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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Description and application of a model of seepage under a weir including mechanical clogging

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Abstract

The paper discusses seepage flow under a damming structure (a weir) in view of mechanical clogging in a thin layer at the upstream site. It was assumed that in this layer flow may be treated as one-dimensional (perpendicular to the layer), while elsewhere flow was modelled as two-dimensional. The solution in both zones was obtained in the discrete form using the finite element method and the Euler method. The effect of the clogging layer on seepage flow was modelled using the third kind boundary condition. Seepage parameters in the clogging layer were estimated based on laboratory tests conducted by SKOLASIŃSKA [2006]. Typical problem was taken to provide simulation and indicate how clogging affects the seepage rate and other parameters of the flow. Results showed that clogging at the upstream site has a significant effect on the distribution of seepage velocity and hydraulic gradients. The flow underneath the structure decreases with time, but these changes are relatively slow.

Key words: *clogging, numerical model, seepage, weir*

INTRODUCTION

Main aim of this work was to develop a numerical model of seepage under a weir including mechanical clogging. For practice it is important to indicate how significantly silted-up layer on the upstream site affects the distributions of hydraulic gradients and piezometric heads. Values of these parameters, especially at the river bed on the upstream site, determine stability conditions of the hydraulic structure.

Seepage under a damming structure is usually accompanied, among other things, by the phenomenon of clogging. Water together with suspension infiltrate at the upstream site. Displaced particles are deposited in pores, thus reducing effective porosity of the soil. As a result, hydraulic conductivity also decreases [CHALFEN, MOLSKI 2011; DRĄGOWSKI *et al.* 2002; MURAT-BŁAŻEJEWSKA, SROKA 1997; PIEKARSKI 2009; WOJTASIK *et al.* 2005]. Clogging may be caused by various factors, mechanical sieving in soil pores, physical and chemical interaction between grain surface and infiltrating water. Typically such a course of the process is assumed that the concentration of the suspension decreases monotonically with the covered distance [TRZASKA, BRODA 2000; TRZASKA, SOBOWSKA 2000; 2007]. In the investigated problem the area exposed to clogging extends along river bed of the upstream site. It was also assumed that an intensive mass exchange between the suspension and the soil grains takes place only in the layer of a limited, small thickness (Fig. 1, $d<<T$). Deeper, water is completely free from suspended matter.

It is also worth to mention that studies on the phenomenon of clogging (both in the qualitative and quantitative aspects) have been discussed in numerous publications, although very few of them concern problems connected with operation of hydro-engineering structures.

DESCRIPTION OF THE PROBLEM

Seepage under a damming structure was investigated as two-dimensional flow in the vertical section (Fig. 1). It was assumed that the foundation of a damming structure (a weir, a concrete dam) rests on a homogeneous isotropic permeable layer of limited thickness. The seepage was reduced by a sheet pile located on the upstream site. Layer I of small thickness d was identified along the upper bottom. Flow of water with suspended matter occurs in this layer and solids are deposited in the pores. Below, in area II, water free of suspended matter seeps towards the downstream side. Considering that the layer I is of limited, small thickness, we may assume that water flow in this area is one-dimensional and perpendicular to the layer. In turn, in section II, seepage movement is two-dimensional. Continuity conditions of flow and piezometric heads between zones I and II must be satisfied. It was assumed that Darcy's law is valid and sought solution is function $h(x,y)$ which prescribe distribution of piezometric heads.

