New pile foundation structures for swelling clay soils

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Abstract. The information on the basics of designing pile foundations on swelling clay soils is presented and analyzed. New designs of conical piles and those with a variable cross-section, in which the soil mass swelling is accompanied by the effect of pile pinching, have been developed. Moreover, new pile foundation structures with protective shells involving a calcium elastic rolling member and some rubbing elements like low-friction plastic and metal braces are proposed.

1. Introduction

Swelling clay soils are common for all continents except Antarctica. The works of (Cromko [1]; Fityuş, Smith and Allman [2]; Peredalsky and Ananyev [3]; Mustafayev [4]; Kulchitsky and Usyarov [5]; Al-Homond, Bagma, Husein Malkavi and Bashabsheh [6]; Olson and Langfelder [7]; Gabibov [8]; Day [9, 10, 11]) and others are devoted to the study of deformations of swelling clay soils and structures built on them. Sorochan [12]; Chen [13]; Day [14]; Doroshkevich and Boym [15]; Nelson and Miller [16]; Gabibov [17] and others studied the construction of pile foundations on swelling clay soils.

2. Basics of designing piles on swelling clay soils

When cutting swelling layers of clay soil by piles and deepening them into the underlying swelling stable soils, the rise of the pile foundation will be practically excluded if the condition is met:

\[ N \geq T - \frac{\theta}{k_e}, \]

where \( N \) is the calculated load on the pile, determined with the overload factor \( n=1 \), including the pile dead load; \( T \) is the resultant of the calculated lifting forces acting on the lateral surface of the pile, determined by the results of their field tests; \( \theta \) is the load-bearing capacity of the pile section located in the underlying non-swelling soil under the action of withstanding loads; \( k_e \) is the safety factor adopted in accordance with national building code for pile foundations design.

The stability of piles to the action of tangential swelling forces during the full cutting of the swelling clay strata is determined by the condition:

\[ \tau \cdot F - N - \eta G \leq (m/k_e) Q, \]

where \( \tau \) is the shear force, \( F \) is the resultant of the calculated lifting forces acting on the lateral surface of the pile; \( m \) is the number of piles; \( k_e \) is the safety factor adopted in accordance with national building code for pile foundations design; \( \eta \) is the load-bearing capacity of the pile section located in the underlying non-swelling soil under the action of withstanding loads; \( Q \) is the load on the pile; \( G \) is the weight of the soil mass.

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where $\tau$ is the tangential force of the swelling clay strata acting on the lateral surface of the pile, determined by field tests; $F$ is the calculated area of the lateral surface of the pile located within the layer of swelling clay soil; $N$ is the calculated constant load acting on the pile; $\eta$ is the tangential resistance force acting on the lower section of the pile, located in the layer of underlying non-swelling soil, under the action of the pulling load; $\eta$ is the estimated area of the lateral surface of the pile located in non-swelling soil; $m$ is the coefficient of working conditions; $k_s$ is the safety factor equal to 1, 2; $Q$ is the calculated value of the force preventing the pile from rising,

$$Q = \sum_{i=1}^{n} R F,$$

where $n$ is the number of elementary layers, the swelling clay stratum is broken into; $R$ is the calculated shear resistance of swelling clay soils along the contact surface for the $i$-th layer.

As one can see from the condition (2), in order to increase the stability of a pile when the full cutting of the swelling soil layer takes place, it is necessary either to minimize the effect of the tangential forces of clay soil swelling on the pile lateral area, or to increase the effect of tangential forces of resistance to the pile withstandings loads.

Among the known technical solutions, the first way to increase the pile stability to the action of holding forces during the process of clay soil swelling involves the use of various technical lubricants, as well as movable clips around the lateral surface of the pile.

The second way is associated with increased material costs and comes down to broadening the piles in their lower part and creating the additional reinforcement to prevent their rupture under the action of pull-out forces, accompanying the swelling of the clay mass around the pile.

3. Development of new pile structures erected on swelling clay soils

The author has proposed to use frustoconical piles in swelling clay soils during the full cutting of the swelling soil mass. During this process, the smaller base of piles is facing the surface, while their larger base rests on the underlying non-swelling soil. This type of pile is recommended for soils exposed to frost heaving. In this case, the deformations and swelling forces of the side walls of the boreholes, in which the conical piles are located, prevent the pile from rising when the surrounding soil swells and, contribute to its pinching in the soil mass. When using the indicated conical piles, it is necessary to drill a pilot borehole with a diameter equal to the diameter of the larger pile base. The gap formed after the installation of the pile between the walls of the cylindrical borehole and the conical pile is filled with fine-grained sand or gumbrine (waste from the technical oils purification production). Such a screen made of a non-cohesive and lowly cohesive soil layer allows to remove negative friction from the lateral surface of the pile during deformations of swelling clay mass directed vertically upward.

