Experience in forecasting long-term settlements of energy facilities based on monitoring data analysis

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Abstract. The article discusses the problem of predicting the long-term settlement of reactor compartments of nuclear power plant with a long history of operation and ongoing creep processes. The features of determining the time of the primary consolidation and the application of the parameters of the secondary consolidation are considered. With regard to the existing buildings of the reactor compartments of a nuclear power plant, a forecast of long-term deformations of the base was made, from the present time to 2062, which is the end of the operation period. The analysis and comparison of the obtained results with the data of geotechnical monitoring were also carried out. Analytical forecasting showed a high accuracy in determining the end time of filtration consolidation, however, a comparison of the values of the obtained creep settlements to date and the rate of their development shows significant differences, which makes it necessary to take into account the real picture of deformation for further forecasting in terms of operation time. Possible technological reasons for discrepancies in the results of calculations and geotechnical monitoring are analyzed, as well as theoretical reasons like imperfections of the analytical method used and the possible application of modern numerical methods.

1. Introduction

Numerical methods are now widely used to predict deformations including creep. These methods give the most informative and convenient for processing and analysis results. However, such calculations require the use of special models containing specific soil parameters, which are difficult to obtain if their definition was not included in the geotechnical survey work program in advance [1,2].

For example, to perform such calculations in the PLAXIS software, the following specific parameters of the Soft soil creep model are required: modified swelling index $k^*$, modified compression index $k^*$, modified creep index $\mu^*$ or set of alternative parameters – compression index $c_s$, swelling index $c_s$, creep index for secondary compression $M$. All that parameters can be determined by the testing curves analysis.

However, such data are not always provided for use, and besides, it is not always possible to perform a full-fledged numerical simulation (for example, in the absence of such works in the project). It is often necessary to perform calculations analytically using standard primary and secondary consolidation parameters[3,4]. In the described case, we are talking about predicting long-term deformations of structures that have been in operation for decades. In such conditions, it becomes necessary not only to make calculations, but also to compare them with the data of long-term observations [5]. This will allow
you to correct the adopted parameters and more accurately predict subsequent deformations of the base [6-8].

The nuclear power facilities under consideration are located on the territory of Russia and represent the structures of reactor departments. The first and second power units were commissioned in 1981 and 1986.

The geotechnical conditions of the power unit operation site are well studied. From the surface, from a depth of 0.5 m to 7 m, there are technogenic, mainly sandy soils with various impurities and inhomogeneities. Under them lie Upper Quaternary glacial clayey deposits up to 11.8 m thick. In the same stratum, glacial-lacustrine and water-glacial deposits are found, represented by loamy interlayers and lenses. Below, there are mid-Quaternary water-glacial deposits, represented by sands of various sizes with a thickness of 0.5 m to 14.5 m. After that, there is a layer of mid-Quaternary moraine clays with a total thickness of up to 12.8 m. Under the Quaternary deposits, there are limestone layers with interlayers of Middle Carboniferous dolomite. In the lower parts of the boreholes, strata of heavy clays are also found. The hydrogeological conditions of the site can be characterized as difficult with three main aquifers.

Based on the systematic geodetic monitoring of settlements of the buildings, which has been carried out since 1977 for block 1 (RC-1) and since 1982 for block 2 (RC-2), it can be seen that the RC-1 building received a settlement of 483.1 mm (with an allowable value of 300 mm). For the RC-2 block, the settlement was 397.7 mm. The maximum relative settlements differences were also significantly exceeded.

Various technical materials on the object indicate various possible reasons for the development of such significant deformations of the base, among them the heterogeneity of the lithological composition of the base soils with different strength and deformation properties, the effect of prolonged dewatering on the site during the construction of an auxiliary building as part of a nuclear power plant, overestimation of the deformation modulus of the clay soils by the designers. Moreover, in the last 10 years, insignificant multidirectional values of vertical displacements of the plate have been recorded annually, which are associated with operational impacts from the station buildings, with seasonal changes in groundwater levels, and in general, in the coming years, further slow accumulation of settlements in the base of the reactor compartments is predicted with an average speed of 0.6-0.8 mm/year.