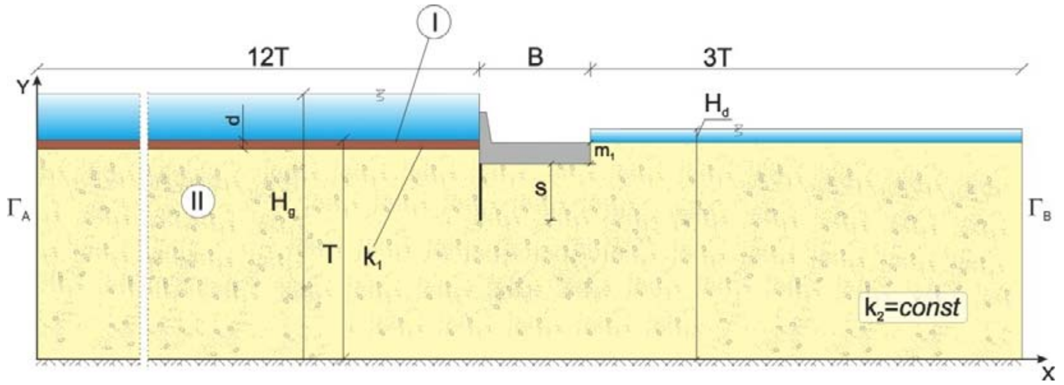

Fig. 1. Scheme of flow area; d, B, T, m_1, s – linear dimensions, m; H_g, H_d – piezometric head at upstream and downstream site, m; k_1 – seepage coefficient in zone I, m·d^{-1}; Γ_A, Γ_B – vertical boundary; x, y – coordinates, m; I, II – zones; source: own study

As a result of depositing suspensions in zone I changes occur with time in the value of the seepage coefficient. It was assumed that the seepage coefficient k_1, averaged along layer thickness d, depends on the mass of deposited clogging material M per unit area of the upstream site:

$$k_1 = k_1(M,x) \tag{1}$$

The above dependence may be derived from an appropriate laboratory experiment. In this paper the study by SKOLASIŃSKA [2006] was used to perform example calculations. These analyses were conducted on four samples of sandy soils differing in their grain size distribution (fluvioglacial sands). Clay was used as clogging material for samples of 30 cm in thickness. The suspension concentration was 2 g·dm^{-3}. It was found that the most intensive clogging took place in the subsurface layer of 4 cm in thickness. The experiment was continued until the averaged seepage coefficient was reduced by an order of magnitude. The author distinguished two stages of the clogging process. In stage one suspension was retained in soil pores, but permeability did not change markedly. In stage two the value of the seepage coefficient decreased rapidly in accordance with the exponential function. A similar course of the process was also reported in his experiments by PIEKARSKI [2009].

In zone I (along the upstream site) the function describing a change of deposited clogging matter mass occurring with time per unit area $M(x,t)$ has to meet the following differential equation:

$$\frac{\partial M(x,t)}{\partial t} = c(t)q_G(x,t)$$

where:

- M – mass of deposited clogging material per unit area, g·m^{-2};
- t – time, d;
- c – clogging material concentration, g·m^{-3};
- q_G – unit flow intensity at upstream site, m·d^{-1};

with the initial condition $M(x,t = 0) = 0$.

Further the discrete formulation of the problem was assumed, taking the form in selected N points located along the upstream site:

$$\frac{dM(x_j,t)}{dt} = c(t)q_G(x_j,t) \quad j = 1, 2, \ldots, N \tag{2}$$

with the initial condition $M(x_j,t = 0) = 0$

where

- $c(t)$ – denotes clogging matter concentration in water seeping to the ground (in the watercourse), g·m^{-3};
- $q_G(x_j,t)$ – denotes infiltration rate at the upstream site in analysed point j, m·d^{-1}.

In zone II seepage flow is two-dimensional. It is determined when the distribution of piezometric heads $h(x,y)$ is known. If a medium is isotropic and homogeneous, the sought function in zone II has to satisfy the following equation:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S_s}{k_2}\frac{\partial h}{\partial t} \tag{3}$$

where:

S_s – specific storage [ZARADNY 1990], m^{-1},
k_2 – seepage coefficient in zone II, m·d^{-1},

while on the boundaries it has to meet the following conditions:

– the normal derivative to the boundary equals zero $\frac{\partial h}{\partial n} = 0$ (the second kind condition) along the base of the permeable layer, foundation and the sheet pile wall,
– prescribed piezometric head along the bottom of the downstream site (the first kind condition – $h = H_D$),
– the normal derivative to the boundary equals zero (the second kind condition) on the Γ_A and Γ_B,
– the third kind condition e.g. [WALCZAK *et al.* 2013] on the boundary with zone I

$$q_{I\_II} + \frac{k_1}{d} H_g - \frac{k_1}{d} h_{I\_II} = 0 \tag{4}$$

where:

q_{I_II} – unit flow intensity at the boundary of subzones I and II, m·d^{-1};
k_1 – seepage coefficient in zone I, m·d^{-1};
d – thickness of clogging area, m;
H_g – piezometric head at upstream site, m;
h_{I_II} – piezometric head, m.

