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NUMERICAL THERMAL ANALYSIS OF WIND TURBINE FOUNDATIONS WITH A FORCED CONCRETE COOLING SYSTEM

Summary: Wind turbine foundations belong to the category of massive concrete structures, in which controlling the temperature rise during the early stage of concrete hardening is of crucial importance for preventing cracks caused by thermal tensile stresses. This paper presents an example of a staged thermal analysis of massive wind turbine foundation within a wind farm in the Republic of Serbia. The analysis was carried out using the finite element method. Special attention was given to the impact of forced concrete cooling systems on the development and attainment of maximum temperatures during the cement hydration process. The calculations were performed in accordance with applicable national and international standards and guidelines, including Eurocode and ACI. The obtained conclusions contribute to a better understanding of the thermal processes and indicate the necessity of applying measures aimed at reducing peak concrete temperatures.

Keywords: thermal analysis, mass concrete, heat of hydration, wind turbine foundation slab, finite element method, forced cooling system

TERMIČKA ANALIZA TEMELJA VETROGENERATORA SA PRIMENOM SISTEMA PRINUDNOG HLAĐENJA BETONA

Rezime: Temeljne ploče vetrogeneratora spadaju u masivne betonske konstrukcije kod kojih je upravljanje porastom temperature u ranoj fazi očvršćavanja betona od presudne važnosti za sprečavanje pojave prslina izazvanih termičkim naponima zatezanja. U radu je prikazan primer fazne termičke analize masivnog temelja vetrogeneratora u okviru jednog vetroparka u Republici Srbiji. Analiza je sprovedena primenom metode konačnih elemenata. Posebna pažnja posvećena je uticaju sistema za prinudno hlađenje betona na razvoj i dostizanje maksimalnih temperatura tokom procesa hidratacije cementa. Proračuni su izvršeni u skladu sa važećim domaćim i međunarodnim standardima i smernicama, uključujući Evrokod i ACI. Dobijeni zaključci doprinose boljem razumevanju termičkih procesa i ukazuju na neophodnost primene mera za snižavanje vršnih temepratura u betonu.

Ključne reči: termička analiza, masivni beton, toplota hidratacije, temelj vetrogeneratora, metoda konačnih elemenata, prinudno hlađenje

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1. INTRODUCTION

Extreme thermal conditions within concrete elements represent one of the main characteristics of mass concrete structures. The temperature rise in such elements represents a serious challenge, as it must remain within the limits prescribed by relevant standards and regulations. Furthermore, the increase in temperature also leads to larger temperature differences between the inner and surface zones of the massive element. These two factors have a decisive influence on concrete quality, on the durability of the concrete mixture and the entire structure throughout its designed service life [1]. Inadequate temperature control in concrete may lead to the development of high thermal stresses and, consequently, to cracking.

The central part of a massive structure is exposed to adiabatic or quasi-adiabatic conditions, which occur when ambient conditions have a negligible influence on temperature rise. In other words, the heat remains "trapped" within the element and dissipates slowly. Experience has shown that adiabatic or quasi-adiabatic conditions occur at depths greater than approximately 0.6 m from the concrete surface. This means that elements thicker than 1.2 m are more susceptible to temperature rise [2]. During the concreting of massive elements, the maximum temperature value in concrete is most commonly reached within the first three days after placement. The maximum temperature within concrete is the sum of the initial temperature of the concrete mix at the time of placement and the temperature rise resulting from the hydration process.

Once concrete has been placed in a mass concrete element, the options for cooling its core become very limited. The removal of previously installed thermal insulation blankets has only a minimal effect on the core temperature. The measures typically considered include modifying the concrete mix design (which is often not feasible due to the high strength requirements of the concrete), dividing the foundation into multiple layers (which is likewise frequently impractical because of construction schedules or other constraints), and installing cooling pipes through which water of a specified temperature and flow rate is circulated (generally regarded as the most effective solution). It should also be noted that controlling the concrete surface temperature relative to the maximum temperature in the core is essential and is commonly achieved by covering the surface with thermal insulation blankets [1].

