IOP Conference Series: Materials Science and Engineering

Consideration of Soil Temperature in the Modeling of Early-Age Mass Concrete Slab

To cite this article: Aneta Zmij *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **603** 022095

IOP Conf. Series: Materials Science and Engineering **603** (2019) 022095 doi:10.1088/1757-899X/603/2/022095

Consideration of Soil Temperature in the Modeling of Early-Age Mass Concrete Slab

Aneta Żmij[1], Barbara Klemczak[1], Miguel Azenha[2], Dirk Schlicke[3]

[1]Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland,
[2]University of Minho, ISISE, Campus de Azurem, 4800-058 Guimarães, Portugal
[3]Graz University of Technology, Institute of Structural Concrete, Lessingstraße 25/1, A-8010 Graz, Austria

aneta.zmij@polsl.pl

Abstract. Modeling the structural behavior of concrete at early ages is one of the most challenging, yet fundamental, tasks for civil engineers working on mass concrete. To obtain a reasonably accurate model, a number of factors should be taken into account. Considerations should include both external influences as well as the changes occurring in the complex structure itself. The modeling of an early-age concrete massive slab requires the proper assignment of initial conditions, including the initial temperature of the analyzed element and the adjacent structures. The temperature distribution in the subsoil is the factor analyzed in this paper. The aim of the study is the determination of the temperature distribution in the ground, which is useful in the process related to the acquisition of the most accurate model of the analyzed structure and reflects the actual conditions in the numerical model. For this purpose, the analytical method described in the literature was applied and subsequently evaluated on the basis of the numerical calculation. The performed calculations allow the estimation of the depth representing the range of the influence of the temperature in the ground and the values of the temperatures corresponding to the successive layers of the subsoil. Moreover, aiming the optimization of the numerical analysis of the massive foundation slab, the legitimacy of such detailed consideration of the temperature development in the underlying subsoil was evaluated by the comparison with the temperature distribution in the slab obtained with simplified consideration of the constant soil temperature.

1. Introduction

The complex geometrical/support constraints of massive concrete structures, which are additionally subjected to the changes related to the cement hydration process as well as the number of the external factors caused by the successively rising challenges for the realistic/accurate early age modeling [1]–[5]. The influence of the thermal-moisture fields and stresses in the massive elements might be significant; therefore they should be taken into account in that kind of considerations. Nevertheless, the structural behavior is affected by such factors in considerably differentiated way. Thus, aiming at the optimization of the numerical modeling of early age mass concrete, their influence on the analysis needs to be properly assessed. The factor considered in this paper is the distribution of the initial temperature in the subsoil. The determination of its development in the successive layers of the ground was performed. At first, the analytical method described in [6], [7] was applied to calculate the initial temperature profile of the soil below the analyzed slab. Following, this analytically determined temperature profile was compared and verified with the results of the numerical computation. Besides this verification, the relevance of such a detailed consideration of the initial temperature profile of the soil on the thermal behavior of the analyzed slab was questioned. Therefore, a comparative numerical analysis was performed in which the temperature distribution in the foundation slab was determined with different initial temperature profiles in the soil, namely the detailed one and a simplified one with constant soil temperature at the beginning.

2. Description of the structure

The subject of this study is a massive foundation slab with the geometry presented in Figure 1. The initial temperature of the subsoil is one from the number of input parameters necessary to assign in the numerical model for thermo-mechanical analysis of the massive structure.

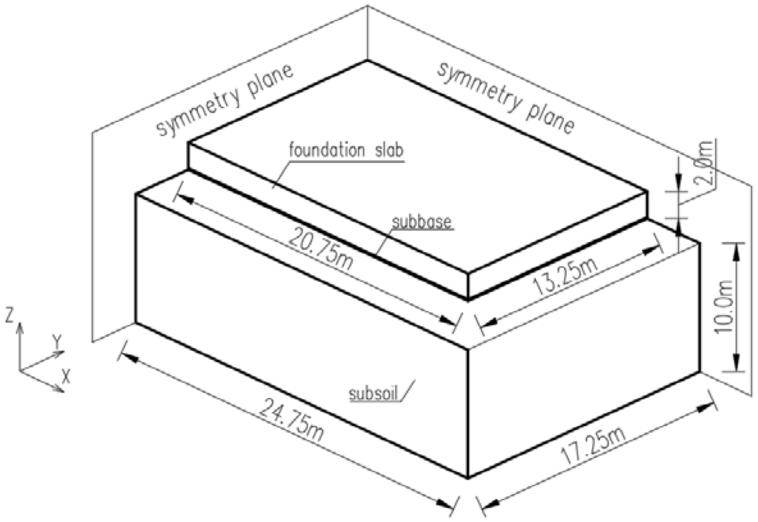


Figure 1. The geometry of the analyzed structure

The initial temperature profile of the subsoil was determined with regard to the environmental temperature registered by a meteorological station located in the nearby area of the executed structure (Braunschweig in the southern part of Lower Saxony, Germany) [8]. Aiming to the reduction of the size of the model, the investigation included the determination of the limit depth, thus, the edge of the influence of the temperature in the ground. The time of casting of the structure corresponded to the summer season (August), the conditions of soil before casting were assumed as for excavation relatively long before.

