Stress-strain state of expansive soils when soaking from above

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Abstract. The article proposes a method for determining additional vertical stresses at any point in the massive of expansive soil, which arise from the weight of unmoistened soil outside the soaking area. A comparison of the results of research stress-strain state of expansive soils when soaking from above, obtained by the proposed method, the finite element method and in accordance with current regulatory documents. The proposed regularity of the distribution of additional stresses from the weight of unmoistened soil outside the soaking area in horizontal sections of the flooded zone is confirmed by the results of numerical studies by the finite element method. For a vertical line passing through the center of the flooded zone, the proposed method gives results that are almost identical to the current regulatory documents. The application of this method allows more accurate determination of the swelling surface, taking into account the unevenness of the geological structure, the shape of the flooded zone and stress fields, and determining the forced displacements of the base or equivalent loads when calculating structures interacting with expansive soil. The conditions are determined under which it is advisable to simulate the impact on the building from the side of swelling soil by equivalent loads acting from the base.

1. Introduction

Expansive soils are those soils that can increase their volume (swell) by more than 4% in the unloaded state when the humidity increases. According to modern representations the main cause of swelling is considered to be absorption of water by the surface of clay particles, increasing thickness of water foils in contacts between soil particles, as well as manifestation of osmotic and capillary processes. The physical nature and mechanism of clay swelling process are reflected in studies [1, 2, 3, 4]. It should be noted that swelling process is reversible: expansive soils when dried are reduced in volume, that is give shrinkage, and with following hydration, they swelling again.

Because of non-uniformity of soils, non-uniformity wetting and drying soil swelling in base of structures is always uneven. At the same time, uneven deformations of base foundation caused by soil swelling can aggravate the uneven deformations caused by the main combination of loads and action, and the distribution capacity of soil [5], decompression of soil in the development of excavation [6] and others factors. Therefore, when designing buildings and structures, it is necessary to proceed from value of raising the base during soil swelling, which is possible with a random, most unfavorable soil soaking at the base.

Determination of non-uniform deformations during construction on expansive soils, as a rule, consists of two stages:
determination of extreme displacement, at some characteristic point of bases, for example in center of flood zone, in center or corners of building, etc.;

approximation of regularity of deformation of bases surface in vicinity of this characteristic point, either by a linear or nonlinear function.

It is also possible to determination displacements at a number of points in base, followed by interpolation on intermediate parts. This method is more accurate, because makes it possible taking into account both the unevenness of geological structure and the unevenness of distribution of stress fields, humidity and temperature, but because of higher labor intensity, it is rarely used.

One of the most modern methods for estimating the stress-strain state of a base from an expansive soil is temperature-humidity analogy proposed by Ter-Martirosyan Z. G. [7]. According to this analogy, the process of swelling clay soil under the influence of external load and changing humidity field is identified with the process of deformation of a continuous medium when exposed to temperature influence.

Modeling of non-uniform deformation of base caused by swelling soil can be performed in various ways. Among them, the most common are:
- equivalent loads acting either on base side or on foundation side, and creating a corresponding curvature of surface [8, 9, 10];
- forced displacements of base [11].

It should be noted that taking into account soil swelling when calculating structures with equivalent loads that coincide in the direction and order of values with loads from the own weight of buildings and structures raises certain doubts, since the redistribution of contact stresses depending on the relative stiffness of Soil-Structure system and can significantly distort the stress-strain state of system elements.

2. Methods

In accordance with current standards [12] rising of bases by swelling soil \( h_{sv} \) determined by formula:

\[
h_{sv} = \sum_{i=1}^{n} \varepsilon_{sv,i} \cdot h_i \cdot k_{sv,i}
\]

where \( \varepsilon_{sv,i} \) – the relative swelling of soil \( i \)-th layer; \( h_i \) – thickness \( i \)-th layer; \( k_{sv,i} \) – coefficient that takes into account the stress state \( i \)-th layer; \( n \) – number of layers that the soil swelling zone is divided into.

Coefficient \( k_{sv} \), included in the formula (1), depending on the total vertical stress \( \sigma_{z,\text{tot}} \) at the considered depth, it is assumed to be equal to: 0.8 at \( \sigma_{z,\text{tot}} = 50 \) kPa and 0.6 at \( \sigma_{z,\text{tot}} = 300 \) kPa, and for intermediate values, it is determined by interpolation.