The key to achieving high-quality mass concrete is the preparation of a proper Thermal Control Plan. A Thermal Control Plan represents a collection of all information regarding materials, placement procedures, and cooling methods required to ensure the proper implementation of the Concrete Design Plan itself. According to the relevant regulation [3], the maximum concrete temperature must be limited to 70.0°C. Additionally, under no circumstances may the maximum concrete temperature exceed 85.0°C. Regulations also often provide guidelines regarding the maximum allowable temperature drop in concrete during the first 24 hours. A good Thermal Control Plan also defines the conditions under which thermal protection measures are terminated, such as the removal of insulation materials or the completion of temperature monitoring, taking into account the limits and/or concrete strength development over time prescribed by regulations [1].

According to the standard SRPS EN 13670 [4], which is applicable in the Republic of Serbia, the concrete temperature shall not exceed 70.0 °C for the purpose of thermal behavior control, unless it can be demonstrated that higher temperatures will not have a significant adverse effect on the properties of the concrete.

The main issue related to exceeding the allowable temperature limits concerns the occurrence of delayed ettringite formation, which is a common product of cement hydration. Its role is to consume most of the sulfates present in the mixture and prevent excessively rapid setting of concrete. Ettringite formed during the early stages is referred to as "primary ettringite." However, when the early-age concrete temperature is excessively high, primary ettringite becomes unstable, which may lead to delayed ettringite formation. The harmful effects may appear only years later, when, in the presence of moisture, ettringite forms again, causing the concrete to expand and crack [1]. This initiates processes that lead to a reduction in the durability, serviceability, and service life of the structure; therefore, the provision in SRPS EN 13670 allowing verification that temperatures exceeding 70.0°C will not have a significant adverse effect is highly problematic.

The American standards ACI 207.1R-05 [2] and ACI 301 [3] provide the following recommendations for the control and monitoring of thermal behavior: the maximum temperature in concrete after placement shall not exceed 70.0 °C; the maximum temperature difference between the center of a mass concrete structure and its surface shall not exceed 20.0 °C; a Thermal Control Plan shall be prepared, containing the following: a description of the materials to be used, the adiabatic temperature rise in the structure, the maximum temperature based on the expected conditions during concrete placement and curing, a description of the measures to be undertaken to ensure that placement temperatures do not exceed the defined limit, the maximum temperature difference based on the expected conditions during placement and curing, a description of the measures to ensure that temperature differences do not exceed the defined limit, a description of the equipment and procedures to be used for monitoring and recording temperatures and temperature differences, drawings showing the locations of measuring equipment, a description of the curing methods and curing duration, and a procedure for submitting data to the engineer.

Reference [5] presents an example of a phased thermal analysis for three massive wind turbine foundations with variations in the initial concrete mixture temperatures in order to predict peak temperatures during the cement hydration process. The results indicate that the predicted peak temperatures exceed the limits prescribed by the regulations, highlighting the necessity of implementing appropriate measures for reducing concrete temperatures.

Within the scope of this paper, which represents a continuation of the research presented in the case study [5], presents a temperature reduction measure for the largest of the analyzed foundations for one selected initial concrete temperature. The proposed measure is based on forced cooling using a pipe system through which water of a predefined temperature circulates.

2. THERMAL PROCESSES IN MASS CONCRETE

2.1. BASIC HEAT TRANSFER EQUATIONS

The temperature variation of a homogeneous isotropic body over time is described by the Fourier heat conduction equation:

$$\rho c \frac{dT}{d\tau} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q, \tag{1}$$

where: ρ is the material density [kg/m^3], c is the specific heat capacity of concrete [J/(kg K)], T is the temperature [°C], k is the thermal conductivity coefficient [W/(m K)] and Q is the volumetric heat flux density of the heat source [W/m^3].

In practical problem-solving, the objective is to determine the solution T(x,y,z,τ) of Equation (1), that satisfies the corresponding initial and boundary conditions.

The initial conditions imply that the temperature distribution at the initial time (τ = 0) is known and defined by the temperature field T(x,y,z,0), while the boundary conditions define the heat flux exchanged between the body (of the concrete structure) and the surrounding environment:

$$-k\left(\frac{\partial T}{\partial n}\right) = q_c + q_r, \tag{2}$$

where: ∂T/∂n represents the temperature field gradients on the concrete surfaces [°C/m], q_c is the convective heat flux [W/m²] (which defines heat conduction), and i q_r is the radiative heat flux [W/m²] (which defines heat exchange between the structure and environment).