The author has developed a new design of a reinforced concrete pile for swelling clay soils, which eliminates the main drawback of the previous design, which is the need to drill a borehole equal to the diameter of the larger base of a frustoconical pile.

This pile (figure 1) has a variable cross-section evenly distributed along the height.

Pile 2 is immersed in the pilot borehole 1 with a diameter slightly smaller (2-4 mm) than its maximum diameter. Naturally, the maximum diameter in the pile refers to the numerous broadened sections 5 located in the thickness of the swelling clay soil 3, and to the root part 7 of the pile located in the layer of the underlying non-swelling soil 4. After the pile is submerged, empty spaces 6 are formed between its lateral surface and the walls of the borehole 1 along the entire height of the pile within the thickness of the swelling clay soil 3.

When swelling, the soil in the zones of voids 6 partially or completely penetrates into these voids, as a result, the pile is pinched and the soil mass freely implements its negative energy. The residual force of negative friction, which manifests itself in the contact zones of the broadening 5 of the pile 1, is insufficient to lift the pile.
For a given pile of a new design, condition (2) will have the form:

\[ \tau \cdot F_1 - N - \eta G \leq (m / k_s)Q + cF_2, \]

where \( F_1 \) is the calculated area of the lateral surface of the pile in the broadening zones 5; \( F_2 \) is the calculated cylindrical surface formed in the zones between the broadening of the pile within the swelling strata; \( c \) is the calculated shear force of wet clay soil.

As it can be seen from condition (4), the wider the height of the swelling zone, the higher the value of the total shear force of the swelling clay soil required to lift the pile. The tangential forces acting on the pile greatly decrease, since the lateral surface of the pile in contact with the borehole walls within the swelling strata is sharply reduced as well.

In this design, there is no need to drill a pilot borehole with a diameter higher than the average diameter of the pile, also, there is no need to increase the length of the root part of the pile. It should also be noted that the lateral surface of the pile, in contact with clay soils, contributes to the implementation of one of the main properties of pile foundations, which consists in transferring part of the load on the soil mass along the height of the pile.

(Rudenko, Redkin and others [18]) proposed the construction of a pile foundation for swelling soils, including a grillage and piles, both of which have an outer cylindrical shell placed thereon with a gap. The grillage is made as a composite along its height, it consists of the upper and lower parts, separated by the layer of antifriction material. The cylindrical shells of the piles are rigidly connected to the lower part of the grillage and are made with the length smaller than the active zone of the swelling clay soil. The pile shafts are rigidly connected to the upper part of the grillage. Each pile is equipped with rollers placed on its lateral surface, which are in contact with the inner surface of the cylindrical shell.

Despite its benefits, this design has a disadvantage associated with the complexity of manufacturing piles with rollers.

The author has developed a number of pile foundation designs of this type, which involve the use of simpler structural elements like rolling and rubbing members instead of rollers.

In the pile foundation structure (Gabibov [19]), during soil 1 swelling (figure 2), the cylindrical shells 6 move up along the special elastic rolling elements 8 together with the lower part 4 of the grillage. The resilient layer 5 between the upper 3 and lower 4 parts of the grillage, made of recycled tyres waste, is compressed. The rolling elements 8 located between the pile shaft 7 and the inner
surface of the cylindrical shell 6 are made autonomously from the resilient rubber rings with a circular cross section.

Moreover, the cross-section diameter of the rolling element, within the limits of its elastic deformability, slightly exceeds the width of the gap between the lateral surface of the pile and the inner surface of the cylindrical shell. The lower part of the piles is buried in the underlying non-swelling soil layer 2.

The specified design of the pile foundation is relatively easy to manufacture, since there is no need to attach rollers to the pile shaft. In the proposed design, in comparison with the previous known design, the contact is provided along the entire circumference in the gap between the pile shaft and the shell. Rubber rolling ring elements 8 perform the role of seismic isolators during seismic impacts on the structure. The proposed resilient layer 1 5 made of rubber waste makes it possible to refuse further improvements in the grillage, since the specified layer proves to be self-regulating and constantly maintains the support contact both during swelling and shrinking of the clay mass.

