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EVALUATION OF PIPING EROSION BY MEANS OF TEMPERATURE ANALYSIS

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Abstract: Piping is the most serious menace to the safety of an earth hydraulic work. We present the study of the piping erosion identification by means of temperature analysis. Extensive steady and unsteady numerical computations for the coupled heat and water transport in the porous domain, with the downstream side pipe opening, are described. Choice of the numerical RANS (Reynolds-averaged Navier–Stokes) model is explained to take into account mixed laminar and turbulent water flow in the pipe. Computation covered the range of hydraulic diffusivity from 10^{-7} to 10^{-4} m^2/s and made use of the finite volume method with the FLUENT numerical modelization platform. The basic principles of the pipe thermal influences are presented with the evaluation of the possibilities of identifying piping parameters with temperature measurements. Correct identification of the pipe thermal influence was found to be important in interpretating thermal data measured that are necessary for hydraulic earthworks.

Streszczenie: Przebicie hydrauliczne jest najpoważniejszym zagrożeniem dla bezpieczeństwa ziemnej budowli piętrzącej. Zanalizowano możliwości rozpoznania przebicia hydraulicznego, stosując metodę analizy termicznej. Opisano szczegółowe modelowanie ustalonego i nieustalonego sprzężonego transportu wody i ciepła w ośrodku porowatym z otworem otwartym na granicy odpowietrznej. Wyjaśniono wybór modelu numerycznego RANS (*Reynolds-averaged Navier–Stokes*), który umożliwia równoczesne modelowanie laminarnego i turbulentnego przepływu cieczy, gdy korzysta się z metody objętości skończonych i platformy obliczeń numerycznych FLUENT. Analiza objęła zakres współczynnika dyfuzji hydraulicznej od 10^{-7} do 10^{-4} m^2/s. Zaprezentowano kluczowe parametry termicznego wpływu otworu oraz ocenę możliwości identyfikacji parametrów przebicia hydraulicznego przez pomiary temperatury. Stwierdzono, że poprawna identyfikacja wpływu termicznego otworu istotnie wpływa na właściwą interpretację pomiarów temperatury ziemnych obiektów hydrotechnicznych.

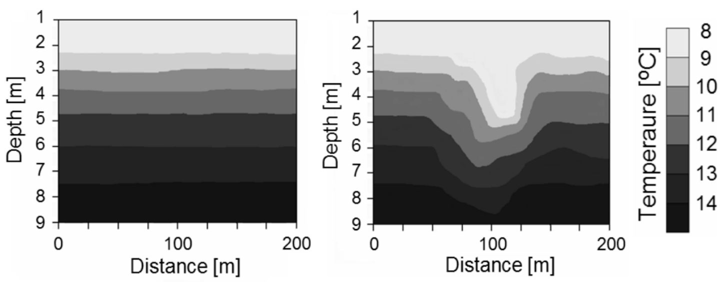
Резюме: Гидравлическая сбойка является самой важной угрозой для безопасности земного водонапорного сооружения. Проведен анализ возможностей обследования гидравлической сбойки с применением метода термического анализа. Подробно описано моделирование сопряженного и несопряженного транспорта воды и тепла в пористой среде с открытым отверстием на воздухоотводящей границе. Выяснен выбор численной модели RANS (*Reynolds-averaged Navier–Stokes*), которая дает возможность одновременного моделирования ламинарного и турбулентного протеканий жидкости, когда используются метод конечных объемов и платформа численных расчетов FLUENT. Анализ охватывал пределы коэффициента гидравлической диффузии от 10^{-7} до 10^{-4} м^2/с. Представлены основные параметры термического влияния отверстия, а также оценку возможностей идентификации параметров гидравлической сбойки посредством измерений температуры. Было установлено, что правильная идентификация термического влияния отверстия существенным образом влияет на правильную интерпретацию измерений температуры земных гидротехнических объектов.

1. INTRODUCTION

Internal erosion as suffusion and piping is one of the main risks to earth dams safety. Of the two modes, piping process is the most dynamic one [5]. In engineering practice, its occurrence is classified as a high danger to the dam safety. Currently there is an important work of the European Working Group (EWG) on Internal Erosion of Embankment Dams of the International Committee of Large Dams (ICOLD) prepares the guidelines for all aspects of the erosion process prevention, identification, protection and risk reduction in the cooperation with experts and researchers. The results of the present research are the part of this work.

In relation to internal erosion, changes found in seepage velocities versus time are interpreted as probably erodibly affected, if influence of other impacts, as for example reservoir water level variation, is excluded.

Thermal methods for seepage velocity (water flow velocity in the porous domain) estimation have proved to be very useful in dams surveillance. It can be realized with a thermal monitoring system of dams, particularly using the optical fiber as a thermical sensor [1], [3]. For decade the optical fibers installed in dams body have been used as the very effective temperature measurement tool in hydraulic earthworks, which allows spatial continuous measurements [7].



A) B)

Fig. 1. Example of temperature distribution in earth dam:
A) low water velocity, no leakage, conductive heat transport domination,
B) thermal leakage influence, local advective heat transport domination

Thermal methods for leakage identification are based on the relationship between water and heat transfer. At the null water velocity there is only conductive, slow temperature transport. With rising the water velocity, temperature from the reservoir is moved quicker with the mass of water (advection process) inward the dam. Variation of temperature distribution (figure 1) in the dam body allows us to identify a leakage and also to estimate a seepage velocity [1], [7].

In the case of the pipe, the recent numerical modelizations performed by GUIDOUX [4] show an important external thermal influence of the pipe (modelization realized for 10-cm pipe radius) which crosses an earth hydraulic structure body (pipe inlet has a direct contact with the reservoir, and its outlet is localized at downstream face of the dam). However it is well known that a pipe with full opening is very dangerous for the dams and this situation ought to be controlled immediately. Normally such an opening is responsible for a very quick reservoir emptying, often with an expensive reparation work; anyway sometimes the dam rupture cam occur [5]. Before this critical state, the pipe develops its length (from the downstream part to the upstream part of the earth hydraulic structure body) and radius, which is called as the backward erosion process.

