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A 2D Model of Temperature Changes in Experimental Embankment

Abstract

The paper presents the results of experimental embankment 2D thermal modeling. The main purpose of modeling was to investigate the influence of air temperature on temperature distribution in such soil structure. Modeling was performed on an oval experimental embankment with the tank in the inter-embankment part. Modeling assumes flooding and discharging the tank, with maximum water level equal to 3.5 m. 2D model was realized using FLAC 7.0 software, which is a two-dimensional explicit finite difference program for engineering mechanics computation. The results of modeling show extent of temperature changes an impact of variable-time air temperature and water temperature.

Keywords: thermal 2D numerical model, embankment, FLAC, ISMOP.

1. Introduction

The modeling presented in this article were performed as a part of the ISMOP project [1]. The main aim of this project is to develop the complex system for embankments monitoring and threat forecasting. The system should be consisted of such elements as: massive and continuous collection of measurement data, optimized data transmission, interpretation and analysis with the use of numerical simulation and the reporting of the results to appropriate authorities. For the purpose of the research an experimental embankment was built on the Vistula river bend in Czernichów near Kraków (Poland).

This soil structure is about 200 meters long, 55 meters width and 4.5 meters high. The experimental embankment has oval shape with the tank in the inter-embankment part. The top view of the embankment and its location is presented in Figure 1.

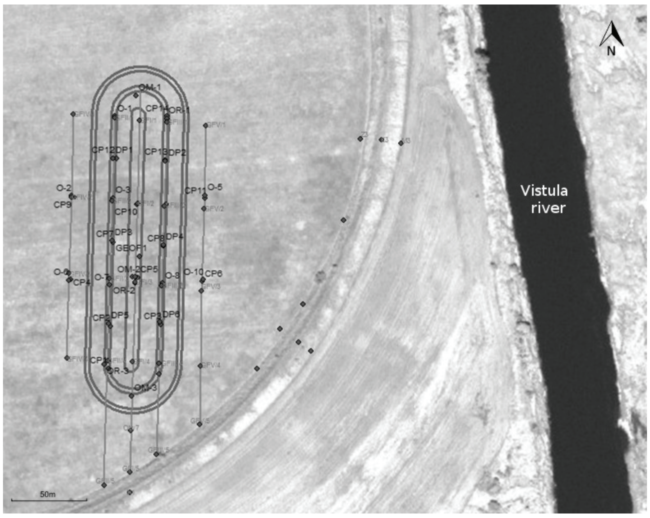

Fig. 1. Experimental embankment location [2]

Before the embankment was conducted the series of geotechnical drilling and geophysical measurements was performed [3]. The Figure 1 also shows the location of geophysical profiles and geotechnical boreholes.

As a result of comprehensive study the 3D numerical model of the subsurface structures was obtained. It is shown in Figure 2. This geological model was the basis for the construction of the 2D computational model used in the presented work.

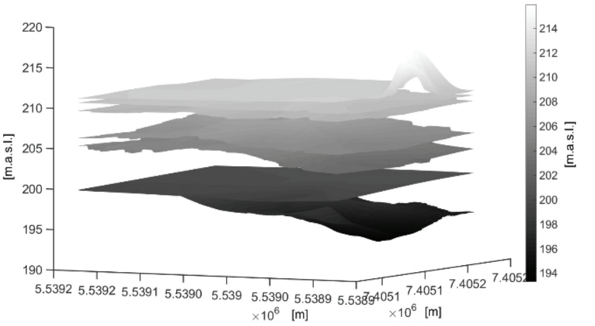

Fig. 2. 3D model of geological layers under the experimental embankment. Surfaces (from top to bottom): subsurface, silty, sands, sands with gravels, gravels, clays, limestone

Left and right side of the experimental embankment are built from different types of material. Left side is made from less permeable and more stable soil than the right one. Sensors such as: piezometers, pore pressure sensors, optical fiber and temperature detectors are placed in the both sides of the experimental embankment [4]. Numerical modeling performed in such type of soil structure is difficult especially when the simulation includes soaking by water and thermal changes.