3. Determination of the temperature distribution in the ground

3.1. Analytical method

3.1.1. The description of the method. The method enabling determination of the temperature distribution in the ground was presented by Baggs in [6]. The study including the algorithm of calculations of the temperature referred to grounds localized in Australia, depending on the specific location on the continent. The formula for determination of the soil temperature as a function of time and depth was provided in the mentioned paper. This formula was adopted to the European conditions on the example of Poznan (Poland) by Popiel et al. [7]. Authors observed convergence of results calculated according to the modified version of the formula with the experimental results. The result of the above-mentioned considerations is the following formula:

$$\mathrm{T(x,t)} = (\mathrm{T_m} \pm \Delta\mathrm{T_m}) - 1.07\mathrm{k_v A_s}\exp(-0.00031552\mathrm{xa}^{-0.5}) \cdot \cos\left[\frac{2\pi}{365}(\mathrm{t} - \mathrm{t_0} + 0.018335\mathrm{xa}^{-0.5})\right] \quad (1)$$

where: a – average annual thermal diffusivity of undisturbed ground, *m^2/s*, A_s – amplitude of annual average air temperature wave, *^oC*, k_v – vegetation coefficient [-], q – heat flux density, *W/m^2*, t – time, *days*, t_0 – phase of air temperature wave, *days*, T - temperature, *^oC*, T_m – average annual air temperature, *^oC*, ΔT_m – the difference between the environmental temperature and the temperature above the ground, *^oC*, x – depth below the ground, *m*.

3.1.2. Assumptions to calculations. The calculation of the temperature in the ground assumed the parameters listed in Table 1 and Table 2. The data were chosen according to the study described in [8], supplemented with the information due to the type of soil [9], [10].

Table 1. Parameters of the subsoil

Property	Symbol	Value	Unit
Density	ρ	2070 [10]	*kg/m^3*
Thermal expansion coefficient	α_T	10×10^{-6} [9]	*$1/\,^0C$*
Conductivity	k	1.4 [8]	*$W/(^0Cm)$*
Heat capacity	C	2.15×10^6 [8]	*$J/(^0Cm^3)$*
Modulus of elasticity	E	30	*MPa*
Poisson's ratio	υ	0.2	-

Table 2. Values of parameters assumed in the formula (1)

Calculated variable	Assumed value	Description
T_m	9.2*^0C*	based on the data obtained in meteorological station in Braunschweig/Southern Saxony/Germany
ΔT_m	0	no data (the temperature above the ground equal to the environmental temperature)
k_v	1.00	depends on the proportion of vegetation projective shade cover; value assumed as for "bare ground in full sun"
A_s	8.25 *^0C*	$A_s = (T_{max} - T_{min})/2$, T_{max}, T_{min} – based on the data from meteorological station
x	variable	analyzed depth: 20 m; determined values for every 0.2 m
a	6.5116×10^{-7} *m^2/s*	a = K/C; K = 1,4 *W/(s°Cm)*, C = 2150000 *J/m^3* (according to Table 1)
t	variable	time of analysis: 3 years; time step: 1 day
t_0	220 *days*	phase of air temperature wave (method of determination shown below)

Taking into account the temperature varying periodically with time:

$$T(x=0,t) = A_s \cos\left[\frac{2\pi}{365}(t - t_0)\right] \tag{2}$$

and the average temperature equal to:

$$T(x=0,t) = T - T_m \tag{3}$$

where: T – the average monthly temperature, ^0C (based on the data from meteorological station); T_m= 9,208 ^0C (according to Tab. 2). Formulas (2) and (3) present two approaches for determination of the value of $T(x=0,t)$, therefore the value of the air temperature wave t_0 may be determined with application of the iterative method consisted in adjustment of the function (2) and (3), as presented in the Figure 2. The time t corresponded to 15th day of every subsequent analyzed month.

