SEEPAGE POWER AS A FACTOR DETERMINING THE PIPING AND SILTING UP THE LOOSE WATER-BEARING SOILS

Marek Rogoż
Central Mining Institute, Katowice, Poland

ABSTRACT

The water, seeping through non-cohesive soils, exerts a certain dynamical pressure on the soil's skeleton, what is known as the seepage force. This force, acting along the seepage path, does work, which is partly converted into heat and partly used for piping the water-bearing soil. The relation of the amount of work used for piping to that converted into heat depends on the seepage power, the grain composition and the compactness of soil. For any soil exists a certain power of seepage equilibrium, at which washing out or deposition of the grains does not occur. Increasing of the seepage power enhances the piping process, whereas its decreasing causes the deposition of fine grains in soil's pores, resulting in the silting up of ground. It can be proved, that the seepage power is proportional to the coefficient of permeability and the square of hydraulic gradient. The washing out of fine grains causes increasing of the permeability and therefore the further increasing of seepage power; the silting up of ground has the opposite effect. This way develop the paths of seepage with washed grains and high values of permeability coefficient as well as the silted zones with high contents of small grains and much lower values of permeability coefficient.

The water, seeping through porous medium, like permeable soil, exerts on its skeleton a certain pressure, called seepage force. The phenomenon is well known and described in numerous handbooks of hydrogeology and geotechnique, for instance Means and Parcher (1963), Sedenko (1962), Wieczysty (1970), Wiłun (1976) and others. The seepage force is volumetric and can be calculated as a product of specific weight of water γ_w and the hydraulic gradient J

$$F_s = \gamma_w \cdot J \qquad /1/$$

There is no agreement in professional papers, if the seepage force determined with the formula /1/ is related to the unit of the water volume or to the unit of porous medium filled with water. After majority of Polish authors the formula /1/ is related to the unit of soil volume, whereas after Means and Parcher (1963) - to the unit of water volume. Sedenko (1962) presents a formula which determines the seepage force as related to the unit of soil volume

$$F_s = n \cdot \gamma_w \cdot J \qquad /2/$$

where n - porosity of soil.

In the two-phase system consisting of porous medium and water, only water can be the energy-carrying agent. Let's imagine an elementary volume of water V_w situated in the aquifer on the height h_1 above the optional datum level. The water has the potential energy $E_1 = V_w \cdot \gamma_w \cdot h_1$. Let's assume that the water volume V_w is shifted in the aquifer along the path l to the place being on the height h_2, with $h_2 < h_1$. The potential energy of water in that place is $E_2 = V_w \cdot \gamma_w \cdot h_2$, with $E_2 < E_1$. Seeping through the porous medium, the water does work W_f used for overcoming the resistance to motion on the path l. This work is determined with formula

$$W_f = E_1 - E_2 = V_w \cdot \gamma_w /h_1 - h_2/ \qquad /3/$$

The seeping water acts on the medium with force being the quotient of the work and path

$$F_s = \frac{W_f}{l} = V_w \cdot \gamma_w \frac{h_1 - h_2}{l} \qquad /4/$$

The quotient $/h_1-h_2/ : l$ is the hydraulic gradient J. Assuming, that the volume of water V_w is equal unity, one receives the formula /1/ valid for the unit of water volume and not of the soil's one. The quantity of water being contained in the unit of medium's volume is numerically equal to its porosity, therefore in relation to the unit of soil's volume the formula /2/ is correct.

The unit of seepage force in the International Units System is newton to cubic meter $/N\ m^{-3}/$.

The seepage of water in the non-cohesive soils, like sands, slimes and similars is very often accompanied by the process of washing out the fine-grained material. That material is moved then by water through the pore spaces and deposited in other parts of aquifer or carried outside the water-bearing layer. It may for instance be discharged into rivers, drainage ditches, mining workings and so on. The process of washing out and transportation of fine-grained material is called "piping" or "internal erosion", whereas the deposition of fine grains in pores, causing the diminution of pore clearance - the "silting up" of soil.

