ESTIMATION OF RECOVERY TIME AND SELF-FLUSHING OUTSIDE AND INSIDE THE WELL SCREEN

ODHAD DOBY REGENERACE A VYUŽITÍ PŘIROZENÉHO GRADIENTU VNĚ A UVNITŘ ZÁRUBNICE

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Abstract

With respect to the detailed survey of underground water contamination, a question arises about the effect of the monitoring well equipment on the representativeness of the underground water samples. The well screen is one of the key well parts. The active and passive sampling in this part of the well has an influence on the contaminant stratification or redistribution. Should we take the original sample, one of the possibilities, according to the author, is to observe the so-called regeneration time. This experiment aspired to determine how great was the actual influence of the well screen and what time delay should be kept after inserting or handling with the sampling equipment. For these purposes, a physical model of the flow medium was built with a well screen mounted. A series of tracing experiments at changing parameters of the porous medium hydraulic conductivity and well screen perforation served to measure the time decrease in the NaCl tracer concentration inside the well screen. The measured data were approximated analytically using the so-called dilution method; the flow speed inside the well screen was obtained as a function of the perforation and hydraulic conductivity of the medium. Furthermore, the so-called drainage effect of the well was taken into account, as it is also influenced by the well screen. It is value was compared with the analytical and numerical solution. The Visual Modflow software was used for numerical modelling, which enabled modelling of the designed equipment and verification of the basic flow parameters of the model. For the given conditions, the drainage effect α = 2,1 was set as a basic value at which the well screen induces zero resistance at approx. 4 % perforation. From the obtained functional relations, coefficients for conversion between the investigated parameters were derived and the tracer delay time inside the well screen. was qualified.. The second stage was the evaluation of the extent to which a change in the natural state failure will manifest itself outside the well screen by inserting sampling equipment. The derived radius of the affected zone around the well screen, which is a function of the volume of water displaced by hydrostatic pressure and the surrounding material porosity, helped to establish the time in which the failure state recovers theoretically. This resulted in the total regeneration time t_C as a total of the time in minutes inside and outside the well screen. The paper aims to point to this time parameter, its suitability and possible approach to the determination in place. This is not, however, a valid value or calculation, but experimental data obtained at a narrow-band hydraulic conductivity and gradient, by interpolation and in ideal laboratory conditions. The regeneration time obtained in this way can only be recommended as a rough estimate.

Abstrakt

S ohledem na detailní průzkum kontaminace podzemních vod vyvstává otázka vlivu výstroje monitorovacích vrtů na reprezentativnost vzorků podzemní vody. Jednou z klíčových částí vrtu je zárubnice. Aktivní i pasivní vzorkování v této části vrtu má vliv na stratifikaci či přerozdělení kontaminantu. Pokud máme odebrat původní vzorek, pak jednou z možností je dle autora dodržení tzv. doby regenerace. Jak velký vliv má právě zárubnice a jaké časové prodlevy po vložení či manipulaci se vzorkovacím zařízením dodržet, bylo snahou dokázat v tomto experimentu. Pro tyto účely byl postaven fyzikální model proudového prostředí s instalovanou zárubnicí. Sérií stopovacích pokusů při měněných parametrech hydraulické vodivosti porézního média a perforace zárubnice byl měřen úbytek koncentrace stopovače NaCl v čase uvnitř zárubnice. Naměřená data byla aproximována analytickým řešením pomocí tzv. zřeďovací metody a získána rychlost proudění uvnitř zárubnice jako funkce perforace a hydraulické vodivosti média. Dále byl zohledněn tzv. drenážní účinek vrtu, který je zárubnicí také ovlivněn. Jeho velikost byla porovnána s analytickým a numerickým řešením. Pro numerické modelování byl použit software Visual Modflow, jehož pomocí bylo namodelováno zkonstruované zařízení a ověřeny základní proudové parametry modelu. Pro dané podmínky byl stanoven drenážní účinek α = 2,1 jako základní hodnota, kdy zárubnice klade nulový odpor při cca 4 % perforaci. Ze získaných funkčních závislostí

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byly odvozeny převodní koeficienty mezi zkoumanými parametry a vyjádřen čas zdržení stopovače uvnitř zárubnice. Druhým krokem bylo posouzení, jak daleko se projeví změna porušení přirozeného stavu mimo zárubnici vložením vzorkovacího zařízení. Pomocí odvozeného poloměru zasažené zóny kolem zárubnice, který je funkcí hydrostaticky vytlačeného objemu vody a pórovitosti okolního materiálu byla stanovena doba, za kterou se porušený stav teoreticky znovu obnoví. Výsledkem je pak celková doba regenerace t_C jako součet doby vně a uvnitř zárubnice v minutách. Snahou článku je poukázat na tento časový parametr, jeho vhodnost a případný přístup k budoucímu stanovení in situ. Nejedná se zde však o platnou veličinu či výpočet, nýbrž o experimentální data získaná při úzkém oboru hydraulické vodivosti a gradientu, získaná interpolací a v ideálních laboratorních podmínkách. Takto získanou dobu regenerace lze doporučit pouze jako hrubý odhad.

Key words: Glass tank model, well screen, capture zone, numerical modelling, dilution test, packer, regeneration time, drainage effect of screen

1 INTRODUCTION

In connection with the growing building trend, the negative influences and intervention of man in the environment undoubtedly rapidly grow as well. One of the affected environments is also the potential foundation soil which naturally involves groundwater as well. Geotechnics involves the effort to gain detailed data on the behaviour and condition of groundwater in the preliminary research stages, within the construction as well as during monitoring. However, even the best laboratory cannot provide us with adequate data on groundwater, including hydraulic properties of foundation soil, unless the samples taken do not correspond to the given state of the foundation soil. Similarly, even ten laboratory tests of hydraulic properties cannot supersede a single test well. Thus the provision of representative groundwater samples for any purposes seems to be crucial for further applications, which is closely connected with groundwater sampling and a correct design of sampling wells. One of the reasons may be non-observance of sufficient time intervals between handling the samplers or pumps inside the well screen and the actual sampling. These time intervals (regeneration time or recovery of the original stratification), are the core subject of this paper.

1.1 Problem development and state of solution

The problem of monitoring well equipment is still topical as well as the development of these wells, represented by such firms as the American SOLINST or Flute, whose results underwent numerous tests [4]. A significant work in this branch was then a series of field tests at Danish and German localities in 1995, and the comparison of equipment types with a strong emphasis on the well screen and its location [11]. The attempt at summarizing the methods and wells with view to vertical zoning of the samples and well screen location can be found in [9]. The need of representative samples with view to their vertical layout is also noticed and recommended in [15]. Most works, however, are only concerned with the well screen location, not considering its perforation and drainage effect, such as [2]. The nature of "contaminant" inlet into the well screen by means of a physical model is dealt with in a very interested work [1], whose author already uses a tracing substance, namely Rhodamine WT. The successive tracer dispersion in the well screen and its gradual decrement is then monitored by photogrammetry. Then [13] is a crucial work directly dealing with the measurement of decrease in the Br-tracer concentration in the well screen of current wells by means of the so-called dilution method. This was already developed about 40 years ago [6]. The employment of tracer decrement in the well screen was and still is used by the so-called one-well method [10] to find the direction and speed of groundwater flow [8] and drainage effect of the well [7]. Until now, at least according to the author, the well screen perforation (given in percents) and its influence on the tracer delay have not yet been explored in detail. Therefore, the below described experiment could, at least partly, contribute to the present and future state of solution,.