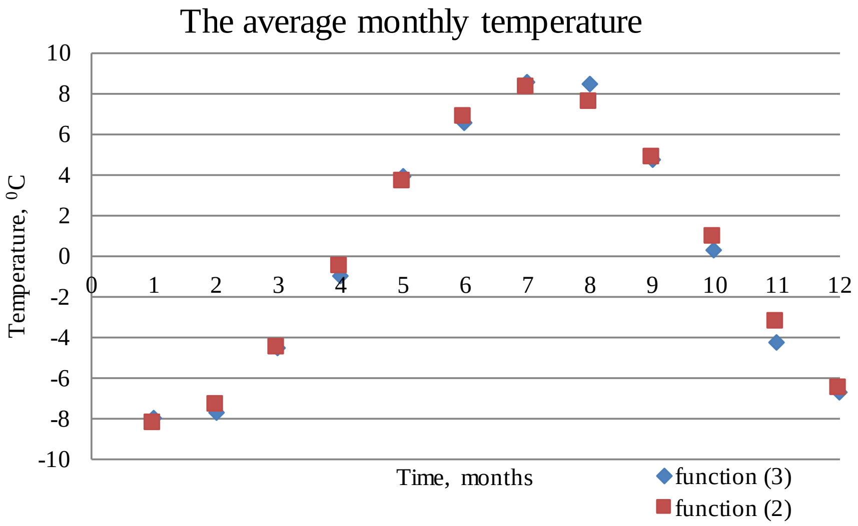


Figure 2. The result of the iterative determination of the parameter t_0 (description in the text)

3.2. Numerical calculations

3.2.1. Distribution of the temperature in the subsoil. The simulation of the temperature distribution in the subsoil was performed with the use of the software DIANA FEA. Aiming to the reduction of both the time required for calculation, and the complexity of the model, the analysis was limited into a single 'thin column' of the subsoil. Thus, a prism of the plan dimensions 0.2 x 0.2 m and the height of 20 m was investigated. The material parameters of the soil were defined according to the Table 1.

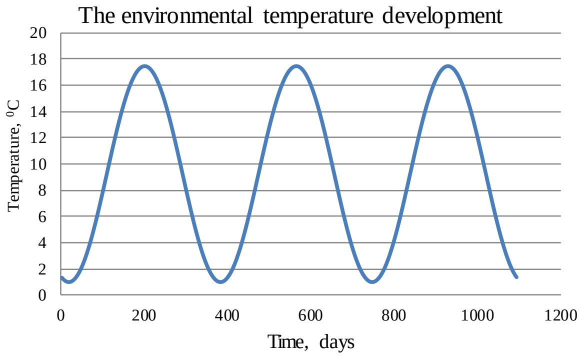


Figure 3. Distribution of the environmental temperature assigned in the software DIANA

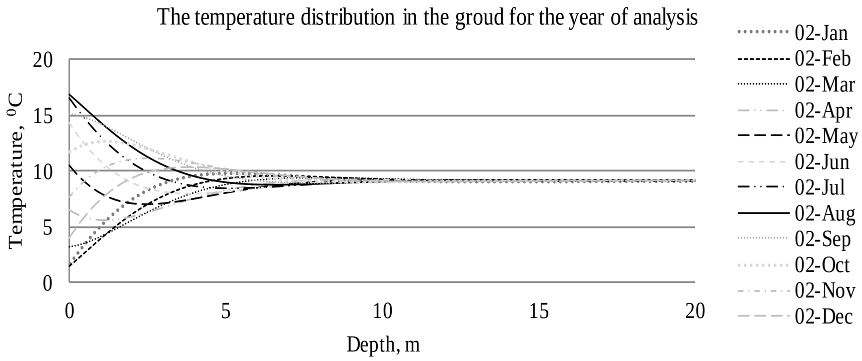


Figure 4. Distribution of the temperature in the ground during one year of analysis, obtained from DIANA

The boundary conditions (environmental temperature and heat transfer coefficient) were assigned to the top surface of the element, while adiabatic conditions were attributed to the remaining surfaces. Environmental temperature applied to the model, calculated based on the relation (2), is presented in the Figure 3. The time of analysis was set as 3 years to provide the stabilized values of obtained temperature. The temperature distribution in the ground corresponding to the 3rd year of analysis is shown in the Figure 4. The calculated temperature was assumed in the target model of massive foundation slab as the initial temperature of the subsoil being the part of the structure. Taking into account the initial time of concreting, which was 2nd August 2005, the temperature values were designated for every 2nd day of subsequent month.

3.2.2. Conclusions resulting from analytical and numerical calculations. The numerical analysis enables the calculation of the temperature profile of the ground for the assumed depth of 20 m. Figure 4 indicates an influence of the external temperature until a depth of 8 m under the ground surface and the value of 10 m as the height of the solid which might be considered as sufficient to be taken into account in a simulation, from this point of view (temperature profile in the soil before casting). On the depth below 10 m, the temperature of the subsoil stands at the level of the initial temperature of the ground (in the analyzed case: $T_m = 9.2°\text{C}$).

Moreover, the comparison between results of analytical (model of equation (1)) and numerical calculations was made. It was found that the analytically and the numerically determined temperature profiles in the soil are almost identical, as shown in Figure 5.