Our research was focused on the possibility of the earliest possible identification of pipe appearance and the estimation of its dimensions (radius and length) and kinetics which should be done before pipe fully crosses the dam body.

2. METHOD

2.1. SYSTEM DESCRIPTION

Numerical modelization of the thermal response of the pipe requires the description of the coupled heat and water transport which consists of the momentum equation (the Darcy equation (1) in a porous domain and the Navier–Stokes equation (2) in the pipe), the mass conservation equation (3) and the energy conservation equation (4). The latter, beside the term for a conductive heat transport, obligatory contains also the term describing advective heat transport (the transport of the heat with the mass of flowing water).

$$\vec{q} = -K\vec{\nabla}H \,, \tag{1}$$

$$\rho_f \left[\frac{\partial \vec{v}}{\partial t} + \vec{\nabla}(\vec{v}\vec{v}) \right] = -\vec{\nabla}p + \vec{\nabla}\underline{\underline{\tau}} \,, \tag{2}$$

$$\vec{\nabla}\vec{v} = S_m \,, \tag{3}$$

$$C_\Theta \frac{\partial T}{\partial t} + C_f n \vec{v}\vec{\nabla}T - \lambda_\Theta \nabla^2 T = 0 \,, \tag{4}$$

where:

q – the water discharge,
K – the hydraulic conductivity,
H – the hydraulic head,
ρ – the water density,
v – the local water velocity,
p – the pressure,
$\underline{\underline{\tau}}$ – the stress tensor,
S_m – the source term,
C_Θ – the volumetric heat capacity of saturated porous domain,
C_f – the volumetric heat capacity of water,
T – the temperature,
n – the effective porosity,
λ_Θ – the thermal conductivity of saturated porous domain.

A hydraulic earth work with the cylindrical hole (pipe), with a downstream outlet and with an upstream water reservoir (figure 2a) was modelized as the cylindrical case with the cylindrical hole (figure 2b). The upstream and downstream charges of temperature and pressure were posed, respectively, at the inlet and outlet cylinder boundaries. Null gravity was used. Various configurations of the radius r_p and the lengths l_p of the pipe were chosen for the different heights R and the lengths L of the system. Maximum thermal gradient used in the modelization, between the upstream (inlet) and downstream (outlet) boundaries of the system, equalled 20 °C and minimum one was 1 °C.

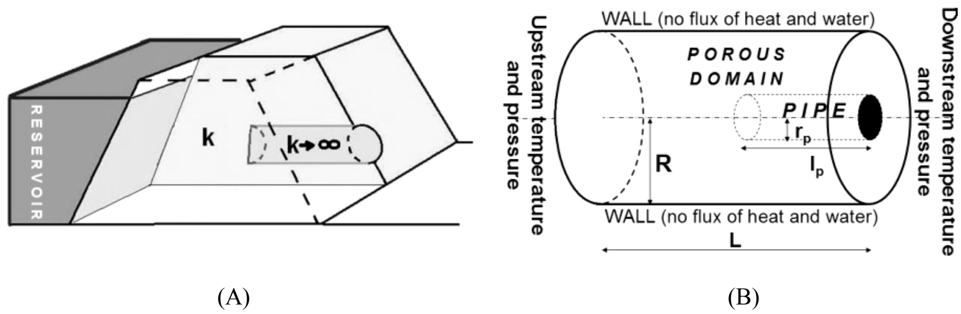


Fig. 2. Scheme of cylindrical domain used for coupled heat and water transport modelization: (A) system under consideration, (B) simplified cylindrical 3D model

Two-dimensional axisymmetrical computations allowed us to modelize three-dimensional cylinder where porous zone was assumed to be isotropic.

Maximum dimensions of the computation mesh elements, particularly for the pipe mesh and for the porous zone close to the pipe, were found using one-dimensional steady and unsteady energy equation close-form solutions, and also two-dimensional preliminary modelization of the extreme possible cases of the thermal charges and the seepage velocity values.

2.2. CHOICE OF NUMERICAL MODEL OF WATER FLOW IN PIPE

An analytical method cannot be used to define beforehand a regime of the water flow in the pipe with a downstream outlet, which is located in porous domain. Porous zone eliminates turbulence in the seepage. However along the pipe, there is a transport of the mass of water to the pipe which rises the water flow velocity inside of it and makes turbulent flow appearance possible.

Four RANS (Reynolds-averaged Navier–Stokes) turbulent flow models (standard, realizable, RNG high turbulent and RNG low turbulent) and also laminar Navier–Stokes model were investigated to choose the best one for the pipe water flow modelization. The computations were carried out by finite volume method using the FLUENT 6 numerical platform. All turbulent flow models have shown low or very low turbulent flow with the maximum turbulence intensity coefficient of the order ranging from 5 to 20 per cent in the outlet part of the hole. Low turbulence intensity excluded the Standard model (it works correctly at the turbulence intensity > 10%) and high turbulent RNG model (it can be used a priori only at a high turbulence intensity).

