The interaction of groundwater with permeable reactive barrier (PRB)

L'interaction des eaux souterraines avec des barrières réactives perméables (BRP)

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ABSTRACT

The paper is focused on interaction of groundwater regime with remediation method of permeable reactive barriers (PRB), which is used for treatment of contaminated groundwater. The main aim is to evaluate influence of PRB on the groundwater regime. The parametric study containing 51 numerical models of different shapes and dimensions of PRB were done. For these models the groundwater flow was computed by MODFLOW program. The backwater in front of PRB, decrease of groundwater level behind the PRB, flow rate through reactive gate, pore water velocity in gate and residential time in reactive medium were observed. These parameters were plot as dependence on parameters of PRB. The contaminant transport through PRB focused on correct remediation function was analysed too. In the last part of the paper innovation of PRB method is described.

RÉSUMÉ

Le document est axé sur l'interaction du régime des eaux souterraines avec la méthode d'assainissement de barrières réactives perméables (BRP), qui est utilisée pour le traitement des eaux souterraines contaminées. L'objectif principal est d'évaluer l'influence de BRP sur le régime des eaux souterraines. L'étude paramétrique contenant 51 modèles numériques de différentes formes et dimensions de BRP a été faite. Pour ces modèles, l'écoulement des eaux souterraines a été calculé par MODFLOW programme. Le courant réversible en face de BRP baisse le niveau des eaux souterraines derrière le BRP, vitesse d´écoulement a travers de la porte reactive, vitesse de l'eau dans les pores de la porte et son temps de résidence moyenne ont été observés. Ces paramètres ont été définis comme dépendants aux paramètres de BRP. Le transport de contaminants par le biais de BRP focalisé sur la fonction exacte d'assainissement a été analysé aussi. Dans la dernière partie l'innovation de la méthode de PRB est décrite.

Keywords :Permeable reactive barrier, PRB, groundwater flow, damming effect, contaminant transport

1 INTRODUCTION

One of the most important environmental problems of last decades is groundwater contamination, which poses significant ecological risks for human health and environment. Development of remediation methods rises with increasing number of contaminated sites in the world.

One of the innovative passive in-situ remediation methods is Permeable reactive barrier method. The principle of the PRB method is shown in figure 1.

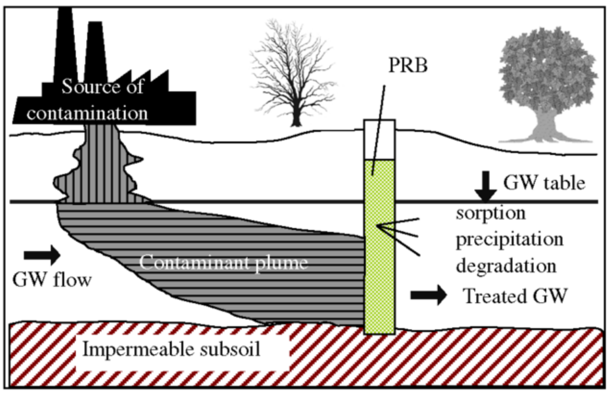


Figure 1. Principle of groundwater remediation by PRB method.

The PRB method is based on creating a vertical permeable wall (perpendicularly to the groundwater flow), which consists of suitable reactive material. The contaminated groundwater flows through the reactive media where treatment processes occur. The reactive materials either immobilise or transform (biologically or abiotically) the pollutants, such that the treated groundwater down hydraulic gradient of the PRB should not pose risk for water resources or other receptors.

Two basic configurations of PRB can be used (see figure 2):

- *Continuous wall* – allows the flow of the contaminant plume through the reactive wall in the whole width of the plume.
- *Funnel and gate system* – consists of impermeable walls which are embedded in the impermeable subsoil. The walls direct the contaminant plume to the permeable gate, which is filled with suitable reactive material and where the treatment reactions arise.

