Method for calculating the settlement of ring pile foundations of tanks

A I Polishchuk\textsuperscript{1,2} and O A Shmidt\textsuperscript{1}

\textsuperscript{1}Basements and Foundations Department, Kuban State Agrarian University, Krasnodar, Kalinina st., 13, Russia

\textsuperscript{2}ofpai@mail.ru

Annotation. A method for calculating the settlement of ring pile foundations of reservoirs on clay soils is considered. The proposed method provides for a separate calculation of the settlement of the central part of the tank (bottom draft) and a reinforced concrete ring pile foundation arranged along its edges (foundation ring settlement). The bottom of the tank is not rigidly connected to the ring foundation. The method of M I Gorbunov-Posadov and others for a flexible round foundation on a linearly deformable base was used. When calculating the settlement of the pile ring, the method of A A Bartolomey was used for strip pile foundations. The work takes into account the assessment of the additional settlement of the bottom and pile ring caused by repeated loading and unloading of the base of the tanks.

1. Introduction

The development of routes for the transportation of oil products requires the construction of new and modernization of existing transport hubs, the main elements of which are vertical steel tanks. During the construction of reservoirs on clay soils, including weak water-saturated, pile foundations are widespread \cite{1, 2, 3}. Specialists of KubSAU carried out large-scale studies, according to the results of which the peculiarities of the operation of pile foundations of reservoirs in clayey soils were established \cite{4, 5}. As a result of research carried out at SPbGASU and other organizations \cite{6, 7}, it was revealed that in most cases the use of ring pile foundations for tanks is the most effective solution, since they receive less settlements and are more economical compared to massive pile-slab or slab foundations. An annular pile foundation provides for the device along the edges of the tank of an annular grillage with a single-row, two- or three-row arrangement of piles and with a displacement of the main vertical axis of the grillage to its center. This annular part of the foundation of the tank will hereinafter be called the foundation of the ring. At the same time, a steel bottom of the tank is arranged on top of the grillage through an intermediate sand cushion (figure 1). For the construction of ring pile foundations of tanks, driven and bored piles are mainly used.

According to the research results \cite{8, 9}, up to 70\% of the recorded tank accidents are associated with uneven precipitation and foundation rolls. It has been established that the excess of the permissible settlement of the foundations of the tanks (S > S_p) can occur after their hydraulic tests, when the tank is in normal operation. The foundations of vertical steel tanks during operation experience the influence of a large number of repeated stages of loading and unloading, which leads to the development of their additional settlement \Delta S. Currently, there are no generally accepted methods for calculating the final settlement S of ring pile foundations of tanks taking into account their unloading and subsequent repeated loading. Therefore, the topic under consideration is relevant.
Figure 1. Ring pile foundation of a vertical steel tank: a - diagram of the structural solution of the foundation; b - the dependence of the settlement of the bottom of the tank \([S_d = f(p_d)]\) and the ring pile foundation \([S_k = f(p_k)]\) on the pressure \(p_d\) and \(p_k\); 1 - ring pile foundation of the tank (ring foundation); 2 - vertical steel tank; 3 - intermediate sand layer; 4 - plot of the tank bottom settlement; 5 - diagram of the settlement of the ring pile foundation (settlement of the ring foundation); 6 - ring grillage; 7 - the bottom of the tank; \(z\) is the central axis of the tank; \(z_p\) - main vertical axis of the grillage, \(p_d\) - pressure at the level of the tank bottom, kPa; \(p_k\) - pressure at the level of the bottom of the ring pile foundation (ring foundation), kPa; \(S_d\) - settlement of the bottom of the tank, cm; \(S_k\) is the settlement of the ring pile foundation (ring foundation), cm; \(S_{d1}\) - settlement of the bottom of the tank at the first stage of loading, cm; \(S_{k1}\) - the same, ring pile foundation, cm; \(\Delta S_{d1}, \Delta S_{d2}, \Delta S_{d3}, \ldots \Delta S_{dn}\) - increment of bottom settlement during repeated and subsequent loading of the tank, cm; \(\Delta S_{k1}, \Delta S_{k2}, \Delta S_{k3}, \ldots \Delta S_{kn}\) - the same, ring pile foundation, cm.