2 STRUCTURAL ELEMENTS OF MONITORING WELL EQUIPMENT

Structural element may be described as the monitoring well part necessary for its correct function. These elements differ according to the monitoring type. Generally, the monitoring well equipment is composed of:

- Well screen
- Filtration packing
- Casing
- Casing head assembly
- Mud pan or pate

- Distance rings - centralizers
- Packing bridges

Well screen

This is the perforated part of the casing. It constitutes the active part of the well, which enables the inflow of groundwater into the well with minimum losses; at the same time, it must not form an increased drainage to prevent suffusion effects in the well vicinity. Particularly, the well screen perforation must be designed correctly so that it does not create an additional resistance together with the filtration packing and also does not drain all surrounding water. Its value, experimentally determined in (23), is a function of several factors, the most important of them being primarily the well drainage effect α [-] [6] and hydraulic conductivity of the surrounding material k [m.s^{-1}]. The perforation value p [%] is determined here as:

$$p = \frac{P_p}{0{,}01 P_z} \qquad (1)$$

where P_p [m^2] is the perforation area and P_z [m^2] is the well screen area. So this relationship has a universal use since it does not depend on the well screen length. Perforation types are another point of view. Briefly, they can be divided into [12]:

- Circular perforation

  inconvenient due to the larger area P_p necessary, resulting in penetration of bigger particles compared with the slot perforation
- Slot perforation

  most widely used; once milled, nowadays stamped sheets or plastics. A special design made of wound triangular wire was launched by the Johnson firm, especially for collection wells.
- Flame-cut perforation – an example of unsuitable perforation and a bad well design; difficult implementation

In terms of the material, the well screen must be strong enough and resistant to any corrosion and dissolution. The most common types of the material used are PVC, HDPE, silicon, Teflon®. Less often, ceramics and steel owing to their high purchase prices; historically, wood, concrete and asbestos-cement.

3 MODELLING PROCEDURE AND METHODOLOGY

Laboratory modelling was amply used for the regeneration time determination. After a careful preparation, the experimental equipment was assembled in conformity with all given criteria. The main criterion for the model was as close simulation of groundwater flow as possible and its best possible design with view to the best accurate determination of hydraulic parameters. To eliminate negative anisotropic effects during natural flow of groundwater, an inert glass fraction was selected and situated in the parallel layers and packing around the well screen maquette.

The modelling aimed to ascertain and subsequently find certain interdependence between the well screen perforation percentage, hydraulic conductivity of the surrounding material and time delay of the tracing substance inside and outside the well screen. This time is a crucial parameter for groundwater sampling. It this time can be estimated by the equipment type and surrounding environment parameters, time intervals between individual samplings can be planned more effectively, e.g., in case of sampling equipment repairs and its reinsertion into the well. This time may still be extended owing to the partial displacement of stagnant water from the well into its surrounding, which is also considered here.

3.1 Model design

The model represents a homogenous isotropic environment with two parallel layers of different hydraulic conductivity and the same thickness. The model is filled with three grain fractions made of ballottini. The first fraction, 0,35÷0,47 mm, was used as the model top layer. The second fraction, 0,5÷0,8 mm, formed the lower, more pervious layer. The third and last fraction, 1÷1,5 mm, was used as the packing material of the suffusion factor 5 and a predetermined well screen mesh size. The water inlet and outlet were provided by equalization tanks (Fig. 1), separated from the active model part by polycarbonate partitions. Their tightness was ensured by three-plate peripheral packing. The model body is made of glass panes of 5 mm thickness, stuck together with water-tight silicon joints. Tap water was selected as the flowing liquid despite certain disadvantages, such as an enhanced content of air holes or increased background ion concentration. The foremost reason was the need of constant inflow of fresh water not containing the injected tracer. The water supply pressure and accurate throttle valves were used to control the inlet and outlet.

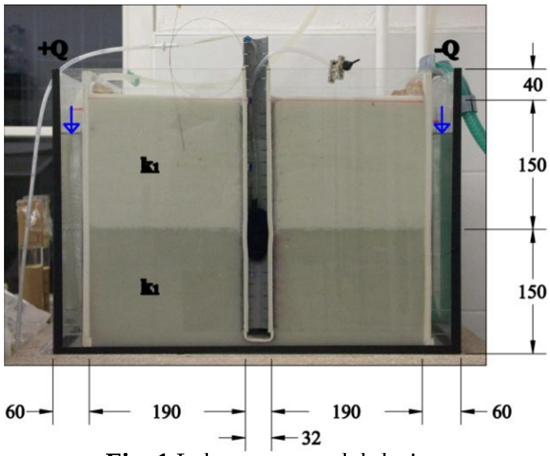

Fig. 1 Laboratory model design

To prevent occurrence of substantial vertical hydraulic gradient inside the well screens, the individual layers were tightly separated from each other by a rubber packer maquette. The gradient formed after this measure was then only a function of the packing overflow value.

After testing the perforation – hydraulic conductivity ratio for the flow speed inside the well screen, three maquettes with three different perforations were made in total (Fig. 2).

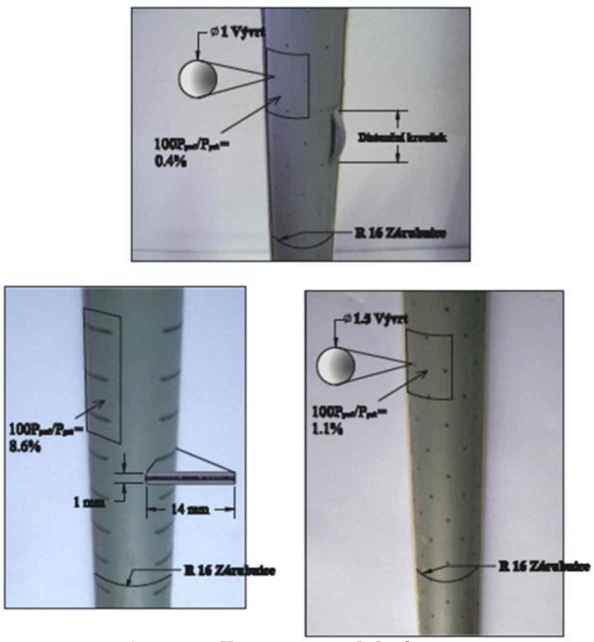

Fig. 2 Well screen models from PVC

The well screens were always provided with packing against the penetration of the surrounding fine-grained fraction. Advisedly, they were located so that the tracing substance motion could be monitored inside the well screen and simultaneously the flow pattern would not be disturbed, e.g. due to untightness. For the tracer, fluorescein disodium salt (pitchblend) was selected for its light green colour and fluorescent properties (flow pattern determination) as well as NaCl solution for its preserving properties (measuring flow speed in the well screen). The tracer was injected by means of a silicon capillary Ø 0,15 mm. Similarly, this capillary was used for sampling (Fig. 3). After the model assembly, its active part could be filled with water. The filling had always to be done very slowly so that as much air as possible could escape from the porous medium and the pores could be saturated utmost. After a few pilot tests, a systematic survey of the basic hydraulic parameters of the model started.