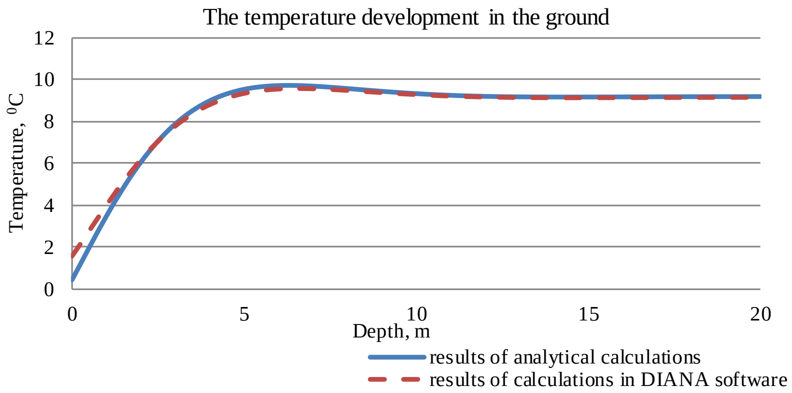


Figure 5. Distribution of the temperature in the soil obtained in analytical and numerical calculations for 2nd August (the beginning of concreting)

It is noted that the values presented here for the analytical calculations include a seasonal shift in regard to the original model that had been proposed for Australia. Therefore, the attempt to determine the relation between times correspondent to particular approaches was made. With the least square method, the following relations have been observed:

a) for periods lasting from January to August: t = 220 – d,
b) for periods lasting from September to December: t = 220 + 366 -d,

where: d – the day of the year from 1st January (for 1st January: d = 1).

4. The influence of the soil temperature on the thermal behavior of the analyzed slab

4.1. Assumptions for analysis

The basic parameters of the sluice slab applied in FEM simulation are listed in the Table 3. The phased concrete casting (division of the sluice slab into 7 layers), corresponding to the construction process, was assumed. Moreover, the boundary conditions were assigned, considering the convective heat transfer between the concrete and the environment by the coefficient h_{eq}. The model of the massive foundation slab with the temperature profile of the ground according to the distribution determined in 3.2. (henceforward labeled as 'case 1a') was compared with the modified model with consideration of initial constant temperature profile of the ground (labeled as 'case 1a_const_soil'). The initial temperature assigned to the soil in the 'case 1a_const_soil' was equal to 16 ^{0}C (i.e., equal to surface temperature at instant of casting), while the temperature profile in 'case 1a' was assigned according to the Table 4. The temperature listed in the Table 3 was calculated as the average from temperatures on the top and on the bottom of the particular layer. The total depth of analyzed subsoil in both cases was limited into 10 m below the surface of the ground, as this was found to be sufficient in section 3.2.2.

Table 3. Parameters of the sluice slab

Property	Symbol	Value	Unit
Density	ρ	2400 [11]	*kg/m^3*
Thermal expansion coefficient	α_T	10 x 10^{-6} [11]	*1/ ^{0}C*
Conductivity	k	3 (α = 0) 2.1 (α = 1) [8]	*W/(^{0}Cm)*
Heat capacity	C	2.3 x 10^6 [8]	*J/(^{0}Cm^3)*
Modulus of elasticity	E	34.4*	*GPa*
Poisson's ratio	υ	0.2 [11]	-
Concrete mix	Cement CEM III/A 32.5N (240kg/m^3); Water 150kg/m^3; Gravel: 0/2mm (703 kg/m^3), 2/8mm (222 kg/m^3), 8/16mm (462 kg/m^3); Fly ash (110kg/m^3), BV 15 (Melius) 1.5% (3.6 kg/m^3)		

*- according to experimental data

Table 4. The initial temperature of the subsoil in the 'case 1a'

Number of layer	Thickness, m	Depth, m	Temperature, ^{0}C
1	0.2	0÷0.2	16.63
2	0.4	0.2÷0.6	15.88
3	0.6	0.6÷1.2	14.63
4	0.8	1.2÷2	13.00
5	1.0	2÷3	11.31
6	1	3÷4	9.99
7	1	4÷5	9.22
8	1	5÷6	8.87
9	1	6÷7	8.77
10	1	7÷8	8.81
11	1	8÷9	8.90
12	1	9÷10	9.00

The temperature development in the analyzed slab was the result of the generated heat during the cement hydration. It was determined with the use of the software DIANA FEA in which the following equation (4) is applied [12]:

$$\rho c_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{dx^2} + \frac{\partial^2 T}{dy^2} + \frac{\partial^2 T}{dz^2}\right) + \dot{q} \tag{4}$$

where: T – temperature, ρ – density of concrete, c_p – specific heat, t – time, k – thermal conductivity, x, y, z – coordinates, $\dot{q}$ – rate of internal heat generation - calculated according to the formula (5):

$$\dot{q} = f(\alpha_T) A_T e^{\frac{-E_a}{RT}} \tag{5}$$

where: $f(\alpha_T)$ – normalized heat generation rate, A_T– rate constant (A_T= 1.75·10^9 *J/(m^{3}s)*), R – the ideal gas constant (R= 8.314 *J/(mol·K)*), E_a – apparent activation energy (E_a= 38500 *J/mol*), estimated according to the data provided for simulation in [8]. Aiming to the investigation of the influence of the initial temperature of the subsoil, the hardening temperature was determined with two models of the ground, differing in the temperature assignment.