Reactor compartment No. 1 refers to the main production facilities and is part of the main production building. In the plan, it is a cylindrical monolithic reinforced concrete structure with a coating in the form of a flat spherical dome, rising to a level of 76 m. The diameter of the cylindrical shell is 47.4 m with a wall thickness of 1.2 m.

Reactor compartment No. 2 is a cylindrical structure with a diameter of 47.4 m and a height of 76.0 m to the top of the dome. The radius of the reactor compartment in the plan is 24.0 m, at a height of 12.30 - 23.7 m.

2. Methods for long-term deformations determining

2.1. Determination of the depth of the compressible strata

To assess the long-term vertical displacements of the base (settlement) of the RO-1 and RO-2 buildings, the well-known methods for determining the base deformations were used, described in ПіНАЕ-5.10-87 "Foundations of reactor departments of nuclear power plants", SP 22.13330.2011 "Soil bases of buildings and structures".

The key point in calculating any type of foundation settlement is to determine the depth of the compressible stratum under the foundation of the structure, for which it is necessary to first construct diagrams of the distribution of natural and additional stresses in the soil base.

To construct the diagrams, data on the results of engineering and geological studies at the facility, as well as information on the bedding of soils within the structure under consideration, were used [9,10,11]. To calculate each base (under blocks 1 and 2), the most characteristic borehole in the contour of each
building was selected. The depth of the compressible strata under the foundation slab of RC-1 was 29.8 m, of RC-2 - 30.7 m. The graphical results are shown in figure 1.

![Figure 1](image)

**Figure 1.** The scheme for determining the depth of the compressible strata under the bottom of the foundation of the RC-1 (values in kPa).

2.2. The settlement due to deformations of sandy layers and silty-clay non-creep soils

At the first stage, the settlement $S_1$ of the base was determined due to deformations of layers of sandy soils, as well as silty-clay soils that do not have pronounced creep properties.

It is calculated using the well-known formula (1):

$$S = \frac{\beta \cdot \sigma_{zp} \cdot h}{E}$$

(1)

- $\sigma_{zp}$ - average vertical additional stress in the elemental soil layer in the compressible strata;
- $\beta$ - lateral expansion failure factor;
- $h$ - layer thickness;
- $E$ - deformation modulus.

The settlement obtained for each elementary soil layer is summed up. The obtained value for the building of the reactor compartment No. 1 is 8.72 cm, for the reactor compartment No. 2 - 5.72 cm.

2.3. Settlement of the base due to deformation of layers of water-saturated silty-clayey soils

The second component of the total settlement of the structure over the entire lifetime of the project is the settlement of the base due to deformation of layers of water-saturated silty-clayey soils.

The settlement for such layers was determined in accordance with the expression (2):

$$S_n(t) = \sum_{i=1}^{n} \sigma_{zp,i} \cdot h_{cl,i} \cdot \left( m_{1,i} \cdot (1 - \exp(-M_{k,i})) + m_{2,i} \cdot \ln \left( \frac{t}{t_p} \right) \right)$$

(2)

- $\sigma_{zp,i}$ - average value of the additional vertical stress of the $i$-th soil layer;
- $h_{cl,i}$ - thickness of the $i$-th saturated clayey soil layer;
- $m_{1,i}$ - relative compression index of the $i$-th soil layer due to additional pressure in soil base;
$M_k$ - damping of the clayey soil layer coefficient;

$m_{c,2,i}$ - relative secondary consolidation index of the $i$-th soil layer due to the additional pressure in soil base;

$t^i$ - secondary consolidation time (in years);

$t_\phi$ - primary consolidation time (in years).

It is also necessary to take into account the condition that determines the relationship between the filtration consolidation coefficient and the time during which 90% of the filtration consolidation process occurs. It is believed that during this time almost all significant precipitation occurs due to this process, the remaining 10% of the time is insignificant

$$e^{-\alpha t} = e^{\frac{-\pi^2 \cdot c_v}{h_{cl}^2}} = 0.1 \quad \text{(3)}$$

For soils showing creep, the primary and secondary consolidation factors have been determined under laboratory conditions (insert from Appendix 1).