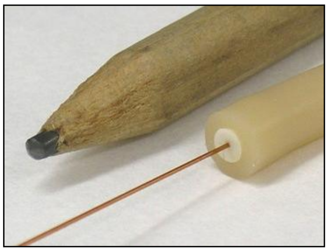

Fig. 3 Silicon capillary

3.2 Determination of basic hydraulic parameters of the laboratory model

Porosity *n* of both layers was determined as a basic characteristic. According to the theory of globular particle arrangement, very similar porosity could be expected in both layers as the individual grains are very close to globular shape. The value of 0,476 corresponds to cubical grain arrangement; the value for octahedric arrangement is 0,259. An empiric value of 0.399 was proved for a random arrangement of globular grains of approximately the same diameter. For both layers, the porosity value was determined as follows:

$$n = \frac{V_p}{V} \qquad (2)$$

where V_p [m^3] is the volume of pores and V [m^3] is the total sample volume. The volume of pores was determined on very precise scales by measuring the weight of a precise volume of charge before, m [kg], and after, m_{sat} [kg], the maximum saturation of charge pores with water, therefore:

$$V_p = \frac{(m_{sat} - m)}{\rho_w} \qquad (3)$$

The value was set at 0,395 for the upper layer, 0,385 for the lower one and 0,405 for the packing material. Another basic parameter is the hydraulic conductivity k [m.s^{-1}]. Its value for both layers was determined in a series of experiments at variable hydraulic gradient with simultaneous measurement of the actual flow speed v_s [m.s^{-1}] by means of the tracer (Fig. 4) and measurement of specific flow q_s [m^2.s^{-1}].

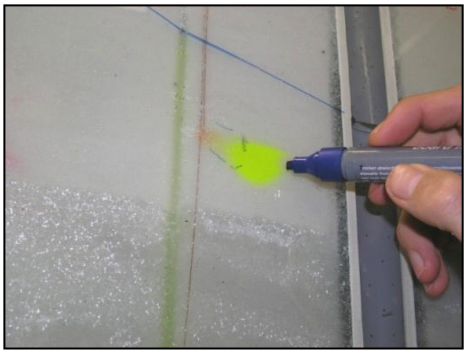

Fig. 4 Measuring the travel-time relationship

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The mean spot speed of flow was determined as:

$$v_s = \frac{\Delta l}{\Delta t} \tag{4}$$

where Δl [m] and Δt [s] is the travel distance of the injected spot centre per a time unit. For the purpose of check and comparison, the mean flow speed was also determined as:

$$\overline{v_s} = \frac{1}{T}\int_0^T v_s\,dt \tag{5}$$

where T [s] is the total observation time. Then, the hydraulic conductivity of individual layers could be determined as:

$$k = -v_S\, n \frac{\Delta x}{\Delta h} \tag{6}$$

where $\Delta h/\Delta x$ [m.m^{-1}] is the hydraulic gradient along the axis x. The hydraulic conductivity of the packing fraction was determined according to Kozena – Carmen Bear as:

$$k = \frac{d^2 n^3 \rho_w g}{180\mu (1-n)^2} \tag{7}$$

where d [m] is the grain diameter, ρ_w [kg.m^{-3}] is water density, so the value equals to k = 1,51.10^{-2} m.s^{-1}. Longitudinal and vertical dispersivity α_x, α_z [m] were set as the additional measurement by a modified relationship [5]:

$$\alpha = \frac{\sigma^2}{2v_s t} - D_e \tag{8}$$

where σ [m] is the injected spot variance from the centre per time t [s]. Diffusion is waived in this case. The dispersivity obtained was also compared with the empiric value by Xu and Eckstein, get by the formula [5]:

$$\alpha_x = 0{,}83(\log l_x)^{2{,}414} \tag{9}$$

where l_x [m] is the migration length. However, the values resulting from this relationship differ substantially from the measured laboratory data because the relationship based on regression of field results obtained by observing the migration is much higher than in case of the model.

The obtained values of hydraulic conductivity of individual layers were subsequently confronted with the geometric analysis of refraction of flowlines at the boundary of both layers (Fig. 5). Pressure and hydraulic height are continuous functions at this boundary, so the hydraulic gradient along the boundary is the same in both layers. So, it is valid that:

$$\alpha_1 = arctg\left(\frac{tg\alpha_2 v_{S1}}{v_{S2}}\right) \tag{10}$$

therefore

$$tg\alpha_1 k_2 = tg\alpha_2 k_1 \tag{11}$$

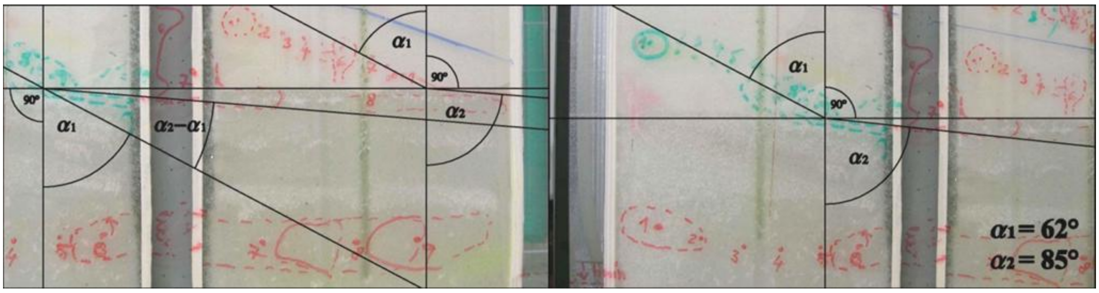

Fig. 5 Determination of flowline refractions from the normal

After substitution and modification (11), the angle tangent ratio equals to 0,165 and the hydraulic conductivities ratio to 0,161. So the obtained values of hydraulic conductivities correspond to the refraction very well.

The last verification of basic hydraulic parameters was the finding of an analytical solution of specific flow q_s [m^2.s^{-1}] per 1 bm in the model by means of Dupuit postulates.

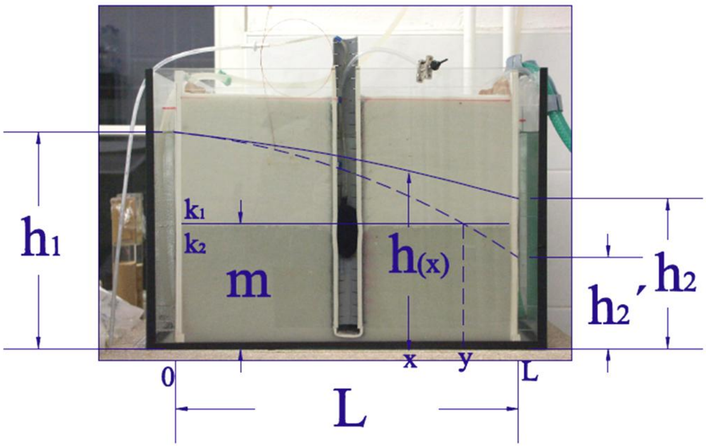

Fig. 6 Analytical flow solution

The results were converted to the real width of the model and compared with the measured flows at the given hydraulic gradients. Different specific flows q_1 and q_2 [$m^2.s^{-1}$] were expected in the upper and lower layer. Their sum should be equal to the measured values at the given model width. The solution (Fig. 6) is based on the approximation of free surface and does not consider the existence of affluent-seepage area or capillary fringe [14]. The analytical solution assumes that:

