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AN ANNUAL CYCLE OF CHANGES IN WATER TEMPERATURE AS A CAUSE OF CRACKING IN MASSIVE CONCRETE HYDRAULIC STRUCTURES

1. Introduction

Technical condition of typical hydraulic structures is strongly affected by a number of factors, including the history of the construction and its use. The primary factors are due to fixed and variable loads acting on the structure, slow annual and fast daily changes in temperature, shrinkage of concrete during construction, water levels, the usage of installed hardware, or even the conditions of generated energy consumption. It is difficult to assess which factor is most important for the safety and durability of the structure. In wide literature on this subject special attention is paid to a few of the possible causes of the deterioration in the condition of these types of structures: the impact of annual temperature changes [1, 2], seismic reasons [6, 8] or failure of the installed generating sets [3]. In the case of all hydraulic structures located in Poland, only one of the mentioned factors is of primary importance, i.e. temperature fluctuation. This paper aims to emphasize the significance of thermal stresses on hydraulic structures. It is shown that an annual cycle of changes in water temperature can lead to an exceedance of the concrete strength and, as a consequence, to cracking in concrete elements.

The paper is organized as follows. In the first section a simple numerical example of transient heat flow is presented. The aim of this analysis is to determine temperature distribution within the concrete wall of a hydraulic structure due to the annual cycle of changes in the temperature of flowing water. Next a strength analysis concerning a hydropower plant subjected to thermal stresses is performed. The strength criterion, used in the analysis, is the Drucker-Prager method. Numerical calculations showed that annual changes in water temperature can lead to stress and strain on the strength of concrete in structural elements. This implies the possible evolution of cracks.

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2. Temperature distribution in concrete element due to annual changes in water temperature

In general, to assess accurately the effect of temperature on hydraulic structures it is necessary to solve the complex initial-boundary value problem of the coupled thermal and mechanical fields. In the case of hydraulic structures, numerical analysis, even for static problems, is complicated due to the complex geometry and therefore usually requires a large CPU-time. Thus, to obtain satisfactory results in a reasonable time some additional assumptions have to be provided. In the paper, slow annual temperature changes are considered, and therefore it is postulated that uniform temperature distribution in concrete elements can be assumed. In the next Section a simple framework example is considered in order to verify the assumption stated above.

2.1 Formulation of the problem

In order to determine the temperature distribution in a massive concrete element due to slow annual changes in water temperature, numerical simulations of transient heat flow were performed. A commercial FE code, namely the FlexPDE [7] was utilized. In what follows we consider a concrete wall with a thickness of 6.0 m. the surfaces of the wall are in continuous contact with water subjected to annual temperature changes determined on the basis of experimental evidence conducted in a hydropower plant located on Vistula river. It is assumed that the temperature fluctuation course can be described as a properly scaled sine function with some phase shift, and can be expressed by the following formula:

$$T = 10.5 + 9.5 \cdot \sin\left(2\pi \cdot \frac{t}{T_{year}}\right) \tag{1}$$

where:

T — temperature [°C],
t — time [s],
T_{year} — the duration of one year.

The fitting function, given by Eq. (1), as well as measurement results of water temperature is graphically presented in figure 1.

A transient heat flow in a concrete element is governed by the following equation:

$$-\frac{k}{\rho \cdot c} \cdot \mathrm{div}(\mathrm{grad}T) + \frac{\partial T}{\partial t} = 0 \tag{2}$$

where:

k — thermal conductance for concrete, $k = 1.7 \cdot 10^{-3}$ [kW/mK]