The first part of expression (2) in brackets defines the settlement due to the primary (filtration) consolidation. The value of such a settlement can be calculated separately using the compression modulus of deformation of the layers under consideration using dependence (4)

$$m_{c,1} = \frac{\beta}{E_k} \quad \text{(4)}$$

The settlement of water-saturated layers of clay soil due to primary consolidation for the base of the reactor compartment No. 1 was 10.6 cm, No. 2 – 11.8 cm.

2.4. Settlement of the base due to creep

The rest of the settlement (the second expression in brackets in (2)) will occur during creep over a long period of time in accordance with the coefficient of secondary consolidation and the corresponding coefficient of relative compressibility during creep.

Let us find the weighted average value of the secondary consolidation coefficient for a stratum of soils with creep with a thickness of 13.9 m (total thickness of creeping layers), taking into account its values in terms of cm$^2$/year

$$\bar{c}_v = \frac{H}{\frac{1.6}{5751.3} + \frac{5.3}{8963.7} + \frac{7}{5026}} = 6150 \text{ (cm}^2\text{/year)} \quad \text{(5)}$$

From expression (3), it is possible to express the passage time of 90% of filtration consolidation by taking the logarithm of both parts of the expression and transformations

$$t = \frac{h_{cl}^2 \cdot \ln 0.1}{-\pi^2 \cdot \bar{c}_v} = 18.32 \text{ (years)} \quad \text{(6)}$$

Since forecasting is carried out for a long period of time (for decades), we will round this value to whole, i.e. up to 18 years (the calculation takes into account that the stratum has the ability to squeeze water out of the pores in two directions, up to the surface of the relief and down into the gravel deposits).

Then it is possible to determine the settlement of the RO-1 building in the period from the beginning of construction to the current state (that is, from 1977 to 2019), taking into account the creep.

Filtration consolidation ended in 1977 + 18 = 1995. Hence, the creep developed in 2019 - 1995 = 24 years.

Then the sediment from the creep process

$$S_{\text{creep}} = \sigma_{p,z} \cdot h_{cl,1} \cdot m_{c,2,i} \cdot \frac{t^i}{t_\phi} \quad \text{(7)}$$

The given weighted average value of the compressibility factor for secondary consolidation is determined by the given formula
\[
\bar{m}_{\alpha} = \bar{c}_{\alpha} \cdot \frac{1}{\sigma} \cdot \frac{80}{18} = 0.00000296
\]

80 years - station operation time, 18 years - the time taken to complete 90% of filtration consolidation

\[
\bar{c}_{\alpha} = \frac{1.6}{13.9} + \frac{5.3}{7} = \frac{0.00114}{0.00000296 \ln \frac{24}{18}} = 0.0068 \text{ (m)}.
\]

3. Calculation results

3.1. Analysis and comparison of calculation results and monitoring data for RC-1

Thus, according to the calculations carried out, the total settlement by 2019 of the RC-1 soil base was:

\[ S = 0.0872 + 0.106 + 0.0068 = 0.2 \text{ (m)} = 20 \text{ cm}. \]

However, according to monitoring data (see figure 2), it can be seen that the settlement of the RO-1 slab is 41.63 cm by this time.

Moreover, the largest part of the settlement occurs before the end of filtration consolidation in 1995 (the curve shows a good correlation of this period with the calculations). Since the end of 90% of filtration consolidation until 2019, the building has accumulated a settlement equal to 3.63 cm. According to creep calculations, this value turns out to be much lower - only 0.68 cm. That is, the average settlement rate over a period of 24 years is 0.28 mm/year (if the average rate of settlement accumulation is determined from 3.63 cm, then it will be 1.5 mm/year). However, monitoring data from 2018 to 2019 (over 1.1 years) show an average rate of settlement increment of 0.88 mm/year. This indicates the impossibility of using the adopted creep parameters to predict the further course of the process in time, since they lead to a strongly underestimated creep settlement. Therefore, it was decided to adjust the coefficient of relative compressibility at the average rate of settlement accumulation, determined during the monitoring process.