Symbols h_{I_II} and q_{I_II} denote piezometric head and unit flow intensity on the boundary of zones I and II. Equation (4) presents a linear dependence between piezometric head and unit flow intensity. Taking into account the assumptions ($d<<T$, flow perpendicular to the layer), in layer I the hydraulic gradient is expressed by the dependence $(H_G–h_{I\_II})/d$.

The seepage area was limited by introducing boundaries Γ_A and Γ_B (Fig. 1). Assumption of the finite flow area made it possible to find a numerical solution.

In zone I flow intensities, due to the limited thickness of the layer, are identical in the upper and lower surface limiting this area, although they vary with the distance from the damming structure:

$$q_{I\_II} = q_G \tag{5}$$

where:

q_{I_II} – unit flow intensity at the boundary of subzones I and II, m·d^{-1};
q_G – unit flow at the upstream site, m·d^{-1}

Initial problem (2) formulated in zone I and boundary problem (3) defined in zone II are obviously conjugate. The parameter linking these problems is first of all flow intensity q_G (equal to q_{I_II}) found on the right side of equation (2) and in boundary condition (4) and seepage coefficient k_I concerning zone I and found in boundary condition (4).

NUMERICAL MODEL

The finite element method (triangular elements with three nodes placed in the vertices) was applied to solve the described problem of seepage in zone II (a boundary problem). Original software developed by the authors was used in the calculations [SROKA *et al.* 2004]. Data, mainly the mesh of elements, was generated using the GEMOF software, calculations using the finite element method were performed with the use of the FILSAT programme and the graphic presentation of results was provided by the GRAPER programme. The mesh was prepared so that numerical error caused by FEM was negligibly small (assumed measure of seepage velocity error was met err_v < 10% [SROKA *et al.* 2004]). The generated mesh of elements consisted of over six thousand nodes and twelve thousand elements.

The distribution of the clogging material mass deposited along the upstream site is described by the system of ordinary differential equations at individual points. The number of points and their distribution were adopted in accordance with FEM discretization applied in zone II (in nodes of the mesh at boundary Γ_{I_II}). In the upstream site we have two hundred nodes, in which the boundary condition was defined (4). Clogging (as described by equation 2) was calculated for these nodes. Such a defined clogging problem was analysed using Eulerian explicit differential scheme. A constant time step equal to one day was used. Simulation was finished after one hundred days.

EXAMPLE SIMULATION

For the example calculations we used a small weir on a lowland river founded on a layer of fluvioglacial sands with thickness T = 10 m. The length of the structure foundation is L = 8 m and it is placed 1 m below the ground level (m_1 = 1 m, Fig. 1). On the upstream site piezometric head is H_G = 13.5 m, while on the downstream site it is H_D = 11.5 m. The sheet pile wall of a length s = 5 m is used as a sealing element. The simulation task was treated as benchmark, which results should indicate whether clogging significantly affects, both qualitatively and quantitatively, seepage under the small damming structure.

Boundaries Γ_A and Γ_B were assumed to be nonpermeable and they were located at a distance of triple thickness of permeable subsoil from the foundation downstream and as much as twelve-fold thickness at the upstream site. Such a considerable distancing of boundary Γ_A from the foundation was introduced to significantly reduce the effect of the assumed boundary condition on the solution.