4.2. The result of the analysis

Aiming at the drawing of conclusions from the analysis, the temperature and the stress distribution in both models were compared to each other. Figure 6 presents the development of the temperature in three characteristic points of the slab: at the bottom, in the middle and on the top of the cross section localized in the axis of symmetry of the slab. The development of the temperature obtained from both analyses are in line, thus, it can be concluded that the different layered temperature of the subsoil has no significant influence on the temperature generated in the present case.

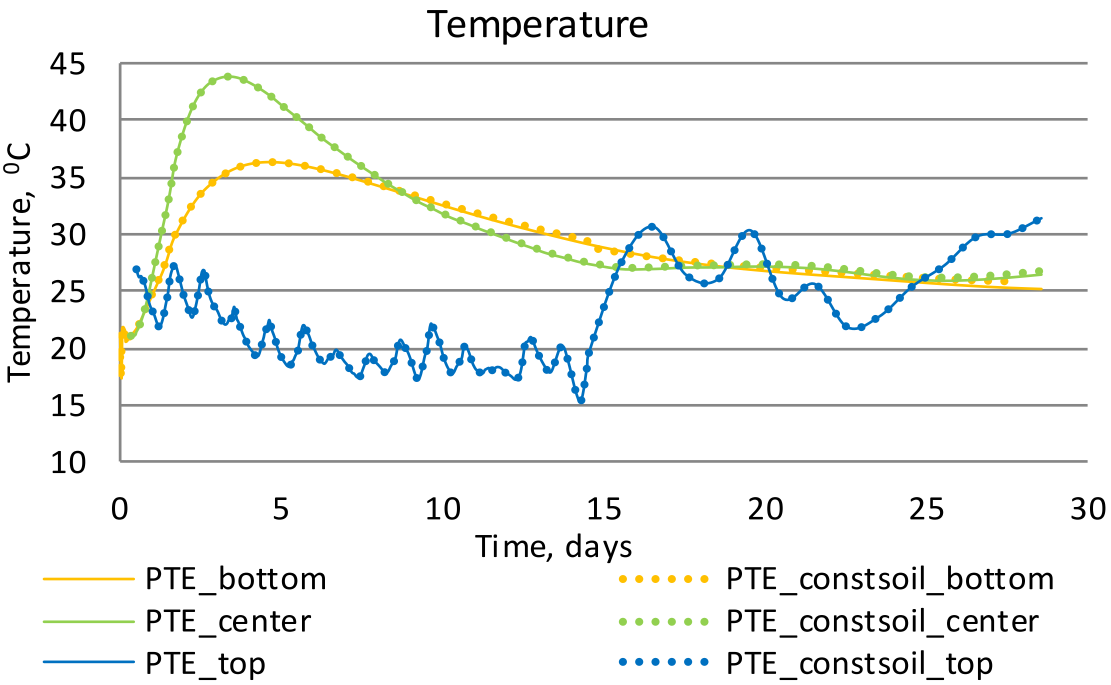


Figure 6. Temperature development

Figure 7 presents maps of the temperature for chosen steps (the same in both cases of analysis). The maps for the cross-section in the plane of symmetry of the structure have been compared. The obtained values of the temperature in the slab in the case_1a (Figure 7a) coincide with the values related with the case_1a_constsoil (Figure 7b). The difference is noticed only in the temperatures of the subsoil. Nevertheless, it has no meaningful influence on the temperature generated in the overlying slab. Even the Figure 7 indicates some negligible differences at the beginning in the top part of the slab, they are not captured in the temperature development at specific points (Figure 6) and they disappear after a short while.