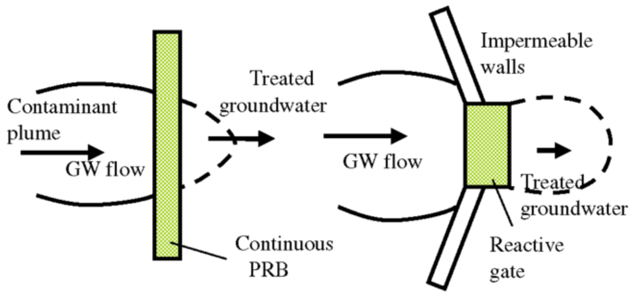


Figure 2. Two basic configurations of the permeable reactive barriers: a) continuous wall, b) funnel and gate system.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2473

2 MAIN PROBLEMS FROM GEOTECHNICAL POINT OF VIEW

2.1 *Influence on hydro-geologic regime*

An important question is how does the PRB affect groundwater flow regime in the aquifer. It might be significantly influenced by funnel and gate system. Impermeable walls dam groundwater flow, which causes groundwater level increase in front of PRB and groundwater level decrease behind PRB. See figure 3. Also increase of flow velocity at the PRB gate may cause shortening of contaminant's residential time in reactive medium.

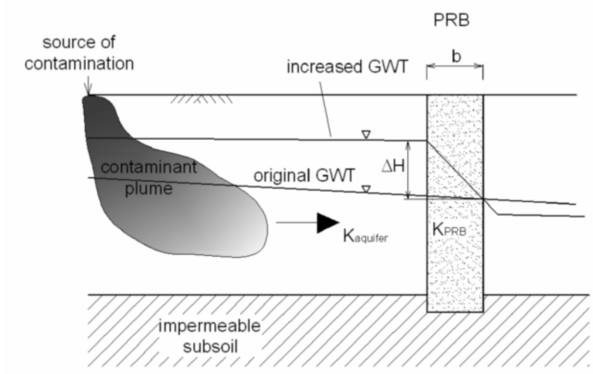


Figure 3. Damming effect of funnel and gate system of PRB.

Groundwater level can vary during the operation of PRB. Infiltration of rainfall or clogging of reactive material with decay products can lead to additional groundwater level increase.

Significant damming effect due to the PRB installation can represent substantial risk not only for environment but also for foundations of neighbouring structures. In extreme case the seepage of contaminated water on the ground level or root zone can occur. Structures could be loaded by uplift pressure on which they weren't originally designed. Other problems can be connected with insufficient waterproofing insulation against aggressive effects of contaminants.

Groundwater level decrease (e.g. behind PRB) can cause settlement of structures situated above.

2.2 *Design of reactive gate and impermeable walls dimensions*

An important condition of successful remediation is requirement that the whole contaminant plume flows through the reactive gate of specified thickness *b* with certain velocity *v*. That means that contaminant will be in contact with reactive medium in specified time t_{res} (residential time). It is important to design sufficient thickness of reactive gate.

The thickness of PRB wall can be estimated according to the following equation (Carey et al.2002):

$$b = v.t_{res}.SF \tag{1}$$

where *b* is thickness of reactive gate, *v* is groundwater velocity in the reactive media, t_{res} is required residence time and *SF is* safety factor.

Attention should also be paid to design of reactive gate width *B* and PRB shape (length of impermeable walls *L* and its connection angle α). In case of wrong PRB design huge damming effect can occur, which may cause contaminant plume bypass. In this case contaminant can flow around in transversal direction. See figure 4a.

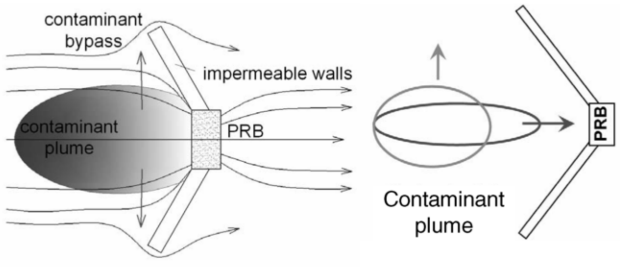


Figure 4 – a) Risk of contaminant plume bypass, b) Various contaminant plume spreading.

2.3 *Influence of spreading of contaminant plume on PRB function*

For optimal choice of reactive material it is necessary to know prediction of input contaminant concentration to the reactive gate. Therefore it is very important to predict contaminant plume spreading in term of time and space. The almost only possibility how to estimate contaminant plume spreading is creating numerical flow and transport model. Input concentration at the gate will be higher in case of narrow contaminant plume and contaminant plume will flow faster than in case of wider contaminant plume. See figure 4b.