**Figure 2.** Pile foundation with annular elastic rolling elements located in the gap between the pile and the cylindrical shell: (a) – longitudinal section; (b) – section A-A; (c) – узел I with a rolling element; Z₀ – active zone of swelling clay soil mass/
The variants of pile structures erected on swelling clay soil, which involve the use of rubbing elements instead of rollers, are also proposed. The rubbing elements are attached to the lateral surface of the pile in the form of embedded parts. In the first version (see figure 3), elastic plastic parts 1 with a low friction coefficient are used as rubbing elements (in our case, we used reinforced teflon), which are located in the gap between the lateral surface of the pile 2 and the inner surface of the cylindrical shell 3. In the second case, metal brace-shaped reinforcing outlets 1 from the lateral surface of the pile 2, connected with the concrete pile reinforcement, are used as rubbing elements (see figure 4). These brace-shaped embedded rubbing elements resiliently abut on the inner surface of the cylindrical shell 3. In both versions, the embedded parts of one separate horizontal level (at least 3 of them) are spaced 120° apart along the circumference of the cross-section of the pile. In figure 3 and 4, there are four of them and they are spaced 90° apart along the circumference of the pile cross-section.
4. Conclusions
1. The full cutting of the swelling clay mass by piles does not prevent the pile from rising during the swelling of the clay body due to the action of the tangential swelling forces on the lateral surface of the pile.
2. The recommended design, with a broadened root section and heavy pile reinforcement along the entire height, is relatively expensive.
3. The author has proposed the design of frustoconical piles with a screen made of an incoherent and poorly connected loose layer, as well as a pile with a variable cross-section evenly distributed along the height. When swelling, the clay body traps the pile in the borehole and freely realizes the rest of its negative energy.
4. The author has also developed pile foundations with rolling and rubbing elements located in the gap between the lateral surface and the inner surface of the cylindrical shell pile. These intermediate elements can also act as seismic isolators.

References
[1] Gromko G J 1974 Review of expansive soils *Journal of Geotechnical Engineering (ASCE)* **100** (6) 667–87
[2] Fityus S G, Smith D W and Allman M A 2004 Expansive soil test site near newcastle *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* **130** (7) 686–95
[3] Peredelskiy L V and Ananiev V P 1987 *Swelling Clay Soils of the North Caucasus* (Rostov-on-Don: Rostov University Publishing House)
[4] Mustafayev A A 1989 *Foundations on Subsiding and Swelling Soils* (Moskow: High School)
[5] Kulchitskiy L I and Vsyarov O G 1981 *Physical and Chemical Bases of Formation of Properties of Clay Soils* (Moscow: Nedra)
[6] Al-Homond A S, Basma A A, Hudein Malkavi A I and Al Bashabsheh M A 1995 Cyclic swelling behavior of clays *Journal of Geotechnical Engineering (ASCE)* **121** (7) 562–5
[7] Olson R E and Langfelder L Y 1965 Pore-water pressures in unsaturated soils *Journal of Soil Mechanics and Foundation (ASCE)* **91** (4) 127–50
[8] Gabibov F G 2011 *Theory and practice of improving properties of structurally unstable clay soils in solving geotechnical and engineering – and – geocological problems* (Baku: Elm)
[9] Day R W 1993 Expansion potential according to uniform building code *Journal of Geotechnical Engineering (ASCE)* **119** (6) 1067–71
[10] Day R W 1996 Study of capillary rise and thermal osmosis *Environmental and Engineering Geoscience* **2** (2) 249–54
[11] Day R W 1997 Hydraulic conductivity of a desiccated clay upon wetting *Environmental and Engineering Geoscience* **3** (2) 308–11
[12] Sorochan E A 1989 *Construction of Structures on Swelling Soils* (Moskow: Stroyizdat)
[13] Chen F H 1988 *Foundation on Expansive Soils* (New York: Elsevier)
[14] Day R W 2010 *Foundation Engineering Handbook: Design and Construction with the 2009 International Building Code* (New York: McGraw Hill)
[15] Doroshkevich N M and Boym V P 1969 To the calculation of pile foundation in swelling soils *Proc. of the SNIS* **66** (Moscow: Transport)
[16] Nelson J D and Miller D J 1992 *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering* (New York: Wiley)
[17] Gabibov F G 1999 *Problems Regulating Properties of Structurally Unstable Clay Soils in Base of Structures* (Baku: Elm)
[18] Rudenko A A, Redkin V I, Galushko A M and Gubenko V I 1983 *Pile Foundation* Patent USSR for the Invention 1038421
[19] Gabibov F G 2011 *Pile Foundation on Swelling Soils* Patent of the Republic of Azerbaijan for the Invention 2011 0033