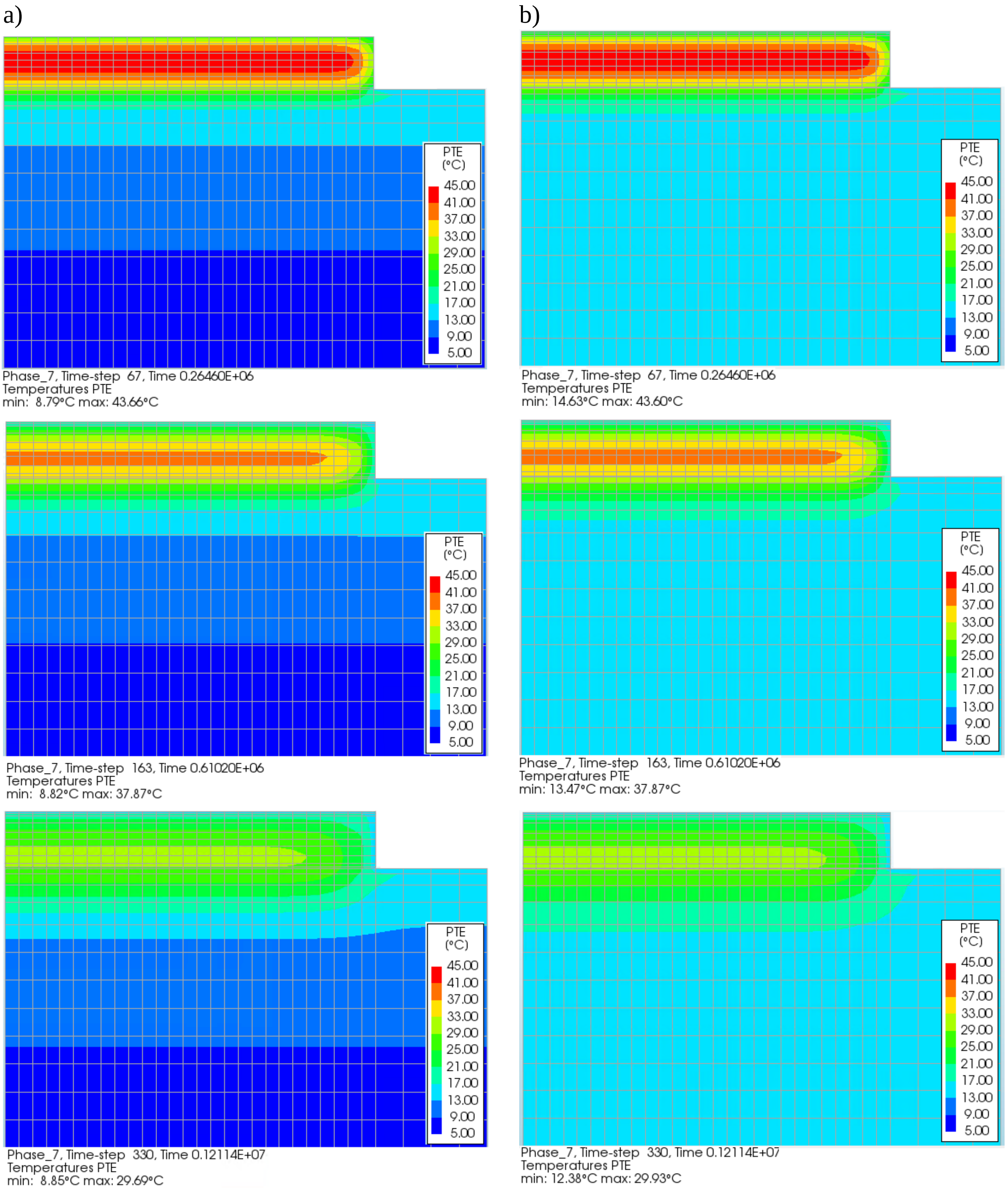


Figure 7. Maps of the temperature in the slab and the soil for chosen steps corresponding to 3 (step 67), 7(step 163) and 14th (step 330) day of analysis obtained a) in the case_1a, b) in the case_1a_const_soil

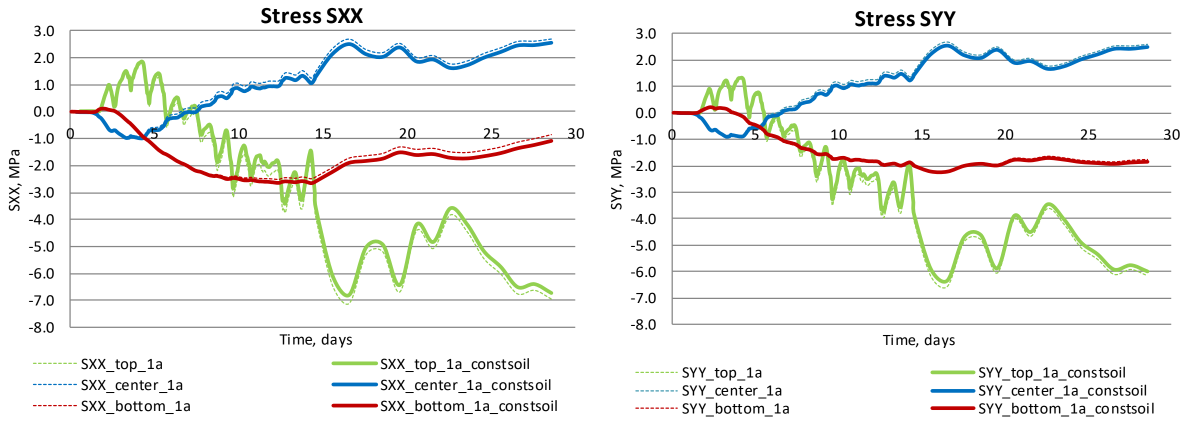
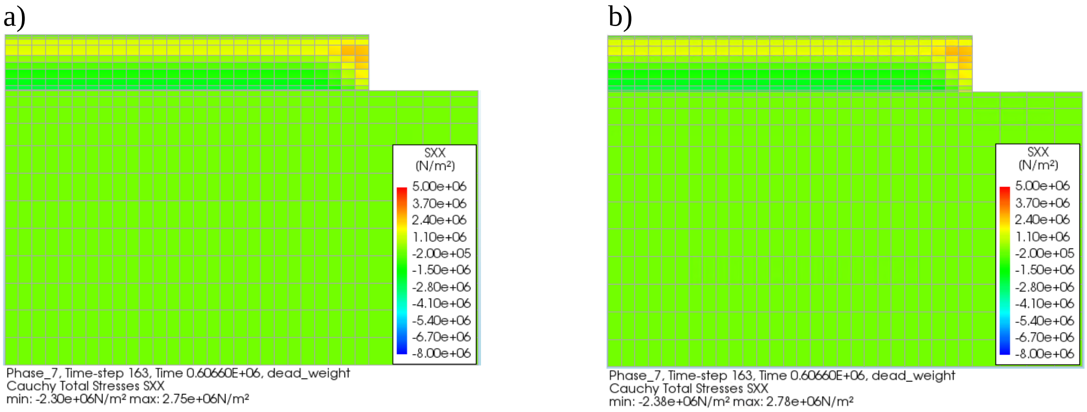