The impact of specific storage on seepage flow was estimated. Assuming the value of S_s as for compacted sand ($S_s = 2·10^{-4}$ m^{-1}) and considering that a change in piezometric head during the 100 days of simulation over a considerable proportion of the area did not exceed 1 m, it was found that the share of the storage component in flow is slight (four orders of magnitude of the total seepage flow). For this reason equation (3) with the zero right-hand side was used in the calculations. We need to stress here the fact that similar values may be estimated for the computational experiment conducted by ZARADNY [1990] showing the effect of the S_s value on obtained results.

Calculations were performed for two soils in the subsoil, identical to those in a study by SKOLASIŃSKA [2006]. She prepared samples (A, B, C, D) from fluvioglacial sands occurring in the surroundings of Poznań. Soil A with seepage coefficient $k_1(0) = 2.67 \cdot 10^{-4}$ $m \cdot s^{-1}$ and soil D, for which $k_1(0) = 9.50 \cdot 10^{-5}$ $m \cdot s^{-1}$ where taken into account in this simulation. Thickness of the soil layer subjected to clogging was assumed to be 0.3 m in accordance with sample length in laboratory analyses. The author used a high concentration of the clogging material ($2\ g \cdot dm^{-3}$), which facilitated measurements to be taken within a relatively short time and yielded a dependence $k_1(M)$. In this study the assumed value was $20\ mg \cdot dm^{-3}$, i.e. the concentration of the clogging material one hundred times lower. It was also assumed that no bed sediment is observed. Measurements taken on lowland rivers justify the adoption of the indicated suspension concentration (e.g. KIEDRZYŃSKA, JÓŹWIK [2006]). In order to conduct calculations for clogging occurring over a longer period results recorded by SKOLASIŃSKA [2006] were extrapolated using polynomial and exponential functions for different segments of the branches to the value of clogging index $\alpha = k_1(0)/k_1(M)$ amounting to approx. 1600. Graphs for the function $k_1(M)$ used for soils A and D are presented in Fig. 2. In both figures, marked points are taken from experiment. Regression functions of each segments were matched using least squares method.

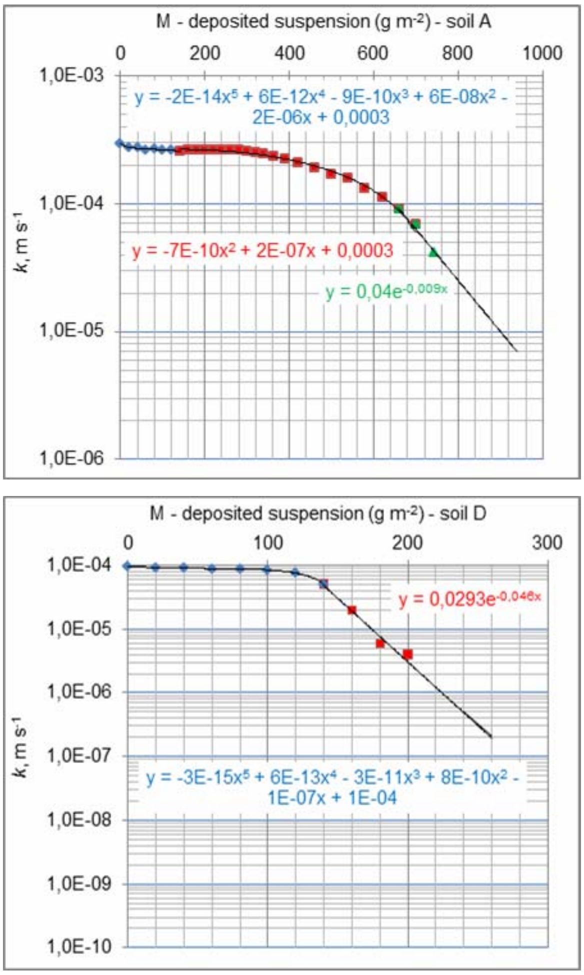

Fig. 2. Relation found between seepage coefficient k_1 and clogging clomatant mass M for soil A and D; source: own study based upon data obtained by SKOLASIŃSKA [2006]