3 PARAMETRIC STUDY OF PRB INFLUENCE ON GROUNDWATER REGIME

3.1 *Basic characteristics of models*

Modules of software GMS 6.0 were used for creating hydraulic numerical models. Program MODFLOW was used for groundwater flow's computing. Governing equation for 3D transient flow can be written according (McDonald & Harbaugh 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W = S_s\frac{\partial h}{\partial t}$$

)

This equation is valid on condition that: K_{xx}, K_{yy}, K_{zz} are hydraulic conductivities along axis, that axis of coordinates system are parallel with main axis of anisotropy x, y, z, *h* is hydraulic head, *W* is volumetric flux per unit volume, which represents sources and/or sinks of water, S_s is specific storage of porous material and *t* is time.

Geometry of the models was designed to correspond with real situation of area situated in fluvial sediments. Upper stratum is 2 m thick and it is made of silty made ground. Below this stratum there is a 10 m thick layer of permeable sandy gravel fluvial sediments. Impermeable stratum lies below aquifer in 12 m depth. Gradient of all strata is constant 1% in the *x*-axis direction. Basic geometry of models is shown in figure 5 and material properties are given in table 1.

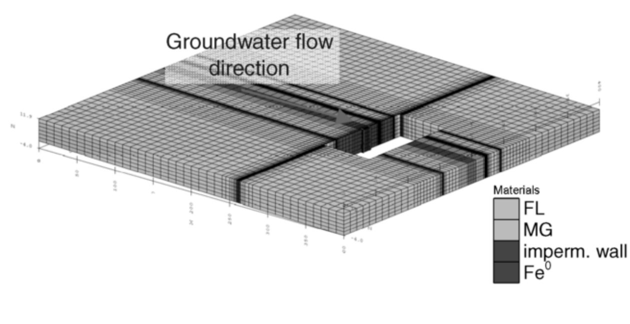


Figure 5. Basic geometry of models

Table 1. Basic material properties used in parametric study

Material	Characteristics	Value	Unit
MG	K_h – horizontal hydraulic conductivity	1.10^{-6}	$m.s^{-1}$
	K_x/K_y – horizontal anisotropy	1	-
	K_h/K_z – vertical anisotropy	1	-
	S_s – specific storage	1.10^{-6}	m^{-1}
	S_y – specific yield	0.18	-
	n – porosity	0.35	-
FL	K_h – horizontal hydraulic conductivity	1.10^{-4}	$m.s^{-1}$
	K_x/K_y – horizontal anisotropy	1	-
	K_h/K_z – vertical anisotropy	1	-
	S_s – specific storage	1.10^{-5}	m^{-1}
	S_y – specific yield	0.25	-
	n – porosity	0.3	-
Fe^0	K_h – horizontal hydraulic conductivity	5.10^{-4}	$m.s^{-1}$
	K_x/K_y – horizontal anisotropy	1	-
	K_h/K_z – vertical anisotropy	1	-
	S_s – specific storage	1.10^{-4}	m^{-1}
	S_y – specific yield	0.25	-
	n – porosity	0.3	-

All models had same plan dimensions 400 x 400 m and height 12 m. Impermeable walls of funnel were created by *HFB package* (Horizontal Flow Barrier package) and they were considered as an absolutely impermeable.

The following boundary and initial condition were set up: impermeable bottom and opposite sides faces of model e.g. $\partial h/dz=0$, $\partial h/dz=0$. The other faces in direction x have specified hydraulic head 9 and 5m, which ensure groundwater flow in direction x. Initial condition was set up by value 5 m of hydraulic head.

In MODFLOW program were in parametric study created 51 PRB models of different reactive gate widths *B* (10 m, 5 m, 2.5 m, 1.25 m) of different impermeable wall lengths *L* (40 m, 60 m, 80 m) and of different connection angles α (45°, 63.43°, 75.96°, 90°). The reactive gate thickness *b* was considered 2.5 m for all models. The scheme of used parameters is shown in figure 6.

For all models the groundwater flow was computed in MODFLOW program. The groundwater level increase in front of PRB and groundwater level decrease behind the PRB, flow rate by reactive gate, pore water velocity in gate and residential time in reactive medium were observed (Jirásko 2008). These parameters were analysed and plot as dependence on parameters of PRB.