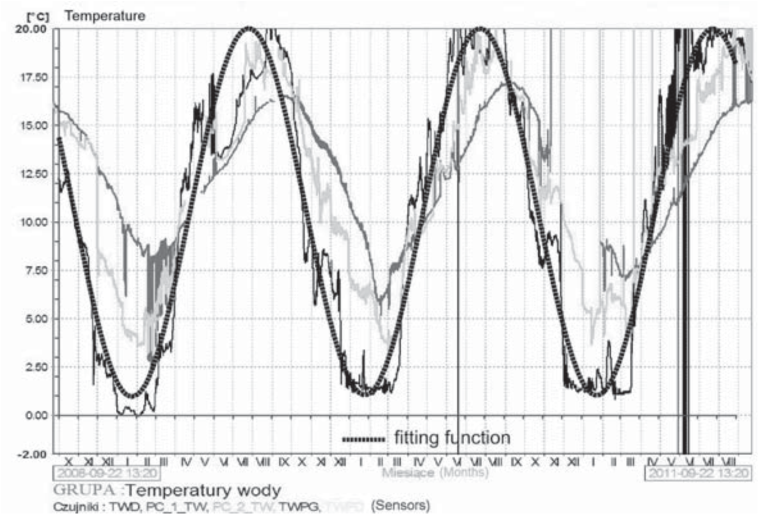

Fig. 1. Fitting function according to formula (1) in the background of measurement results of water temperature in Vistula river

ρ — concrete density, $\rho = 2.5$ [t/m^3],
c — heat capacity of concrete, $c = 850$ [kJ/t·K].

Assuming that the wall is infinitely long, the heat transfer takes place only in the direction perpendicular to the wall surface. This allows one to limit the calculation domain to an extracted cubicoid section of the wall (Fig. 2) with suitable boundary conditions. In this case, the domain is a cuboid with dimensions of 0.1×0.1×3.0 m. with, the following boundary conditions prescribed:

- bottom surface (according to the Fig. 2) — no heat flow (due to symmetry),
- the lateral surfaces of considered cuboid — no heat flow (due to assumption that heat flow takes place only in the direction perpendicular to the surface of the wall),
- top surface (the surface of the wall) — the temperature according to the formula (1).

Calculations were performed for three different initial conditions, i.e. $T(t = 0) = 30°C$, $T(t = 0) = 20°C$, $T(t = 0) = 5°C$, where the physical meaning of these values is the reference to the temperature of the wall at the moment of completion of its construction.

2.2. Results of numerical calculations

The results, namely the distributions of concrete temperature as a function of time for 3 different initial conditions are presented in figures 3–5. A description of the curves for all the plots (Figs. 3–5) is: a (purple line) — the temperature on the wall surface, b, c, d, e, f, g, h, i, j — the temperatures at distances of 0.3, 0.6, 0.9, 1.2 , 1.5, 1.8, 2.1, 2.4, 2.7 m from the wall surface, respectively; k (red line) — the temperature at a distance of 3.0 m from the surface, in the middle point of the wall.

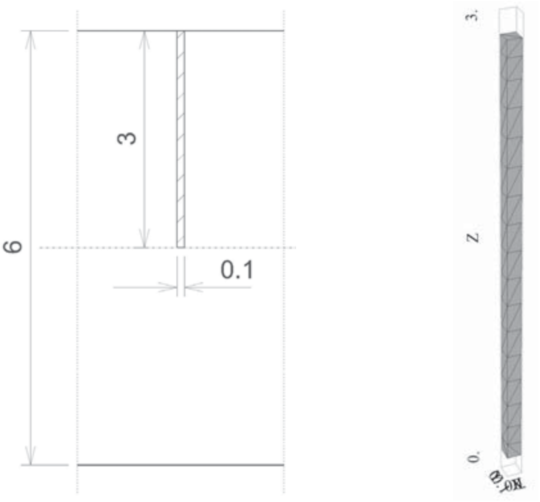

Fig. 2. An outline of the problem – left: 6 m thick wall with extracted section considered in the computation; right: FE mesh