2. Description of the design model and the assumptions made

The proposed method provides for a separate calculation of the settlement of the central part of the tank bottom (bottom draft) and of a reinforced concrete ring pile foundation arranged along its edges (ring foundation settlement). At the same time, the bottom of the tank does not have a rigid connection with the foundation of the ring. We assume that the sand cushion at the bottom of the bottom of the tank has a thickness equal to 30-40 cm and more (figure 1(a)). The pillow is made with a layer-by-layer compaction of coarse or medium-sized sand. In this case, the sand is classified as low-compressive and its deformation characteristics practically do not affect the calculation of the reservoir bottom settlement. The edges of the bottom of the tank rest on the foundation of the ring and their movements are limited by its sediments. Consequently, the bottom of the tank can be thought of as a flexible round plate on a linearly deformable base. In this case, the bottom has different sediment values in its center and at the edges. The foundation of the ring at the edges of the tank can be viewed as an array of piles, grillage and soil. It can be classified as an annular rigid punch with a width equal to the size \(bc\) and a depth equal to the length of the piles \(dc\) (figure 1(a))

3. Results

3.1 Calculation of the settlement of the bottom and foundation of the ring

To calculate the settlement of the bottom of the tank \(S_{bh}\), we will use the method of M I Gorbunov-Posadov et al. [10] for a flexible round foundation on a linearly deformable base. In this case, the settlement of the edges of the bottom of the tank will correspond to the vertical displacements (settlement) of the foundation of the ring, which is allowed to be limited from the sides by vertical planes passing along the outer edges of the ring grillage. The bottom mark of the ring foundation foot
should correspond to the bottom ends of the piles (figure 1 (a)). The settlement of the bottom of the tank $S_{d1}$ (in the center) at the first stage of its loading can be determined by the formula (figure 1(b)):

$$S_{d1} = \frac{2 \cdot (1 - \nu^2) \cdot p_{d} \cdot R}{E_{d}}$$

(1)

where $S_{d1}$ is the sediment of the bottom of the tank in its center at the first stage of loading the base, cm; $\nu$ is Poisson's ratio; $p_{d}$ - pressure at the bottom of the tank, kPa; $R$ is the radius of the inner diameter of the grillage, m; $E_{d}$ is the modulus of soil deformation at the base of the tank bottom at the first stage of its loading, kPa.

The final settlement of the central part of the bottom of the tank $S_{d}$, taking into account its repeated loading, should be determined by the formula (figure 1 (b)):

$$S_{d} = S_{d1} + \Delta S_{d1}$$

(2)

where $S_{d}$ is the final settlement of the bottom of the tank (in its center), taking into account repeated loading, cm; $S_{d1}$ - the same as in (1), cm; $\Delta S_{d1}$ is the total increment in the bottom settlement of the tank under repeated loading, see.

The total sediment increment $\Delta S_{d1}$ of the bottom of the tank (in its center) can be established from the expression:

$$\Delta S_{d1} = \sum_{i=1}^{n} \frac{2 \cdot (1 - \nu^2) \cdot p_{d} \cdot R}{E_{d1}}$$

(3)

where $\nu$, $p_{d}$, $R$ - the same as in formula (1); $E_{d1}$ — modulus of soil deformation at the $i$-th stage of loading, kPa.

The settlement increment $\Delta S_{d1}$ in formula (3) is recommended to be determined for three stages of loading the bottom of the tank, since during the subsequent stages of their loading, there is practically no increase in the settlement. The characteristics of the modulus of deformation of soils $E_{d1}$ in formula (3) are usually determined during compression tests (GOST 12248) according to a method that takes into account unloading and subsequent repeated stages of base loading. In this case, the values of $E_{d1}$ in formula (3) are recommended to be determined for the second and third stages of loading. Soil tests at subsequent stages of loading can be omitted, since the values of $E_{d1}$ remain practically unchanged. It is allowed for clay soils to correct the results of compression tests ($E_{d1}$ values) using increasing coefficients $m_{ned}$ to the results corresponding to stamp tests of soils, according to the recommendations of regulatory documents (SP 22.13330.2016, Table 5.1, etc.). Calculation of the foundation settlement of the ringy $S_{k1}$ at the first stage of its loading is carried out using the method of A. A. Bartholomew [12]. In this case, the final settlement $S_{k}$ is determined as for a strip pile foundation (a section with a length of 1 m is considered). The width of the foundation of the ring $b_{c}$ is taken along the outer edges of the ring grillage, the depth $d_{c}$ - according to the elevation of the lower ends of the piles. The soil is considered linearly deformable (figure 1 (a)). As a result of solving the problem of the interaction of the foundation with the foundation soil (the problem of the theory of elasticity), the following formula was proposed [12]:

$$S_{k1} = \frac{p_{k} \cdot (1 - \nu^2)}{\pi E_{k}} \delta_{0}$$

(4)

where $E_{k}$ is the soil deformation modulus at the base of the ring foundation, installed at the first stage of its loading, kPa; $\nu$ is Poisson's ratio; $p_{k}$ - pressure at the level mark of the ring foundation sole, kPa; $\delta_{0}$ - coefficient of proportionality, taken according to [2, 12].