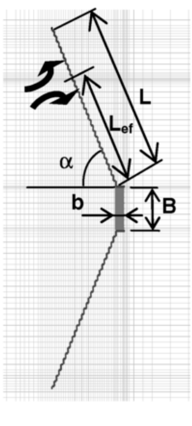


Figure 6. Scheme of used parameters in parametric study

The basic four shapes of modelled PRB (mA1, mB1, mC1 and mD1) with computed and plotted hydraulic heads are shown in figure 7. Figure 8 shows example of vertical cross section by centre of reactive gate and by place of maximum groundwater level increase for model mA15.

mA1

mB1

mC1

mD1

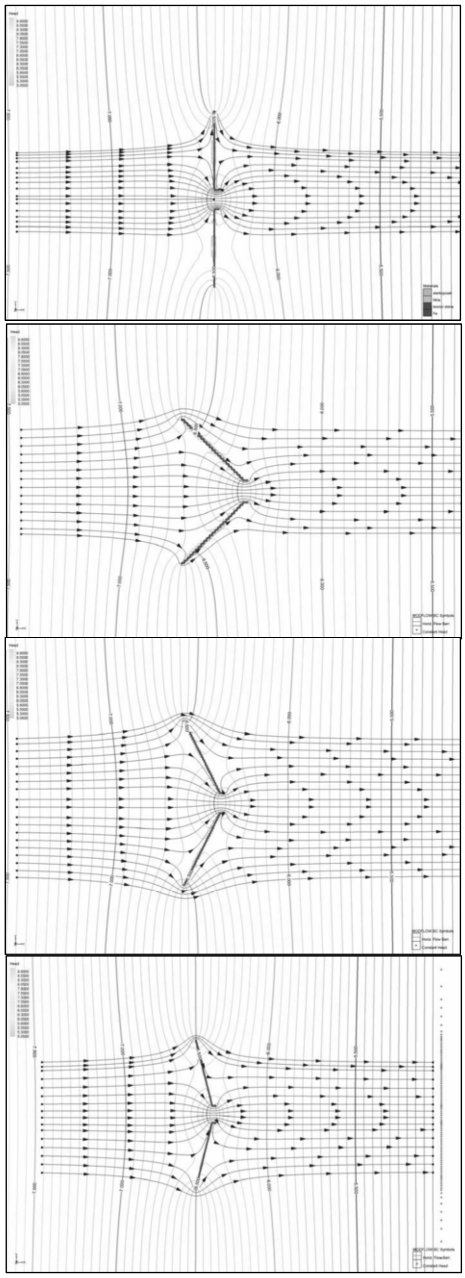


Figure 7. Contours of hydraulic head in plan view – models mA1, mB1, mC1 and mD1.

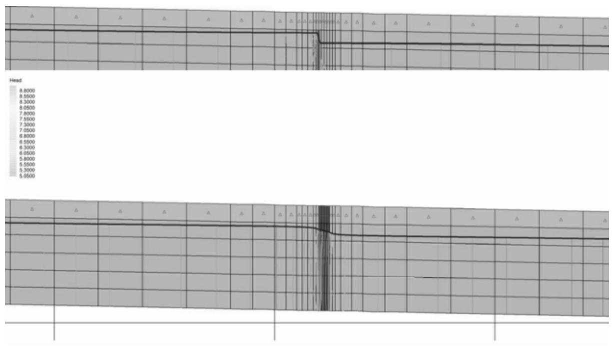


Figure 8. Vertical cross sections of centre of reactive gate and of place of maximum groundwater level increase – model mA15

3.2 *Parametric study evaluation*

Maximum groundwater level increase in front of PRB (in case of original hydraulic gradient 1%) is in the order of tens of centimetres. It depends on reactive gate width and impermeable walls length. In most of the cases the damming effect will probably not pose a significant problem. The maximum groundwater level increase is 0.65 m (for model mA15: α=45°, B= 1.25 m, L=80 m).

The damming effect behaviour is shown in figure 9 as a dependence on reactive gate width for various impermeable wall lengths. Generally speaking, damming effect increases with decreasing gate width and increasing impermeable walls lengths. For lower angles α the lower damming effect occurs. The lower groundwater level increase is for low angles α.

Hydraulic conductivity of aquifer does not affect the damming effect in front of PRB.

