Role of temperature factor in the work of a cellular reinforced concrete ice-resistant platform

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Abstract. The article presents materials reflecting the results of calculations by the finite element method on a computer (according to a special program) of the thermal state of the cellular fragment of the reinforced concrete support block LSP taking into account the influence of seasonal and decadal outdoor temperatures, as well as the effect of changes in the thermal characteristics of the backfill soil on the thermal state of the ice-resistant stationary platform. This made it possible for the first time to evaluate the joint work of a thin reinforced concrete frame and a massive body of backfill soil under temperature effects. In the case of the operation of the cellular structure without the backfill soil, seasonal and ten-day temperature fluctuations create a more unfavourable temperature regime in comparison with the cellular structure with the backfill soil. In the absence of backfill soil, negative temperatures penetrate most deeply into the thickness of the structure. The presented data can also serve as the basis for a preliminary assessment of the thermal state of LSP in the form of a fully cellular reinforced concrete structure and in the future to determine its thermally stressed state. Only considering the combined effect of ice, wave and temperature loads can we really evaluate the operation of such a complex structure in terms of its reliability and safety.

1. Introduction

It is known that the most numerous groups of structures used on the sea shelf are used for oil and gas field structures. Depending on their mobility, they are divided into stationary and mobile. Stationary platforms are of gravitational type and often pile construction.

Most platforms are erected from metal structures, whose service life in sea water is 2–3 times shorter than on land [1-4].

Another variety of gravity platform are reinforced concrete gravity platforms with the partial use of cells filled with sand to increase the stability of the structure.

Unfortunately, to date, little attention has been paid to the work of structures on temperature effects. It is proposed to take into account the behaviour of the structure in the zone of variable water level [5-7], however, having zero degrees in the underwater part and up to -50 °C in the surface part, the whole spectrum of the annual course of outdoor temperatures (including seasonal and ten-day temperature fluctuations) should be taken into account. At the same time, it is necessary to consider the possibility of contact between the produced hot oil and the walls of the structure and the significant temperature difference created in this structure. Regulatory documents of the 1980s (BCH 41.88) classify temperature effects as special loads along with seismic, wave and ice loads.

We propose to consider a fully cellular design of the platform with a concrete cellular frame filled with backfill soil (Figure 1). It is economical, more resilient, fire resistant and most effectively absorbs vibration created by equipment. On the other hand, the use of cellular concrete (or reinforced concrete)
structures with backfill soil, as well as hydroelectric power station floating blocks, is also justified by the following criteria: safety of construction and installation works, low operating costs, high construction speed (including fast transportation), high reliability and the strength of structures under the influence of all external forces, including special (in emergency situations) and various temperature effects. The cellular structures of such structures can be built in various climatic and geological conditions (on rocky and non-rocky foundations), and any local soil of useful excavations can be used as backfill soil for cells. According to [8-10] “reinforced concrete is the most acceptable material of support blocks for work in seismic areas and in emergency situations”.

Unfortunately, a few issues related to the design and calculations of these structures did not find a sufficiently complete justification. Currently, there are several approximate calculation methods based on various assumptions.

There are practically no calculations that implement the joint work of the concrete frame of the cellular structure and the backfill soil, taking into account the temperature effects.

At ONIL “Strength and Sustainability” of the Department of Hydrotechnical Structures of the Institute of Land Reclamation, Water Management and Construction named after A.N. Kostyakov Russian State Agrarian University - Moscow Timiryazev Agricultural Academy for a number of years carried out model studies and computer calculations of cellular structures of hydraulic structures taking into account the influence of backfill soil and base.

As the results of earlier laboratory studies have shown, various temperature effects have a significant impact on the operation of such structures. The objective of this work was to determine the thermal state of the cellular structure from seasonal and ten-day fluctuations in outdoor temperatures, taking into account changes in the thermophysical properties of soils.

2. Materials and methods

The cellular type structures [9] are a reinforced concrete frame consisting of mutually intersecting radial and annular bulkheads made up of flat fragments that form cells filled or unfilled with soil (Figure 1).