The heat exchanged between the concrete surfaces and air, is given by Newton's law of cooling:

$$q_c = h_c(T - T_a), \tag{3}$$

where: T is the concrete surface temperature [°C], T_a is the ambient air temperature [°C], and h_c is the convective heat transfer coefficient [W/m²·K].

The heat exchanged by radiation between the concrete surfaces and the environment is described by the linearized Stefan-Boltzmann radiation law:

$$q_r = h_r(T - T_a), \tag{4}$$

where h_r is the linearized radiation coefficient [W/m²·K], defined by the following [6]:

$$h_r = \varepsilon\sigma(T^2 + T_a^2)(T + T_a), \tag{5}$$

where ε is the surface emissivity and σ is the Stefan–Boltzmann constant (5.669·10⁻⁸ W/m²).

Taking into account Equations (3) and (4), the boundary condition (2) can be written in the following form:

$$-k\left(\frac{\partial T}{\partial n}\right) = h(T - T_a), \tag{6}$$

where h is the combined (h_c+h_r) convective coefficient [W/m²·K].

2.2. HYDRATION PROCESS

During concrete hardening, heat is released through the cement hydration process, depending on the chemical and mineralogical composition of the cement.

The hydration heat release curve is often approximated by the following equation [7]:

$$Q_t(\tau) = Q_{max}(1 - e^{-m\cdot\tau}) \tag{7}$$

where: $Q_t(\tau)$ is the released hydration heat from concrete at time τ [J], Q_{max} is the maximum amount of hydration heat that can be released from concrete of a given composition under complete cement hydration [J], m is an empirical parameter depending on the cement type [1/h], and τ is time [h].

Experimental studies have shown that during the first 7 to 10 days of concrete hardening, up to 80.0% of the heat generated by cement hydration is released, while in the later stages of hardening the heat release process slows down [7, 8].

The temperature increase caused by the heat generated during cement hydration may induce the highest tensile stresses in concrete during the construction period, since the adiabatic temperature rise can exceed 50.0°C [7], and is determined using the following equation:

$$T_h = \frac{q_t \cdot K}{c \cdot \rho} \tag{8}$$

where: T_h is the temperature increase caused by the heat of cement hydration [°C], q_t is the amount of released heat [J/kg], K is the mass of cement per unit volume [kg/m³], c is the specific heat capacity of concrete [J/(kg·K)], and ρ is the density of concrete [kg/m³].

2.3. TEMPERATURE OF FRESH CONCRETE MIX

The formation and development of the temperature field in mass concrete structures are strongly influenced by the temperature of the fresh concrete mix at the time of mixing and placement. [9, 10].

In order to reduce the initial temperature of the concrete mix, the following measures are applied: the use of low-heat (slow-hardening) cements, reduction of cement content, application of retarders, cooling of mixing water, use of ice, and protection of silos and aggregates from direct solar radiation, and similar measures. From the standpoint of construction technology, additional measures include staged concreting, concreting during nighttime, cooling and curing of concrete surfaces, the use of forced cooling systems through embedded pipes, or the use of precast elements in which the hydration process has already been completed [5].

2.4. HEAT EXCHANGE FROM EXPOSED AND PROTECTED SURFACES

Heat exchange between a concrete structure and the surrounding environment occurs due to temperature differences between the concrete surface and the ambient air temperature. The intensity and rate of this process depend on the magnitude of the temperature difference (influenced by air temperature, solar radiation, and cement hydration), material properties, and the environmental conditions in which the structure is placed [5].

In the case of exposed concrete surfaces that are directly subjected to environmental conditions, heat exchange occurs more intensively. Heat is transferred by convection between the concrete surface and the air, by radiation to the surroundings (particularly during nighttime when the concrete surface cools by emitting heat to a colder environment), and by evaporation of water from the concrete surface. In contrast, for protected concrete surfaces, heat exchange is significantly slower. Protection may be provided in the form of formwork, thermal insulation blankets, protective foils, insulation layers, or other materials that reduce direct contact between concrete and the environment. These protective layers act as a barrier that slows down heat transfer between the concrete and its surroundings, thereby ensuring a more uniform cooling of the structure [5].