Figure 8. The comparison of the distribution of stresses σ_{xx} and σ_{yy} in time

Furthermore, the developments of stresses σ_{xx} and σ_{yy} in time of analysis were summarized and compared. The results are presented in the Figure 8. The distributions are corresponding to the same points, as in the case of the temperature development. Based on the following diagrams, similar observation might be pointed, that the simplified method of assuming the initial temperature profile of the ground as constant had negligible influence on the obtained results.

The distribution of the stress σ_{xx} in the cross - section localized in the plane of symmetry of the structure is presented in the Figure 9. The maps of the stress σ_{xx} are corresponding to the chosen steps of the analysis (related to the 7th, 14th and 28th day of analysis). The results obtained in both cases are similar to each other, the differences in values and distributions of the stress are negligible. The variations between particular values calculated in the case_1a (Figure 9a) and case_1a_constsoil (Figure 9b) are within 3%.



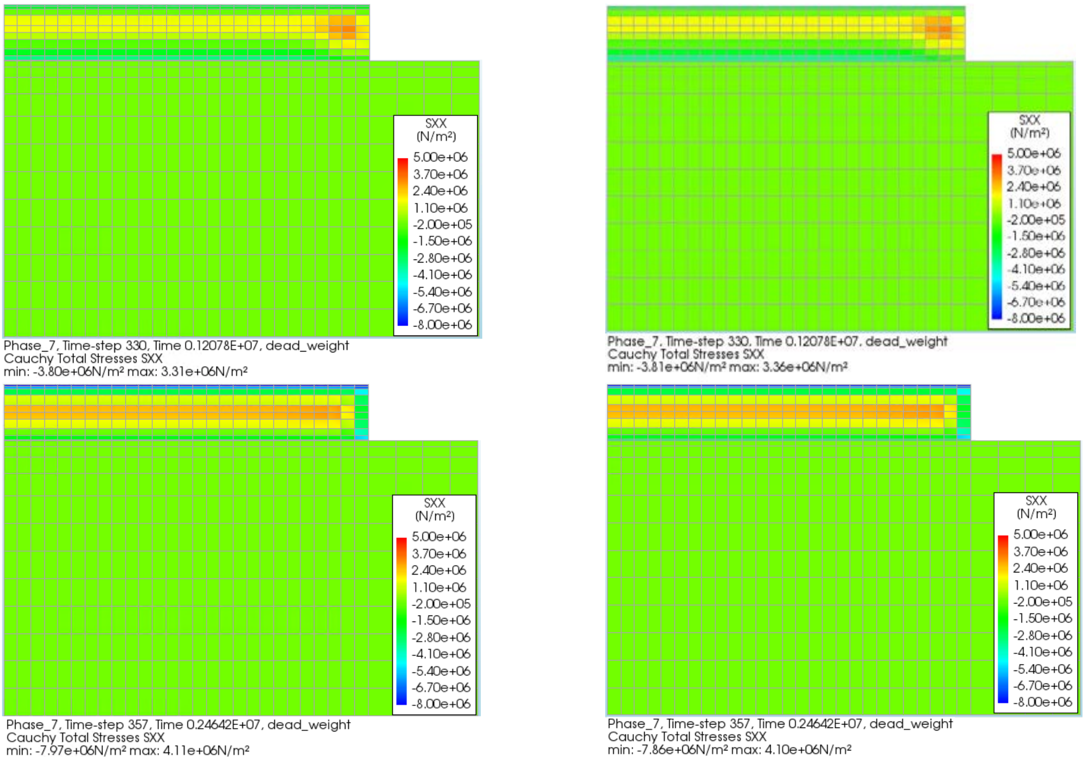


Figure 9. Maps of stress σ_{xx} for chosen steps corresponding to the 7th (step 163), 14th (step 330) and 28th (step 357) day of analysis obtained a) in the case_1a, b) in the case_1a_constsoil