![Figure 1](image-url)
The cellular structures of hydraulic structures are classified as gravitational shear. Existing computer software packages that implement the finite element method, as applied to the calculations of cellular structures, do not fully reflect the physics of the phenomena occurring in such structures. Great difficulties arise when considering the joint work of a thin reinforced concrete frame and a massive backfill body. The physics of the phenomena and its mathematical description regarding the joint work of the base soil, the backfill soil, and the carcass are not completely clear.

The numerical studies of the thermal state of the cellular structure presented in this paper were carried out according to the Quasis program. The objective of this work was to determine the thermal state of the cellular structure from seasonal and ten-day fluctuations in outdoor temperatures, considering changes in the thermophysical properties of the backfill soil.

When determining the thermal regime of the cellular structures of the LSP, we considered the effect of ambient temperatures (water, air) from the front wall for a series of flat horizontal sections and from the front and top walls for the vertical section of the LSP (LSP-V) (Figure 1).

The temperature regime of the honeycomb structure under consideration is formed under the influence of heat exchange with the environment at the borders of the selected computational domain (Figure 1). To determine the thermal regime of a cellular structure, it is necessary to have physical and mechanical and thermophysical characteristics of the carcass material (concrete or reinforced concrete) and the soil of the cell backfill.

The thermophysical characteristics of the frame and the soil of the cell backfill determine the intensity of the change in the temperature field of the structure in time and in coordinates. Physical and mechanical and thermophysical characteristics of the materials of the construction considered in the calculations are shown in Table 1.

Table 1. The main thermophysical and physical and mechanical characteristics of the materials of the frame and filling the cells LSP

| Material | Thermophysical and physical and mechanical characteristics of materials of the computational domain | Notes |
|----------|-------------------------------------------------------------------------------------------------|-------|
| Concrete | $\lambda_\mathrm{x}=\lambda_\mathrm{y}$, $\alpha_\mathrm{x}$, $c_\mathrm{r}$, $E_\mathrm{r}$, $\mu$, $\gamma$, $\alpha$ |       |
| Concrete-air | 23.26, 2.55, 1.0048, 29000, 0.15, 24000, 1*10^-5 |       |
| Concrete-water | 232.6, 2.55, 1.0006, 26, 0.235, 18000, 1*10^-5 |       |
| Backfill cells (sand) | 0.58, - | Simulated air gap $e\rightarrow 0$ |
| No cell filling (air) | 0.58, - |       |

* $\lambda_\mathrm{x}$ and $\lambda_\mathrm{y}$, $c$, $\gamma$ vary with moisture and material density

To carry out the calculations, the real annual course of average monthly temperatures was brought to a harmonic form $t = t_{\mathrm{cp.r.}} + A_\mathrm{r} \cos(\omega \tau + \epsilon_\tau)$ degrees Celsius, where

- $t$ - the temperature of the external environment at time $\tau$, degrees Celsius;
- $A_\mathrm{r}$ – the full amplitude of the fluctuations in the monthly average ambient temperatures relative to $t_{\mathrm{cp.r.}}$, degrees Celsius;
- $t_{\mathrm{cp.r.}}$ – average annual temperature, degrees Celsius;
- $\tau$ – time, counted from the beginning of the year, hours;
- $\tau_{\mathrm{ord.}}$ – period, number of hours in a year, $\tau_{\mathrm{ord.}} = 8760$ hours;
- $\epsilon_\tau$ – is the initial phase of harmonic oscillations;
- $\epsilon_\tau = \text{hours} = 0.2619$ radians;
ω = \frac{2\pi}{\tau_{0,\alpha}} - \text{cyclic frequency},

\omega_s = 0.00071726 \text{ radians / hour.}

Thus, the calculated harmonic temperature fluctuations of the external environment have the following form with the seasonal course of temperatures:

a) outdoor air
\[ t = -3.16.25 \cos (0.00071726 \tau - 0.2619) \text{ degrees Celsius}; \]

b) water on the horizon 0.0m
\[ t = 2.88 - 6.35 \cos (0.00071726 \tau - 0.2619) \text{ degrees Celsius}; \]