2.5. TEMPERATURE OF THE FOUNDATION MEDIUM

The temperature of the surrounding medium at the foundation level is practically unaffected by seasonal variations in air temperature and, except for the near-surface layer, may be assumed to remain constant and equal to the long-term average temperature measured at a depth of approximately 50 cm below ground level [9, 10].

3. NUMERICAL MODEL FOR THERMAL ANALYSIS

3.1. BASIC DATA ON THE STRUCTURE AND NUMERICAL MODEL

For the foundation of a wind turbine, a concrete footing with a volume of 1142.0 m³ and a diameter of ⌀26.2 m is designed (Figures 1 and 2). The foundation concrete is class C45/55, using cement CEM II/A-L 42.5 R in an amount of 430.0 kg/m³. In the central part of the foundation cross-section, a steel anchor cage for the installation of the tower structure is located, as well as pipes (Figure 2, shown in blue) used for routing installations from the wind turbine. Beneath the structure, a blinding layer is provided, serving to improve bearing capacity [5].

Concrete placement on site, located in the mountainous region of eastern Serbia, was carried out between October and January. Minimum ambient temperatures at the site occur in February (-6.0°C), while maximum temperatures occur in August (23.0°C). The average temperature in spring and autumn is about 15.0°C, while the average winter temperature is about 2.5°C.

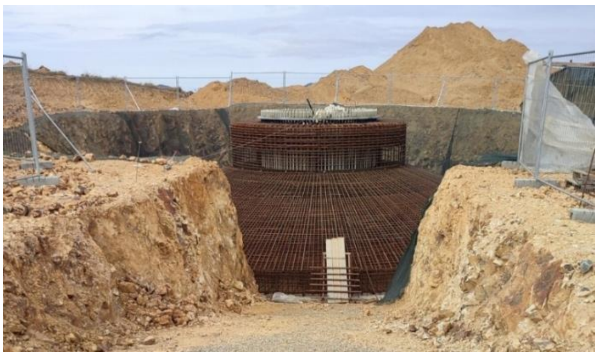

Figure 1: Layout of the reinforcing cage of the wind turbine foundation at the construction site

The three-dimensional structural model of the foundation includes the concrete slab together with the lean concrete layer. Modeling the lean concrete layer enables a more realistic simulation of phenomena in the foundation interface zone, as well as heat exchange between the medium and the concrete structure.

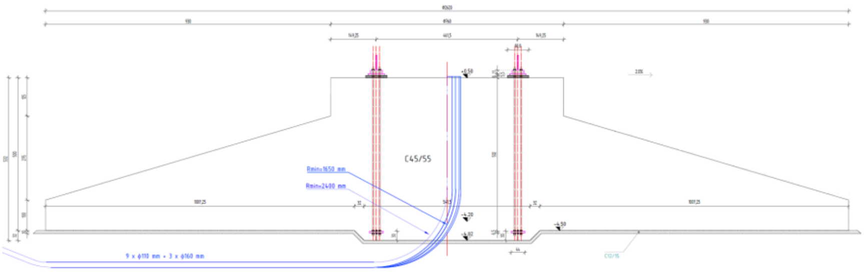

Figure 2: Cross-section of the wind turbine foundation slab

For the purpose of modeling thermal processes, a three-dimensional finite element (FEM) model was developed (Figure 3). The total number of finite elements in the model is 125,531.

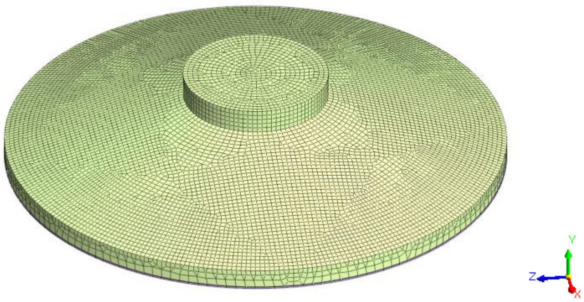

Figure 3: Finite element mesh of the wind turbine foundation slab

The developed numerical model includes the construction phase of the lean concrete layer at a constant temperature, assumed equal to the adopted medium temperature, as well as the concrete placement phase of the slab in which the cement hydration process is considered. The following thermal and concrete hydration parameters were used for the thermal analysis:

- thermal conductivity coefficient: $k = 2{,}50$ W/(m K)
- specific heat capacity: $c = 900{,}0$ J/(kg K)
- thermal expansion coefficient: $\alpha = 10 \cdot 10^{-6}$ 1/°C
- combined convective heat transfer coefficient: $h_1 = 25{,}0$ J/(m² K)
- cement content in concrete mix: 430,0 kg/m³

The calculations were performed using a cement hydration curve corresponding to Portland cement with high early strength for each of the three foundations [5, 11].