In the technical materials on the conducted geodetic observations of the movements of the RO-1 building, carried out by specialists of NPO Gidrotekhproekt LLC in 2019, the following conclusions were drawn:

![Figure 2](image-url)

**Figure 2.** The curve of absolute settlement (blue line) and settlement rate (orange line) of the RC-1 foundation slab for the period 01.04.1977-29.07.2019 (NPO Gidrotekhproekt LLC).
1. The total settlement of the center of the foundation slab of the reactor compartment No. 1 for the period 01.04.1977 - 12.02.1991 is -379.1 mm.

The settlement of the plate center for the period June 25, 2018 - July 29, 2019 is -1.0 mm. The average annual precipitation rate for a period of 1.1 years is 0.88 mm/year.

The average settlement of the foundation slab for the period 12.02.1991 - 29.07.2019, with a duration of 28.6 years was -37.2 mm.

2. The total settlement of the center of the RO-1 foundation slab from the beginning of observations on 04/01/1977 to 07/29/2019 is -416.3 mm. This value was obtained by summing the settlement values over the observation periods 01.04.1977 - 12.02.1991 and 02/12/1991 - 06/25/2018 (-379.1) and (-37.2) mm.

3. The admissible values of the settlement of the reactor compartment’s base are considered to be equal to 300 mm. Measured since 1977 to 2019 the average settlement of the RC-1 slab center exceeds the permissible value by 116.3 mm.

Figure 2 shows that the rate of settlement accumulation due to creep is close to the value of 0.792 mm/year (in the straight section from 2007-2017. Let us determine the value of the coefficient of relative compressibility during creep for a given speed. At this average rate of settlement for 24 years (from 1995 to 2019) will be 24*0.792 = 19 mm = 0.0190 m.

So the relative compressibility index due to creep is:

\[ 0.0190 = 574.3 \cdot 13.9 \cdot m'_c \cdot \ln \left( \frac{24}{18} \right). \]

Then \( m'_c = 0.00000826 \).

Further, the total settlement from the creep process was calculated for different periods of time:

\[ S_{1995-2030} = 574.3 \cdot 13.9 \cdot 0.00000826 \cdot \ln \left( \frac{35}{18} \right) = 0.0438 \text{ (m)}; \]

\[ S_{1995-2040} = 574.3 \cdot 13.9 \cdot 0.00000826 \cdot \ln \left( \frac{45}{18} \right) = 0.0600 \text{ (m)}; \]

\[ S_{1995-2050} = 574.3 \cdot 13.9 \cdot 0.00000826 \cdot \ln \left( \frac{55}{18} \right) = 0.0736 \text{ (m)}; \]

\[ S_{1995-2057} = 574.3 \cdot 13.9 \cdot 0.00000826 \cdot \ln \left( \frac{62}{18} \right) = 0.0815 \text{ (m)}. \]

Having received the full value of the creep settlement accumulated from 1995 to 2030, 2040, 2050 and 2057 (end of operation, \( t = 80 \) years), it is necessary to take into account that 3.63 cm has already been accumulated at the moment for the period from 1995-2019 according to monitoring data.

Therefore, was calculated the settlement increment that can be expected from now to 2030, 2040, 2050 and 2057:

- By 2030: 4.38 -3.63 = 0.75 cm.
- By 2040: 6.0-3.63 = 2.37 cm.
- By 2050: 7.36-3.63 = 3.73 cm.

By the end of the service life in 2057: 8.15-3.63 = 4.52 cm.

You can also separately consider the pessimistic scenario, in which the rate of settlement accumulation is 0.88 mm/year (which was recorded for the period of 1.1 years from 2018 to 2019).

Having carried out similar calculations, it is possible to obtain the following characteristic values of the increment of the foundation settlement to the years under consideration:

- By 2030: 4.88 -3.63 = 1.25 cm.
- By 2040: 6.72-3.63 = 3.36 cm.
- By 2050: 8.19-3.63 = 4.56 cm.

By the end of the service life in 2057: 9.07-3.63 = 5.44 cm.