в) water on the horizon 10.0m
\[ t = 1.7 - 4.875 \cos (0.00071726 \tau - 0.2619) \text{ degrees Celsius}; \]

г) water on the horizon 20.0m
\[ t = 0.91 - 3.45 \cos (0.00071726 \tau - 0.2619) \text{ degrees Celsius}; \]

3. Results

As a result of the thermal calculation according to the calculation schemes described above, the thermal fields were determined for 12 months on the 15th day of each month for the annual temperature course and for 12 steps of 20 hours for a ten-day temperature course in a quasi-stationary setting of the ambient temperature course.

Figure 2 shows the effect of the annual temperature variation on the distribution of temperature fields in a structure in January over horizontal sections, and in Figure 3 - in April over horizontal sections. As can be seen from Figure 2, seasonal fluctuations in outdoor temperatures in January have a significant effect on the formation of the thermal state of the upper part of the platform (from the 28.00 m mark to the 40.00 m mark), their most significant effect is felt in its cantilever part, and complete attenuation occurs only inside the middle part of the structure (in the “glass”) at the end of the fifth from the front wall of the cell (along the P-I axis).

Figure 2. The effect of the annual temperature variation on the distribution of temperature fields in a structure in January over horizontal sections (the water level is located at 1.53 m).
In this case, at around 28.00 m at the end of the third from the front wall of the cell (along the axes A3 and A4), the transition of negative temperatures to positive is observed. As can be seen from Figure 3, in April, a certain effect of seasonal fluctuations in the temperature of the outside air (taking into account fluctuations in water temperature) on the thermal state of the structure as a whole and also the most significant on its upper part is again noted. The above results show that the cantilever part of the LSP is most susceptible to adverse effects of temperature.

**Figure 3.** The effect of the annual temperature variation on the distribution of temperature fields in a structure in April over horizontal sections.

The temperature distribution obtained by horizontal sections allows you to fully evaluate the thermal state of the specified design of the cellular type.

From the temperature distribution shown in Figure 3 in April, the temperature regime established in the structure is somewhat more favourable than in January. An exception is the cantilever part at 34.0 m and 28.0 m, where, because of a delay in temperature over time, negative temperatures penetrate deeper into the thickness of the structure. At around 34.0 m, they are marked along the entire perimeter of the structure.

At levels of 1.53 m and -8.0 m in April, negative temperatures also penetrate deeper into the structure (about one cell). The same pattern appears at the base.

The above results show that the cantilever part of the LSP is most susceptible to adverse effects of temperature. It is a prismatic structure of complex shape (see figure 1).

*The influence of decadal temperatures on the distribution of temperature fields in a structure/

The temperature distribution in the building, respectively, in the fourth part of the decade (4th 20 hours) for a few vertical sections is presented in Figure 4.

From the temperature diagrams shown in Figure 4, it can also be noted that the effect of decade temperatures is limited by the cantilever part of the LSP (within two cells along the axes A - 1, A - 2, and A - 3).
From the mark of 28.0 m to the mark of 10.0 m, the decadal temperatures decay at less than 1/3 of the size of the cells located at the front surface.

Figure 4. Influence of the ten-day course of temperatures on the distribution of temperature fields in a structure in the fourth 20 hours of a decade over vertical section.

The presence of water (mark 1.53 m) almost completely removes the effect of ten-day temperatures on the thermal state of the structure. So below the -2.0 m mark, a constant temperature field is almost fixed.

The paper also assesses the role of the thermophysical characteristics of the backfill soil in the formation of the thermal state of the cellular fragment. Figure 5 shows the temperature distribution over the LSP cross section at around 16.0 m (figure 1) from the seasonal outdoor temperature fluctuation in the backfill soil, depending on the soil thermal conductivity coefficient \( \lambda_r \) for the amplitude \( A_r = 1 \) degree in January.