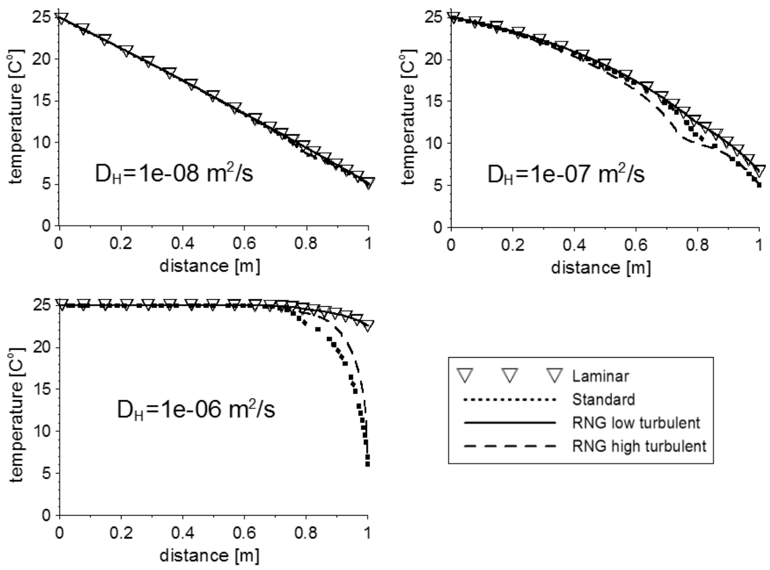


Fig. 3. Comparison of pipe water flow models. Temperature measured in axis of system. Cylinder length, 1 m; pipe length, 0.2 m; pipe radius, 2 mm. Inlet and outlet temperatures of 25 °C and 5 °C, respectively. Hydraulic diffusivity (m^2/s) defined for system without pipe. Steady-state modelizations

Moreover for a very low turbulence intensity (about 0.05%), the realizable model produced drastic thermal field changes (compared with those produced by the laminar model). This implied no physical turbulence intensity influence which also excluded this model from the next modelizations. Finally, RNG low turbulent model and laminar Navier–Stokes model comparison showed insignificant differences in water flow velocity and in temperature values distribution between these models as is presented in figure 3. Linear model as the fastest one was selected for the definitive modelizations.

Temperature-dependent viscosity was used in the computation, which was found to be important for the steady and unsteady modelization results.

2.3. STEADY STATE CONDITION MODELIZATION

At the beginning, stationary modelizations were carried out to define the main aspects of the pipe thermal influence. Different inlet and outlet temperatures as well as different hydraulic diffusivity D_h were used. Two lengths of the system, i.e. 1 m and 10 m, were modelized. In the first one, most modelizations were realized to define the principles of the pipe thermal influence. The second one was used for scale effect verification.

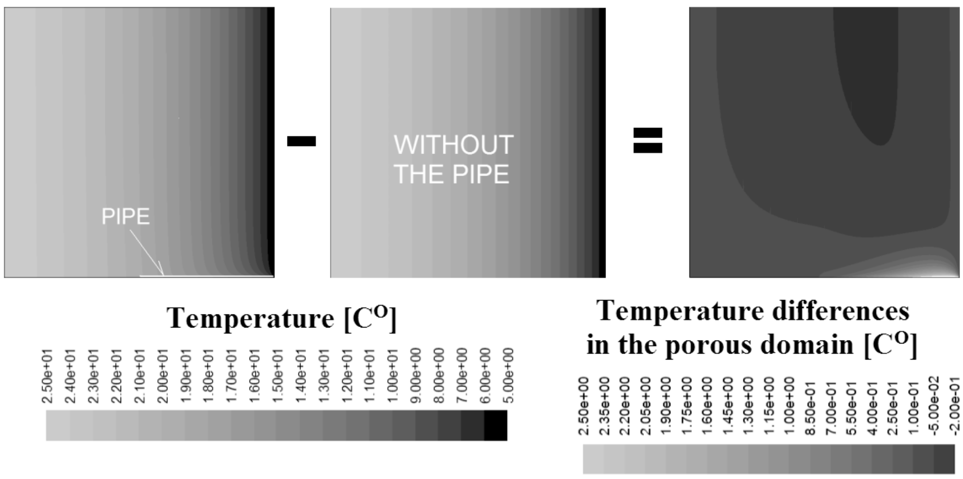


Fig. 4. Scheme of pipe thermal influence extracting

Every field of temperatures obtained by coupled water and heat transport modelization with the pipe presence was compared with another field representing the system without the pipe. This allowed extracting the limits and the values of the pipe thermal influence. An example of this procedure is depicted in figure 4. The positive values in final, extracted field of the thermal differences represent the inlet temperature influence domination. Conversely, negative ones represent the inlet temperature influence decreasing. The following reasoning was taken into consideration: If there is a porous zone with known hydraulic properties, what changes in temperature field will show the pipe appearance?

In fact, for the stationary system without the pipe, three values of hydraulic diffusivity D_h were calculated in relation to the Peclet number:

$D_h = 10^{-7}$ m^2/s in the system without pipe corresponds to $Pe << 1$.

$D_h = 10^{-6}$ m^2/s in the system without pipe corresponds to $Pe \approx 1$.

$D_h = 10^{-5}$ m^2/s in the system without pipe corresponds to $Pe \approx 10$.

Hydraulic diffusivity to follow the Bousinesq hypothesis is defined as the linear relationship being calculated for the system without the pipe:

$$D_h = qL = k(H_1 - H_2), \tag{5}$$

where q is the Darcy velocity, L is the length of the seepage path (cylinder's length), k is the permeability and H_1 and H_2 are the upstream and downstream water levels, respectively.

Permeability is defined as:

$$k = \frac{Kg}{\nu}, \tag{6}$$

where K is the hydraulic conductivity, g is the acceleration of gravity, and ν is the kinematic viscosity.

The Peclet number describes the relationship between conductive and advective heat transport. At Pe number being equal to 0, there is no flow of water, hence no heat transport by water flow. Only conductive heat transport takes place. At increasing water velocity more heat is transported with water, so the Pe values also increase. The Peclet number is given by:

$$Pe = \frac{qC_f L}{\lambda_\Theta} = \frac{k(H_1 - H_2)C_f}{\lambda_\Theta}, \tag{7}$$

where C_f is the volumetric heat capacity of water and λ_Θ is the thermal conductivity of fluid–soil system. This is classical relation of estimating water velocities with temperature measurements.

As we can see, according to equations (5) and (7) the Peclet number and hydraulic diffusivity are independent of the cylinder length. In practice, constant values of upstream and downstream water levels were adopted to modelizations. This allowed us to calculate hydraulic permeabilities for the aforementioned hydraulic diffusivities in the system without the pipe. The same values of the hydraulic conductivity were then used to modelize the system with the pipe.

