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CONTRIBUTIONS TO HYDROGEOLOGICAL PROTECTION PERIMETER SIZE CALCULATION UNDER SEVERE AND RESTRAINING REGIME

BY

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Abstract. Starting from the observation that the self-purification processes in aquifers is negligible and the most intense water pollution phenomena occur, in fact, in the layers above the aquifer, the paper presents a method for calculating the required time for a pollutant particle potential traverse the layers above the aquifer. The method is based upon constitutive equations of unsaturated porous medium, the harmonic composition law for equivalent hydraulic conductivity and on Gardner's equation to calculate the variation of vertical load standpipes, ψ. It involves determining the hydrodynamic load and the velocity gradient apparent and real – which leads to the calculation of the time to go to each of the aquifer coating. Once this time known, we believe that it should be summed with the travel time of contaminated water in aquifer, calculated by the methods already established before. Therefore, the distances of the sanitary protection area will correspond to the rated “transit time” (20 days under severe conditions and 50 days under restriction regime) decreased with the time, *Tt*, which is the time needed for the particle to get through the distance between the ground surface and the groundwater level.

Key words: aquifer; transit time.

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1. Introduction

One of the most important measures to protect groundwater quality which are taken for potable reasons is the establishment of the hydro-geological protection perimeters in severe conditions and also in case of the severely restricted regime. These perimeters are delimited on the ground surface around the pit capture, and they are designed to prevent the contamination of the groundwater with elements, substances, products and/or pathogenic micro-organisms character.

The basic idea from the present time, for constituting the hydro-geological protection perimeter in severe conditions and for restriction regime is that in the aquifer takes place a process of self-purification. Under these conditions hydro-geological protection perimeter was designed in the literature of our country (Hotărârea nr. *930*/11.08.2005 [8]), based on a so-called "transit time" defined as: the needed to set, conduct and completion of physical, chemical and biological remediation of any items, substances and/or products with characters pollutant in groundwater. Because it takes place in the hydrodynamic regime (groundwater movement) "transit time" corresponds to a distance traveled by the drop of pollutant in the aquifer. This distance is the most important dimension of the hydro-geological protection perimeter in severe conditions and for restriction regime and it is measured in the direction of the groundwater abstraction point upstream of water.

The differentiation of the dimensions in "strict conditions" and "restriction regime" is made by the duration of the "transit time":

a) 20 days under severe conditions;

b) 50 days under the restriction regime.

A review of the researches to the present time upon the self-purification processes taking place in the aquifer shows that the aquifer is almost nonexistent self treatment (Cojocaru, 1995). The intense process of self-purification occurs in the layers above the aquifer so that the water from different sources and that crosses under the action of gravity, these layers is subjected to a complex physical, chemical and biological processes of self-purification (*Le rol epurateur du sol*, 1989 [7]; Gobjilă, 1985). Among the physical factors of remediation the filtration, the water retention and the transfer of the water are cited. Among the chemical factors of natural remediation on soil and subsoil the aeration, the retention by adsorption of ions and the precipitation are cited. Among the biological factors are mentioned: the turning non-nitrogenous organic substances, the substances containing nitrogen, the nitrification, the denitrification, the conversion of the sulfide hydrogen, the conversion of the compounds of phosphorus etc. As a support for the above statement is that the microorganisms with scrubber role living in particular on the surface of the lithosphere horizons and only the anaerobic ones, extremely small size and usually pathogenic, may reach, together with percolation water in the aquifers.

Compared to the foregoing, it is clear that the calculation of the transit time must necessarily take into account the time needed for the pollutant drop to cover the vertical distance from the ground surface to the underground water. Thus we propose that *the "transit time" for an amount between the parties covering travel time and travel time zone of the aquifer to the point of capture.*

Since the calculation of the transit time in the aquifer is treated in various papers (Bârsan, 2001) in this paper we present details upon the calculation of the transit time of cover groundwater formations.

2. The Mathematical Model

The mathematical model is presented for calculating the time necessary for crossing the distance between the ground surface and the phreatic layer.