$$q_2 = \int_0^m v_x dz = \int_0^m \left(-k_2 \frac{dh}{dx}\right) dz \qquad (12) \qquad\qquad q_1 = \int_m^{h(x)} v_x dz = \int_m^{h(x)} \left(-k_1 \frac{dh}{dx}\right) dz \qquad (13)$$

and, after substitution of edge conditions, $x = 0, h = h_1$ *a* $x = L, h = h_2$, subsequent integration [14] and conversion to the model width B [m], the following relationship was set:

$$Q = B(q_1 + q_2) = B\left[\frac{k_1(h_1 - h_2)}{2L}\left(h_1 + h_2 - 2m + 2m\frac{k_2}{k_1}\right)\right] \qquad (14)$$

where Q [$m^3.s^{-1}$] is the theoretic flow value. In one case, however, the free surface intersected the lower layer owing to a high hydraulic gradient. Therefore, this relationship had to be modified, including new edge conditions ($x = 0, h = h_1$ *a* $x = y$, $h = m$) and ($x = y, h = m$ *a* $x = L\text{-}y, h = h_2'$) (Fig. 6). Solution of two equations in two unknowns resulted in the relationship:

$$Q = B(q_1 + q_2) = B\left[\frac{k_2 m}{L}(h_1 - m) + \frac{k_1}{2L}(h_1 - m)^2 + \frac{k_2}{2L}(m^2 - h_2'^2)\right] \qquad (15)$$

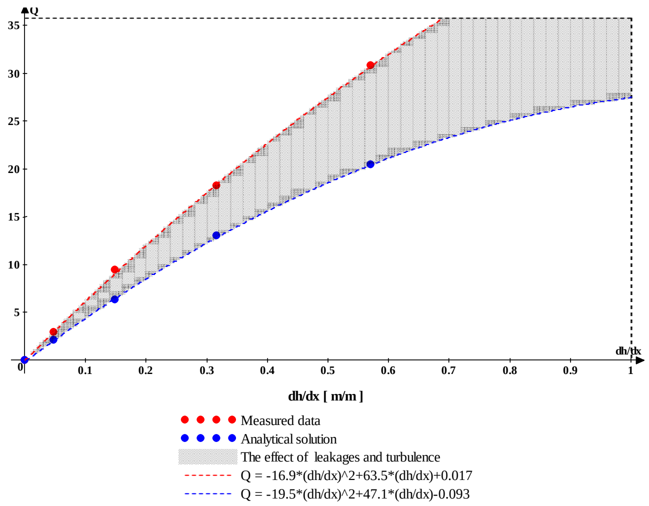

Fig. 7 Experimental and analytical flow solution

Comparing of the experimental and analytical solution (Fig. 7) reveals a great difference between values with increasing gradient. The difference is minimum for low gradient values close to 0. The differences are not caused by wrong determination of basic hydraulic parameters; but they are due to both the influence of simplified Dupuit solution of surface shape (omission of the effluent-seepage area) and possible slight leakage along the packing partitions and the subsequent turbulent flow. Therefore, all other experiments were executed right in the area of minimum deviation from the analytical solution.

3.3 Verification of selected parameters by means of numerical modelling

Numerical modelling was done by means of the Visual Modflow Pro software with the 3D extension. A conceptual model was created (Fig. 8), fully corresponding to the experimental equipment (Fig. 6) including all parameters. The calculation was done at standing mode of flowing with free surface and standard edge conditions. The well screen was also modelled by the Wall function as well as the sealing balloon by means of the impermeable boundary. The method of MOC characteristics was selected as the solver; the Choleski method produced the same results.

Basic model parameters:

- Dimensions : 0,415 m x 0,255 m x 0,34 m
- Cell number : 100 x 50 x 6 (r, c, l)
- Hydraulic gradient : 0,048 m.m-1
- Hydraulic conductivity of upper layer : 1,68.10-4 m.s-1
- Hydraulic conductivity of lower layer : 1,01.10-3 m.s-1
- Hydraulic conductivity of packing : 1,51.10-2 m.s-1
- Porosity of upper layer : 0,395 m3.m-3
- Porosity of lower layer : 0,385 m3.m-3
- Porosity of packing : 0,4 m3.m-3
- Anisotropic coefficient : 1
- Well screen diameter : 0,032 m

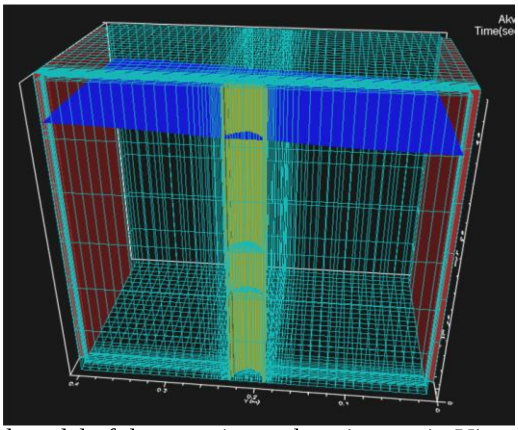

Fig. 8 Conceptual model of the experimental equipment in Visual Modflow (no scale)

After the conceptual model was assembled (Fig. 8), the obtained flow speeds were compared in both modelled layers and the well screen.

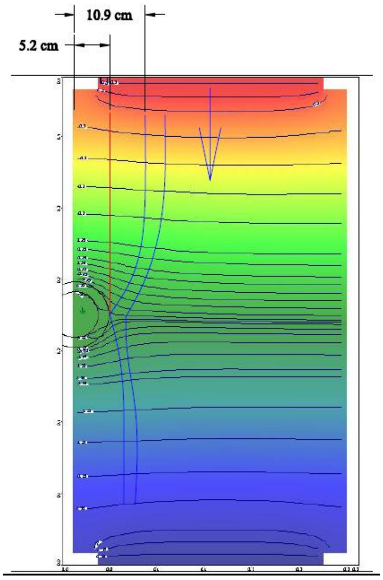

Fig. 9 Drainage effect of the well screen with packing in ground plan (no scale)

At the same time, the well drainage size α [2] was verified in the upper, less permeable layer on condition that:

$$k_1 > k_2 > k_3 \wedge r_1 \neq r_2 \qquad (16)$$

where k_1, k_2, k_3 [m.s^{-1}] are hydraulic conductivities of the well screen, packing, surrounding environment; r_1 and r_2 [m] are the internal and external well screen diameters. Under these conditions, the well drainage effect has the value of $\alpha = 2$ [5]. The condition was verified after drawing the flow pattern by means of the PMPATH sub-processor (Fig. 9).

The well drainage effect value was determined as:

$$\alpha = \frac{B}{2r} = \frac{10,9}{5,2} \qquad (17)$$

therefore, α = 2,1, which satisfies the given conditions. The model speeds were always 1,2÷1,5 times lower than the experimental data, which is also a very good coincidence.