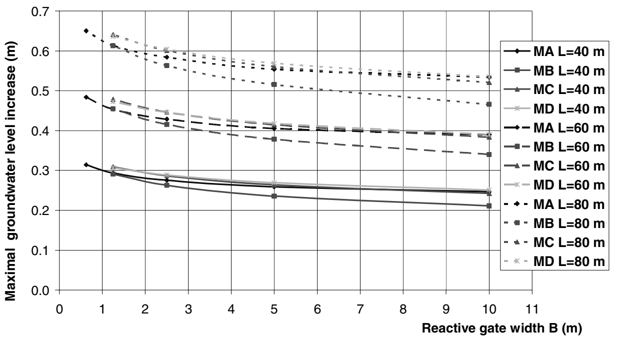


Figure 9. Behaviour of groundwater increase plotted as a dependence on reactive gate width for different impermeable wall lengths.

Figure 10 implies that impermeable walls connection angle does not significantly affect the groundwater level increase in front of PRB. The differences are in the order of units of centimetres. For larger gate widths (e.g. B=10 m) maximum groundwater level increases for angles α=75° - 90°. For smaller gate widths (B=1.25 m) maximum groundwater level increases for angles approximately α=65°.

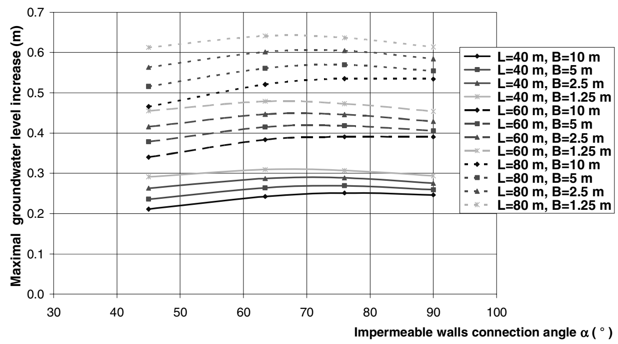


Figure 10. Behaviour of groundwater increase plotted as a dependence on connection angle of impermeable walls for different gate widths and impermeable walls lengths.

Pore water velocity in reactive gate is in inverse proportion to flow surface and impermeable wall length. Behaviour of pore water velocity in reactive gate as a dependence on gate width is shown in figure 11. For large gate width (e.g.10 m) pore water velocities are approximately 1 m.d^{-1}. This is valid for all models regardless of impermeable wall length and connection angle α.

For smaller gate widths, (e.g. 1.25 m) pore water velocities differ significantly in range from 3.7 m.d^{-1} (model with α=45° L=40 m) to 8.4 m.d^{-1} (model with α=90° L=80 m).

Dependence of pore water velocity v_p on gate width B can be well described by function in general form $v_p = c_1 B^{c2}$, where c_1, c_2 are constants.

Specific value of pore water velocity (or residential time) for PRB can be reached by various ways (by various combinations of gate widths and impermeable wall lengths).

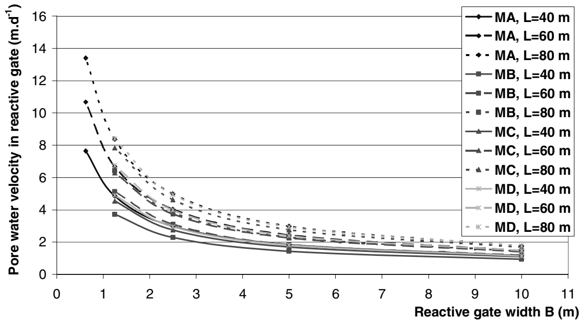


Figure 11. Behaviour of pore water velocity plotted as a dependence on reactive gate width for different impermeable wall lengths.

Another observed parameter was residential time of contaminant in reactive gate for gate thickness 2.5 m. See figure 12. Residential time is in direct proportion to gate width. The largest residential time is for PRB of small angles α and lengths *L*. Values of residential time for parametric study models are in the range of 4 - 58.7 hours.

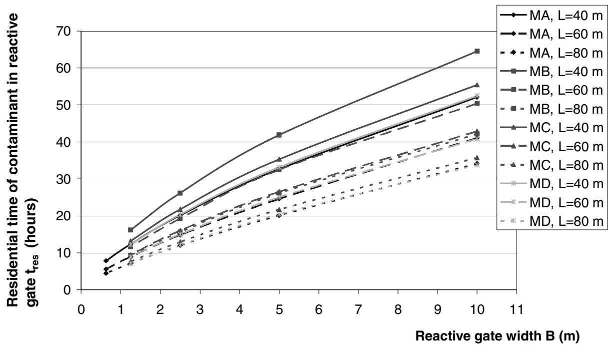


Figure 12. Behaviour of residential time plotted as a dependence on reactive gate width for different impermeable wall lengths.

