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TRACER METHOD FOR DETERMINING THE VELOCITY OF FLOW IN A CONFINED KARSTIC AQUIFER

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ABSTRACT

The control of karstic water inrush presents continuous difficulties at the Dorog coal-mines in the north-western part of Hungary. The efforts to control water inrush call for continuous research work. The problem was to determine the rate of recharge per unit area from a terrain situated a few hundred metres from the mine workings and in this connection the velocity of flow.

Fluorescein was used as tracer material which was introduced through a borehole into the water-bearing formation. Samples were retrieved from water which entered the mine at several points. The tracer material was observed first 49 days after introduction, at a point of inrush situated 426 m distant from the point of introduction, i.e., the borehole (fig. 1).

Calculations of flow velocity were based on the geometry pattern of a single point sink, or flow towards this sink. Basic criteria were the velocity computed on the basis of straight-line flow and the constant discharges at the point of inrush and introduced into the borehole absorbing the dye. From these data the dimensions of zones could be determined where the velocity of flow was higher than the average value (fig. 2). Information was gained thereby also on the time of residence of dyed water in the high velocity zones, and thence on the spontaneous flow velocity of karstic water.

THE FIELD EXPERIMENT AND THE DATA OBSERVED

The experiment to be described subsequently has been carried out in the autumn of 1967 by the Research Institute for Water Resources Development, in connection with studies into the methods of mine water control. The site of the experiment was in the north-western part of Hungary, in the Transdanubian Mountain Range, on the area of the Dorog coal mines. At the particular site the karstic dolomite water bearing formation is overlain by impervious layers of several hundred metres thickness. Coal is extracted from fields situated in the lower part of the impervious formation, separated by 20 to 30 m thick impervious layers from the water bearing rock. In the neighbouring mountains the latter emerges to the surface and receives abundant recharge from precipitation. At weak points of the underlying separating layer the mine is permanently threatened by the inrush of water.

The problem was to determine the velocity of karstic water flowing from the more distant surroundings towards the mine and appearing there as inrush water, in order to derive therefrom information on the rate of flow through the unit area. 80 kg of flourescein were used as tracer material, considering that this dye is detectable even if regular sampling is suspended for some reason, or if the sampling point does not coincide with the point of main water inrush.

The dye was dissolved in the ratio 1 : 10 in commercially available ammonia and introduced into the water bearing formation through a borehole serving originally for the observation of water levels. The date of introduction was 15th September, 1967. For ten days thereafter (to the 25th September) water was filled into the borehole at the rate of 12 cu. m/hour. Samples were retrieved from water that entered the mine at a distance of several hundred metres, but some sampling points were located at even greater distances.

Up to the time of analysis the water samples were preserved in a dark location (in the mine, or in a dark-room prepared for this purpose) to prevent loss of colour. The analysis

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consisted in comparing the samples in ultra-violet light with a set of standard solutions. Using this method, the samples containing the dye in excess of 0,01 milligrammes per litre could be selected with absolute reliability. The distincion of samples containing the dye in an even smaller concentration was disturbed by the spontaneous fluorescent light emitted by the water arriving through abandoned working faces and polluted by organic substances. Consequently, these samples could no more be included in the evaluation.

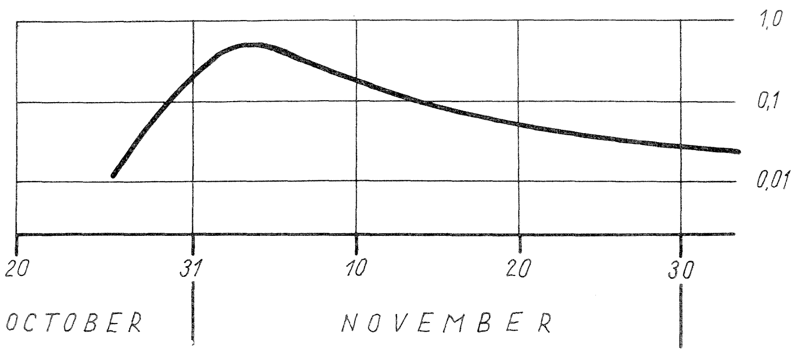

Fig. 1 — Variation of fluorescein concentration in the water entering the mine.