2.4. UNSTEADY TEMPERATURE MODELIZATION

In addition, some unsteady modelizations with temperature step at inlet were realized to complete and verify the results of the stationary ones and also to analyze the temperature field at higher values of the hydraulic diffusivity ($D_h \approx 10^{-4}$ m^2/s). This was necessary, because in the latter case, the advective heat transport was so important that with the stationary modelization, most part of the domain was filled only with the exact value of the inlet temperature, which excludes the possibility of pipe thermal influence analysis.

Three values of the hydraulic diffusivity D_h were modelized for the unsteady computations:

$D_h = 10^{-6}$ m^2/s in the system without pipe corresponds to $Pe \approx 1$.

$D_h = 10^{-5}$ m^2/s in the system without pipe corresponds to $Pe \approx 10$.

$D_h = 10^{-4}$ m^2/s in the system without pipe corresponds to $Pe \approx 100$.

Totally, in the steady and unsteady modelizations, the hydraulic diffusivity D_h from 10^{-7} to 10^{-4} m^2/s was taken into consideration which corresponded to the Peclet number range from $Pe \approx 0.1$ to $Pe \approx 100$.

3. RESULTS

3.1. BACKGROUND

Both pipe appearing and its development affect initial temperature field. Four characteristic zones of the pipe thermal influence have been found. Three are located outside the pipe (zones *A*, *B*, *C*, figure 5) and the fourth one is located inside the pipe.

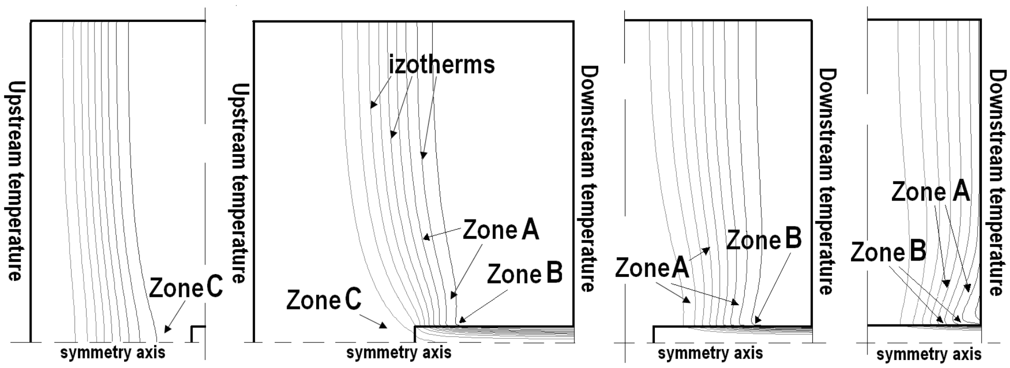


Fig. 5. Example of thermal front passage through highly diffusive porous domain (hydraulic diffusivity of 10^{-4} m^2/s defined for system before pipe appearance). Pipe length, 500 mm; pipe radius, 50 mm; length and height of system, 1000 mm

Pipe works like a drain. It collects water from the porous domain which conducts water and heat flow. The example of the water velocity field disturbance due to the pipe presense can be seen in figure 6.

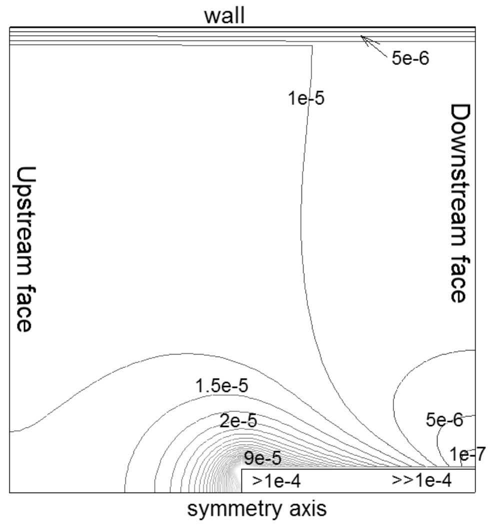


Fig. 6. Example of scalar water velocity field (m/s) in porous zone, evoked by pipe presence. Hydraulic diffusivity, 10^{-5} m^2/s (defined for system before pipe appearance). Cylinder length, 1 m; cylinder radius, 1 m.; pipe length, 0.5 m; pipe radius, 50 mm

In the upstream part of the system, more intensive transport of heat from the upstream boundary towards the upstream end of the hole can be found as a result of the local velocity rising owing to the shortest seepage path (Zone *C*, figure 5). Outside the pipe, depending on the values of seepage velocity vectors and their directions, we can observe an increasing or conversely a decreasing of the inlet temperature influence (Zone *A*, figure 5) due to the changes in the advective heat transport direction and its intensity. Finally, because of the heat transport towards the pipe, the accumulation of this heat in the pipe results in the thermal, diffusive pipe influence on porous domain (Zone *B*, figure 5).

3.2. EXTERNAL THERMAL INFLUENCE OF PIPE

Zone between upstream end of the pipe and reservoir boundary. The shortest seepage path between the reservoir and the upstream end of the pipe accelerates water flow (because of the largest hydraulic gradient) and simultaneously advective heat transport towards the pipe (Zone *C*, figure 5). This augments an inlet temperature influence in the zone which has the form of cylinder with its fore-part at the upstream (reservoir) system boundary. Close to the upstream end of the pipe, this cylinder takes the form of funnel with the tip connected with the end of pipe. If the upstream end of the pipe is close to the upstream boundary of the system, or the length of the system is short, the base of the funnel can touch directly this boundary (without transitional cylindrical section). The zone described is characterized by permanent domination of the inlet temperature influence compared with that of the system without the pipe (figure 8).