It is assumed, that the intensity of piping and silting up processes depend on the granular composition of soil and the seepage force. The dependence is obvious as granular composition is concerned, but the relation between intensity of the process and the seepage force leads to the contradiction. It is well known, that when water is seeping through the inhomogenous medium, the greatest hydraulic gradients, and thereby the greatest seepage forces, take place in the parts of aquifer which have the lowest permeability. However, in these parts of aquifer the piping does not occur or is negligible, because the seepage intensity is there lower, than in the parts of lower hydraulic gradients, but of higher permeability. This observation inclined the author to use the seepage power as a factor defining conditions of piping occurrence.

In accordance with the previous discussion, the water seeping along the path l, determined by the current line, does the work W_f, which is related to the unit of water volume, as defined with formula

$$W_f = F_s \cdot l \qquad /5/$$

The same seepage work can be done in different time, therefore the seepage power P_f can be defined as relation of the seepage work to time t

$$P_f = \frac{W_f}{t} \qquad /6/$$

Substituting the right sides of expressions /1/ and /5/ to /6/ one receives

$$P_f = \gamma_w \cdot \frac{l}{t} \cdot J \qquad /7/$$

The formula /7/ defines the seepage power of the unit of seeping water's volume. The seepage power of the water's volume V_w is determined with formula

$$P_{fV} = \gamma_w \cdot V_w \cdot \frac{l}{t} \cdot J \qquad /8/$$

Introducing the seepage intensity $Q = V_w/t$ into formula /8/, one can receive the expression defining the seepage power of the stream of intensity Q on the path l

$$P_{fQ} = \gamma_w \cdot Q \cdot l \cdot J \qquad /9/$$

In accordance with the Darcy's law, the seepage intensity is a product of the coefficient of permeability k, the cross-section area of the stream of seepage A and the hydraulic gradient J

$$Q = k \cdot A \cdot J \qquad /10/$$

The cross-section of the stream of seepage is perpendicular to the stream line and the area comprises the porous medium together with seeping water. Introducing the right side of equation /10/ into formula /9/ one receives

$$P_{fQ} = \gamma_w \cdot k \cdot A \cdot l \cdot J^2 \qquad /11/$$

The seepage power of the stream having the cross-section area A = 1, on the length l = 1, corresponds with seepage power related to the unit of soil's volume and is defined with formula

$$P_f = \gamma_w \cdot k \cdot J^2 \qquad /12/$$

The unit of seepage power in the International System is watt /W/, what can be easily proved using the dimensional analysis.

A part of seepage work is converted into heat resulted from the friction between water particles as well as between water and porous medium, the other part however is used for piping process, that is, for washing out the fine grains from among the greater ones and their transportation along the seepage path. The relation of the quantity of work being converted into heat to that used for piping, depends on the stability of porous medium, which can be the function of seepage power. In the loose soil, like sand, when the seepage power is small one, even the finest grains may be too heavy to be moved off by water and transported through porous spaces. In such a case the whole seepage work is converted into heat and dissipated. The increase of seepage power may cause motion of some grains and therefore a part of work is used for piping.

The introduction of the concept of seepage power in the hydrogeology and geomechanics has important practical consequences since it makes possible to explain some phenomena being till now known and described, but not fully elucidated. One of such phenomena is a great differentiation of the grain composition and of permeability coefficient in quaternary sands of buried river valleys both in horizontal and vertical directions. According to Wieczysty (1970), the variety index of the permeability coefficient, defined as the relation of its maximal values to minimal ones, varies from 1.35 to 700.0.

The increase of the seepage power in sandy aquifer causes the increase of piping intensity. This process subsequently leads to the increase of the permeability and again to further rise of the seepage power and piping intensity. It is then the positive backfeeding. The process will continue till only the washed sand remains, so its further washing with the given seepage power will not be possible.

In some parts of sand layer, where permeability is lower, the seepage power may be too small to make further displacement of fine grains possible. In such parts the deposition of grains in pore spaces takes place. The effect of that is silting up of the water-bearing layer, that causes decreasing of permeability and then, according to the formula /12/, the further decreasing of seepage power.