RESULTS

Clogging at the upstream site obviously results in a reduction of total seepage discharge. Changes of this value in time are shown in Fig. 3. Seepage flow is reduced gradually. Within the initial 30 days for soil A and 10 days for soil D flow practically does not change. Only at a later phase it is gradually reduced. At the end of simulation (after 100 days) discharge still amounted to over 1/2 of the initial value. Moreover, changes in clogging index α (layer **I**) were analysed in Fig. 4. Origin of the coordinate system is identical with scheme on Fig. 1. The edge of the structure is located at x = 120 m. High values of this parameter were found only in the vicinity of the foundation.

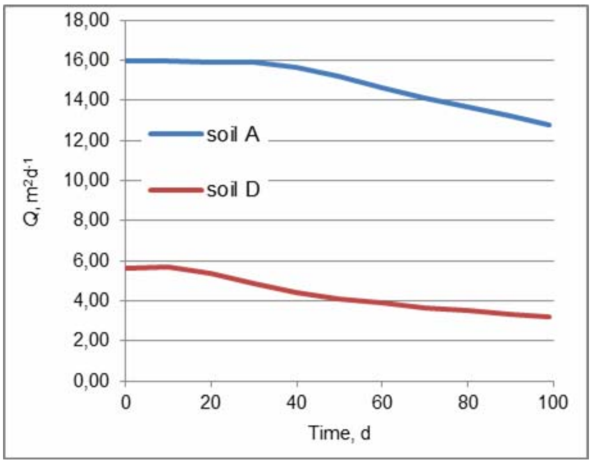

Fig. 3. Seepage flow; source: own study

Significant changes may be observed in the distributions of seepage velocity along soil surface on the upstream site and particular the changes in time (Figs. 5 and 6). Initially high velocities are recorded immediately at the structure and they decrease rapidly in the upstream direction away from the structure. Clogging causes a reduction of soil permeability in places where high seepage velocities are found, which drop rapidly as a result of clogging of layer I. A local extreme appears, which value decreases with time and away from the structure.

Changes are also observed in the distribution of piezometric heads in the area under the structure.