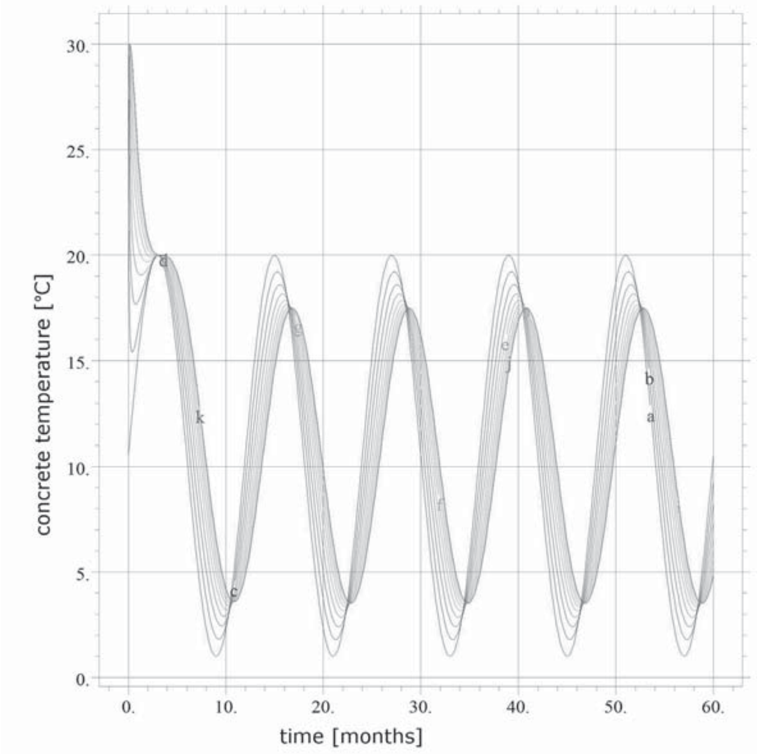

Fig. 3. A plot of the concrete temperature at different distances from the wall surface within five years after its construction completion; the initial temperature $T(t = 0) = 30°C$

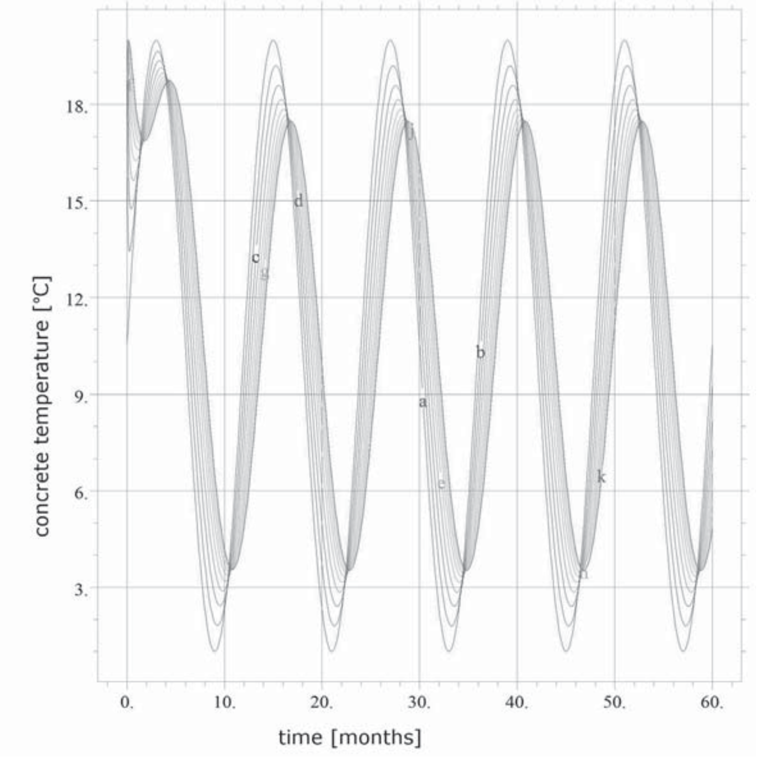

Fig. 4. A plot of the concrete temperature at different distances from the wall surface within five years after its construction completion; the initial temperature $T(t = 0) = 20°\mathrm{C}$

2.3. Discussion of results

The above results show that annual changes in the temperature of water are slow enough to affect the temperature distribution within the whole structure, even for elements with a large thickness. The differences between water temperature and the temperature inside the concrete are not significant. The maximum phase shift at a depth of 3 m from the wall surface is approximately one and a half months. The reduction in the amplitude of temperature with depth reaches a maximum value of 25% at a depth of 3 m — in the middle of the wall. In addition, the concrete temperature variation for different depths is not significant. In other words, it can be concluded that a massive concrete structure subjected to annual cyclic changes in temperature, associated with annual changes in water temperature is not excessive. Moreover, the initial temperature effect is noticeable only within a limited time period from the beginning of the process. Approximately one year after the start of operation of the hydraulic structure (which involves the submission of the structure in constant contact with water) concrete temperature fluctuates around the average temperature of water. The results presented for numerical simulations also show that