Consider a sequence of $n \geq 2$ layers above the aquifer (Fig. 1) each characterized by δ_j thickness and saturated conductivity K_{sj}.

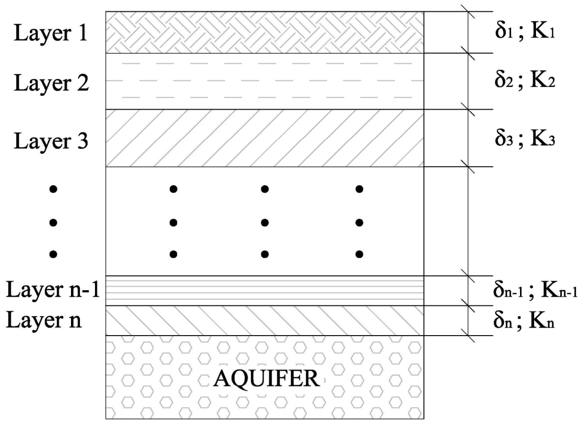

Fig. 1 – The sequence of the layers above the aquifer layer which produces the vertical flow infiltration.

The equivalent filtration coefficient of the earth layers traversed vertically in series, by the flow of infiltration, can be measured by the relationship:

$$K_{\text{ech}} = \frac{\sum_{j=1}^{n} \delta_j}{\sum_{j=1}^{n} \delta_j / K_{sj}}. \qquad (1)$$

The water saturation S_w and relative hydraulic conductivity K_r are dependent on the piezometric height ψ, according to the relations:

$$S_w = S_w(\psi)\,; \quad K_r = K_r(\psi)\,. \tag{2}$$

The relations (2) are called *constitutive equations* of porous medium (saturation-capillary pressure head, and respectively, relative hydraulic conductivity, capillary pressure head).

For the constitutive eqs. (2) we may use the following model (Philip, JR-1969):

$$S_w(\psi) = \begin{cases} S_w^r + (S_w^s - S_w^r)\mathrm{e}^{\alpha(\psi-\psi_a)} \text{ for } \psi < \psi_a, \\ S_w^s \text{ for } \psi \geq \psi_a, \end{cases} \tag{3}$$

$$K_r(\psi) = \begin{cases} \mathrm{e}^{\alpha(\psi-\psi_a)} \text{ for } \psi < \psi_a, \\ 1 \text{ for } \psi \geq \psi_a, \end{cases} \tag{4}$$

where: ψ_a is the piezometric height air from the pores (usually, $\psi_a \cong 0$), [m]; S_w^s and S_w^r – maximum the degree of saturation ($S_w^s \cong 1$), and, respectively the degree of residual saturation; α – the exponent of the constitutive equations of unsaturated porous medium proposed by Phillip (Tabel 1.)

Tabel 1

The Parameter α of the Porous Medium (Lee.C.C. 2007)

No.	Ground texture	α
1	Sand	14.5
2	Loamy sand	12.4
3	Sandy loam	7.5
4	Sandy clay loam	5.9
5	Sandy clay	2.7
6	Loam	3.6
7	Silty loam	2.0
8	Clay loam	1.9
9	Silt	1.6
10	Silty clay loam	1.0
11	Silty clay	0.5

For the layers vertical column, located above the ceiling of the aquifer layer of length L, where $L = \sum_{j=1}^{n} \delta_j$, crossed by water flow which containing pollutants and having intensity ε, [m/day], the vertical variation (z axis pointing down, with the origin $z = 0$ at the ground level) of the piezometric load is given by the eq. ψ of Gardner (Diersch, 2002):

$$\psi(z) = -\frac{1}{\alpha}\ln\left\{\frac{1}{K_{\text{ech}}}\left[\varepsilon + \left(K_{\text{ech}} - \varepsilon\right)e^{-\alpha(L-z)}\right]\right\}. \tag{5}$$