3.4 Experimental determination of regeneration time inside the well screen

The regeneration time means the time interval between the failure of natural state inside and outside the well screen by an external influence and its recovery. The external influence means, for example, handling the sampling equipment inside the well equipment. The laboratory measurements were done by means of the combined ion selective Cl^- electrode – type CL 800, manufacturer WTW (Wissenschafltlich-Technische Werkstätten GmbH). The sampling was executed by means of the abovementioned silicon capillary (Fig. 3), specifically in the amount of 1 ml ± 0,5 ml. This amount was satisfactory if a sufficiently small measuring cell was used. The electrode accuracy was checked by calibration (Fig. 10).

Concentrated solution of NaCl was used as the tracing substance, injected inside the well screen by means of the capillary. The injection was executed uniformly from the lower parts in the upward direction. The tracer concentration was selected with respect to the well screen volume and detection capacity of the electrode, specifically about 60 ppm of Cl^- per the amount of approx. 20 ml. Shortly after the injection, the time t_0 and concentration C_0 were determined. The sample was always sucked with the capillary from at least two points in order to eliminate the differences in density and temperature along the well screen height as much as possible, but without exceeding the sample amount of 1,5 ml. The measured values were then converted to relative concentration Cl^- and plotted in dependence on the time of their collection.

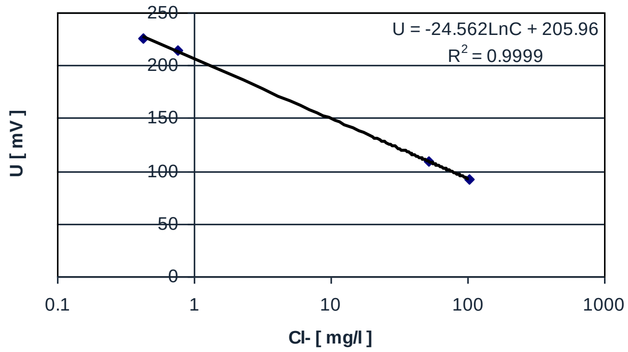

Fig. 10 Four-point calibration WTW CL800 Kombi

The next step involved determination of the change of flow speed and regeneration time inside the well screen in relation to the perforation and hydraulic conductivity of the surrounding material. For these purposes, the “Tracer dilution method” was applied. Its application was published in [2] and, according to the International Atomic Energy Agency, it became a world-recognized method of establishing the amount and direction of water flow in the well; thus, it is also applicable in hydrogeology, geotechnics and engineering practice in general. Its principle consists in measuring the decrease in the tracer concentration in time. The following relation holds for it:

$$\frac{C}{C_0} = e^{\frac{-v_v A (t - t_0)}{V}} \qquad (18)$$

where C/C_0 [-] is the relative concentration in the time span $t–t_0$ [s]; v_v [m.s^{-1}] is the flow speed inside the well screen; V [m^3] is the volume of the monitored part of the well screen; and A [m^2] is the well screen sectional area perpendicular to the flow direction.

The relative sample concentrations obtained were plotted in graphs and interwoven with the analytical solution (blue curves). The interpolation was done numerically by means of the Advanced Grapher 2.11 program. The below graphs (Fig. 11) clearly show the dispersion influence represented by the area D_z. Its presence had always to be eliminated graphically, although a certain time delay was observed between the NaCl tracer injection and the first sampling. Negative influence of the vertical flow was also evident as a result of the flow in the filtration packing, although both well screen parts were separated tightly. The convection stream inside the well screen also had its effect, causing an evident stepping of the measured values despite the fact that every sample was an average of collections at two well screen points. Each graph also contains a type curve indicating the flow speed in the well screen at zero resistance, i.e. the value of α = 2,1 (red curves). To eliminate the negative influences as much as possible, regeneration times were deducted (Fig. 11, black arrows) and the obtained flow speeds inside the well screens were plotted in relation to time and perforation percentage (Fig. 12).