Lower border of swelling zone \( H_{sv} \) when infiltration of moisture is taken at a depth where the total vertical stress \( \sigma_{z,\text{tot}} \) equal to swelling pressure \( p_{sv} \).

The total vertical stress \( \sigma_{z,\text{tot},i} \) at depth \( z_i \) from the foundations foot (figure 1) determined by formula:

\[
\sigma_{z,\text{tot},i} = \sigma_{z,\text{p},i} + \sigma_{z,\text{q},i} + \sigma_{z,\text{ad},i}
\]

where \( \sigma_{z,\text{ad},i} \) – additional vertical pressure (when soaking on top), which is caused by influence of weight the non-wetted part massive of soils outside the soaking area above the considered depth \( z_i \).
Additional vertical pressure that takes into account the weight of the non-wetted part of soils massive outside the soaking area is determined by the formula:

\[ \sigma_{z,ad,i} = k_{g,i} \cdot \gamma \cdot (d + z) \]  

where \( k_{g,i} \) – coefficient that depends on ratio of geometric parameters soaking area \( L_w/B_w \) and relative depth of layer \( (d+z)/B_w \); \( L_w \) and \( B_w \) – accordingly, a larger and smaller size of soaking area.

Coefficient \( k_{g,i} \) for a vertical that passes through the center of soaking area, it is calibrated in regulatory document for designing bases [12].

### 2.1. Method for constructing the surface of swelling

The parameters of the surface of swelling depend significantly on the size of expansive soils, the shape and area of soaking area. When soaking a large area in the center of surface of swelling, it is perhaps appearance to form a flat part with the maximum value rising of base. The size of flat part is comparable to the size of soaking area. Width surface of swelling \( B_{sw} \) depends on width of soaking \( B_w \) and the distance of spreading of water within the zone of swelling \( H_{sw} \). Outside the flat part of the surface of swelling which is somewhat smaller than \( B_w \), there are curvilinear parts, the curvature of which varies, as a rule, within \( 0.022 - 0.025 \) m\(^{-1} \) (\( R = 40 - 45 \) m).

In this paper, the surface of swelling it is proposed to build using surface rising values defined at various points into account the nonuniformity geological structure of soil massive, flooded zones and stress fields, both from the self-weight soil and external loads (figure 2a).

Regulatory document [12] allow to determine additional vertical pressures from the weight of non-wetted part of soil massive only at vertically, passing through the center of soaked area. Therefore, in order to determine the stresses and climb of surface along other verticals, it is proposed to accept distribution of additional pressures in form of linear triangular diagrams (figure 2b). The area of the diagrams is equal to the mass of the corresponding influencing unmoistened part of the soil mass. When overlaying diagrams on each other, they are summed, including in mutually perpendicular planes.

Since influence of non-wetted areas of soil massive changes when displacement relative to center of soaking (figure 2b) for determine coefficient \( k_{g,i} \) at random point of soil massive, it is proposed as follows.
Figure 2. Schema to definition: a – surface of swelling; b – additional vertical stresses from the weight of non-wetted part of massive of soil; \( \beta \) – water spreading angle; \( \alpha \) – stress distribution angle.

For a rectangular soaking area at any point of soil massive with coordinates \((x, y, z_i)\):

\[
k_{g,i}(x, y) = k_{g,i}(x) + k_{g,i}(y) \tag{4}
\]

where \( k_{g,i}(x) \) and \( k_{g,i}(y) \) – coefficients that take into account the influence of non-wetted parts of soil massive located on both sides of soaking area along the short and long sides, respectively; \( x \) and \( y \) – the distance from soaking center to considered point along the short and long sides of soaking area, respectively; \( z_i \) – depth of considered point from the surface of soil massive.