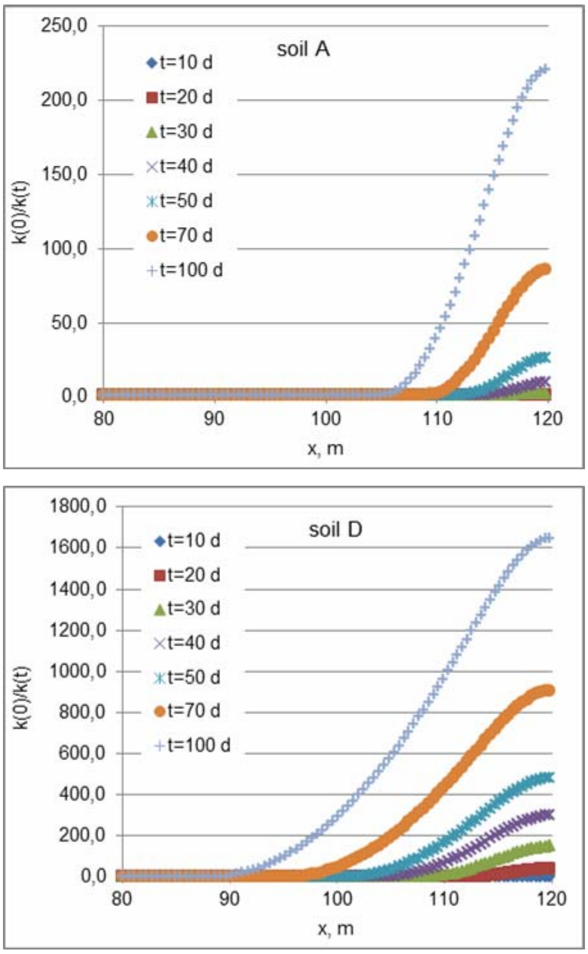

Fig. 4. Clogging index α (layer I) for soil A and D; source: own study

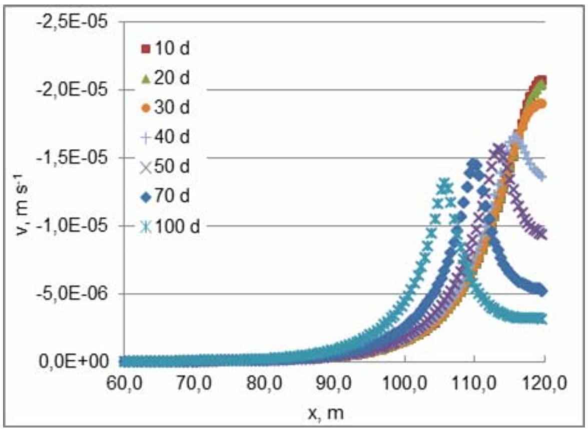

Fig. 5. Velocity distribution along the bottom of the channel on the upstream site (soil A); source: own study

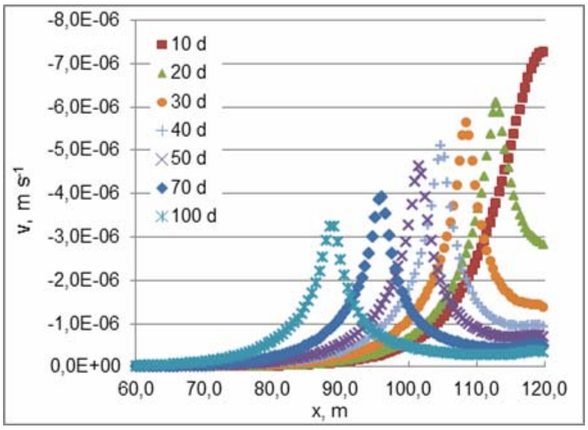

Fig. 6. Velocity distribution along the bottom of the channel on the upstream site (soil D); source: own study

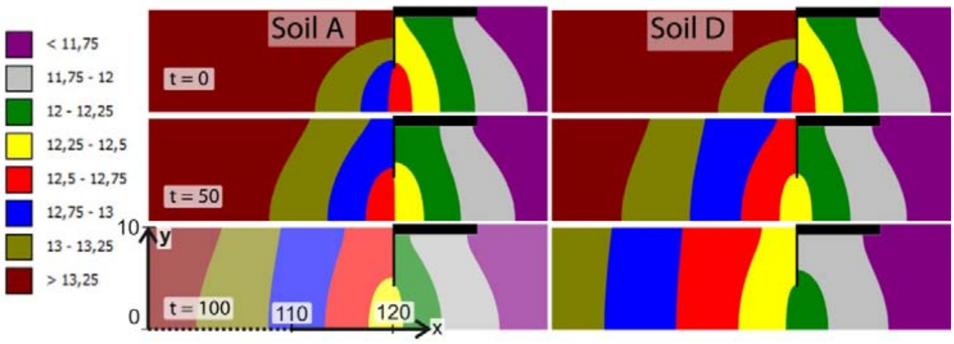

Fig. 7. Piezometric head distribution in layer **II** for $t = 0$, $t = 50$ d and $t = 100$ d; source: own study

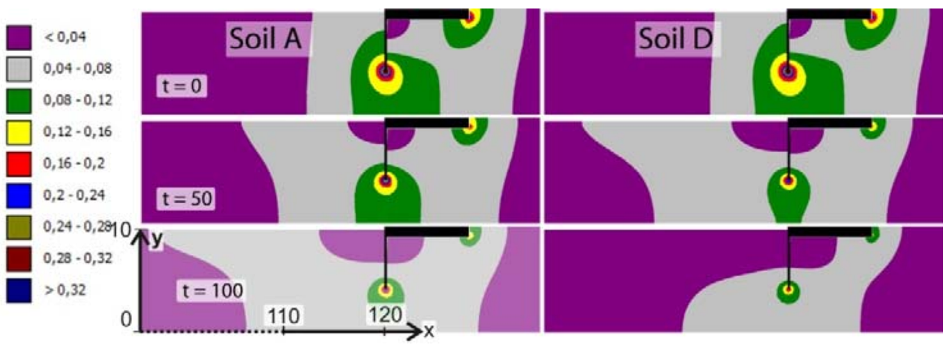

Fig. 8. Distribution of modulus of hydraulic gradient in layer II for $t = 0$, $t = 50$ d and $t = 100$ d; source: own study