Gradually in the water-bearing layer arises a state of equilibrium, proper to the given system of hydraulic gradients and permeability. Any change of the hydraulic gradient in whichever part of the aquifer disturbs this state. The increase of seepage power sets in motion the piping process while its decreasing - the deposition of grains carried by water. The seepage power, which does not cause piping nor silting up of the aquifer, is suggested to be called the power of seepage equilibrium. Its value depends on granular and mineralogical composition of the soil as well as on its compactness and is characteristic for any soil.

The described process of piping and silting up of soil cause the important differentiation of transmissivity within an aquifer. This way develop the paths of seepage with washed grains and of high values of the permeability coefficient as well as the silted zones with high contents of small grains and with much lower values of permeability coefficient. The wells situated in zones of washed sand have high yield, whereas ones situated in silted zones have generally small yield and easily get sealed.

The washed zones in a sandy aquifer are situated not completely chaoticaly, but they are arranged in stripes more or less parallel to the lines of current. One can notice a certain similarity to the disposition of streams in the sandy river bed in its lower cours during the low water. As a far analogie one can compare the disposition of the washed zones to the net of blood-vessels, what could justify the term "water vein" commonly used by dowsers.

To verify the presented discussion, the numerical model of a confined water-bearing layer, subjected to the piping and silting up processes, has been elaborated. In the model the intensity of both processes is proportional to the seepage power determined with formula /12/. The model, based on the finite difference method (Rogoż, 1979), contains 3894 nodes disposed in

66 rows and 59 columns. The nodes in successive rows are mutually displaced in such a way, that the mesh is rhombic /Fig.1/. To nodes in the first and the last rows have been assigned hydraulic heads of 100 and 10 m respectively. Then the water flow through the whole field from the northern boundary (the first row) to the southern one (the last row) has been simulated. In every node the lines of current have been splited as it is shown on Fig.1.

For the process initiation, the same value of transmissivity, namely 10^{-4} m^2/s, have been assigned to all internodal connections. In the confined aquifer the seepage is linear, so identical hydraulic gradient and identical initial seepage power P_o have been in all internodal connections. Next, with help of the generator of pseudorandon numbers, the transmissivity in each internodal connection has been disturbed within limits of $\pm$ 1 % in order to simulate the primary minor heterogenity of the aquifer.

The further procedure consisted on the multiple, iterative calculation of the values of hydraulic heads in particular nodes and then, after every calculation, the values of internodal transmissivity were modified. Namely for any internodal connection the seepage power P_n after n-1 modification was calculated and the actual transmissivity was multiplied by P_n/P_o and by damping function exp/0.01-100 T/ which prevented against raising the transmissivity above 10^{-2} m^2/s. The simplified flow diagram of the computer program is presented on Fig.2. The program has been elaborated in Algol 1204 language and calculations were carried out on the Polish computer Odra 1204 in the Central Mining Institute. The distribution of the transmissivity values within the model directly after differentiation with pseudorandom numbers was completely chaotic. After 10 iteration steps one could see the distinct paths of filtration disposed randomely, but approximatively parallel to the current lines as it was shown on Fig.3. The result of the numerical experiment confirmed the correctness of the presented discussion.

The theory of seepage power enables to explain the way of development the collapses of embankments of water reservoirs, settling tanks, river beds and other earth constructions.