The hydrodynamic load (relative to the horizontal plane which includes the bottom of the column) under which the infiltration occurs, has the following expression:

$$H(z) = (L - z) + \psi(z). \tag{6}$$

For the hydrodynamic load gradient dH/dz, taking account of the expressions (6) and (5), we obtain the following expression:

$$\frac{dH(z)}{dz} = -1 - \frac{(K_{\text{ech}} - \varepsilon)e^{-\alpha(L-z)}}{\varepsilon + (K_{\text{ech}} - \varepsilon)e^{-\alpha(L-z)}}. \tag{7}$$

Inserting eq. (5) into (4), results the following expression for the constitutive eq. of the relative hydraulic conductivity–capillary pressure head:

$$K_r(\psi) = \begin{cases} \dfrac{K_{\text{ech}}}{\varepsilon + (K_{\text{ech}} - \varepsilon)e^{-\alpha(L-z)}} & \text{for } \psi < \psi_a, \\ 1 \text{ for } \psi \geq \psi_a. \end{cases} \tag{8}$$

The apparent velocity, q, is determined by Darcy's eq. for the saturated porous medium:

$$q(z) = -K_r(\psi)K_s(z)\frac{dH(z)}{dz}. \tag{9}$$

where: $K_r(\psi)$ and $dH(z)/dz$ are known (eqs. (8) and respectively, (7)) while the hydraulic conductivity $K_s(z)$ is considered known and constant on the vertical of each layer j considered in the calculation.

The real infiltration speed, $v(z)$ is determined using the following eq.

$$v(z) = \frac{q(z)}{n_e(z)S_w(z)} \tag{10}$$

where: $q(z)$ is the apparent speed of the layer at depth z; $n_e(z)$ – the effective porosity or drainable of the layer at depth z; $S_w(z)$ – the degree of saturation in the layer at a depth z.

The effective porosity value can be deduced from the following equation of correlation between effective porosity - hydraulic conductivity (Cojocaru, 1985)

$$n_e(z) = \frac{28 K_{\text{ech}}(z)}{K_{\text{ech}} + 1}. \tag{11}$$

The degree of saturation in the layer at a depth z can be evaluated from the eqs. (3) and (5) resulting

$$S_w(z) = \begin{cases} S_w^r(z) + \left(1 - S_w^r(z)\right) \dfrac{K_{\text{ech}}}{\varepsilon + (K_{\text{ech}} - \varepsilon)\mathrm{e}^{-\alpha(L-z)}} \text{ for } \psi < \psi_a, \\ S_w^s = 1 \text{ for } \psi \geq \psi_a. \end{cases} \tag{12}$$

For each layer j considering constant values (corresponding coordinate from the center of each layer z_{mj}) for functions in the right-of eqs. (9) and (10), we obtain the following set of constant values for the real speed $v(z)$,

$$v_j = v(z_{mj}), \quad j = 1,2, \ldots, N_{\text{str}}, \tag{13}$$

where: N_{str} is the total number of layers from the sounding until the underground water level (thus, for $j = N_{\text{str}}$ layer, corresponding aquifer should be considered partial thickness δ_P, that satisfies the condition $0 \leq \delta_P < \delta_{N_{\text{str}}}$).

With the above specifications, in the end, the total duration t_{RI} between the travel land surface and the underground water level will be calculated by the following amount:

$$t_{RI} = \sum_{j=1}^{N_{\text{str}}} t_j = \sum_{j=1}^{N_{\text{str}}-1} \frac{\delta_j}{v_j} + \frac{\delta_p}{v_{N_{\text{str}}}} \tag{14}$$

where: t_j is the travel time by water current layer j; $v_{N_{\text{str}}}$ – vertical water flow velocity in the layer $j = N_{\text{str}}$.

3. The Obtained Results (Practical Application of the Proposed Method)

Let it be a land which between the surface and waterproof layer includes two layers (Fig. 2). The main features of these layers is also shown in Fig. 2.

The granulometric composition of those two layers is:

a) layer 1: silty clay – 31%; loam – 49%; sand – 20%;

b) layer 2: silty clay – 48%; loam – 47%; sand – 5%.

