b is foundation width.

Depending on the value of the expected slumping and additional sagging, the following cases of loess foundation stress state may happen.

Slumping value S_1 and additional sagging S_2 of the foundation are within the limits when corresponding equivalent loads $P_{eq}^{S_1}$ and $P_{eq}^{S_2}$ totaled with average pressure along foundation footing - P_0 do not exceed the calculated value onto the footing - R , calculated for loess foundation of natural structure and dampness, that is:

$$P_{eq}^{S_1} + P_{eq}^{S_2} + P_0 \leq R.$$

The greater the sum $P_{eq}^{S_1} + P_{eq}^{S_2}$, the less the value of P_0 .

Observing the last equation, the necessary condition of calculating footing by deformations according to Construction Rules and Regulations 2.02.01-83 is fulfilled. It can be recommended to calculate footing deformation according to the formula CRR 2.02.01-83, that is:

$$S = \sum_1^n P_i h_i \frac{\beta}{E_i}. \quad (5)$$

In formula (1.5), P_i is a half-sum of vertical calculated pressures.

Appearing on the upper and lower boundaries of the i -th soil layer, pressure, $P_{eq}^{S_1} + P_{eq}^{S_2} + P_0$ is calculated by the formula:

$$P_y = \alpha (P_{eq}^{S_1} + P_{eq}^{S_2} + P_0).$$

Coefficient α is determined from table 1 supplement 2, CRR 2.02.01-83, depending on the shape and size of the foundation. Thus, the calculation is done by formula (5) of the expected footing deformation, which must be equal or less than the upper limits, that is $S_{calculated} \leq S_{supposed}$.

The upper limit is set according to CRR 2.02.01-83. If the last equation is satisfied, the constructions are erected without additional actions, as on non-subsiding soils. If the equation is not satisfied, different actions to eliminate foundation subsiding are taken. Herewith, according to CRR 2.02.01-83, the method of eliminating foundation sagging is chosen by technical and economic analysis depending on the expected subsiding, nature and purpose of the designed object.

The second characteristic case of foundation calculation can take place in calculating the following equation: $P_{eq}^{S_1} + P_{eq}^{S_2} > R$.

In this case it is necessary to eliminate foundation subsiding.

If in some loess soils there is no sagging because of the soil dead weight, then in other cases of the loess foundation additional sagging takes place. That is why the last equation for soil conditions of the first type (CRR 2.02.01-83) will be:

$$P_{eq}^{S_2} > R.$$

To provide stability and operational integrity of the erected constructions in this case it is necessary to eliminate subsiding only in the surface soil. Apparently there are cases when

$$P_{eq}^{S_2} < R, \text{ as well } P_{eq}^{S_2} + P_0 < R.$$

In both last cases, foundation calculation is based on deformations, and when the main condition of the calculation is not satisfied ($S < S_{supposed}$), according to the degree of the expected deformation, some actions to minimize sagging are taken or some water blocking constructive measures are taken.

In soils of the second type (according to CRR 2.02.01-83) for calculating conditions, the value of the subsiding artificial load is important as it is much bigger than artificial load of additional sagging. That is why this is for soils of the second type:

The following condition is interesting: $P_{eq}^{S_1} > R$.

In this case, foundation state $P_{eq}^{S_1} > R$ is equivalent to the last phase of the stressed state that is progressive soil flow. That is why, foundation analysis by deformations is violated. For the calculation condition to be executable, perhaps it is necessary to eliminate the artificial load on the foundation. It means that it is necessary to eliminate sagging soil properties, before the construction with one of the methods mentioned in CRR 2.02.01-83.

In case of the second type of loess soil, which is met in sufficiently high soil stratum, methods of soil compacting with heavy tamping, constructing soil bedding of forest clayey soils by explosion methods depth compacting with ground piles, are actions minimizing possible sagging. To eliminate sagging soil properties within the whole stratum, the method of preliminary soaking is the most effective (or preliminary soaking with explosions in ground piles) with further compacting of the top soil with heavy tamping, ground piles, ground bedding construction, or tamping the construction pit [14...21].

To eliminate sagging properties in loess foundation bottom layers, let us apply preliminary the soaking method. As the result, starting with the depth determined by formula $\left[g_0 = \frac{1}{\gamma_0} \left(\frac{0.01}{\beta} \right) m, \text{ where } \sigma = \gamma_0 y \right]$; soil sagging happens from gravity weight.