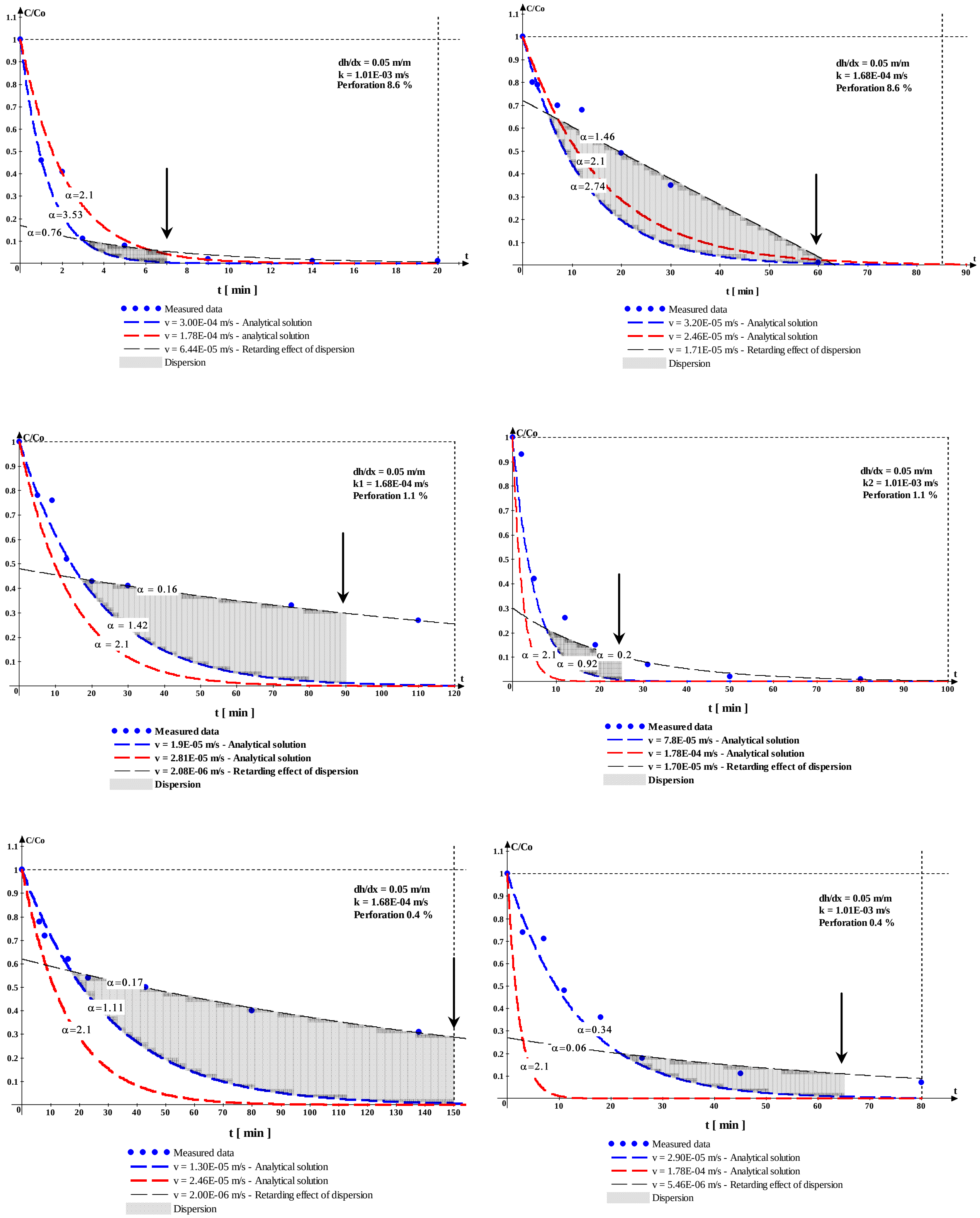

Fig. 11 Measured and analytical solution of the tracer decrement

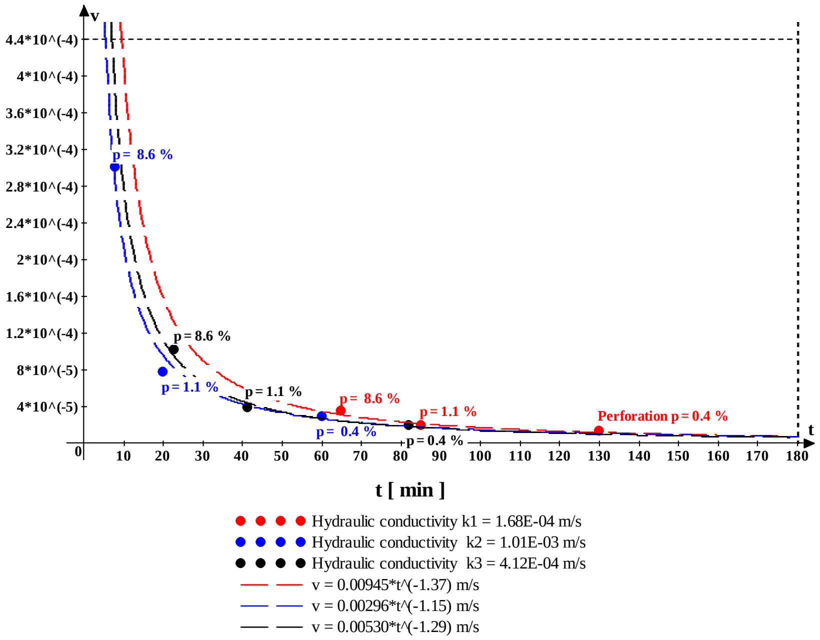

Fig. 12 Relationship of regeneration time to speed and perforation

The graph (Fig. 12) clearly shows not only the influence of hydraulic conductivity, but above all the substantial reduction of regeneration time if higher perforation percentage is used. To be able to determine a certain relationship at this number of unknowns, the third value of hydraulic conductivity and regeneration time had to be interpolated by means of the geometrical mean (black curve). Next, the regeneration time – perforation relationship was established (Fig. 13) as well as the relationship of relative drainage effect of the well α/α_0 [-] to the perforation (Fig. 14). Hydraulic conductivity was always the third variable.

The relative resistance value R [-] is either positive (well screen offers resistance) or negative (well screen offers no resistance), theoretically (+∞, -∞). So it can be recorded as follows:

$$\operatorname{sgn} R \in 1 - \frac{\alpha}{\alpha_0} \tag{19}$$

where α [-] is the drainage effect of the well, or well screen, at the given perforation, and α_0 [-] is the drainage effect at R = 0; therefore, α_0 = 2,1 (17).

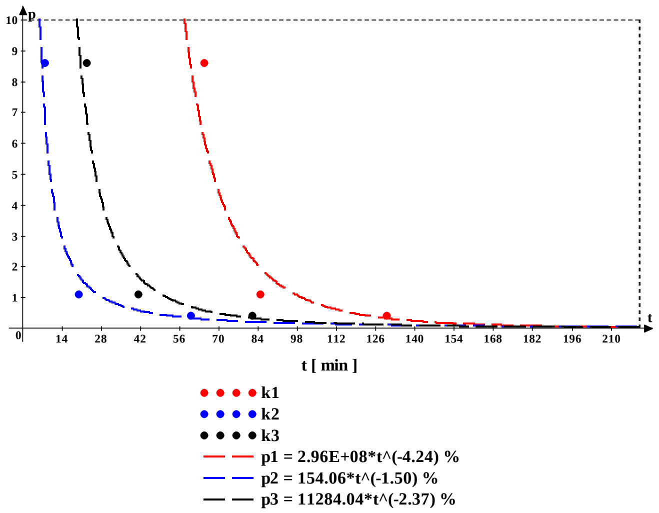

Fig. 13 Regeneration time – perforation relationship

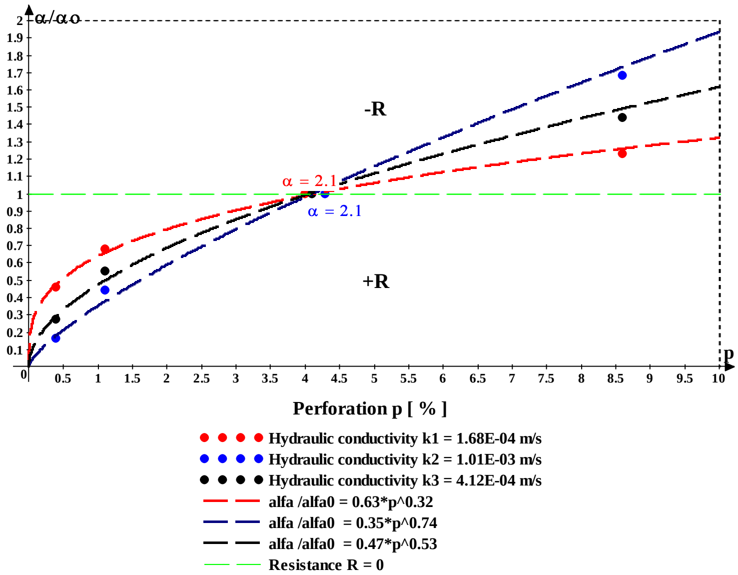

Fig. 14 Drainage effect – perforation relationship

The real value of the well drainage effect α was always determined for the given speed and perforation directly, because it holds that [6]:

$$v_v = \alpha v_f + (v_Z + v_H + v_T + v_D) \tag{20}$$

where the term in brackets represents components of the vertical flow speed, density flow of the tracer, disproportionately high artificial mixing of the volume measured and the diffusion speed component. These negative effects were either eliminated or neglected.