3.2. BOUNDARY CONDITIONS FOR THERMAL ANALYSIS

In the thermal analysis, the following boundary conditions were considered: the interface between previously cast and newly placed concrete layers, concrete surfaces in contact with air, the temperature of the fresh concrete mix of the foundation, the temperature of the cooling water in the forced cooling system, and the medium temperature.

A thermal boundary condition allowing free heat conduction between concrete layers was assigned to the foundation, at the locations of contact surfaces. On concrete surfaces exposed to air, ambient temperatures were prescribed according to the function shown in Figure 4. The influence of solar radiation was not considered in this model, taking into account the duration of the thermal analysis and the fact that during concreting and subsequent hardening, the concrete surface was covered with lightweight opaque PVC protective foils. The initial temperature of the fresh concrete mix (T_{init}) was assumed to be 15.0 °C, while the medium temperature was taken as 13.0 °C [5]. The temperature of the cooling water in the forced cooling system (T_{water}) was assumed to be 20.0 °C. The concrete curing process during hardening was not considered within the developed model.

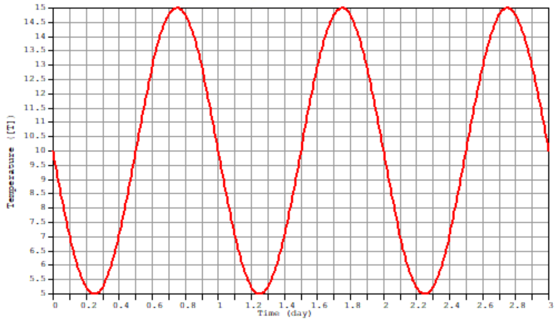

Figure 4: Ambient air temperature values

In accordance with the concreting schedule, the thermal analysis assumes that the foundation is cast within a single day, while the calculations were performed over a total period of 7.0 days in order to determine peak temperatures resulting from the cement hydration process, which is most pronounced during the first 3 days after concreting [5].

4. CALCULATION RESULTS

4.1. PRESENTATION OF TEMPERATURE FIELD RESULTS

Figures 5-8 show the temperature field distribution in the mass concrete of the wind turbine foundation for selected days within the analysis period.

The influence of low air temperatures is clearly visible in the near-surface zones of the structure.

A similar effect is also observed in the foundation interface zone, where the temperature of the rock mass significantly contributes to the cooling of the concrete.