Both components are determined depending on of which zone of influence not moistened parts of soil massive gets considered point:

- \(|x| \geq 0.5 \cdot B_w + z_i \cdot \tan \beta\) considered point is located on border of moistened soil massive or outside it, respectively \( k_{g,i}(x) = 0 \);
- by \( 0.5 \cdot B_w > z_i \cdot \tan \alpha \) and \(|x| \leq 0.5 \cdot B_w - z_i \cdot \tan \alpha \) considered point is located outside the zone of influence of not moistened parts of soil massive, located on the x-axis on both sides of soaked area, respectively \( k_{g,i}(x) = 0 \);
- by \( 0.5 \cdot B_w > z_i \cdot \tan \alpha \) and \( 0.5 \cdot B_w - z_i \cdot \tan \alpha < |x| \leq 0.5 \cdot B_w + z_i \cdot \tan \beta \) considered point falls within the zone of influence only of nearest not moistened part of soil massive, respectively

\[
k_{g,i}(x) = \frac{z_i \cdot \tan \alpha - 0.5 \cdot B_w + |x|}{2 \cdot z_i \cdot (\tan \beta + \tan \alpha)} \tag{5}
\]

- by \( 0.5 \cdot B_w \leq z_i \cdot \tan \alpha \) and \(|x| \geq z_i \cdot \tan \alpha - 0.5 \cdot B_w \) considered point also falls within the zone of influence only of nearest not moistened part of soils massive, respectively \( k_{g,i}(x) \) determined by formula (5);
- by \( 0.5 \cdot B_w \leq z_i \cdot \tan \alpha \) and \(|x| < z_i \cdot \tan \alpha - 0.5 \cdot B_w \) considered point falls into the zone of influence of not moistened parts of soils massive on both sides of the moistened zone, respectively

\[
k_{g,i}(x) = \frac{(z_i \cdot \tan \alpha - 0.5 \cdot B_w + x) + (z_i \cdot \tan \alpha - 0.5 \cdot B_w - x)}{2 \cdot z_i \cdot (\tan \beta + \tan \alpha)} \tag{6}
\]

The formulas (5-6) do not take into account the influence of not moistened parts of soils massive located at the corners of the watered zone.

The obtained formulas (5-6) were tested for convergence with the dependencies set out in regulatory document [12] for the vertical through the soaking center at different values of the angles \( \alpha \).
and $\beta$. The best convergence for the main control points was achieved at $\alpha=45^\circ$ and $\beta=35^\circ$ (figure 3). For indicated angles values, the formulas (5-6) will take the following form

$$k_{g,i}(x) = \frac{z_i - 0.5 \cdot B_w + |x|}{3.4 \cdot z_i}$$ (7)

$$k_{g,i}(x) = \frac{(z_i - 0.5 \cdot B_w + x) + (z_i - 0.5 \cdot B_w - x)}{3.4 \cdot z_i}$$ (8)

Coefficient $k_{g,i}(y)$ defined similarly, using the formulas (7 – 8) with replacement in them respectively $x$ on $y$ and $B_w$ on $L_w$.

For a round soaking area, the coefficient $k_{g,i}(r)$ can be determined in the same way, where $r$ – distance from the soaking center to considered point in the radial direction.

The analysis of obtained dependencies showed that they more correctly take into account the influence of not moistened parts of soils massive located in direction of long side of soaking area, compared with the dependencies calibrated [1, 12]. (figure 3). This is also confirmed by the presence in later resources [12] corrections of particular table values given in [1], which indicates attempts to correct the influence of more remote not moistened areas of soils massives.

**Figure 3.** The dependence of the coefficient $k_g$ at the axis located in the center of soaking, on the relative depth of the layer $(d+z)/B_w$ at various ratios $L_w/B_w$: solid lines [1, 12]; dashed line according to the proposed method.

When determining deformations caused by soil swelling, the method of layer-by-layer summation along verticals passing at a certain distance from the center of soaking, in each elementary layer, a check is performed - whether this elementary layer falls into the soaked zone and, accordingly, whether there are swelling deformations there. This, if sufficient initial data is available, allows us to take into account not only the trapezoidal shape of soaked zone, but also other possible forms of it.

2.2. Determination of the equivalent load from soil swelling

If pressure on base exceeds the swelling pressure ($p>p_{sw,0}$) and there is no swelling zone in the lower layers, forced displacements caused by soil swelling may be absent. However, for strip and slab foundations, it is possible to redistribute the contact pressures by footing and, as a result, change the forces in foundation structures. In this regard, in this situation, the influence of soil swelling on foundation can be represented as equivalent load acting from the base (figure 4b).
The value of additional equivalent load acting on foot of foundation at the $i$-th point from the side of the base is determined by formula:

$$p_{sw,i} = p_{sw,o} \cdot \frac{h_{sw,i}}{h_{sw,o}}$$  \hspace{1cm} (9)$$

where $h_{sw,o}$ – maximum rising of base with free swelling soil, m; $p_{sw,o}$ – equivalent load in center of soaking zone.