2. Theoretical background

2D model was realized using FLAC 7.0 (Fast Lagrangian Analysis of Continua) software, which is a two-dimensional, explicit finite difference program for engineering mechanics computation. FLAC 7.0 simulates the behavior of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Thermal analysis of FLAC 7.0 incorporates both the conduction (simulation of transient heat conduction in materials and the development of thermally induced displacements and stresses) and advection (transport of heat by convection) models. The conduction models allow simulate temperature-dependent fluid density and thermal advection in the fluid [5].

The variables involved in heat conduction in FLAC 7.0 – temperature and components of the heat flux – are related through the energy balance equation of heat conduction:

$$-\nabla \cdot q^T + q_v^T = \rho C_v \frac{\partial T}{\partial t}, \qquad (1)$$

where:

q^T - heat-flux vector. W/m^2,
q_v^T - volumetric heat-source intensity/m^3,
ρ - density, kg/m^3,
C_v - specific heat at constant volume, J/(kg·°C),
T - temperature, °C,
t - time, s.

The basic law that defines the relation between the heat-flux vector and the temperature gradient is Fourier's law. The heat transfer may be coupled to the groundwater calculation by taking into account pore pressure change caused by thermal expansion of the fluid and solid constituents.

The mechanisms of convective heat transfer in porous media (advection) considered in the FLAC 7.0 implementation are two kinds of convection: forced convection and free convection. In case of forced convection the heat is carried by the fluid motion. Free convection is caused by density differences due to temperature variations. Free convection accounts for fluid motion. Energy balance for convective-diffusive heat transport can be written as:

$$c^T \frac{\partial T}{\partial t} + \nabla \cdot q^T + \rho_0 c_w q_w \cdot \nabla T - q_v^T = 0, \qquad (2)$$

where:

q_w - fluid specific discharge, m/s,
c_w - specific heat of the fluid, J/(kg·°C),
ρ_0 - density of the fluid, kg/m^3,
c^T - the effective specific heat, defined as:

$$c^T = \rho_d C_v + n S \rho_0 c_w, \qquad (3)$$

where:

ρ_d - solid matrix bulk density, kg/m^3,
C_v - bulk specific heat J/(kg·°C),
n - porosity $[-]$,
S - saturation $[-]$.

Fluid specific discharge is velocity of moving fluid. It determines velocity for flow through a pipe, but doesn't account for the extra travel path length that water molecules take in a porous medium. Saturation is water content of soil pore volume.

The working assumptions are those of local thermal equilibrium (flow at low Reynolds number is considered) and small density variations (Boussinesq approximation applies).

In FLAC 7.0 five types of boundary conditions are considered. They are corresponding to: given temperature, given component of the flux normal to the boundary, convective boundaries, radiative boundaries and insulated (adiabatic) boundaries.

3. Model description

The numerical model was built for central cross section of the embankment with varied material of left and right embankment' side and geological layers of the substrate. The geometry and construction of the model is showed in Figure 3. Model comprises a cross section through the experimental oval embankment (in cross section two embankments) and an area of 30 m.

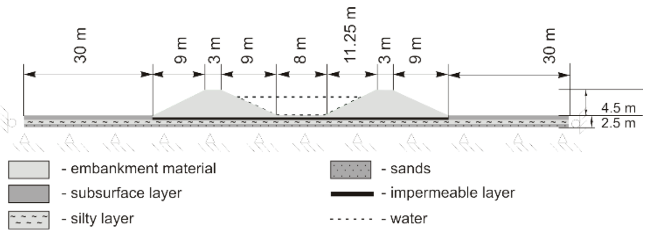

Fig. 3. Experimental embankment 2D model.