Unsteady modelization presents important temperature changes in this zone at the hydraulic diffusivity of 10^{-4} m^2/s, particularly in the case of the extension of the pipe axis, closely to the upstream end of the pipe. However, they decrease quickly towards outside. Finally, the length of the zone of the significant temperature changes approaches 20% of the system length for the pipe length ranging from 10% to 30% of the system length, starting from the upstream end of the pipe towards the water reservoir. At the pipe length equal to ca. 50% of the system length and longer, some important changes in thermal field approach almost the upstream boundary of the system. Maximum radius of the zone equals about 30–40 cm (where radius of the pipe is 5 cm for unsteady simulation).

Zone outside the pipe. Outside the pipes, in the zone of the pipe influence, seepage velocity vectors are directed obliquely towards the pipe. Close to the limits of the pipe they are nearly perpendicular to it.

This causes that along the length of the pipe there is a water from soil, drained by the pipe. In effect, a gradual reduction of seepage velocity towards the system downstream face takes place. The analysis of the directions of the seepage velocity vectors and their values allows us to explain the principles of the temperature distribution outside the pipe, which can have two basic opposite forms. It can be the increasing or decreasing of the inlet temperature influence compared with the temperature field without the pipe.

The first one, the increasing of the inlet temperature influence, is characteristic of the hydraulic diffusivity (defined for the system without the pipe) of the order of 10^{-6} m^2/s and lower. It corresponds to low Peclet number (also defined for the system without the pipe) of the order of one and lower. In effect it is characterized by a conductive heat transport without advection domination.

In this range of hydraulic values, an appearance of the pipe and its development accelerate not so much seepage velocity in porous domain. Seepage velocity vectors are directed still more towards the downstream face of the system than towards the pipe boundary (beyond these ones which are very near the pipe). In effect the heat from the upstream part of the system outside the pipe is transported quicker to the downstream part of the porous zone. Moreover, a heat accumulation in the pipe is responsible for the diffusional external pipe thermal influence which amplifies the increasing of the inlet temperature influence closely to the pipe (figure 7b and c).

Thermal intensity of this zone and its dimensions depend largely on the temperature gradient between upstream and downstream parts, the length of the pipe and the length of the system.

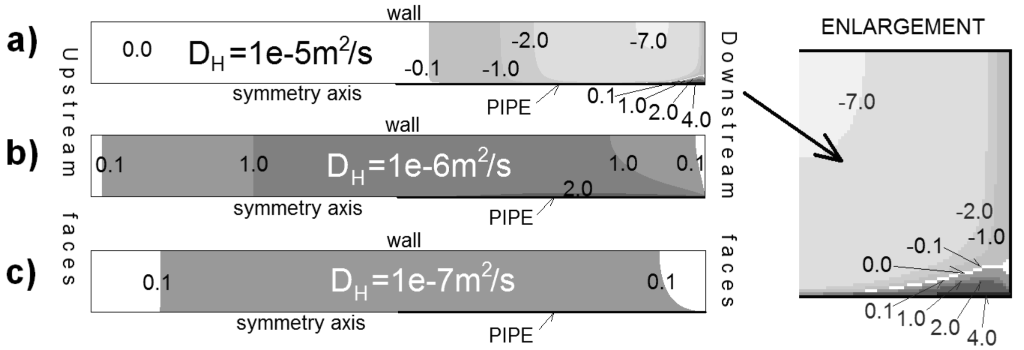


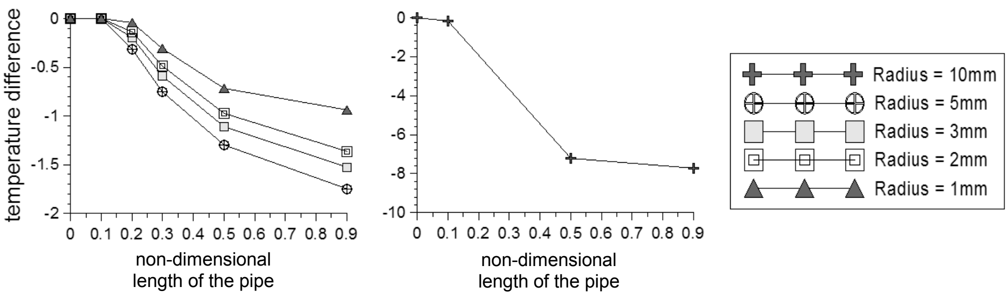
Fig. 7. Extracted thermal influence of pipe at different hydraulic diffusivity values (defined for system before pipe appearance) for steady-state modelizations. System length, 10 m; height, 1 m. Pipe radius, 1 cm; pipe length, 0.5 m. Inlet and outlet temperatures equal to 25 °C and 5 °C, respectively

For the modelizations of the system of 1-m length, thermal changes were smaller than 0.1 °C (for large, 20 °C at the maximum gradient of temperature between inlet and outlet of the system) and very limited in space. For the system of the length of 10 m and for the pipe whose length was 5 m and greater, thermal influence of the pipe proved to be not only relatively significant at the hydraulic diffusivity of the order of 10^{-6} m^2/s, but also great in space (figure 7b). For lower hydraulic diffusivity it was still almost invisible (figure 7c). However, this inlet temperature influence increasing with the length of the system increasing, can imply that for longer systems a significant temperature change will be visible even at the hydraulic diffusivity of 10^{-7} m^2/s and lower.

The second type of the thermal zone outside the pipe is primarily characterized by the inlet temperature influence decreasing. It is developed at the hydraulic diffusivity (defined for the system without the pipe) of the order of 10^{-5} m^2/s and higher. It corresponds to the Peclet number equal to 10 and higher (also defined for the system without the pipe) which characterizes the advective heat transport domination.

In this range of hydraulic values, the mass of water from the porous zone outside the pipe is transported quicker and more clearly directed towards the pipe than in the case described in the previous paragraphs. This results in very fast reduction of seepage velocity in the porous zone, along the pipe, towards the downstream system boundary. Because of the same direction of simultaneous advective coupled heat transport decreasing, the zone of the inlet temperature influence deficiency is created (figure 7a).