Following the introduction of the dye into the borehole on the 15th September, a new spring developed in the mine beside the existing springs on the 24th October, and yielded 150 cu. m of water per hour on the average. The presence of fluorescein in the water of this new spring was detected first on the 18th day of its operation, on the 11th November. As revealed by the records available the highest concentration of the dye solution was observed on the 3rd November, 49 days after the dye had been introduced into the borehole (fig. 1).

Dye was subsequently detected in other, more remote springs as well, but the concentrations observed were appreciably lower.

Flow velocity of the dyed water

Fluorescein was observed in the highest concentration (about 0,5 milligrammes per litre) and at the earliest date in the water of the newly developed spring. Consequently peak flow velocities are likely to have occured along the line between the borehole used for feeding and the new spring.

As a first approximation the dye solution was assumed to have followed a completely straight path and to have moved at a completely uniform velocity between the feeding borehole and the spring. The distance along this line was

$$L = 426 \text{ m.}$$

The length of the period of time between the date of introduction (15th September) and the probable date on which the highest concentration was observed (3rd November) was $T = 49$ days. Using these data the estimated average flow velocity is obtained as

$$v^{\mathrm{I}} = 8{,}7 \text{ metre/day} = 0{,}362 \text{ metre/hour.}$$

It should be obvious at the same time that at two points—around the feeding borehole and in the vicinity of the spring where the dye was first observed—the velocity of flow was considerably in excess of the above average value. At the feeding borehole, e.g.,—assuming that at the end of the lining tube (lined section of the borehole) the water filled continuously at the rate of 12 cu.m/hour discharged through the full cross-section—the outflow velocity may be estimated at 945 metre/hour.

On the basis of the relative position of the impervious and water bearing formations in the vicinity of the investigation area, a simple geometrical approach may be introduced (fig. 2).

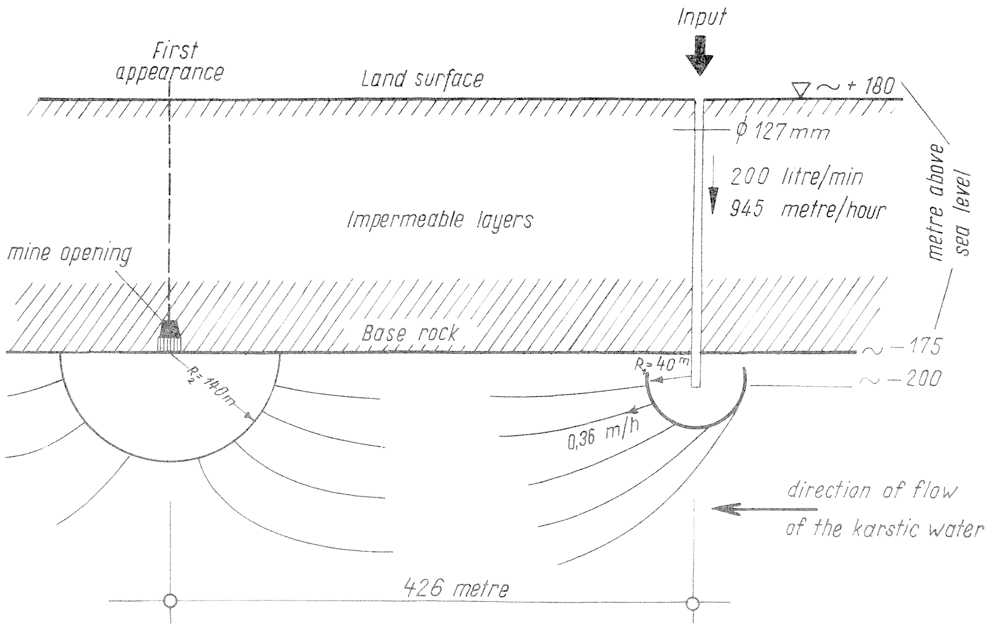

Fig. 2 — Diagrammatical sketch showing the principle of velocity estimation.