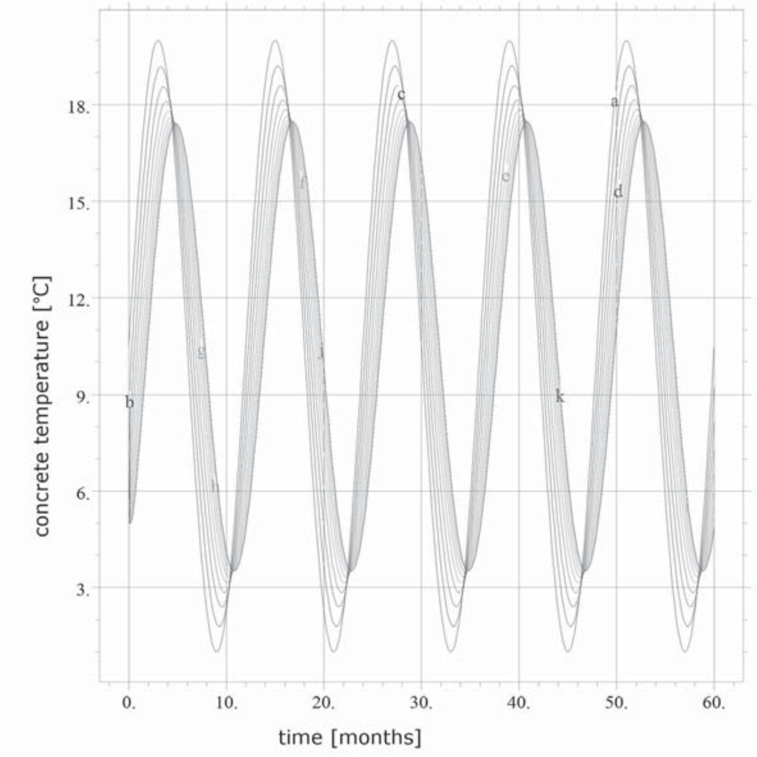

Fig. 5. A plot of the concrete with a temperature at different distances from the wall surface within five years after its construction completion; the initial temperature $T(t = 0) = 5°C$

the effect of slow changes in water temperature (annual changes) for concrete structures with a wall thickness up to 6 m, induces an almost uniform temperature distribution within the structure. This implies that, in the case of massive concrete structures the assumption of spatial uniform temperature distribution is reasonable in assessing the impact of annual changes in water temperature.

3. Numerical analysis of stress/strain state on the elements of hydropower plant structure

3.1. Hydropower plant — numerical model

In order to verify the influence of temperature changes on a block of typical hydroelectric plant concrete, numerical calculations were carried out using FEM. As previously FlexPDE software was used. In this case the model consists of one block of hydroelectric plant concrete and extracted region of ground. The geometry of the block and the ground domain with the FE mesh is shown in figure 6.

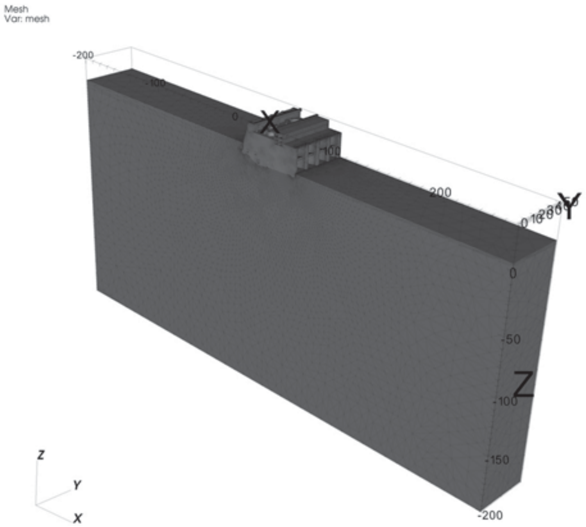

Fig. 6. Geometric model of the block and the ground domain with the FE mesh

The width of both the plant block and the ground is approximately 50m. Depth of the soil layer below the bottom of the structure is set large enough (200 m) so as to neglect boundary the effect. In the same manner the distance between the structure and the truncation surfaces is also equal to 200 m. the oedometric boundary conditions are prescribed on the truncation surfaces of the ground region. In other words, displacements in the direction normal to all truncation surfaces are fixed. Lateral surfaces (settlement joints) of the concrete block have a one-sided displacement boundary condition prescribed, i.e. outward displacement is restrained.