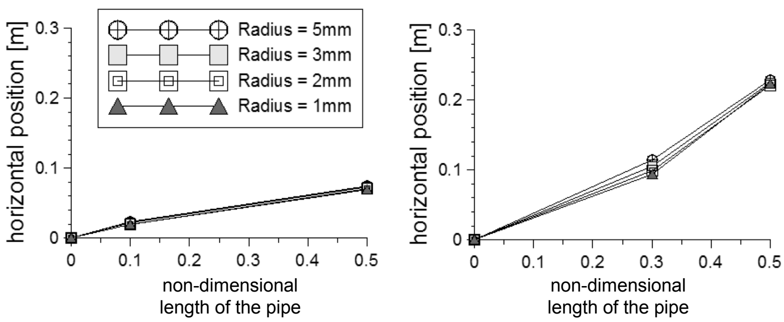
Thermal intensity of this zone and its vertical and horizontal dimensions depend particularly on the temperature gradient between upstream and downstream parts, the length of the pipe and the length of the system (figure 8). The influence of the pipe radius is less important but also must be taken into consideration (figure 8a).



(A) (B)

Fig. 8. Maximum values of inlet temperature deficiency in field of extracted thermal influence of pipe versus non-dimensional pipe length. Steady-state modelizations. Hydraulic diffusivity, 10^{-5} m^2/s (defined for system before pipe appearance). Inlet and outlet temperatures equal to 25 °C and 5 °C, respectively. Length of the system: (A) 1 m, (B) 10 m

At the length of the system of 10 m and the pipe length equal to 5 m, the range of the significant vertical thermal influence was greater than 1 m and had some meters of the horizontal length, beginning from the downstream face of the system (figures 7a and 8b). For longer pipes it develops its dimensions and intensity. Thermal influence of the pipe was much slighter at shorter length of the system.

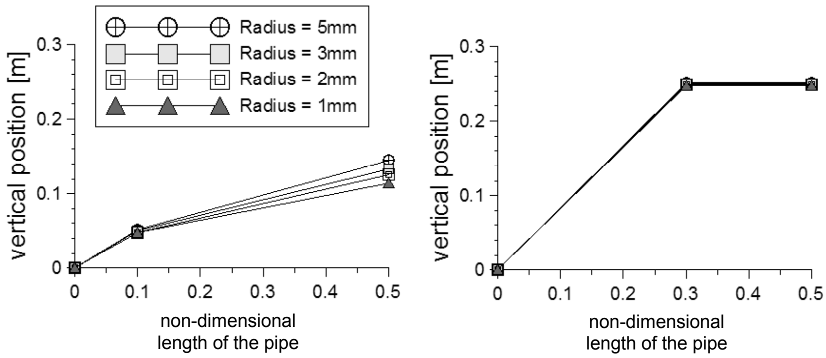


(A) (B)

Fig. 9. Variation of horizontal position of point of maximum values of inlet temperature deficiency in field of extracted thermal influence of pipe versus non-dimensional pipe length. Steady-state modelizations. Inlet and outlet temperatures equal to 25 °C and 5 °C, respectively. Length and height of system, 1 m. Hydraulic diffusivity (defined for system before pipe appearance): (A) 10^{-5} m^2/s, (B) 10^{-6} m^2/s

We observed again an inlet temperature influence increasing with the system length increasing, which can be used probably for pipe thermal identification in large hydraulic works.

Furthermore, we found that the location of the point of the maximum inlet temperature deficiency depends largely on the length of the pipe, and only weakly on its radius (figures 9 and 10). It is located always in the downstream part of the system, not farther than at the distance being 20% of the length of the system from the downstream system boundary.



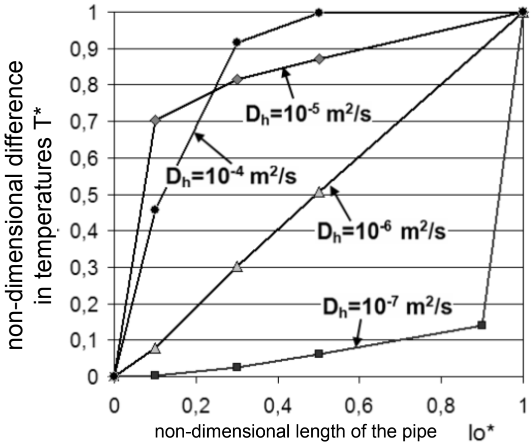
(A) (B)

Fig. 10. Variation of vertical position for maximum value point of inlet temperature deficiency in field of extracted thermal influence of pipe versus non-dimensional pipe length. Steady-state modelizations. Inlet and outlet temperatures equal to 25 °C and 5 °C, respectively. Length and height of system, 1 m. Hydraulic diffusivity (defined for system before pipe appearance): (A) 10^{-5} m^2/s, (B) 10^{-6} m^2/s

Due to seepage vectors' directions towards the pipe and their important values, diffusion of the heat from the pipe to the porous zone is close to null despite a strong inlet temperature accumulation in the pipe. As a result, the boundary of the inlet temperature influence deficiency zone is localized almost at the side of the pipe. Only very closely to the outlet of the pipe, where water velocity in the porous zone is reduced significantly, we can observe the zone of the inlet temperature influence domination, however very limited in the space (figure 7a).