4 CONTAMINANT TRANSPORT MODELING IN PRB

Contaminant transport modelling in PRB for various hydraulic conductivities of aquifer is based on results of previous hydraulic simulations. Contaminant transport was modelled in program MT3DMS, which is part of software GMS 6.0.

Governing equation of 3D transient contaminant transport in porous material is defined (Zheng & Wang 1999):

$$\frac{\partial (nC^k)}{\partial t} = \frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial C^k}{\partial x_j}\right) - \frac{\partial}{\partial x_i}\left(nv_p C^k\right) + q_s C_s^k + \sum R_n \qquad (3)$$

where: n is porosity, C^k is dissolved concentration of species k, t is time, D_{ij} hydrodynamic dispersion coefficient tensor, v_p is pore water velocity, q_s is volumetric flow rate per unit volume of aquifer representing fluid sources and sinks, C_s^k is concentration of the source or sink flux for species k, ΣR_n is chemical reaction term.

4.1 *Basic characteristics of models*

The geometry of model mB7 (α=45°, *L*= 60 m, *b*=2.5 m *B*=2.5 m) was chosen for simulation. Gradient, strata, and boundary conditions were assumed based on parametric study. Advection, dispersion, diffusion, and chemical degradation processes were taking in account. Sorption was not assumed. Dispersivity differs in relation to problem scale. Value of longitudinal dispersivity α_L was considered according to Yeh (1992) as 0.1 x model scale. For 50 m distance between contamination source and reactive gate, longitudinal dispersivity 5 m was used. Transversal horizontal and transversal vertical dispersivity was considered as 1/3 of longitudinal dispersivity value.

The trichlorethen TCE (C_2HCL_3) contaminant was considered. TCE is often used in chemical cleaners and engineering plants and it is often present in contaminated subsoil. Removal of TCE using zero valent iron Fe^0 seems to be a good solution. The degradation occurs according to first order decay. First order decay coefficient for TCE and zero valent iron λ=16.72 d^{-1} was simplifiedly adopted from Elizabeth City site in North Carolina – (EPA 1999). Diffusion coefficient of TCE is $1.01.10^{-5}$ $cm^2.s^{-1}$ – EPA (1999)

Starting TCE concentration C_0=1000 $mg.l^{-1}$ was put 50 m from reactive gate in depth 4 - 6 m on the area 6.25 x 6.25 m as shown in figure 13.

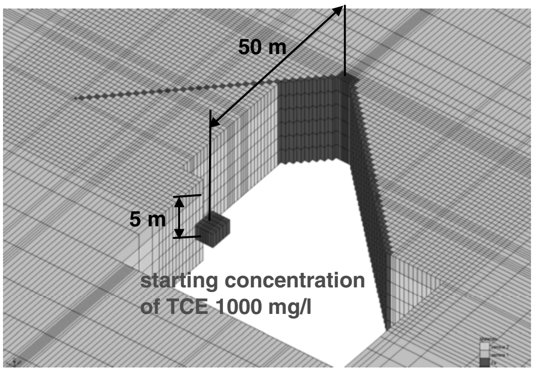


Figure 13. Scheme of transport model.

4.2 *Contaminant transport modelling results*

Contaminant transport simulations were run for various values of hydraulic conductivity K=1.10^{-4}, 1.10^{-5}, 1.10^{-6} $m.s^{-1}$. Time behaviour of contaminant plume spreading in cells was observed in front and behind of reactive gate and at the ends of impermeable wall. Total time needed for remediation was observed too. As a limit target TCE concentration 0.05 $mg.l^{-1}$ was considered, which corresponds with criterion C of methodical directions from 1996 - "Criteria of contaminated soil and groundwater" by Ministry of Environment of the Czech Republic. Observed parameters are given in table 2.