The temperature effect is taken into account by cooling down the structure by the temperature difference |ΔT|=10°C. It reflects the maximum difference between the average temperature and minimum temperature of the structure occurring in the winter. The soil is assumed not to be sensitive to temperature changes. The value of the coefficient of linear expansion for concrete is α = 9e–5 [1/K].

To obtain reliable results temperature changes were considered together with other typical loads acting on the structure. These loads are as follows:

— dead weight of concrete and soil, with parameters summarized in table 1,

TABLE 1

Material parameters of the model being analyzed

	Young's modulus *E* **[kPa]**	**Poisson's ratio** ν	**Unit weight** γ **[kN/m^3]**
concrete	33600000	0.18	24
soil	20000	0.4	19

- the weight of turbines and generators,
- the weight of the crane,
- useful load in halls, office areas $q = 5.0$ kN/m^2,
- load exerted by vehicles $q = 40.0$ kN/m^2,
- water pressure.

3.2. Strength criterion for concrete

The analysis of a massive concrete structure requires the use of plasticity/strength criterion due to the complex state of stress occurring in the volume of the structure. There are a large number of strength criteria for concrete existing in literature e.g. [9, 10]. In this paper a relatively simple and widely spread linear Drucker-Prager criterion [4, 5] is utilized. This criterion can be expressed as follows:

$$F_{ij}(\sigma_{ij}) = \frac{c_1 \cdot \sqrt{J_2}}{f_c} - \left(c_3 - \frac{I_1}{f_c}\right) \leq 0 \tag{3}$$

where:

$$J_2 = \frac{1}{2} \cdot \tau_{ij} \cdot \tau_{ij} \tag{4}$$

and

$$I_1 = \sigma_x + \sigma_y + \sigma_z \tag{5}$$

are the second invariant of the deviatoric stress tensor and the first invariant of stress tensor, respectively. Constants c_1, c_3 are defined by the following formulas:

$$\begin{aligned} c_1 &= \sqrt{3} \cdot \frac{m+1}{m-1} \\ c_3 &= \frac{2}{m-1} \\ m &= \frac{f_c}{f_t} \end{aligned} \tag{6}$$

where: f_c and f_t denote the uniaxial compressive strength and the tensile strength, respectively.

For concrete structure analyzed the following values of strength are assumed: $f_c = 25$ MPa and $m = 17$ which implies:

$$c_1 = \frac{9\sqrt{3}}{8}$$
$$c_3 = \frac{1}{8} \tag{7}$$

All calculations are presented further in this paper and are carried out assuming the elastic deformations within the concrete volume. The results of the stress state is then verified using the Drucker-Prager criterion. If a strong inequality (3) is satisfied at each point of the structure, the deformation within the structure is elastic. On the contrary, if the calculated stress state does not satisfy inequality (3) then in some points of the volume take an inelastic deformation process occurs. In other words, the regions for which the calculated stress condition implies:

$$F(\sigma_{ij}) \geq 0 \tag{4}$$

are the areas where the concrete strength has been exceeded.

3.3. Results of the calculations and discussion

The figures below (Figs. 7–9) present the values of $F(\sigma_{ij})$. Note that only positive values are displayed while the areas for which $F(\sigma_{ij}) < 0$ are transparent. Therefore only areas where the concrete strength according to the Drucker-Prager criterion (3) is exceeded are apparent.