3.3. IMPORTANT INTERNAL THERMAL RESPONSE OF PIPE

As was mentioned, pipe drains the heat with the mass of water from the porous zone. This results in the accumulation of heat in the void which is transported outside the pipe at the velocities much higher than those in the porous domain. There is a significant difference between the temperatures inside and outside the pipe which rises in the direction of downstream outlet of the void, to reach its maximum value in the vicinity of the outlet. Variation of the temperature at this point is very characteristic and can easily be measured in the pipe outlet flow.



$$lo^* = \frac{l_O}{L} \qquad T^* = \frac{Max(T_{out\ without\ hole} - T_{out\ with\ hole})}{Max(T_{out\ without\ hole} - T_{in\ with\ hole})}$$

Where:

l_o – length of the pipe

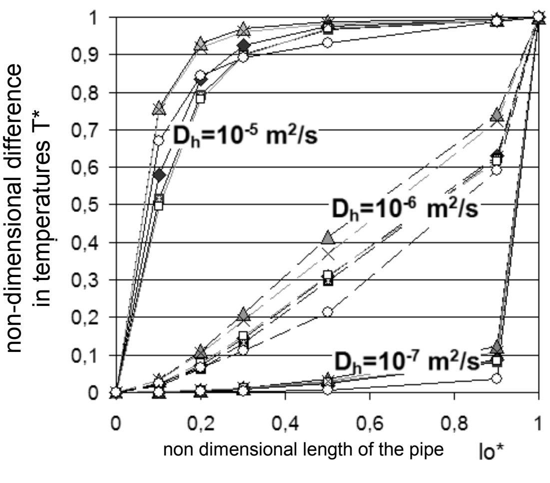
L – length of the system

$T_{out\ without\ hole}$ – temperature at the pipe outlet location, however without pipe temperature influence

$T_{out\ with\ hole}$ – temperature of the pipe outlet flow

$T_{in\ with\ hole}$ – temperature at inlet of the pipe in the case of full pipe opening, which equals to inlet boundary temperature

Fig. 11. Extracted, non-dimensional differences in pipe outlet flow temperatures versus non-dimensional pipe length. Unsteady-state modelizations. System length, 1 m; height, 1 m. Pipe radius, 5 cm. Minimum and maximum step temperatures are, respectively, 5 °C and 25 °C



Line	Inlet temperature [°C]	Outlet temperature [°C]	Length of the system [m]	Height of the system [m]
–△– (triangle)	25	5	1	1
–◆– (filled diamond)	10	5	1	1
–✱– (star square)	6	5	1	1
–□– (square)	5	25	1	1
–×– (cross)	25	5	1	0,25
–○– (circle)	25	5	10	1

$$L^* = \frac{l_O}{L} \qquad T^* = \frac{T_{out\ without\ hole} - T_{out\ with\ hole}}{T_{out\ without\ hole} - T_{in\ with\ hole}}$$

Fig. 12. Extracted, non-dimensional differences in pipe outlet flow temperatures versus non-dimensional pipe length. Steady-state modelizations. Pipe radius, 5 cm

We found that besides hydraulic diffusivity value of the porous domain and temperature gradient between upstream and downstream parts, there is a non-dimensional length of the pipe which is essential for the pipe outflow temperature (figures 11 and 12). Ten non-dimensional length of the pipe is defined as the relationship between the length of the pipe and the length of the system. Very slight influence of the radius of the pipe was identified (figure 13). This important relationship between the outlet temperature and the non-dimensional length of the pipe is visible in a full range of the hydraulic diffusivity, ranging from 10^{-4} to 10^{-7} m^2/s (hydraulic diffusivity value calculated for the system before the pipe occurrence) and even for a small temperature gradient between upstream and downstream faces.

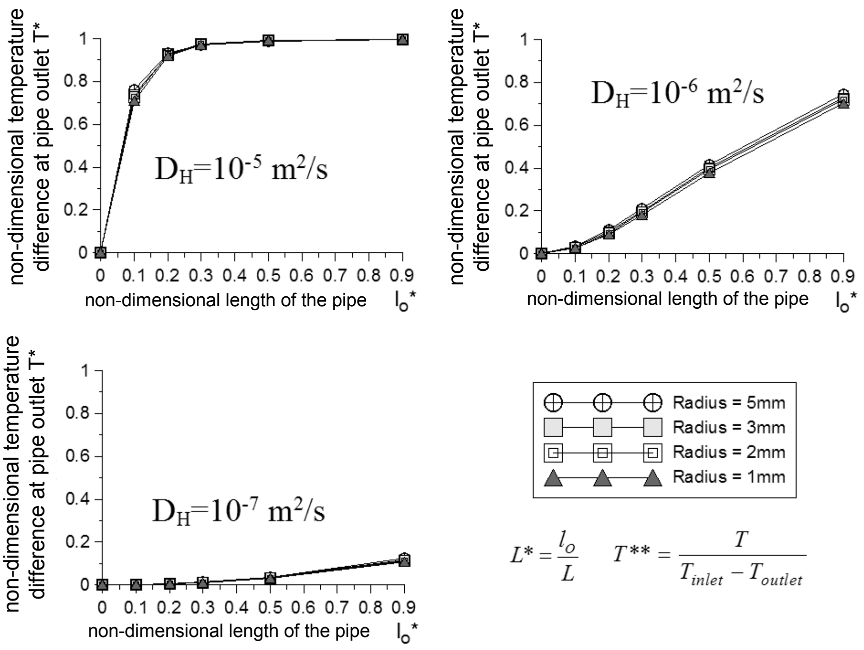


Fig. 13. Extracted, non-dimensional temperature differences in pipe outlet flow versus non-dimensional pipe length at different radii of pipe. Steady-state modelizations. Inlet and outlet temperatures equal to 25 °C and 5 °C, respectively. Length of system, 1 m

In contrast to the outside pipe thermal influence, the variation of temperature in the pipe outlet flow is always dominated by heat from the upstream system boundary. In steady and unsteady modelizations, maximum temperature differences measured at the pipe outflow increases significantly at the pipe length development. However, the kinetics of this process depends largely on the value of the hydraulic diffusivity (defined for the system before the pipe appearance).