The final settlement of the foundation of the ring $S_{k}$, taking into account its repeated loads, is determined by the formula:
where $S_{k1}$ is the same as in (4), cm; $\Delta S_{ki}$ is the total increment of the foundation settlement of the tank ring during its repeated loading, see.

The total settlement increment $\Delta S_{ki}$ can be established from the expression:

$$\Delta S_{ki} = \sum_{i=1}^{n} p_k \cdot (1 - v^2) \cdot \delta_0 \pi E_{ki}$$

(6)

where $v$, $p_k$, $\delta_0$ - the same as in formula (4); $E_{cl}$ - modulus of soil deformation at the base of the ring foundation at the i-th (considered) loading stage, kPa;

The settlement increment $\Delta S_{ki}$ in formula (6), as well as for the tank bottom [see formula (3)], is recommended to be determined for three stages of ring foundation loading. To obtain reliable results for determining the settlement $\Delta S_{ki}$, the soil deformation modulus $E_{ki}$ in formula (6) is recommended to be taken not based on the results of compression tests (at the stage of geotechnical surveys), but based on the results of evaluating its values at the base of the lower end of the piles used (for specific loading stage under consideration). This is due to the fact that the base of the foundation of the ring is almost always in a complex stress-strain state, taking into account the external load $N$, the actual settlement of the piles $S$ and the conventionally accepted width of the base of the foundation $b_c$ (figure 1 (a)). Therefore, the characteristic $E_{ki}$ is determined under the current stress-strain state of the base of the ring foundation, acting loads and settlement of full-scale piles. The method for determining the characteristics of $E_{ki}$ based on the test results of full-scale piles was proposed by I.Z. Goldfeld (2011) [12, 13]. The author of the method in his calculations calls the characteristic $E_{ki}$ the reduced modulus of deformation of the foundation soil $E_{np,i}$. Taking into account the notation adopted in the article, we have that $E_{ki} = E_{np,i}$, which is used further in this work.

3.2. Method for determining the reduced modulus of soil deformation

The method provides for the determination of the characteristics of the reduced modulus of soil deformation $E_{np}$ based on the results of testing single full-scale piles (driven, bored) with a static indentation load. Moreover, if the operation of tank foundations is considered, then testing of full-scale piles should be carried out taking into account their unloading and subsequent repeated loading (figure 2). The formula for determining the characteristic $E_{np}$, proposed by I.Z. Goldfeld, has the form [12, 13]:

$$E_{np} = \frac{(1 - v^2) \cdot N}{0.53D \cdot S}$$

(7)

where $S$ is the settlement of a full-scale pile at a given external load, cm; $N$ - acting external load on the pile, kN; $D$ is the width of the base of the conditional foundation, taken taking into account the angle of dissipation of stresses of the compressive load [14], m; $v$ - Poisson's ratio.

Determination of the $E_{np}$ characteristics at the first stage of base loading should be considered in the range of loads on the pile from $N_f$ to $N_\phi$. With an external load $N_f$, the linear dependence on the graph of the pile settlement $S=f(N)$ ends (linear section $oa$, figure 2 (a)). This settlement $S$, corresponding to the limiting state of clay soil on the lateral surface of the pile, is called shear $S_{s,a}$ [1, 14]. Before the load $N_f$, the pile works mainly due to the soil resistance along the lateral surface, and the lower end of the pile in the considered loading interval (in the section $oa$) practically does not work, which is noted in the studies of F K Lapshin et al [14]. A further increase in the external load $N$ (from $N_f$ to $N_\phi$) leads to the fact that the lower end of the pile is included in the work. With a load of $N = N_\phi$, the pile receives a draft $S=S_{s,a}$, and its lower end begins to work as a recessed rigid punch. Then, the entire external load $N$, as it increases on the pile in section $ab$, is transferred to the base by its lower end. This allows you to calculate the characteristics of the reduced modulus of soil deformation $E_{np}$ at
its base (for section ab) at the first stage of pile loading. Substitute in the formula (7) instead of $S$ the expression $(S - S_{ca})$, instead of $N$ the expression $(N_d - N_f)$, we get:

$$E_{np} = \frac{(1 - \nu^2) \cdot (N_d - N_f)}{0.53 D \cdot (S - S_{ca})} \quad (8)$$

where $S_{ca}$ is the shear settlement of the pile; $N_d$ is permissible load on the pile, kN; $N_f$ is the load on the pile transmitted to the ground by its lateral surface, kN; $D$ is the width of the base of the conditional foundation for the considered single pile, m.