To be able to express explicitly the relationship of two equations in three unknowns, certain conversion coefficients had to be set, which enabled the entry (Fig. 15 and 16). Their values were tabulated for general values of hydraulic conductivity and are based on designing the regression of individual coefficients *a*, *b* of the above functions. Their explicit expression (21 and 22) is adapted for easier application and substitution of other than the tabulated values.

$$a_\alpha = \left(\frac{411}{10^7 k}\right)^{\frac{20}{61}} \qquad b_\alpha = \left(\frac{237k}{500}\right)^{\frac{4023}{200}} \tag{21}$$

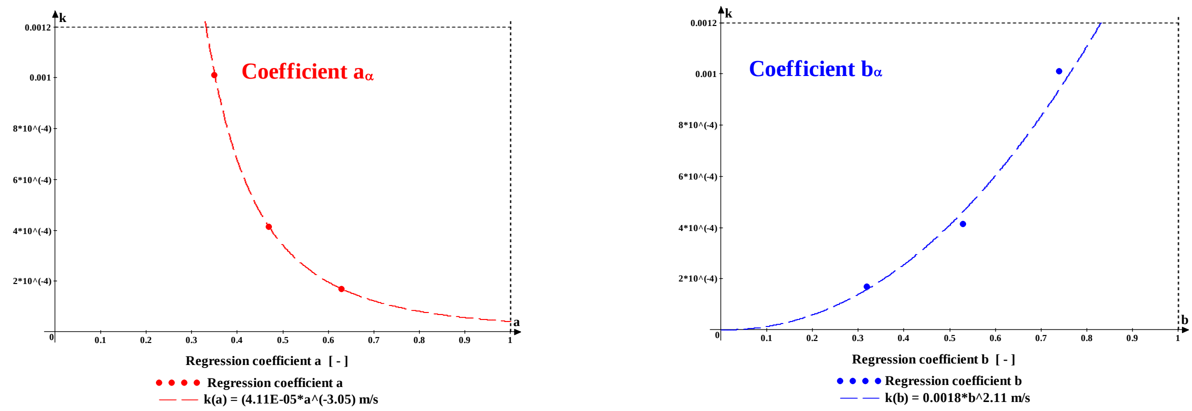

Fig. 15 Regression coefficients a_α, b_α

$$a_t = \left(\frac{1}{625k}\right)^{\frac{25}{3}} \qquad b_t = -\frac{19795}{10^7 k + 3439} \tag{22}$$

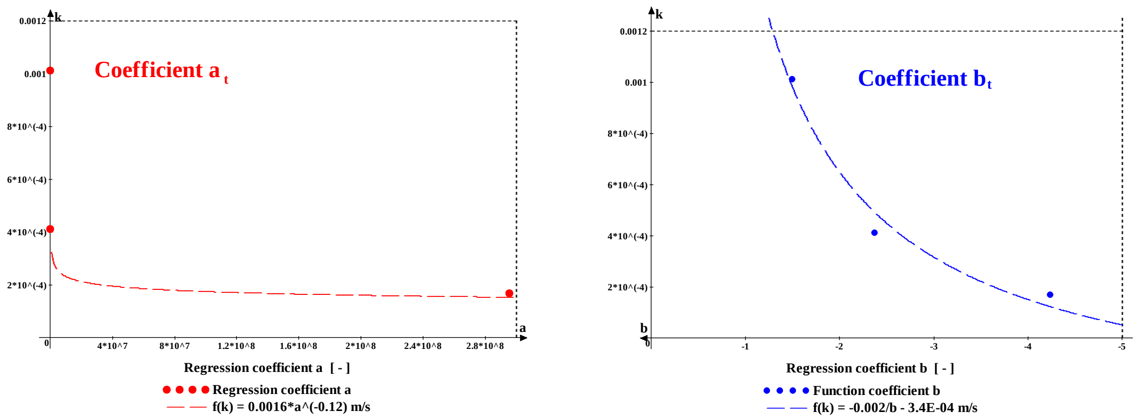

Fig. 16 Regression coefficients a_t, b_t

where k [m.s^{-1}] is the hydraulic conductivity of the environment.

Then it was possible to enter the relationship of the corresponding minimum perforation to the drainage effect of the well and the hydraulic conductivity (Fig. 14), (21) as follows:

$$p_{\min} = \left(\frac{\alpha_{1,2}}{\alpha_0 a_\alpha}\right)^{\frac{1}{b_\alpha}} \qquad (23)$$

where α_0 is the general well drainage effect at zero resistance (17) and $\alpha_{1,2}$ is the well drainage effect related to the perforation and hydraulic conductivity.

Its value may well be established without any measurement by means of the Ogilvie formula [5] for wells without packing:

$$\alpha_1 = \frac{4}{\left\{\left[1+\left(\frac{r_1}{r_2}\right)^2\right] + \frac{k_2}{k_1}\left[1-\left(\frac{r_1}{r_2}\right)^2\right]\right\}} \qquad (24)$$

where r_1, r_2 [m] are the internal and external radius of the well screen and k_2, k_1 [m.s^{-1}] is the hydraulic conductivity of the environment and the well screen. Then, for wells with packing, the most accurate determination formula at present is [5]:

$$\alpha_2 = \frac{8}{\left(1+\frac{k_3}{k_2}\right)\left\{1+\left(\frac{r_1}{r_2}\right)^2 + \frac{k_2}{k_1}\left[1-\left(\frac{r_1}{r_2}\right)^2\right]\right\}} + \frac{8}{\left(1-\frac{k_3}{k_2}\right)\left\{1+\left(\frac{r_1}{r_3}\right)^2 + \left(\frac{r_2}{r_3}\right)^2 + \frac{k_2}{k_1}\left[\left(\frac{r_1}{r_3}\right)^2 - \left(\frac{r_2}{r_3}\right)^2\right]\right\}} \qquad (25)$$

where r_3 [m] is the well radius; k_2, k_1 a k_3 [m.s^{-1}] is the hydraulic conductivity of the environment, well screen and packing. The last step was expressing the regeneration time relationship to the perforation resulting from the relationship (23). Additionally, the relationship is modified with the comparative value of hydraulic gradient, since, according to the relationship (20), the flow speed in the well increases linearly with the filtration speed and accordingly with the hydraulic gradient as well. The comparative value established was the real value of the hydraulic gradient in x and z directions, as against the constant value at which the experiments were executed, which is approximately 0,05 m.m^{-1}. After modification and substitution of (22) and (23), the relationship for time t [min] inside the well screen was obtained in the form of:

$$t = \frac{1}{20}\left(\frac{p_{\min}}{a_t}\right)^{\frac{1}{b_t}}\left[\left(\frac{\Delta h}{\Delta x}\right)^2 + \left(\frac{\Delta h}{\Delta z}\right)^2\right]^{-\frac{1}{2}} \qquad (26)$$

where $\Delta h/\Delta x$ and $\Delta h/\Delta z$ [m.m^{-1}] are the horizontal and vertical hydraulic gradient.

3.5 Derivation of regeneration time outside the well screen

The reasoning is based on determination of the affected zone radius thanks to the partial displacement of stagnant water from the well screen to the environment and its backflow through the internal diameter of the well screen down in the natural gradient direction. The necessary total time t_C was considered. Illustratively, sampling by means of packers is given here, but the procedure can be generalized for other equipment as well. Let us start from the initial sketch (Fig. 17).