As can be seen from Figure 5, in January, with a decrease in the value of \( \lambda_r \), a decrease in the zone of negative temperatures in the soil is noted, which shifts to the front surface (curve 2). In this case, curve 1 corresponds to the temperature distribution along the concrete wall of the cellular structure of the LSP.

The absence of backfill soil (curve 3) negative temperatures penetrate deep into the thickness of the structure.

The curve numbers correspond to the variant numbers in table 2, column 1.
Figure 5. The influence of the thermal conductivity coefficient $\lambda$, soil filling cells LSP on the temperature distribution in January over the section “wall - soil” (mark 16.0 m in figure 1) with seasonal fluctuations in outdoor temperature $t = -1.0 \cos \omega \tau$, degrees for $t_{ср.} = 0.0$ degrees.

Table 2. The main thermophysical and physical and mechanical characteristics of the materials of the frame and soil of the backfill of the cellular structure of the LSP according to the options $b$

| Variant of the curve in the graph of Figure 5 | Material of the computational domain | $\lambda_X = \lambda_Y$ Bт/м•К | $\alpha_{in}$ Bт/м$^2$•К | $C$, КДж/кг•К | $\gamma$, H/м$^3$ | $\alpha$, 1/degree |
|---------------------------------------------|-----------------------------------|-----------------|-----------------|----------------|----------------|-----------------|
| 1                                           | Concrete                           | 2.56            | 23.26           | 1.0048         | 24000          | $1\times10^{-5}$ |
| 2                                           | Concrete (sand)                    | 2.56            | 23.26           | 1.0048         | 24000          | $1\times10^{-5}$ |
| 3                                           | Concrete                           | 0.58            | 1.0006          | 18000          |                |                 |
| 3                                           | Concrete                           | 0.58            | 0.0008          | 18000          |                |                 |

$b\lambda_X$ and $\lambda_Y$, $C$, $\gamma$ – vary with moisture and material density

4. Findings

1. New physical ideas about the behaviour of the structure of the type under consideration under temperature effects are obtained. As the real calculations on the definition of the thermal state of the soil have shown of a fragment working together with the backfill soil, along with seasonal fluctuations in the temperature of the outside air, it is necessary to take into account the ten-day fluctuations in the temperature of the outside air. The presence of large temperature differences between the front wall and adjacent bulkheads can lead to the appearance of significant values of temperature stresses.

2. The use of soil cells with different values of the coefficient of thermal conductivity as a backfill primarily affects the thermal regime of the soil massif (changes the values of temperature amplitudes and the degree of their attenuation along the depth of the structure). To a lesser extent, this affects the thermal state of the reinforced concrete frame.

3. In the case of the filling of the cellular fragment without soil, seasonal and ten-day temperature fluctuations create a more unfavourable temperature regime inside the structure compared to the structure filled with soil. In the absence of backfill soil, negative temperatures penetrate most deeply into the thickness of the structure.

4. The presented data can serve as a sufficient basis not only for a preliminary assessment of the thermal state of the specified structure, but in the future to determine its thermally stressed state.
5. In sections of the structure located below the water edge, insignificant temperatures are observed and their attenuation along the depth of the structure occurs much faster than in sections that are directly affected by outside air.

6. The combination of the properties of the floating blocks of hydroelectric power stations built in the regions of Western and Eastern Siberia allows us to conclude that the efficiency of the delivery of these cellular structures to any given location ensures high reliability of the structure according to the main parameters.

7. According to the current regulatory documents, the following gradation of temperature loads for LSPs can be given: 1) temporary loads - temperature effects (for a year with an average amplitude of average monthly temperatures); 2) special loads — external influences with maximum parameters — temperature effects determined for a year with a maximum amplitude of average monthly temperatures or a maximum low amplitude of average monthly temperatures; decade-long outdoor temperature fluctuations with a maximum average temperature per decade. These temperature effects are mandatory for design considerations.

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