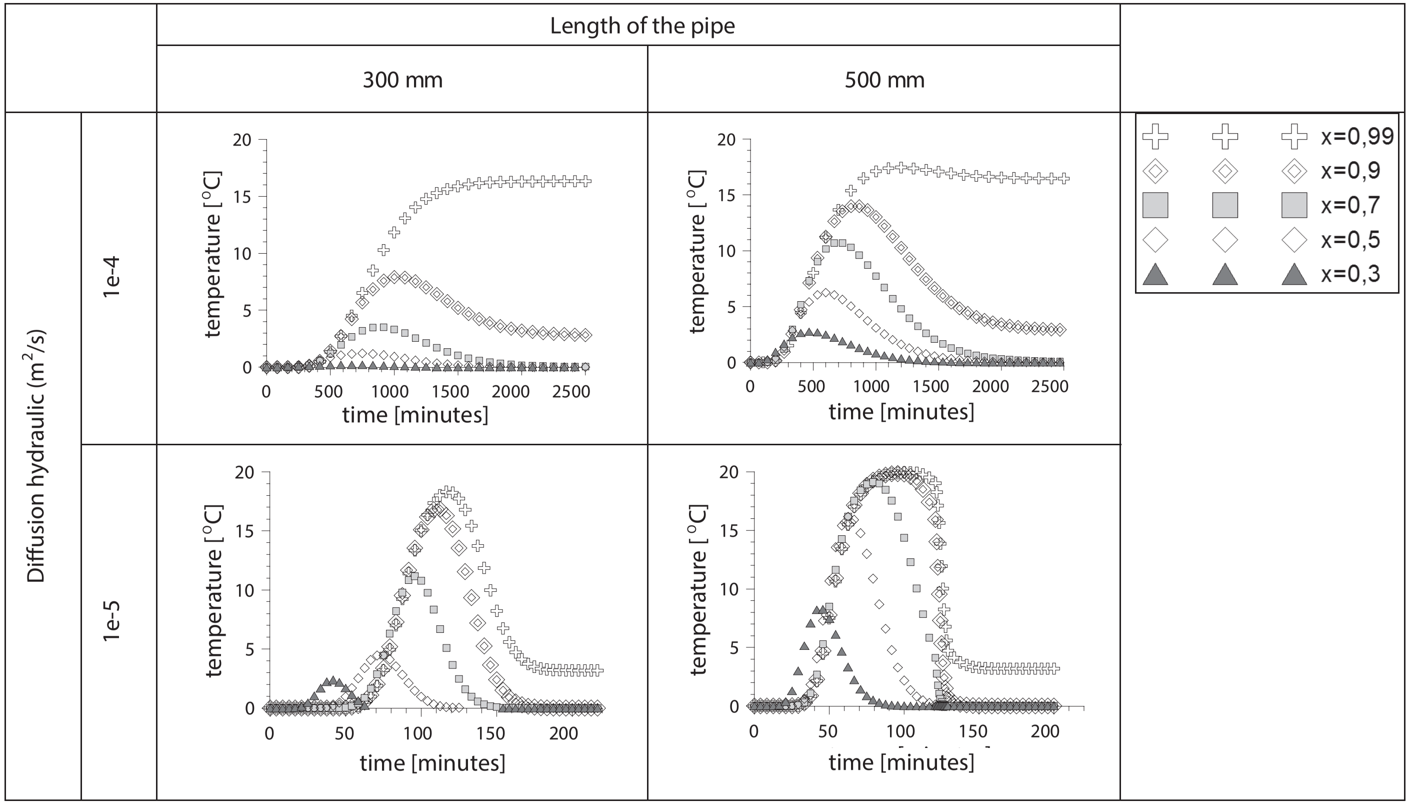


Fig. 14. Variation of extracted pipe thermal influence with time at chosen points of system for inlet temperature step. System length – 1 m and height – 1 m. Pipe radius – 5 cm. Minimum and maximum steps of temperature, 5 °C and 25 °C, respectively

In the case of small hydraulic diffusivity of the order of 10^{-7} m^2/s, pipe length development influences slightly the outlet flow temperatures, practically until full pipe opening. Just before it, the inlet temperature dominance grows very quickly. At hydraulic diffusivity of 10^{-6} m^2/s this relation rises systematically for all lengths of the pipe. Finally at the hydraulic diffusivity of 10^{-5} m^2/s and higher, the advective heat transport dominance is no longer so important and it is the pipe length development that influences very strongly the outlet flow temperatures. When the non-dimensional length of the pipe equals about 0.2, this growing trend slows down. And at the non-dimensional length of 0.5 m and greater this influence is small or even null, depending on the hydraulic diffusivity values.

4. CONCLUSION

The basic principles of the pipe thermal influence, its appearance and development were identified. The investigation concerned the whole range of hydraulic diffusivity which can be found in the hydraulic earthworks. Numerous combinations of pipe dimensions versus system dimensions were investigated, representing the different scales and stages of the backward piping erosion. The results show the possibility of the pipe thermal identification and its kinetic and geometrical parameters assessing. Moreover, the information obtained is important for a correct analysis of temperature data, which is measured by the thermal control systems based on hydraulic work. The main aspects and the results obtained are the following:

- The easiest and the most effective thermal method for identifying the pipe length and its kinetics is the analysis of temperature of the pipe outlet flow, which greately depends on the non-dimensional length of the pipe, and practically does not depend on its radius. It is limited, of course, by the necessity of the first pipe outlet localizing at the downstream face of the hydraulic earthwork.
- Surprisingly, the decreasing of the system inlet (upstream boundary) temperature influence in the porous zone as well as a deep penetration of system outlet (downstream boundary) temperature are not indicative of leakage, but they testify to pipe existing and its development in the vicinity of the thermal sensor.
- The pipe outside thermal influence in the porous zone can be used for the pipe existing identification and probably is also the process development indicator. This zone is very significant in the space, particularly at the pipe length equal to about 50% of the system length and extensive hydraulic earthworks. However, precise parametrical pipe analysis can be difficult, taking into account the numerous parameters which influence the values of this thermal zone.

The modelizations were carried out based on simplified thermal boundary conditions. This gives stronger external pipe thermal influence than in reality. Final modelizations based on the real geometry and the extent of the hydraulic earthworks and on the real thermal charges are necessary to verify the results presented. The work in this field is still going on.

Our conclusion has not concerned the case of full pipe length opening, between downstream and upstream faces, which was not the subject of the present research.

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