Now if we take into account the maximum infiltration caused by a light rain whose intensity is 94 mm/day, in determination of the time to go by a drop of water considered polluted, on vertically, until the ceiling aquifer, the following stages are necessary:

1. The equivalent hydraulic conductivity of the layers will be determine:

a) layer 1, $K_{\text{ech}}^{1} = K_1 = 0.011$ m/day;

b) layer 1 + 2,

$$K_{\text{ech}}^{2} = \frac{\delta_1 + \delta_2}{\delta_1 / K_1 + \delta_2 / K_2} = 0.0106 \text{ m/day.}$$

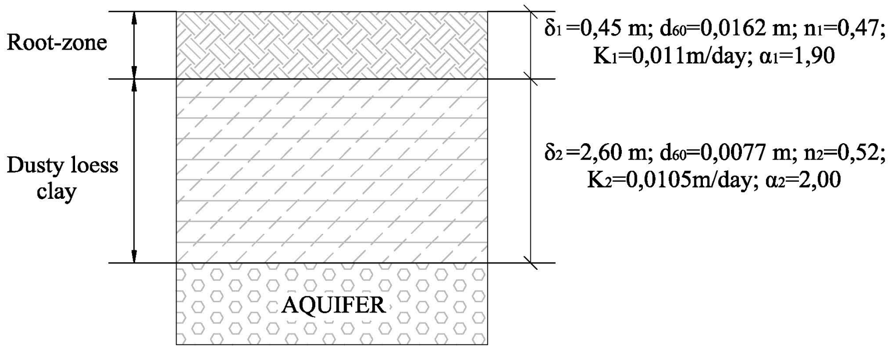

Fig. 2 – The stratification of land until the underground water.

2. The equivalent values of α will be determine:

a) layer 1, $\alpha_{\text{ech}}^{1} = 1.9$;

b) layer 1 + 2,

$$\alpha_{\text{ech}}^{2} = \frac{\delta_1 \alpha_1 + \delta_2 \alpha_2}{\delta_1 + \delta_2} = 1.973.$$

3. The vertical distance from the ground surface to the middle layer until which the calculation is made:

a) the distance to the middle layer 1: $z_1 = \delta_1/2 = 0.225$ m;

b) the distance to the middle layer 2: $z_1 = \delta_1 + \delta_2/2 = 1.75$ m;

4. The piezometric load by the equation of Gardner (eq. 5) will be determined:

a) the middle of the layer 1:

$$\psi_1 = \frac{1}{\alpha_1} \ln\left\{ \frac{1}{K_{\text{ech}}^{1}} \left[\varepsilon + \left(K_{\text{ech}}^{1} - \varepsilon \right) \mathrm{e}^{-\alpha_1 (L - z_1)} \right] \right\} = 1.127$$

where: L is the distance from the surface of the ground to the underground water level,

$$L = \delta_1 + \delta_2 = 3.05 \text{ m}$$

b) the middle of the layer 2:

$$\psi_2 = \frac{1}{\alpha_2}\ln\left\{\frac{1}{K_{\text{ech}}^2}\left[\varepsilon + \left(K_{\text{ech}}^2 - \varepsilon\right)e^{-\alpha_2(L-z_2)}\right]\right\} = 1.066\,.$$

5. We calculate the values:

a) for layer 1:

$$\frac{\text{d}H(z)}{\text{d}z} = -1 - \frac{\left(K_{\text{ech}}^1 - \varepsilon\right)e^{-\alpha_1(L-z_1)}}{\varepsilon + \left(K_{\text{ech}}^1 - \varepsilon\right)e^{-\alpha_1(L-z_1)}} = -0.996$$

which from (8) and (12) results: $K_{r1} = 1$ and $S_{w1} = 1$

b) for layer 2:

$$\frac{\text{d}H(z)}{\text{d}z} = -1 - \frac{\left(K_{\text{ech}}^2 - \varepsilon\right)e^{-\alpha_2(L-z_2)}}{\varepsilon + \left(K_{\text{ech}}^2 - \varepsilon\right)e^{-\alpha_2(L-z_2)}} = -0.928$$

which from (8) and (12) results: $K_{r2} = 1$ and $S_{w2} = 1$.