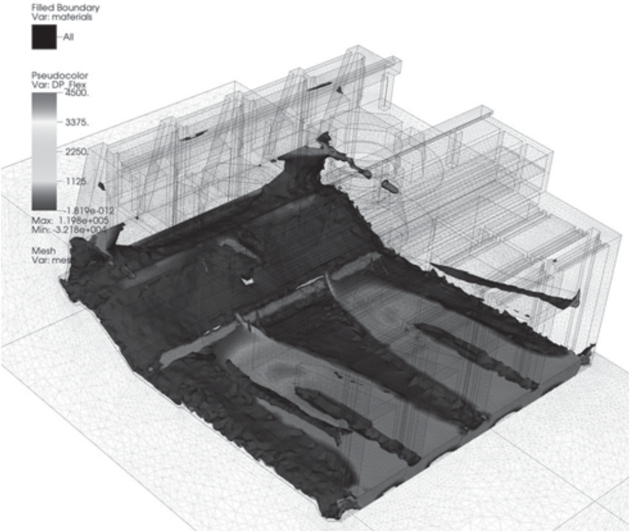

Fig. 7. Areas of exceeded Drucker-Prager criterion for the block of hydroenergy plant — axonometric view

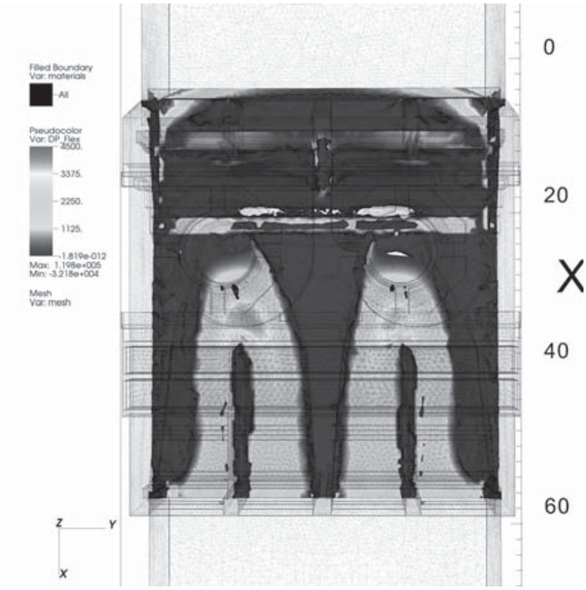

Fig. 8. Areas of exceeded Drucker-Prager criterion
for the block of hydroenergy plant — top view

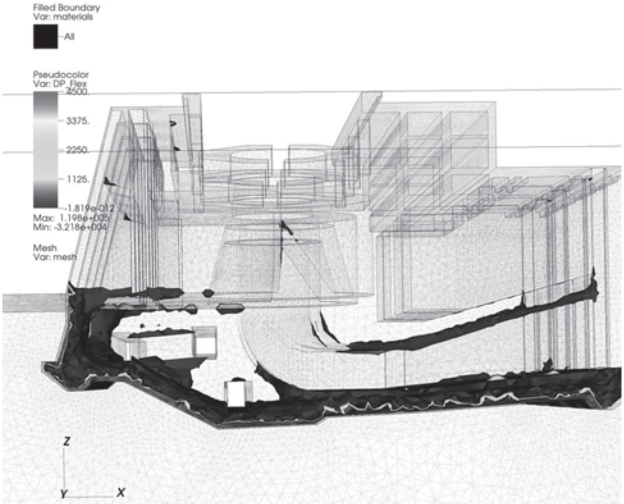

Fig. 9. Areas of exceeded Drucker-Prager criterion for the block
of hydroenergy plant — side view

The results of the numerical simulation clearly indicate that a temperature change of $\Delta T = -10°\text{C}$ induces large areas of exceeded strength in structural concrete elements. These areas are located near the surface of contact between ground base and structure, i.e. in suction pipes and in the galleries. The aforementioned areas strongly affect concrete elements and on the whole their thickness — which may induce cracking throughout.

4. Summary

1) It was shown that in assessing the impact of slow annual changes in temperature for a massive concrete structure, the uniform distribution of temperature is a reasonable assumption.
2) An annual cycle of changes in water temperature can lead to excesses in the strength of concrete and, as a consequence, cause cracking throughout in concrete elements. The numerical analysis has proved that a temperature change of $\Delta T = -10°\mathrm{C}$ induces large areas of exceeded strength in structural concrete elements.
3) For the considered geometry of hydropower the largest values of criterion function $F(\sigma_{ij})$ are observed in suction pipes and in the inspection galleries.

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