With a known width surface of swelling and maximum rising of base, can determine the approximate radius of curvature of swelling surface (figure 4a) using the formula:

$$R_{sw} = \frac{B_{sw}^2}{8 \cdot h_{sw,o}}$$  \hspace{1cm} (10)$$

In this case, forced displacement caused by swelling soil within the surface of swelling can be taken according to the formula:

$$h_{sw,i} = h_{sw,o} - \frac{x_i^2}{2 \cdot R_{sw}}$$  \hspace{1cm} (11)$$

where $x_i$ – distance from center surface of swelling to the $i$-th point, m.

3. Results and Discussion

To verify proposed scheme the distribution of additional vertical stress from its own weight not moistened part of soils massive and formation of surface of swelling, numerical studies were performed in 2D Plaxis program at different relative depth layer of swelling soil. In this case, the depth $z$ was assumed to be constant, and size of soaked zone in plan changed. Soil model was used is the Mohr-Coulomb model [13, 14, 15]. The swelling was modelled by forced displacements applied to upper boundary of swelling layer within the soaked zone and equal to size of swelling.

Parts of the results of numerical studies are shown in the figures 5.
In accordance with the proposed algorithm and current regulatory document [12], value of surface of climb from soil swelling was determined for various parameters of soaking zone, the depth and characteristics of swelling soil. The obtained dependences of surface of climb in the center of soaking area on its relative dimensions at a constant depth of swelling soil layer ($H_{sw}=10$ m) are shown in figure 6.

Figure 5. Shadings of deformations (at left) and vertical stresses (at right):

a – by $z/B_w = 0.5$; b – by $z/B_w = 1$; c – by $z/B_w = 2.5$; d – by $z/B_w = 5$. 
Figure 6. Dependence of rising of surface in center of soaking area on the relative size of soaking area (solid lines according to the author’s method, dashed lines - [12], $h_{sw}$ – rising of surface that corresponds to soaking over a large area, such as when the water table rises. The study of interaction building with base of swelling soils was performed by the finite element method. At the same time, we considered:

– two ways to model the effects of soil swelling on a building: in the form of forced displacement of bases and in form of additional "equivalent" loads;

– two main schemes of non-uniform deformations of base caused by different locations of soaking source: the building flexion when the soaking source is located under center of building and building deflection when the soaking source is located in the corner (end) of building.

4. Conclusions

1. The pattern of distribution of vertical stresses in the soil massive (figure 5) confirmed the author's hypothesis about the distribution of additional vertical stresses in the horizontal cross section from not moistened part of soils massive in form of close to linear triangular diagrams, with peak values at border of soaked zone.

2. When the relative depth of swelling layer increases, the diagrams of additional vertical stresses is superimposed on each other, as a result of which they are added together.

3. The shape of surface of swelling obtained as a result of numerical studies qualitatively corresponds to the descriptions in [1, 9, 10].

4. The rising of surface in the center of soaking area, determined by proposed algorithm and current regulatory documents, differ by no more than 3%.

5. With an increase in soaking area, the rising of unloaded surface increases and reaches its maximum value with the width of soaking area approximately twice the thickness of swelling zone. At the same time, after the width of soaking area exceeds the thickness of swelling zone, there is a decrease non-uniform deformations of base caused by swelling of soil, and consequently additional forces in building structures.

6. Since the distributional capacity of soil and its decompression in the excavation, as a rule, leads to deflection of building, in this case, the source location for soaking under the corner (end) of building leads to an increase in non-uniform deformation of base, and the source soaking location in center on contrary reduces the non-uniformity of deformation. This is especially noticeable when soaking width is comparable to size of building.

7. When calculating buildings on expansive soils, non-uniform deformations of base caused by swelling should be simulated by forced displacements. Modeling by equivalent loads acting on the
foot of foundation from the base can be used in cases where pressure on the foot of foundation exceeds the swelling pressure and there is no rising of base, respectively.

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