Both obtained variants of forecasting the precipitation, taking into account different rates of development of precipitation, are shown in figure 3.
3.2. Analysis and comparison of calculation results and monitoring data for RC-2

Thus, according to the calculations carried out earlier, the total settlement by 2019 was:

\[ S = 0.0572 + 0.118 + 0.0073 = 0.1825 \text{ (m) = 18.25 cm).} \]

However, according to monitoring data (see Fig. 4), it can be seen that the settlement of the RC-2 slab is 33.58 cm by this time. Moreover, the largest part of the settlement occurs before the end of filtration consolidation in 1998 (the graph shows a good correlation of this period with the calculations).

Since the end of 90% of filtration consolidation until 2019 (1998-2019), the building has accumulated a settlement equal to 335.8-327.56 = 8.24 mm = 0.00824 m. According to creep calculations, this value turns out to be less - 0.0073 cm. That is, the average settlement rate over a period of 21 years is 0.35 mm / year (according to forecast calculations) and 0.39 mm / year (according to monitoring data). Therefore, to predict the further course of creep settlement, we will accept the two considered rates as optimistic and pessimistic scenarios.

Figure 3. Curves of the increment of the RC-1 base settlement, starting from 2020 according to two scenarios (orange line due to rate of settlements of 0.88 mm/year, blue line due to rate of settlements of 0.79 mm/year), Axis X – time in years, axis Y – predicted settlement.

Figure 4. Curves of absolute settlement and settlement rate of the RC-2 foundation slab for the period 01.04.1977-29.07.2019 (NPO Gidrotekhproekt LLC).
The report on the conducted geodetic observations of the movements of the RC-2 building was made by specialists of NPO Gidrotekhproekt LLC in 2019.

Based on the observation results, the following conclusions were made.

1. The total settlement of the center of the foundation slab of the reactor compartment No. 2 for the period 04.11.1982 - 12.02.1991 is -316.00 mm.
   Settlement of the plate center for the period of June 27, 2018 - 2.08.2019 is -0.7 mm.
   The average annual precipitation rate is 0.6 mm / year.
   The average settlement of the foundation slab for the period 12.02.1991 - 2.08.2019, lasting 28.5 years, was -19.8 mm.

2. The total settlement of the center of the RC-2 basement slab from the beginning of observations 01.04.1982 to 2.08.2019. is -335.8 mm. This value was obtained by summing the settlement values over the observation periods 04.11.1982 - 12.02.1991 and 12.02.1991 - 2.06.2019. (-316.00) and (-19.8) mm.
   The admissible values of the settlement of the base of the reactor compartment are considered to be 300 mm. Measured since 1982 by 2019, the average settlement of the center of the RC-2 slab exceeds the permissible value by 35.8 mm.
   For the rates obtained, the method described above was used to calculate the increments of settlement for two variants of the rate of its accumulation.
   With a maximum settlement accumulation rate of 0.35 mm / year, the maximum value will be reached in 2062 with a value of 2.89 cm. Under a pessimistic scenario, with a rate of 0.39 mm / year (according to monitoring results), starting from 2020 and by the end of the service life, the increment in the settlement will be 3.38 cm.

4. Conclusions and discussion
   According to the calculations performed, the following conclusions can be drawn.
   1. The applied methodology for predicting the settlements accumulation in reactor compartments showed good agreement with the monitoring data in determining the time of the end of the primary consolidation (18 years for RC-1 and 16 years for RC-2), however, the settlement values obtained by this time do not converge with calculations. This is possible for various reasons, including the inaccuracy and inadequacy of the determination of the deformation characteristics of the considered soils, taken for analytical calculation, as well as the imperfection of the model adopted in the analytical method, given its relative simplicity, for example, in comparison with numerical methods.
   2. Analysis of the geotechnical monitoring data over the past years indicates the practical stabilization of the sediment of the base of the reactor compartment vessels, which ended in 2008-2009. However, recent data indicate a slow and constant accumulation of deformations at a rate of up to 0.6-0.8 mm / year. This may be due to seasonal changes in groundwater levels, technological impacts during the operation of the station equipment.
   3. In general, the predicted values of base deformations, taken for the calculation taking into account the data of geotechnical monitoring, look quite realistic in accordance with the long period of time remaining until the end of operation of the reactor compartments. However, 45.2 and 28.9 mm until 2057 and 2062, respectively, are significant values, given that the settlements of the departments has long exceeded the standard values established for this type of structure.

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