Figure 2. Schemes for determining the characteristics of the reduced modulus of soil deformation $E_{np}$ at the base of a full-scale pile: a is graph of the dependence of the settlement of the pile $S$ on the external load $N$ at the first stage of loading, during unloading and subsequent repeated loading; b - a diagram of the interaction of a full-scale pile with the soil; 1 - pile; 2 - area of compacted soil; $N$ - external load acting on the pile, kN; $d$ - pile width, m; $D$ is the width of the base of the conditional foundation, m; $S$ - pile settlement, mm; $S_{ca}$ - pile settlement, mm; $N_d$ - permissible load on the pile, kN; $\alpha$ is the angle of stress dissipation.

The width of the base of the conditional foundation $D$ is determined at the level of the lower end of the pile by the intersection of a horizontal straight line with a dashed line drawn at an angle of stress dissipation $\alpha$ to the vertical (figure 2 (b)). The angle $\alpha$ is equal to $\phi_1/4$, where $\phi_1$ is the calculated value of the angle of internal friction of the soil, established according to the results of engineering and geological surveys.

The permissible load on the pile $N_d$ is determined from the expression:

$$N_d = F_d/\gamma_k \quad (8a)$$

where $F_d$ is the bearing capacity of the pile, kN; $\gamma_k$ - the coefficient of reliability on the ground, taken equal to $\gamma_k = 1.2$ according to SP 24.13330.2011.

The shear settlement of the pile $S_{ca}$ in formula (8) can be determined from experimental data depending on the type of soil lying around the pile in question. For this, you can use the data of B I Dalmatov, F K Lapshin and others (table 1) [1]. Experimental data on $S_{ca}$ values were obtained from the analysis of graphs of numerous static tests of full-scale piles performed by Leningraddorstroy specialists (1965-1975). On the logarithmic school of graphs for static tests of piles, the authors identified break points with a sharp increase in the angle of inclination of the tangent to the test graph. These points, according to B I Dalmatov, F K Lapshin, and others, testified to the ultimate soil resistance along the lateral surface of the piles and corresponded to their shear settlement $S_{ca}$. 
Table 1. Shear settlement of piles $S_{cd}$ in various soils.

| Soil                                         | $S_{cd}$, mm |
|----------------------------------------------|--------------|
| Fine-grained sand, medium density            | 5            |
| Silty sandy loam, medium density             | 6            |
| Silty soft sandy loam                        | 7            |
| Hard-plastic loam                           | 8            |
| Silty loam with gravel, soft plastic (moraine)| 10           |
| Silty layered soft-plastic loam              | 15           |
| Loamy silty tape soft-plastic                | 18           |
| Dusty tape refractory clay                   | 22           |
| Dusty tape soft-plastic clay                 | 25           |

3.3. Preparation of initial data and the procedure for performing the calculation of the settlement

In general, the preparation of initial data and the procedure for calculating the settlement of ring pile foundations of tanks can be performed according to the following algorithm:

1. A program is being prepared and compression tests are carried out on soils lying at the bottom of the bottom of the tank, with unloading and subsequent repeated loading. Based on the test results, the values of the soil deformation modulus at the bottom of the tank bottom are determined at the first $E_{d1}$ and repeated $E_{d1}$ stages of loading. It is recommended that the compression test data be corrected using increasing coefficients $m_{oed}$ to the results corresponding to stamp tests of soils (SP 22.13330.2016, Table 5.1, etc.). The obtained values of $E_{d1}$ and $E_{d2}$ are used to determine the settlement of the tank bottom at the first $S_{d1}$ and subsequent $\Delta S_{d2}$ stages of loading, as well as its final settlement $S_{du}$ using formulas (1), (2) and (3).

2. A program is being prepared and full-scale piles are tested with a static indentation load with intermediate unloading and subsequent repeated loading. Pile tests are carried out at a constant loading rate until the specified load $N$ is reached, which corresponds to:
   - for tanks with a capacity of 10 thousand m$^3$ - in 2.25 hours;
   - for tanks with a capacity of 20-40 thousand m$^3$ - in 3 hours;
   - for tanks with a capacity of over 40 thousand m$^3$ - in 5 hours.