6. The apparent speeds (q) and the real speeds (υ) from those two layers will be calculated:

a) in layer 1, $q^1 = -K_{r1}K_1\frac{\text{d}H(z_1)}{\text{d}z} = 0.011$ m/day,

$$\upsilon^1 = \frac{\upsilon_{ap}^1}{n_e^1 S_{w1}} = 0.36 \text{ m/day;}$$

b) in layer 2, $q^2 = -K_{r2}K_2\frac{\text{d}H(z_2)}{\text{d}z} = 0.0097$ m/day,

$$\upsilon^2 = \frac{\upsilon_{ap}^2}{n_e^2 S_{w2}} = 0.33 \text{ m/day.}$$

The values of n_e^1 and n_e^2 were calculated using eq. (11).

7. The travel time of those two layers Shall is calculated:

a) in layer 1, $t_1 = \delta_1/\upsilon_r^1 = 1.25$ days;

b) in layer 2, $t_2 = \delta_2/\upsilon_r^2 = 7.82$ days.

8. The total time (T_t) of crossing by a potential polluted water drop from the surface of the ground to the groundwater level, in this case, is:

$$T_t = t_1 + t_2 = 9.07 \text{ days.}$$

3. Conclusions

If we accept the fact that the phenomenon of water remediation starts from the soil surface and not from the aquifer level, the method of calculating the time necessary for crossing the distance between the ground level and the top level of the aquifer, presented in this paper, is applicable to any practical situation that can be found in the nature nomatter of the number of layers, the thickness and their hydraulic characteristics.

The presented method is based upon the constitutive equations of the unsaturated porous medium, the harmonic composition law for equivalent hydraulic conductivity and the Gardner's equation for the change in vertical piezometric load ψ and it involves the hydrodynamic gradients load and the real and apparent velocities – leading to the calculation of the time to go to each for covering layer.

Once this time known we believe that it should be summed with the travel time of the contaminated water in aquifer which is calculated by the methods already established before. Therefore, the distances of the sanitary protection area will correspond to the rated "transit time" (20 days under severe conditions, 50 days under the restraining regime) decreased with the time (T_t), of travelling the vertical distance between the ground surface and the underground water level.

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CALCULUL DISTANŢEI ÎNTRE DRENURI ÎN TEREN MULTISTRAT (NEOMOGEN) ÎN REGIM DE FUNCŢIONARE PERMANENT

(Rezumat)

Plecând de la observaţia că în acvifere procesele de autoepurare sunt nesemnificative şi cele mai intense fenomene de depoluare se produc, de fapt, în straturile situate deasupra acviferului, în lucrare se prezintă o metodă de calcul a timpului necesar ca o particulă potenţial poluată să străbată straturile situate deasupra acviferului. Metoda se bazează pe ecuaţiile constitutive ale mediului poros nesaturat, pe legea de compunere armonică pentru conductivitatea hidraulică echivalentă, pe ecuaţia lui Gardner pentru calculul variaţiei pe verticală a sarcinii piezometrice ψ şi presupune determinarea gradientului sarcinii hidrodinamice şi a vitezelor aparente şi reale - care să conducă la calculul timpului de parcurs a fiecărui strat de acoperire a acviferului. Odată cunoscut acest timp noi considerăm că trebuie însumat cu timpul de parcurs al apei contaminate în acvifer, calculat după metodele consacrate deja; astfel distanţele de protecţie sanitară vor fi corespunzătoare "timpului de tranzit" normat (20 de zile în regim sever; 50 de zile în regim de restricţie) diminuat cu timpul (T_t), de parcurgere a distanţei verticale dintre suprafaţa terenului şi nivelul pânzei freatice.