Table 2. Contaminant transport modelling results

model	hydraulic conductivity ($m.s^{-1}$)	remediation time (years)	max. concentration in front of PRB ($mg.l^{-1}$)	max. concentration behind PRB($mg.l^{-1}$)	max. concentration at the end of impermeable wall($mg.l^{-1}$)	flow rate by reactive gate ($m^3.d^{-1}$)	pore water velocity v_p($m.d^{-1}$)	residential time t_{res}=b.v_p(hours)	correct PRB function
mK1	1.10^{-4}	2.24	0.81	**0.114**	0.024	21.2	3.28	18	**N**
mK2	1.10^{-5}	21.5	0.32	0.0018	0.025	2.21	0.32	185	**Y**
mK3	1.10^{-6}	>200	0,38	$1.23.10^{-5}$	0.024	0.2	0.03	1841	**Y**

The whole contaminant plume flowed through the reactive gate for all models. The limit target concentration TCE 0.05 mg/l was not reached at the end of impermeable walls and it was exceeded only in the model of high hydraulic conductivity mK1 behind the reactive gate. Modelling proved an evident influence of dispersion represented by dispersivities not only on contaminant spreading - in longitudinal and transversal direction - but also on PRB function.

High dispersion in combination with high pore water velocities in gate in specific time period causes exceeding of concentration on the output from reactive gate. This is valid although the required reactive gate thickness is fulfilled according to equation 1. See figures 14 and 15.

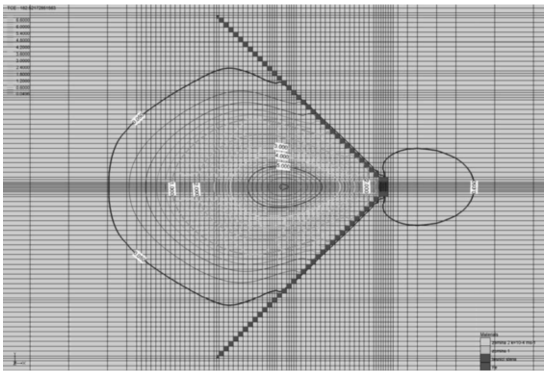


Figure 14. Contours of TCE concentration in time 0.5 year - plan view of the model mK1 (K=10^{-4} $m.s^{-1}$).

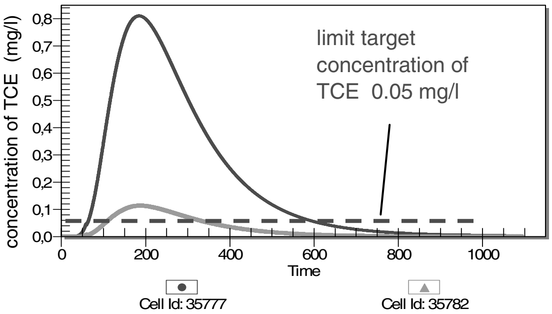


Figure 15. Behaviour of TCE concentration in time at input to the reactive gate and output from the reactive gate - model mK1 (K=1.10^{-4} $m.s^{-1}$).

Common requirement for reactive gate thickness according to equation 1 is not accurate for high pore water velocities and dispersivities because it only includes advection but no dispersion. More suitable seems to be reactive advection-dispersive analytical model for one dimensional transport described (Van Genuchten & Alves 1982):

$$\frac{C}{C_0} = \exp\left[\left(\frac{b}{2\alpha_L v_p}\right)\left(v_p - \sqrt{v_p^2 + 4\lambda\alpha_L v_p}\right)\right] \qquad (4)$$

where C is concentration of contaminant in reactive gate output, C_0 is concentration of contaminant in reactive gate input, b is reactive gate thickness, α_L is longitudinal dispersivity, λ is first order decay coefficient and v_p is pore water velocity.

Boundary conditions are $C(0)=C0$, $dC/dx(\infty)=0$. The reactive gate thickness can be derived from equation 4:

$$b = 2\alpha_L v_p \ln\left(\frac{C}{C_0}\right)\frac{1}{\left(v_p - \sqrt{v_p^2 + 4\lambda\alpha_L v_p}\right)} \qquad (5)$$

5 PROPOSED INNOVATION FOR PRB METHOD

From contaminant concentration time behaviour it is evident that input concentration at the reactive gate significantly differs in operation time. Therefore it would be useful to regulate degradation processes according to actual requirements.

The proposed innovation is based on principle of two or more regulable damming plates that would be installed inside the permeable reactive gate. See figure 16. The regulation of remediation processes (flow rate, residential time) can be simply provided by various positions of damming plates. More damming plates of various heights arranged in series may be used for the regulation. From Technical point of view it is possible to use in situ implementation (e.g. sheet piles) or off site structure (e.g. vessel).