With time an increasingly great portion of total pressure head is taken over by the clogged soil layer at the upstream site (layer I). Figure 7 presents distributions of piezometric heads for both soils (A and D) at the initial time point and after fifty and one hundred days of simulation. Piezometric head (function of two variables) was visualized as contour graph with constant interval (0.25 m) of isolines. Figure 8 presents the distribution of the modulus of hydraulic gradient for layer II. In the course of time (with an increase in clogging in layer I) zones of high gradient values decrease in vicinity of the sheet pile edge and immediately behind the foundation on the downstream site.

CONCLUDING REMARKS

Example calculations were performed for a typical hydraulic structure (weir) founded on a permeable layer of limited thickness. It was assumed that course of clogging is analogously as during laboratory analyses [SKOLASIŃSKA 2006]. The calculations may be treated as a kind of benchmark facilitating identification of these seepage parameters, on which the clogging process affected strongest. A solution of each practical problem will require laboratory clogging tests so that characteristics of both the soil and the suspension meet conditions observed in reality. Such tests would have to be conducted until clogging index α of at least 100 is obtained. It is difficult to obtain higher values of α (around 1000), due to the time required for the experiment. Extrapolation of the value of seepage coefficient for $\alpha > 100$ will be practically inevitable in the case of computer simulations covering longer duration periods of the phenomenon.

For the problem analysed in this study numerical calculations were conducted limiting simulations to 100 days. After that time (over three months) seepage discharge was found to decrease by 20% for soil A and 43% for soil D. In turn, the distribution of seepage velocity and hydraulic gradients changed highly significant. Results recorded for the analysed problem (benchmark) indicate a significant effect of clogging on seepage flow. Thus for real engineering problems, as far as it is feasible, analysis of seepage flow should also consider clogging at the upstream site.

The finite element method applied to construct the numerical model has been used for many years in the analysis of seepage problems. Conjugation with the solution of the initial problem describing the clogging process is simple and requires only a slight adaptation of existing software.

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Opis i zastosowanie pewnego modelu filtracji pod budowlą piętrzącą z uwzględnieniem kolmatacji mechanicznej

STRESZCZENIE

Słowa kluczowe: *budowla piętrząca, filtracja, kolmatacja, model numeryczny*

W artykule rozpatrywano filtrację pod budowlą piętrzącą (jazem) z uwzględnieniem kolmatacji mechanicznej na stanowisku górnym w warstwie o niewielkiej miąższości. Przyjęto, że przepływ można w niej traktować jako jednowymiarowy (na kierunku prostopadłym do warstwy), natomiast w pozostałym obszarze przepływ modelowano jako dwuwymiarowy. Rozwiązanie w obu strefach uzyskano w postaci dyskretnej z zastosowaniem metody elementów skończonych oraz metody Eulera. Wpływ warstwy kolmatacyjnej na przepływ filtracyjny modelowano poprzez warunek brzegowy trzeciego rodzaju. Parametry filtracyjne warstwy kolmatacyjnej oszacowano na podstawie laboratoryjnych badań przeprowadzonych przez SKOLASIŃSKĄ [2006]. Przyjęto zadania modelowe, dla których przeprowadzono symulacje przebiegu zjawiska. Uzyskane rezultaty świadczą, że kolmatacja na stanowisku górnym w istotny sposób wpływa na rozkład prędkości i gradientów hydraulicznych. Wydatek filtracyjny ulega zmniejszeniu wraz z upływem czasu, ale następuje to stosunkowo powoli.