REFERENCES

Means, R.E., 1963. Physical properties of soils, Charles E. Merrill Books Inc., Columbus, Ohio

Rogoż, M., 1979, Modelowanie warstwy wodonośnej metodą różnicową (Modelling of water-bearing layer with finite-difference method), Prace GIG, Seria dodatkowa, Katowice

Sedenko, M.W., 1962, Gidrogeologija i inzeniernaja gieologia, (Hydrogeology and engineering geology), Gosgeoltechizdat, Moskwa

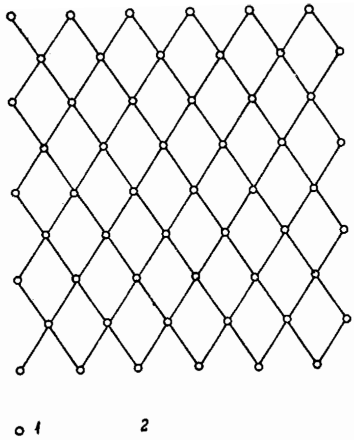


Fig. 1 Arrangement of nodes in the numerical model of water bearing layer

1 - node , 2 - internodal connection

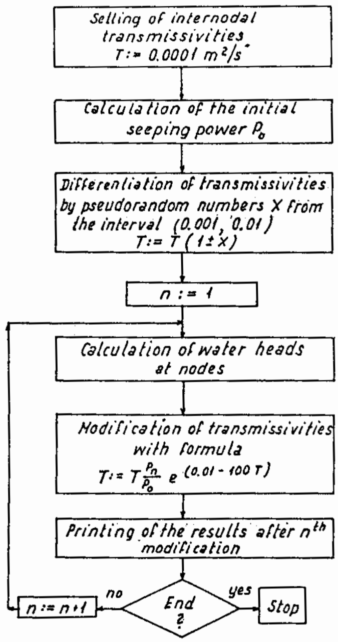
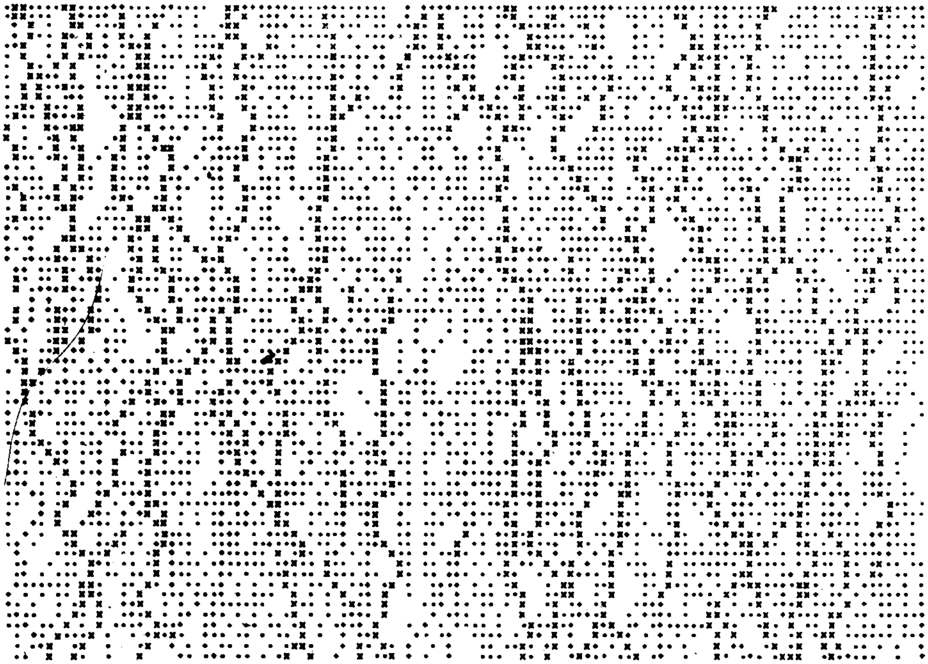


Fig. 2 Simplified flow diagram of the computer program



x - $T > 10^{-3}$ + - $10^{-4} < T < 10^{-3}$ • - $10^{-8} < T < 10^{-4}$ no sign - $T < 10^{-8}$

Fig. 3. Distribution of transmissivity as a result of piping and silting up processes

Wieczysty, A., 1970, Hydrogeologia inżynierska, (Engineering hydrogeology), PWN, Warszawa - Kraków

Wiłun, Z., 1976, Zarys geotechniki (Outline of geotechnique), Wyd.Komunikacji i Łączności, Warszawa