The impermeable layer, so called the bentomat layer was built into artificial embankment. The objective of bentomat layer was to prevent the water migration processes and to enable the observation of processes inside the embankment.

Mechanical part of numerical modeling was based on Mohr-Coulomb model, which was defined by parameters: cohesion, fiction angle. The elastic behavior of the soil was defined by bulk modulus and shear modulus. Table 1 presents parameters used in simulation for every element of the model.

Thermal parameters assumed for all layers are as follows: thermal conductivity equal to 1.6 W/(m^3·°C), and specific heat equal to 840 J/(kg·°C) [6]. Water thermal conductivity and water specific heat are equal to 0.6 W/(m·°C) and 4189 J/(kg·°C) respectively. Computational model will be validated after the series of measurements conducted during the construction of the experimental embankment.

Tab. 1. Parameters of embankment model

	Left embankment	Right embankment	Subsurface layer	Silty layer	Sands	Impermeable layer
Volumetric density, kg/m^3	2080	2070	2100	1890	1825	2100
Cohesion, Pa	16 900	24 100	10 300	13 700	9750	10300
Angle of internal friction °	37.6	35.6	32.9	22.5	35.8	35.8
Bulk modulus, Pa	$1.01 \cdot 10^7$	$7.25 \cdot 10^6$	$7.25 \cdot 10^6$	$1.62 \cdot 10^7$	$3{,}63 \cdot 10^7$	$7.25 \cdot 10^6$
Shear modulus, Pa	$6.04 \cdot 10^6$	$3.35 \cdot 10^6$	$3.43 \cdot 10^6$	$6.63 \cdot 10^6$	$2.18 \cdot 10^7$	$3.35 \cdot 10^6$
Porosity, %	0.27	0.27	0.27	0.4	0.35	0.001
Permeability, m^2/(Pa·s)	$1.2 \cdot 10^{-9}$	$1.84 \cdot 10^{-9}$	$1.52 \cdot 10^{-9}$	$1.35 \cdot 10^{-9}$	$5.6 \cdot 10^{-11}$	$4.50 \cdot 10^{-16}$

The main purpose of this modeling is to estimate the influence of environmental conditions, especially air temperature, on distribution of temperature inside the embankment. Therefore, calculations have been made for air temperatures on three levels, corresponding to autumn conditions in Poland. For high level the values of temperature are from 12°C to 24°C, for medium level are from 7°C to 19°C and for low level are from 2°C to 14°C. The daily temperature variation was established on the basis of a two-day weather forecast [7]. The soil and water temperatures were equal to 8°C and 11°C respectively. Temperature fluctuations assumed in the modeling are shown in Figure 4.

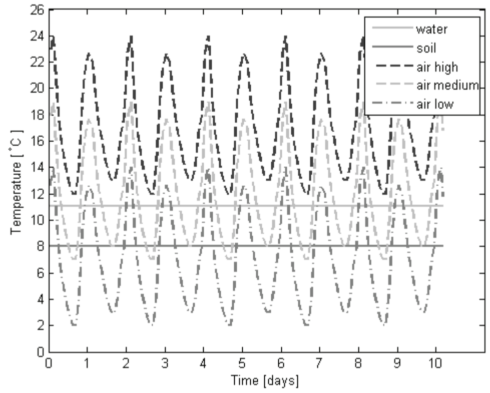

Fig. 4. Temperatures used in modeling

Modeling was performed for 10 days with time step (saving results) equal to 1 hour. Flooding and discharging scenario presented in Figure 5 implies the variation of the water column height in embankment tank.

