Application of a base reinforced with a horizontal geosynthetic layer for the foundation of a steel tank

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Abstract. Erection of structures on soft soils is a difficult task. The cost of the foundation in such cases can be up to 30-35\% of the cost of the entire structure. Therefore, an urgent task is the use of effective foundation structures. The use of reinforcing geosynthetic materials is one such method. The article describes the experience of using geosynthetic reinforcing materials in the construction of the foundation for steel cylindrical vertical tanks with a volume of 630 m\textsuperscript{3}. The results of calculations of the settlement of tank foundations by the analytical method and the finite element method are presented. The obtained values of vertical displacements were compared with the results of geodesic measurements of the constructed reservoirs. The analysis of the results obtained showed good convergence of the calculation results by the analytical method with the actual measurements of the vertical displacements of the foundations. Also, the economic efficiency of using a foundation on a reinforced base was determined.

1. Introduction

During the reconstruction at one of the power plants in Perm, it became necessary to build steel cylindrical vertical tanks of coagulated water. The structures of the tanks are designed for a volume of 630 m\textsuperscript{3} each. In recent years, the rise of groundwater has occurred in this area and the strength and deformation characteristics of soils have deteriorated significantly. The sampling of the foundation soil was carried out to determine the actual state of the bases soils and determine their physical and mechanical characteristics. As a result of the studies carried out, it was established that the level of groundwater is at a depth of 1.05–1.25 m. Loam of fluid consistency is the bearing soil of the base. It has the following characteristics:

- specific gravity $\gamma = 1.86$ kH/m\textsuperscript{3};
- specific gravity of dry soil $\gamma_d = 14.3$ kH/m\textsuperscript{3};
- humidity $w = 0.3$;
- degree of humidity $S_r = 0.91$;
- coefficient of porosity $e = 0.9$;
- general modulus of deformation $E_{1-2} = 7.51$ MPa;
- specific cohesion $c = 14.0$ kPa;
- angle of internal friction $\phi = 12^\circ$.

The calculated bearing capacity of the bases soil was only 83 kPa.

The construction of a compacted soil pad under the reservoirs was foreseen in the original design. The soil pad was made of a sand-gravel mixture treated with bitumen and had a thickness of 2.0 m.
2. Construction of the tank foundation on a reinforced base

One of the ways to increase the bearing capacity and reduce the settlement of foundations on highly compressible soils is the use of reinforced soils. In many cases, the use of reinforced soils can significantly reduce the cost of building foundations, and, consequently, the cost of the entire construction.

A great contribution to the study of reinforced soils was made by the staff of the Department of Construction Operations and Geotechnics Perm National Research Polytechnic University A B Ponomarev [1], D A Tatyannikov [2], D G Zolotozubov [3] and V I Kleveko [4]. On the basis of their research, the construction of the foundation on a reinforced base was proposed. It was a 1.0 m thick soil pad made of sand and gravel, which was reinforced with geosynthetic material. A geogrid made of polyester monofilament No. 16 with a diameter of 0.3 mm according to TU13-0381151-21-89 with a tensile strength of at least 390 kN/m was used. The construction of the foundation is shown in the figure 1. The construction of a reinforced base included the following main operations:

- digging a pit (the bottom of the pit was not compacted due to the high level of groundwater);
- laying of geosynthetic material;
- construction of a cushion made of sand and gravel mixture and its compaction to a compaction factor of 0.95.

3. Calculations of the tank foundation on a reinforced base

The dimensions of the foundation slab are taken, based on design considerations, 10.6×10.6×0.4 m. The technological solution with a temperature of 30-40°C circulates in the tank, therefore, it is not required to deepen the foundation into the ground. The initial data for calculating the tank foundation are given in table 1.

An analytical calculation method and a numerical calculation method implemented using the finite element method were used to calculate the reservoir foundation. The tensile stiffness of the reinforcing layer and the coefficient taking into account the effect of friction between the reinforcing layer and the base soil $k_f$ were determined on the basis of the research of A B Ponomarev, D A Tatyannikova and V I Kleveko [5, 6].