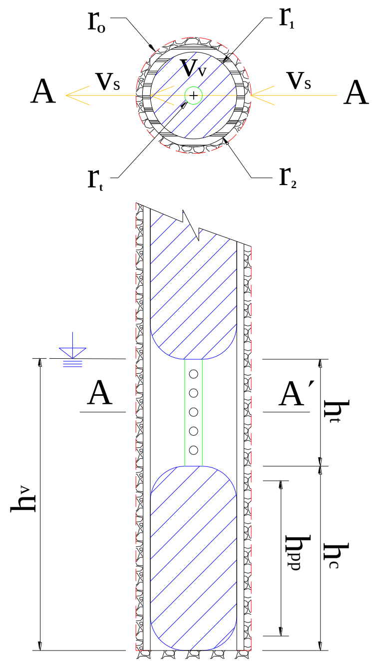

Fig. 17 Initial sketch for derivation (no scale)

In the first step, all the internal equipment had to be converted to the internal radius r_1 of the well screen, in which the correct heights of the equipment are obtained. Since the sealing packer us not an ideal cylinder, his end parts were replaced here with spherical surfaces, in which way the correct height was obtained by a simple modification:

$$h_{pp} = h_c - \frac{2}{3} r_1 \tag{27}$$

Next came the calculation of connecting rods, or other rotary equipment, by another simple modification to the reduced height:

$$h_{tt} = h_t \left(\frac{r_t}{r_1} \right)^2 \tag{28}$$

and, in case of a square section, where $A = a.b$

$$h_{tt} = \frac{h_t A}{\pi r_1^2} \tag{29}$$

The total height of the internal well equipment reduced to the internal diameter of the well screen equals to:

$$h_p = \sum h_{pp} + \sum h_{tt} \tag{30}$$

and after substituting (27) and (30):

$$h_p = \frac{3h_c r_1^2 - 2r_1^3 + 3h_t r_t^2}{3r_1^2} \tag{31}$$

The second step involved determination of the distance into which the volume of stagnant water will be hydrostatically displaced by the volume of the sampling equipment (Fig. 17). It was assumed that the water would uniformly spread along the well screen height h_z. Then it must hold that:

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$$V_p = n(V_O - V_z) \tag{32}$$

where V_p, V_o and V_z [m^3] are the volumes of the sampling equipment, affected zone and well screen; n is the porosity. After the modification it can be written that:

$$\pi r_1^2 h_p = n \pi h_Z (r_O^2 - r_1^2) \tag{33}$$

where h_z [m] is the well screen height; and by the expression

$$r_O = r_1 \sqrt{\left(\frac{h_p}{h_z n} + 1\right)} \tag{34}$$

we obtain the affected zone volume.

The third step was determination of the time in which the displaced water must be regenerated. The total time t_C equals to the time spent outside the well screen and the time inside it. Therefore, the water must cover the path $s = 2r_o$, along which it will move in this total time:

$$t_C = t + 2\frac{(r_O - r_2)}{v_S} \tag{35}$$

3.6 Determination of the total regeneration time

Now, the regeneration times inside and outside the well screen are defined. However, before establishing the total regeneration time t_C, it was necessary to set the limits of validity of the minimum sum height of the internal well equipment. If it is valid that:

then it is valid that:

$$h_p < h_{p\min} \tag{36}$$

$$t_C = t \tag{37}$$

and the total regeneration time will correspond only to the experimental value from the relationship (26). If the relationship (35) should be valid, the maximum sum height h_p must be higher that the minimum value. So it must be satisfied that:

$$\sqrt{r_1^2\left(\frac{h_{p\min}}{h_z n} + 1\right)} - r_2 > 0 \tag{38}$$

and after the modification

$$h_{p\min} > h_z n\left(\frac{r_2^2}{r_1^2} - 1\right) \tag{39}$$

So if the condition is satisfied that:

$$h_p > h_{p\min} \tag{40}$$

then the value of the total regeneration time can be expressed by modifying the relationship (26) and (38), with the substitution into the equation (35) as:

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$$t_C = \frac{1}{20}\left(\frac{p_{\min}}{a_t}\right)^{\frac{1}{b_t}}\left[\left(\frac{\Delta h}{\Delta x}\right)^2 + \left(\frac{\Delta h}{\Delta z}\right)^2\right]^{-\frac{1}{2}} + \frac{r_1\left(\frac{h_p}{h_z n}+1\right)^{\frac{1}{2}} - r_2}{0.5 v_S} \qquad (41)$$

The expression is universal and thus applicable for all equipment types except MLS, where no sampling equipment or immersion pumps have to be plunged.

4 CONCLUSION

The solution of well hydraulics by means of the dilution method is well-known in hydrogeology and geotechnics. The author finds the application of the indicated procedure outcome limited in practice, particularly the design of perforation and time before beginning the sampling by means of one well. To facilitate the application, the general procedure was organized by a simple algorithm in the table editor MS Excel 2003, which enables the entry of as many as 15 input data considering the influence of the well equipment on the regeneration time and thus on the groundwater sampling as well; it can be tested by agreement. These are, however, data unverified by field tests, obtained experimentally, numerically with interpolation and significant extrapolation at a narrow range of hydraulic conductivity and gradient. The author is therefore aware of their informative value and recommends them for a rough estimate. For practical purposes, much more extensive measurement must be done under different conditions, preferably on the screen.

ACKNOWLEDGEMENTS

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RESUMÉ

Práce se zabývá jednou z klíčových částí vrtu a to zárubnicí a jejím vlivem na zdržení stopovací látky-kontaminantu. Aktivní i pasivní vzorkování v této části vrtu má vliv na stratifikaci či přerozdělení kontaminantu. Pokud máme odebrat původní vzorek, pak jednou z možností je dle autora dodržení tzv. doby regenerace. Jak velký vliv má právě zárubnice a jaké časové prodlevy po vložení či manipulaci se vzorkovacím zařízením dodržet, bylo snahou dokázat v tomto experimentu. Pro tyto účely byl postaven fyzikální model proudového prostředí s instalovanou zárubnicí. Sérií stopovacích pokusů při měněných parametrech hydraulické vodivosti porézního média a perforace zárubnice byl měřen úbytek koncentrace stopovače NaCl v čase uvnitř zárubnice. Naměřená data byla aproximována analytickým řešením pomocí tzv. zřeďovací metody a získána rychlost proudění uvnitř zárubnice jako funkce perforace a hydraulické vodivosti média. Dále byl zohledněn tzv. drenážní účinek vrtu, který je zárubnicí také ovlivněn. Jeho velikost byla porovnána s analytickým a numerickým řešením. Pro numerické modelování byl použit software Visual Modflow, jehož pomocí bylo namodelováno zkonstruované zařízení a ověřeny základní proudové parametry modelu. Pro dané podmínky byl stanoven drenážní účinek α = 2,1 jako základní hodnota, kdy zárubnice klade nulový odpor při cca 4 % perforaci. Ze získaných funkčních závislostí byly odvozeny převodní koeficienty mezi zkoumanými parametry a vyjádřen čas zdržení stopovače uvnitř zárubnice. Druhým krokem bylo posouzení, jak daleko se projeví změna porušení přirozeného stavu mimo zárubnici vložením vzorkovacího zařízení. Pomocí odvozeného poloměru zasažené zóny kolem zárubnice, který je funkcí hydrostaticky vytlačeného objemu vody a pórovitosti okolního materiálu, byla stanovena doba, za kterou se porušený stav teoreticky znovu obnoví. Výsledkem je pak celková doba regenerace t_C jako součet doby vně a uvnitř zárubnice v minutách. Snahou článku je poukázat na tento časový parametr, jeho vhodnost a případný přístup k budoucímu stanovení in situ. Nejedná se zde však o platnou veličinu či výpočet, nýbrž o experimentální data získaná při úzkém oboru hydraulické vodivosti a gradientu, získaná interpolací a v ideálních laboratorních podmínkách. Takto získanou dobu regenerace lze doporučit pouze jako hrubý odhad.