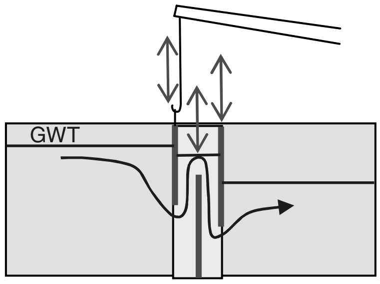


Figure 16. Principle of remediation processes regulation by regulable PRB.

The following text describes a model application of regulable PRB with three damming plates. Parameters of the hydraulic model were based on previous simulations of parametric study in GMS 6.0 and calculation ran in MODFLOW.

Three damming plates were created by HFB package. From the ground surface two impermeable boundary plates of constant height 7 m were installed. The centre regulable damming plate was embedded into the impermeable subsoil and its height has been gradually changed. Flow rate was observed. Tracking particles representing the residential time in reactive gate were set up in program MODPATH. Figure 17 shows six selected phases of central damming plate. Blue lines are paths of tracking particles and arrows are their positions after each day of residential time in reactive gate. Results are displayed in graph in figure 18.

The results show that thanks to the damming plates it is possible to effectively change the requested residential time and flow rate in the gate. Flow rate decrease may, however, prolong the time of remediation.

6 CONCLUSIONS

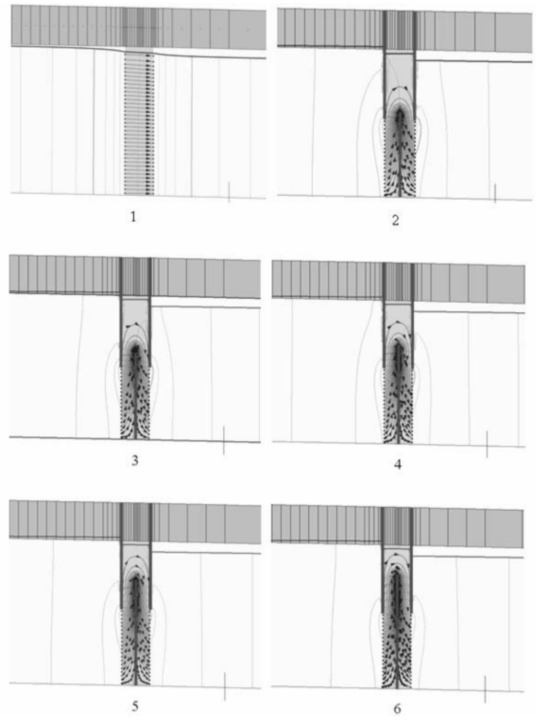
PRB installation (especially funnel and gate system) can affect hydro-geologic regime in the aquifer. Influenced groundwater poses a risk for surrounding structures and environment. Change of groundwater flow regime influences function of PRB as well. Therefore it is necessary to access all parameters mentioned in chapter 3. For this access numerical modelling should be used. Main parameters that should be observed are groundwater increase and decrease, flow velocity, flow direction and residential time in reactive gate.

Numerical modelling in specific cases proved significant influence of dispersion on remediation process in reactive gate. The dispersivity should be included in reactive gate thickness equation.

Time variability of contaminant's concentration entering the PBR raises a demand for remediation processes regulation. This demand may be satisfied by regulated PBR, which may be a suitable option especially for cases with a large time interval of the input concentration variation as well as for the contaminants with long half-life.

ACKNOWLEDGEMENT

This research was supported by Ministry of Education of the Czech Republic - Sustainable construction (MSM 6840770005)



.Figure 17. Modelled phases of regulable PRB

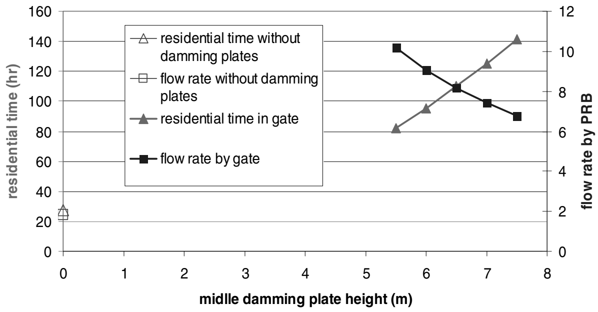


Figure 18. Results of modelled regulable PRB.

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