![Figure 1. Scheme of a tank with a foundation on a reinforced base.](image-url)
Table 1. Initial data for the foundation calculation.

| Indicators                                           | Value  |
|------------------------------------------------------|--------|
| Specific cohesion $c$ (kPa)                          | 14     |
| Angle of internal friction of soil $\varphi$ (degrees)| 12     |
| General modulus of deformation $E_o$ (kPa)           | 7510   |
| Tensile strength of the reinforcing layer $F$ (kN/m) | 390    |
| Tensile stiffness of the reinforcing layer $G_{rf}$ (kN/m) | 2035 |
| Coefficient of friction between the reinforcing layer and the base soil $k_f$ | 0.8    |
| Base load when calculating settlement $P_i$ (kPa)    | 92.5   |
| Design load on the base $P_{II}$ (kPa)               | 105.4  |

3.1. Analytical method of calculation

To determine the settlement of the reservoir foundation, a technique was used, which is described in detail in the works of V Kleveko [4, 7]. This technique is based on the layer-by-layer summation method presented in the design standards SP 22.13330.2016 “Foundations of buildings and structures”. It involves performing all the required calculations, including checking for a weak sub-base. However, a number of changes are included in our proposed method for calculating the settlement of a reinforced base.

The essence of the technique lies in the fact that to assess the effect of reinforcement, the coefficient $K_r$ is introduced, which is equal to the ratio of the deformation modulus of reinforced soil $E_{rf}$ to the modulus of deformation of unreinforced soil $E_o$.

$$K_r = \frac{E_{rf}}{E_o}$$

The deformation modulus of reinforced soil $E_{rf}$ can be found knowing the values of $K_r$ and the modulus of deformation of unreinforced soil $E_o$ by the formula:

$$E_{rf} = K_r E_o$$

The value of $K_r$ can be determined using the table or graphs given in [4, 7]. The results of calculating the foundation on a reinforced base are given in table 2.

Table 2. The results of calculating the foundation by the analytical method.

| Indicators                                           | Value  |
|------------------------------------------------------|--------|
| Design bearing capacity of the reinforced base $R_r$ (kPa) | 124.8  |
| Deformation modulus of reinforced soil $E_{rf}$ (kPa)  | 11420  |
| Foundation settlement $s$ taking into account $E_{rf}$ (mm) | 33.4   |
| Tensile force in the reinforcing layer $N_{rs}$ (kN/m)   | 13.8   |
| Design tensile strength of the reinforcing layer $F_{rf}$ (kN/m) | 125.8  |
| Reinforcing layer width $L$ (m)                       | 21.2   |

3.2. Numerical method of calculation

The PLAXIS 2D software was used to calculate the foundation on a reinforced base. The calculation used the Mohr-Coulomb elastic-plastic soil model and 15-node triangular finite elements. The calculation results are shown in figure 2.
Figure 2. Results of calculating the vertical settlement of the foundation by the finite element method.

4. Results of observation of vertical settlement of tanks

Two tanks on reinforced soil cushions were erected. The general view is shown in figure 3.

Figure 3. General view of steel cylindrical vertical tanks of coagulated water.

Four marks were installed around the perimeter of each tank to control vertical movement (see figure 4). The hydraulic tests were carried out after the construction of the tanks, i.e. they were filled with water.
During these tests, geodetic measurements of the displacements of the marks fixed on the walls of the tanks were carried out. The following values of vertical displacements of marks were obtained from the results of geodetic measurements:

- maximum vertical displacement – 19.5 mm;
- the maximum difference in vertical displacements of two adjacent marks located at a distance of 6.0 m from each other – 4.0 mm;
- maximum vertical displacements difference between the two diametrically opposed marks – 6.5 mm;
- the maximum roll of the foundation – 0.00062.

Subsequently, within one year, regular observations of vertical displacements of the reservoir foundations were continued, the final measurement results are shown in Table 3.