Preliminary soaking efficiency will be provided if at the top soil sagging the true stress from the construction is less or equal to the initial stress. Otherwise, sagging of the compacted soaked bottom layer adds to the under compacted top layer subsiding.

Let us show the order of calculation providing efficiency of the preliminary soaking. Additional soil pressure in the horizontal plan below the foundation base according to CRR 2.02.01-83 is determined by formula:

$$P_y = \alpha(P - P_b),$$

where a is a coefficient of changing additional soil pressure with the account of the foundation base shape determined according to table 1, appendix 2 to the CRR 2.02.01-83, depending on $m = \frac{2y}{a}$ and $n = \frac{1}{a}$.

The last equation may be shown as:

$$P_y = \alpha(P - P_b).$$

Here $\sum N$ is a sum of vertical calculated loads at the level of the foundation base; $h_{average}$ is depth of foundation; a is less side of the rectangular foundation base. From the condition:

$$y = m \frac{a}{2} = y_0 = \frac{1}{\gamma_0} \left(\frac{0.01}{\beta} \right)^{1/m},$$

let us find the width of the foundation base, depending on the value m :

$$a = 2 \frac{y_0}{m} = \frac{z}{m\gamma_0} \left(\frac{0.01}{\beta} \right)^{1/m}.$$

Further we have a condition:

$$\alpha \left(\frac{\sum N}{na^2} - \gamma h_{cp} \right) \leq \sigma = \left(\frac{0.01}{\beta} \right)^{1/m}. \quad (6)$$

For calculation let us take value m and by formula (5) let us find a corresponding value of a . Further, according to the predetermined value m , from table 1, appendix 2 CRR 2.02.01-83, we find coefficient α and check the equation (6). If the condition (6) is not satisfied or has a wide limit, one changes m and calculates again.

Apparently, in this case the foundation is a two-layered soil: the upper is an uncompacted sagging layer and a lower bedding layer is a compacted non-subsiding layer.

That is why, pressure distribution from the construction in the soaked bottom must be determined by solving theory of elasticity for two-layered stratum. It is known that the presence of the less compressed bedding subsoil increases pressure in the top layer (comparing with homogenous base). If in this case we take into account the approximated calculation scheme, considering vertical normal stress distribution in the soaked foundation to be rectilinear, we get:

$$P_y = (P_0 - P_b) - \frac{(P_0 - P_b) - P_{contact}}{y_0} y. \quad (7)$$

Here y_0 is upper limit of the sagging area, determined by formula:

$$\left[y_0 = \frac{1}{\gamma_0} \left(\frac{0.01}{\beta} \right)^{1/m} \right],$$

$P_{contact}$ is the value of normal stress at the contact of two layers, which is found by solving theory of elasticity for two-layered foundation [6...10].

The calculation in this case is aimed at determining additional construction sagging within the top uncompacted soaked layer of the foundation:

$$S_2 = \int_0^{y_0} \beta \sigma^m dy = \int_0^y \beta \left[(P_0 - P_b) - \frac{(P_0 - P_b) - P_{contact}}{y_0} \right]^m dy.$$

Taking the parameters values β , m , average weighted or maximal, within the limits of the studied soil layer, after computing the integral, we get:

$$S_2 = \frac{\beta y_0}{1+m} \cdot \frac{P_{contact}^{1+m} - (P_0 - P_b)^{1+m}}{P_{contact} - (P_0 - P_b)}.$$

Or with the account of the equation for an upper limit of the sagging area, we will have:

$$S_2 = \frac{\beta^{\frac{m-1}{m}} (0,01)^{1+m}}{\gamma_0 (1+m)} \cdot \frac{P_{contact}^{1+m} - (P_0 - P_b)^{1+m}}{P_{contact} - (P_0 - P_b)}. \quad (8)$$

If the soaking is effective, that is, if the fore going calculation requirement is fulfilled, then sagging below depth y_0 is eliminated.

In these conditions, pressure value during the contact of two layers $P_{contact}$, perhaps should be equal to the initial pressure. For this case, the formula (8) becomes:

$$S_2 = \frac{\beta^{\frac{m-1}{m}} (0,01)^{1+m}}{\gamma_0 (1+m)} \cdot \frac{(P_0 - P_b)^{1+m} - \left(\frac{0,01}{\beta}\right)^{\frac{1+m}{n_1}}}{(P_0 - P_b) - \left(\frac{0,01}{\beta}\right)^{\frac{1}{m}}}. \quad (9)$$

It follows from the last equation that soaked loess foundation deformation will be zero if the specific pressure along the foundation base is equal to the initial pressure.

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