5. Conclusions

The initial temperature profile of the subsoil is one of a number of parameters, which is required for the thermal-mechanical simulation of the massive foundation slab. The current study is an attempt to determine both the initial temperature profile in the ground and the minimum height of the subsoil, which is needed to be taken into account during the analysis. The temperature of the subsoil was calculated with an analytical method available in the literature. The obtained results were evaluated by numerical calculations. The suitability of the analytical method was confirmed by the good convergence of results obtained from both the numerical and the analytical approach. The performed calculations allow the determination of the depth representing the range of influence of the temperature in the ground. It was estimated as 10 m in the case studied herein. That conclusion is relevant from the practical modeling point of view, because it allows a reduction of the total size of the model and the number of the finite elements.

Moreover, the study allowed the verification of the necessity of the detailed (layered) determination of the initial temperature profile in the ground, thus, varying at the height of the analyzed solid of the soil. The study allowed observing the negligible effect of such precise assumptions of the soil temperature in this case study – the assumed constant temperature soil did not cause any changes in the temperature and stress development in the massive foundation slab. The study has shown that the assumption of the constant temperature over the entire height of the soil, which is a less time-consuming approach, enables obtaining similar results.

Acknowledgment(s)

The publication is financed by BKM-547/RB6/2018 resources. Funding provided by the Portuguese Foundation for Science and Technology (FCT) to the Research Project IntegraCrete PTDC/ECM-EST/1056/2014 (POCI-01-0145-FEDER-016841), as well to the Research Unit ISISE (POCI-01-0145-FEDER-007633) is also gratefully acknowledged.

References

[1] B. Klemczak, A. Żmij, and M. Azenha, 'Numerical Study on Restraints Effects in Massive Foundation Slabs', Procedia Engineering, vol. 193, pp. 226–233, 2017.

[2] B. Klemczak, M. Batog, Z. Giergiczny, and A. Żmij, 'Complex Effect of Concrete Composition on the Thermo-Mechanical Behaviour of Mass Concrete', Materials, vol. 11, no. 11, p. 2207, Nov. 2018.

[3] D. P. Bentz, M. A. Peltz, and J. Winpigler, 'Early-Age Properties of Cement-Based Materials. II: Influence of Water-to-Cement Ratio', Journal of Materials in Civil Engineering, vol. 21, no. 9, pp. 512–517, Sep. 2009.

[4] J. Zreiki, F. Bouchelaghem, and M. Chaouche, 'Early-age behaviour of concrete in massive structures, experimentation and modelling', Nuclear Engineering and Design, vol. 240, no. 10, pp. 2643–2654, Oct. 2010.

[5] M. Azenha, C. Sousa, R. Faria, and A. Neves, 'Thermo–hygro–mechanical modelling of self-induced stresses during the service life of RC structures', Engineering Structures, vol. 33, no. 12, pp. 3442–3453, Dec. 2011.

[6] S. A. Baggs, 'Remote prediction of ground temperature in Australian soils and mapping its distribution', Solar Energy, vol. 30, no. 4, pp. 351–366, 1983.

[7] C. O. Popiel, J. Wojtkowiak, and B. Biernacka, 'Measurements of temperature distribution in ground', Experimental Thermal and Fluid Science, vol. 25, no. 5, pp. 301–309, 2001.

[8] N. V. Tue, D. Schlicke, and J. Bödefeld, 'Beanspruchungen in dicken Bodenplatten infolge des Abfließens der Hydratationswärme', Bautechnik, vol. 84, no. Heft 10, pp. 702–710, 2007.

[9] T. L. Bergman, A. S. Lavine, and F. P. Incropera, Fundamentals of Heat and Mass Transfer, 7th Edition. John Wiley & Sons, Incorporated, 2011.

[10] R. Weil, 'The Nature and Properties of Soils. 15th edition: Appendix C: Properties of soils', pp. 1396–1400, 2016.

[11] CEN, 'EN 1992-1 European Standard Eurocode 2: Design of concrete structures - Part 1: general rules and rules for buildings', 2004.

[12] M. Azenha, R. Faria, and H. Figueiras, 'Thermography as a technique for monitoring early age temperatures of hardening concrete', Construction and Building Materials, vol. 25, no. 11, pp. 4232–4240, 2011.