### Table 3. The results of measuring the vertical displacements of the marks of tanks.

| Marks | Vertical displacements of the marks, S, (mm) | Vertical displacements difference between the two diametrically opposed marks $\Delta S_p$, (mm) | Tank roll | Average settlement of the tank foundation (mm) |
|-------|---------------------------------------------|-------------------------------------------------|-----------|-----------------------------------------------|
|       | Actual | Maximum permissible | Actual | Maximum permissible |                     |
|-------|--------|---------------------|--------|---------------------|---------------------|
| Tank No. 1 |
| M1    | 21.3   | 12.4                |        | 0.0012              |                     |
| M2    | 35.3   | 15.6                |        | 0.0015              |                     |
| M3    | 33.7   | 12.4                | 25     | 0.0012              | 0.0017              |
| M4    | 19.7   | 15.6                | 4.3    | 0.0015              | 27.5                |
| Tank No. 2 |
| M1    | 19.7   | 0.4                 |        | 0.000038            |                     |
| M2    | 19.0   | 4.3                 |        | 0.00041             |                     |
| M3    | 19.3   | 0.4                 | 25     | 0.000038            | 0.0017              |
| M4    | 23.3   | 4.3                 |        | 0.00041             | 20.3                |
5. Research results.
Analysis of the research results showed that all the necessary checks are being carried out. The obtained values of vertical displacements and rolls of foundations do not exceed the maximum permissible standard values. This testifies to the high rigidity of the foundation made of reinforced soil and the effectiveness of the use of such structures in construction.

Table 4 shows the results of calculating the vertical displacements of tank foundations and comparing them with the calculated values obtained by the analytical method and the finite element method. The smallest error of 18-39% was shown by the analytical method of calculation.

Table 4. Comparison of the calculation results for the settlement of tank foundations.

| Tank | Actual | Calculated by the analytical method [4] | Calculated according to PLAXIS |
|------|--------|----------------------------------------|-------------------------------|
| 1    | 27.5   | 33.4                                   | 56.7                          |
| 2    | 20.3   | 33.4                                   | 56.7                          |

To determine the technical and economic efficiency of the use of reinforced foundations, calculations of three types of equal-strength foundations were performed. A detailed calculation is given in [4]. Compared were the costs of building a foundation on a bed of sand and gravel mixture treated with bitumen (initial design), a pile foundation and a foundation built on a reinforced foundation. The lowest cost has a foundation on a reinforced base. Compared to a foundation on a reinforced base, a pile foundation is 29% more expensive, and a traditional foundation on a pad of sand and gravel is 25% more expensive.

6. Conclusions
1. The use of a reinforced base in the construction of foundations of steel cylindrical vertical tanks can reduce the cost of their construction by 25-29%.
2. For the calculation of reinforced foundations, both analytical and numerical methods can be used. However, analytical calculation methods determine the foundation settlement more accurately than numerical methods.

References
[1] Ponomarev A B and Tat'yannikov D A 2020 Analysis of the performance of sand cushions reinforced with horizontal geosynthetic elements Soil Mechanics and Foundation Engineering 56 371–7
[2] Tat'yanikov D A and Ponomaryov A B 2019 Forecast bearing capacity of soil cushions with variable reinforcement spacing. Proc. of the Conf. on Geotechnics Fundamentals and Applications in Construction: New Materials, Structures, Technologies and Calculations (Saint Petersburg) pp 378–83
[3] Ponomaryov A and Zolotozubov D 2014 Several approaches for the design of reinforced bases on karst areas Geotextiles and Geomembranes 42 48–51
[4] Kleveko V I 2002 Assessment of the stress-strain state of reinforced bases in silty-clayey soils Ph D thesis (Perm: Perm state technical universitet)
[5] Ponomarev A B, Tat'yannikov D A and Kleveko V I 2013 Determination of linear stiffness of geosynthetic materials Internet bulletin VolgGASU. Polythematic 2 (27)
[6] Tat'yanikov D A and Kleveko V I 2015 Investigation of the interaction of geosynthetics with ground on the example of shear test and pull-out test Proc. of the XVI European Conf. on Soil Mechanics and Geotechnical Engineering, ECSMGE 2015. 16, Geotechnical Engineering for Infrastructure and Development 2015 pp 3389–94
[7] Kleveko V I 2012. Estimate of the settlement of the foundation on clay grounds reinforced with horizontal layers PNRPU Bulletin. Environmental protection, transport, security of life 1 89–98