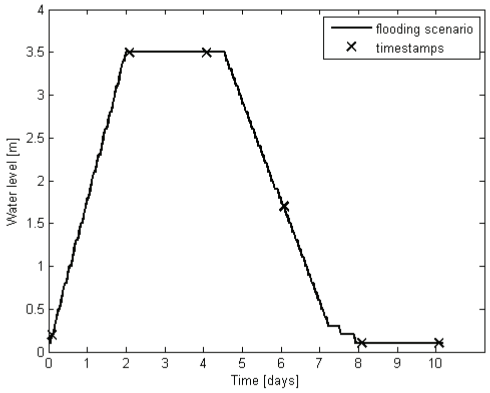

Fig. 5. Flooding and discharging scenario

The rate of flooding and discharging of the tank is adjusted to pumps placed on the experimental embankment. Assumed plateau is the typical average duration of a flood wave observed during seasonal floods in Poland.

Boundary conditions for velocity and displacement were fixed in the distance 30 m from embankment in horizontal direction [8]. The velocity and displacement forces as well as the temperature value were also fixed in the bottom of the computational model. The air temperature changes were implemented as the fix condition, updated or every time step.

4. Results

Figure 6 presents the results of modeling in timestamps (showed in Figure 5) for three levels of air temperatures (showed in Figure 4).

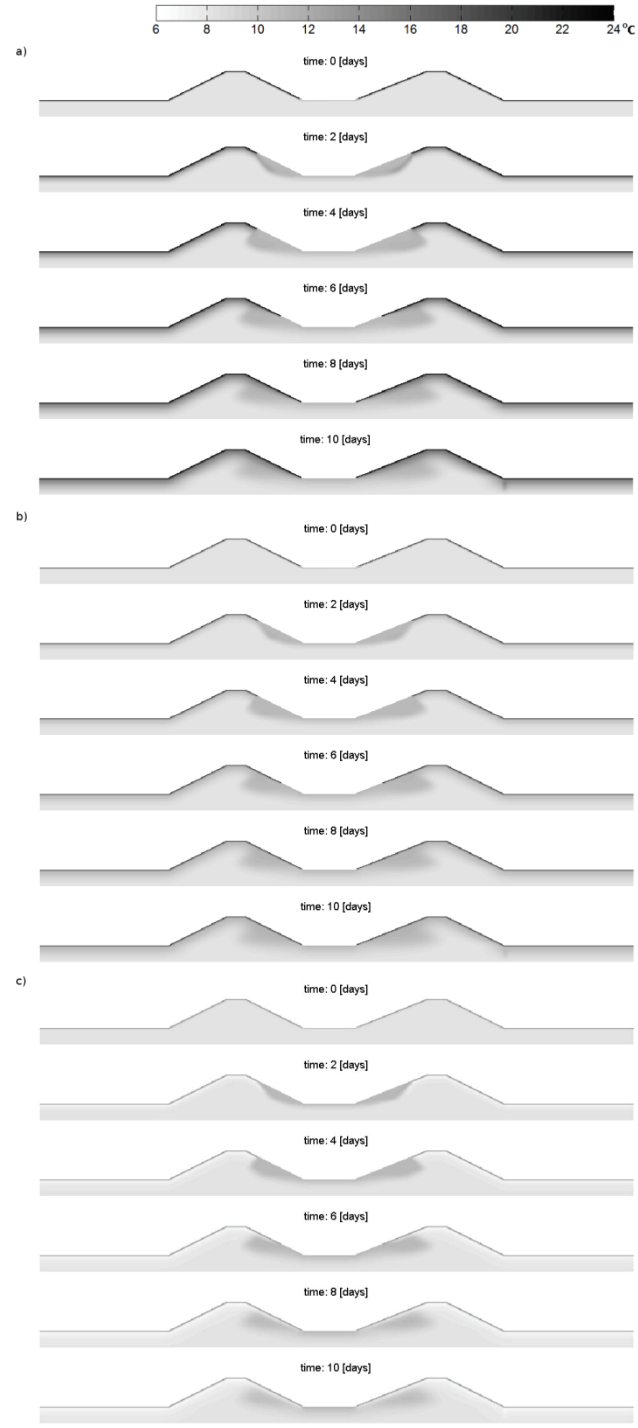

Fig. 6. The results of modeling in timestamps (showed in Fig. 5) for a) high, b) medium, c) low values of air temperature (presented in Fig. 4)