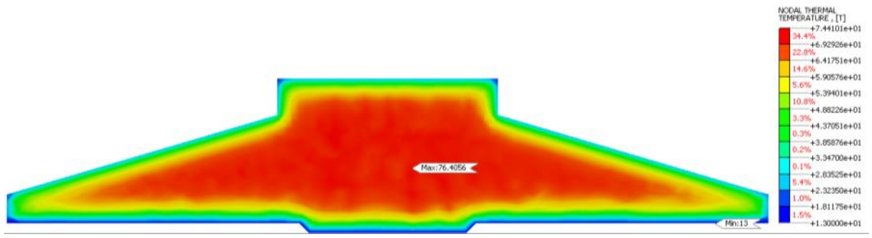

Figure 5: Temperature field: Day 1

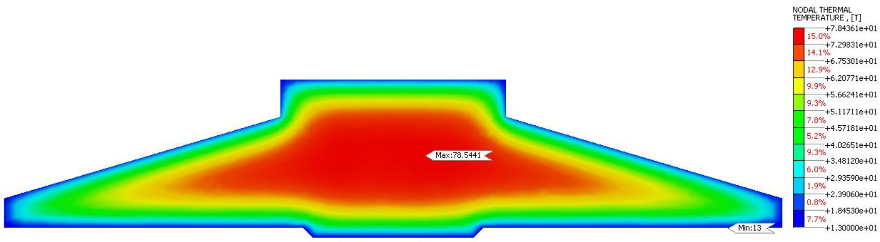

Figure 6: Temperature field: Day 3

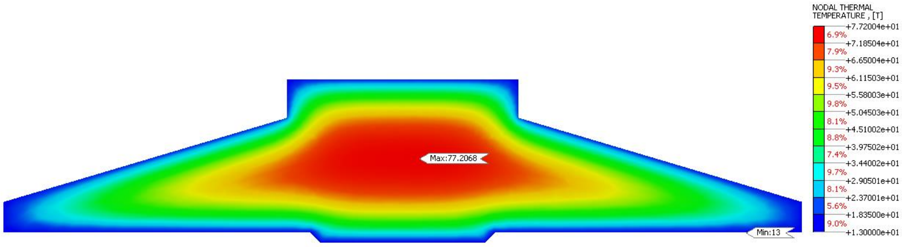

Figure 7: Temperature field: Day 5

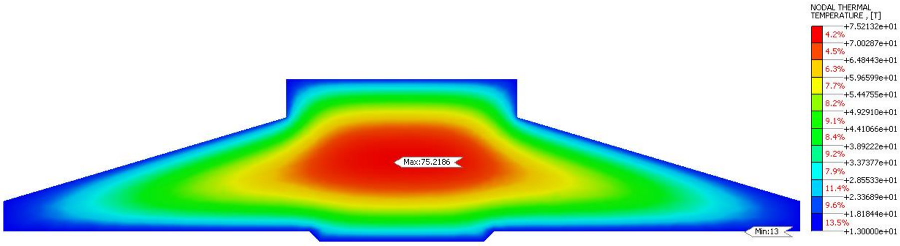

Figure 8: Temperature field: Day 7

4.2. EFFECT OF THE FORCED CONCRETE COOLING SYSTEM

In Figures 9-11, the influence of the forced cooling system on the extreme temperature values in the concrete occurring on the second day after construction is presented.

The figures clearly show a reduction in the maximum concrete temperature to a value below the limit specified by the national regulation (70.0 °C) [4]. This effect was achieved through an optimal arrangement of cooling pipes in both the horizontal and vertical directions, as well as through control of the cooling water temperature within the forced cooling system for mass concrete.

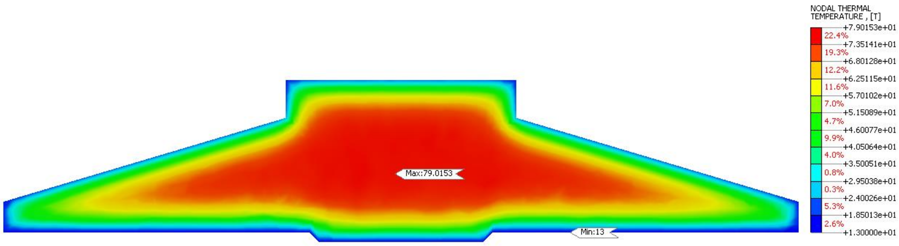

Figure 9: Temperature field: Day 2 (Tmax)

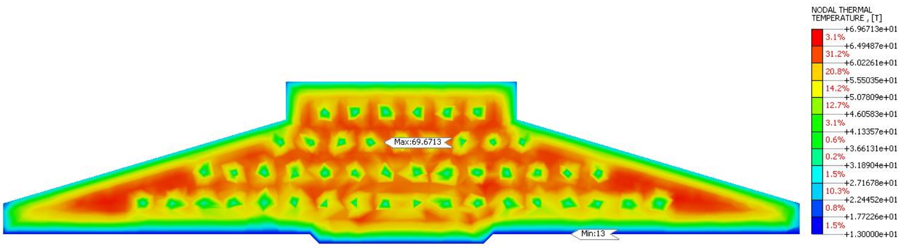

Figure 10: Temperature field with forced cooling: Day 1 (Tmax)