   The choice of the test duration is due to the rate of filling the tanks with oil products. Upon reaching the specified load $N$, the pile settlement should be stabilized until the criterion is reached, equal to the settlement rate of less than 0.1 mm per 1 hour of observation. The unloading of piles is performed at a constant speed in the same period of time as during loading. The number of stages of pile loading should be at least three. It is recommended to take the maximum allowable settlement rate corresponding to the value of 1.2 mm/min as the criterion for the exhaustion of the pile bearing capacity $F_{d}$ [2, 15]. According to the test results, graphs of the pile settlement $S$ from the applied external load $N$ [$S=f(N)$] (Figure 2) are plotted to determine the characteristics $E_{np}$, $N_{o}$ and $N_{f}$.

3. The values of the reduced modulus of soil deformation $E_{np}$ are determined for each tested pile according to the formula (8). In this case, the parameters $N_{o}$, $N_{f}$ and $S$ in the formula (8) are set according to the schedule $S=f(N)$ according to this section according to clause 2. The obtained values of $E_{k1}$ and $E_{kl}$ are used to determine the foundation settlement of the ring on the first $S_{k1}$ and subsequent $\Delta S_{kl}$ stages of loading, as well as its final settlement $S_{k}$ using formulas (4), (5) and (6). In the calculations, it should be taken into account that $E_{k1} = E_{np1}$, and $E_{kl} = E_{np1}$.

4. The obtained values of the subsidence of the bottom of the tank $S_{d}$, the settlements of the foundation of the ring $S_{k}$ of the tank are compared with the maximum permissible values of $S_{max}$, $S_{var}$. According to the results of the calculation, if necessary, appropriate adjustments are made to the constructive solution of the foundations.
4. Discussion
Consideration of the issues of the operation of ring pile foundations of tanks made it possible to develop a method for calculating the final settlement on clayey soils, taking into account their repeated loading and unloading. The proposed method provides for a separate calculation of the settlement of the central part of the tank (bottom draft) and a reinforced concrete ring pile foundation arranged along its edges (foundation ring settlement). The obtained research results can be used by design organizations of the oil and gas industry at the stage of designing the foundations of tanks for storing oil and oil products in clay soils.

References
[1] Dalmatov B I, Lapshin F K and Rossikhin Yu V 1975 Design of pile foundations in conditions of weak soils (Leningrad: Stroyizdat)
[2] Il'ichev V A et al 2014 Geotechnical Handbook. Bases, foundations and underground structures eds Il'ichev V A and Mangushev R A (Moscow: ASV) pp 227–339
[3] Polishchuk A I, Tarasov A A and Shalginov R V 2009 Injection pile Patent RU no 87718
[4] Shadunts K Sh 2005 Foundations of large reservoirs in the zone of tectonic faults (Technologies of STC "Geoproject") Bases, foundations and soil mechanics 6 28–32
[5] Shadunts K Sh 2006 Reliability of foundations of isothermal reservoirs on Taman Energy supply and water treatment 1 (39) 63–4
[6] Ivanov Yu K, Konovalov P A, Mangushev R A and Sotnikov S N 1989 Tank bases and foundation (Moscow: Stroyizdat)
[7] Konovalov P A et al 2009 Foundations of steel tanks and deformation of their foundations (Moscow: ASV)
[8] Chepur P V and Tarasenko A A 2014 Influence of non-uniform sediment parameters on the occurrence of limiting states in a reservoir Fundamental research 8-7 1560–4
[9] Kondrashova O G and Nazarova M N 2004 Cause-and-effect analysis of accidents of vertical steel tanks Oil and Gas Business 2 8
[10] Gorbunov-Posadov M I 1984 Calculation of structures on an elastic foundation (Moscow: Stroyizdat)
[11] Bartholomew A A 1970 Calculation of the sediment of single-row and multi-row pile foundations (Perm: Polytechnic Institute)
[12] Goldfeld I Z and Smirnova E A 2011 Graphic-analytical processing of the results of static soil tests with driven piles and sounding Bases, foundations and soil mechanics 5 35–40
[13] Goldfeld I Z 2013 Practice of extended analysis of the results of field tests of soils with piles and sounding Geotechnics 3 48–66
[14] Lapshin F K 1979 Calculation of piles by limiting distances (Saratov: Saratov Publishing House. University)
[15] Shmidt O A 2017 Selection of the criterion for the exhaustion of the bearing capacity of a pile during static tests with a gradually increasing load Actual problems of the humanities and natural sciences 3 (3) 97–102