The results of modeling show ranges of temperature changes as the effect of air temperature which varies with time. For higher air temperature changes in the area of dry embankment and substrate is greater than for lower air temperatures. The water-saturated part of embankment is similar, the external temperature ranges influence is negligible. In this area a major factor for the embankment temperature changes is water temperature. The rate of transfer of thermal wave is faster in the saturated area of the embankment than in the dry one. Heat distribution does not keep up with water penetrating into the embankment - this process is much slower and is dependent on the material permeability. The range of thermal changes in embankment does not coincide with the area fully saturated.

Changes in temperature in the embankment below the area of impact air temperature testify to the existence of filtration processes.

Figure 7 presents the temperature changes over time for some characteristic nodes of the model. Coordinates for each presented lines corresponding to nodes are: 1-(20,100), 2-(10,100), 3-(40,250), 4-(40,300), 5-(40,350), 6-(10,450), 7-(20,450).

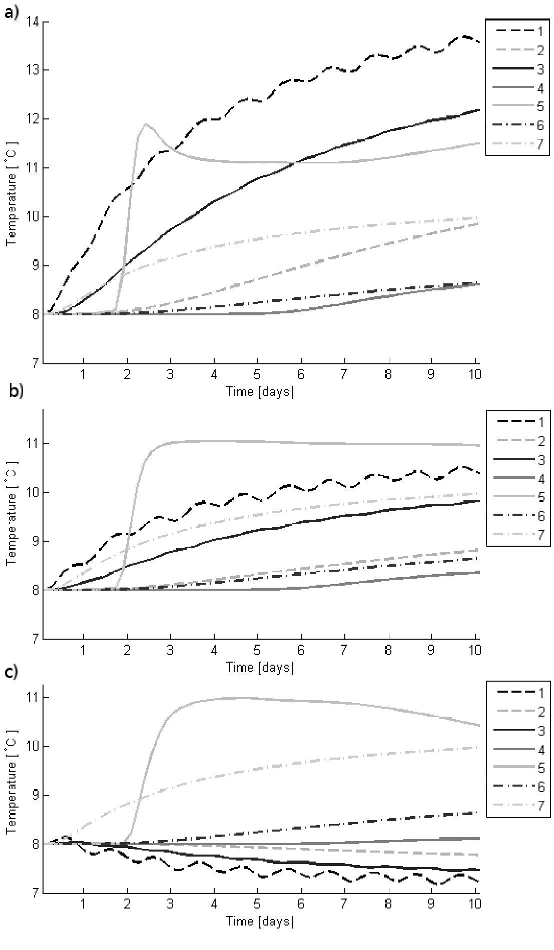

Fig. 7. The temperature changes over time in nodes 1-7 for: a) high, b) medium, c) low air temperature values

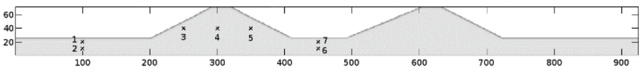

Fig. 8. Location of 1-7nodes in the embankment model

Nodes location in the model is presented in Figure 8. Points 1 and 2 are localized in subsurface layer outside the reservoir, points 3, 4, 5 in the embankment, points 6 and 7 in the subsurface layers, under the reservoir.

The highest influence of air temperature is at points 1 and 3, where the diurnal oscillations are visible, lower influence of air temperature is at points 2, 4 and the lowest at points 6, 7 (under the reservoir). At point 5 both temperatures, water and air has high influence for its temperature.

5. Conclusions

Next work is planned to validate the model with measurements obtained during field realization of scenarios on real experimental embankment. The most valuable are measurements in that parts of in the embankment, where influence of external conditions is minimal. It is also planned to compare the estimated temperature distribution with indication of the temperature sensors localized near surface. It would be also possible to incorporate the results of measurements performed using infrared camera.

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