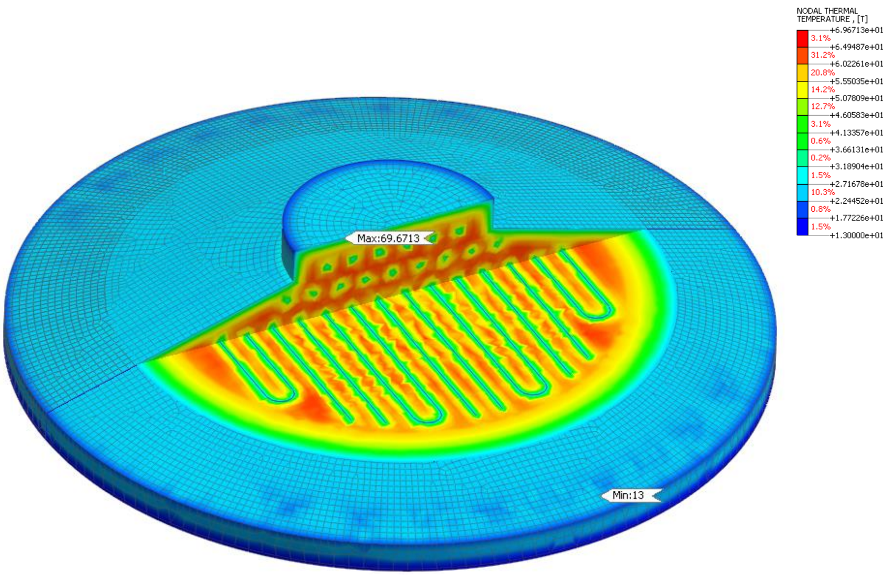

Figure 11: Temperature field with forced cooling (combined vertical section with a horizontal section through the third layer from the top): Day 1 (Tmax)

4.3. TABULAR PRESENTATION AND DISCUSSION OF CALCULATION RESULTS

The obtained calculation results are presented in Table 1.

Table 1: Maximum temperature values for each day of the analysis period.

T_{init} [°C]	T_{water} [°C]	Temperature for the considered day [°C]						
		1.	2.	3.	4.	5.	6.	7.
15,0	-	76,41	**79,02**	78,54	77,95	77,21	76,31	75,22
15,0	20,0	**69,67**	65,54	57,67	49,95	43,38	38,04	33,72
	Difference:	**6,74**	**13,48**	**20,87**	**28,0**	**33,83**	**38,27**	**41,50**

It can be observed that the extreme concrete temperature, when the forced cooling system is not used, occurs on the second day after concreting, when the temperature reaches 79.02 °C, which is significantly above the limit prescribed by both domestic and international standards.

On the other hand, the maximum concrete temperature in the case where the forced cooling system is applied occurs on the first day after concreting and amounts to 69.67 °C, which demonstrates the effectiveness of the presented cooling system.

The system provides a significant reduction in maximum concrete temperatures (by more than 40.0 °C in cases where it remains active even after 7 days of concreting), as well as a reduction in temperature gradients between the core and the surface of the structure, thereby effectively reducing the risk of tensile thermal stresses.

Through precise definition of the system geometry and parameters using numerical modelling, it is possible to accurately control the heat removal process from a massive concrete element.

In order to properly operate such a system, real-time monitoring of concrete temperature development is necessary. Devices for continuous measurement and data recording are recommended. As a minimum, one temperature sensor should be installed at the center of each foundation and one near the surface, at a depth of 50.0-75.0 mm.

Concrete curing procedures should be initiated immediately after the placement of each concrete layer. Concrete surfaces must be protected from rapid drying and excessive heat exchange between the concrete and the surrounding environment.

5. CONCLUSION

Based on the presented findings, the principal contribution of this research is the development of a procedure for conducting phased thermal analysis of mass concrete foundations that includes a forced concrete cooling system.

The presented results show that the temperature rise in the foundation is most strongly influenced by the concreting sequence (placing a large volume of concrete in a single day), as well as the cement hydration process during the first days after casting. As a result, despite relatively low external air temperatures, concrete temperatures of up to 80.0 °C occur within the structure, thereby exceeding the allowable limit defined by the relevant regulations for concrete construction.

These findings indicate the necessity of applying forced cooling measures using embedded pipes through which cooling water circulates. The arrangement of pipes, water temperature, and flow rate can be determined through thermal analysis based on the finite element method.

The findings of the analysis provide a better understanding of thermal processes in mass concrete and may support design decision-making aimed at improving the durability, serviceability, and long-term reliability of mass concrete structures.

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