Let it be assumed that water starts to flow at the same velocity in every direction once it leaves the lined section of the borehole, while it is filled at the rate of 12 cu.m/hour after the dye solution. In this case the points of identical velocities will be situated on a sphere. The velocity of flow is bound to decrease rapidly as the surface of the sphere increases. At a certain distance from the well the velocity of outflow will equal the average flow velocity estimated at 0,362 metre/hour. The front area of the outflowing water volume (the open cross-sectional area of rock passages and joints participating in flow) is then

$$F_1 = \frac{Q_1}{v} = \frac{12}{0{,}362} = 33 \text{ sq.m.}$$

In the test area a porosity of 0,3 % has been observed repeatedly and accepted as an overall average value for the area. Using this value the radius of the half-sphere shown in figure 2 may be calculated as

$$R_1 = \sqrt{\frac{33}{2 \cdot \pi \cdot 0{,}003}} = 40 \text{ metres.}$$

The point of water inrush, on the other hand may be regarded as a well towards which flow occurs at uniform velocity from all directions.

At the distance R_2 the entrance velocity will equal the average value of 0,362 metre/hour, i.e., flow occurs through a surface area

$$F_2 = \frac{Q_2}{v} = \frac{150}{0,362} = 414 \text{ sq.m.}$$

Using the foregoing porosity value the radius of the corresponding half-sphere is

$$R_2 = \sqrt{\frac{414}{2 \cdot \pi \cdot 0,003}} = 140 \text{ metres.}$$

The velocities in these ranges must be taken into consideration when estimating the average flow velocity over the distance between the two high-velocity ranges. For this purpose information is required on the length of the period of time during which water moved through the high-velocity ranges.

In the vicinity of the feeding well the velocity of outflow, under the conditions mentioned earlier, is described in terms of the radius of the sphere by the following expression:

$$V_1 = \frac{Q}{0,003 \cdot F} = 0,64 \cdot 10^3 \cdot \frac{1}{R^2}$$

The time of residence in the high-velocity range is the sum of the elementary time increments:

$$\sum \mathrm{d}t = \sum \frac{\mathrm{d}R}{v}$$

The time of passage is accordingly

$$t_1 = \int \frac{\mathrm{d}R}{V} = \frac{\mathrm{d}R}{0,64 \cdot 10^3 \cdot 1/R^2} = \frac{1}{A} \int_0^{R_1} R^2 \, \mathrm{d}R$$

$$t_1 = \left[\frac{1}{3A} \cdot R^3\right]_0^{140} = 33,4 \text{ hours.}$$

In the vicinity of the point of inrush a uniformly pervious area of 20 sq.m is assumed in the impervious protection layer at the invert of the coal drift. The entire water volume is assumed to enter over this area. The porosity here is taken as 1 per cent (which is higher than the average, but probably justified in the vicinity of the spring) and so the flow velocity obtained is

$$v_{max} = \frac{150}{20 \,.\, 0,01} = 750 \text{ metre/hour.}$$

The velocity of inflow in terms of the sphere radius is expressed (returning now to the use of the 0,3 % porosity value) as

$$v_2 = 7,95 \cdot 10^3 \cdot \frac{1}{R^2}$$

The time of passage is

$$t_2 = \int \frac{\mathrm{d}R}{7{,}95 \cdot 10^3 \cdot 1/R^2} = \frac{1}{B} \int_0^{R_2} R^2 \,\mathrm{d}R$$

$$t_2 = \left[\frac{1}{3B} R^3\right]_0^{140} = 115 \text{ hours.}$$

The total time spent in the two high-velocity ranges is thus

$$33{,}4 + 115{,}0 = 148{,}4 \text{ hours.}$$

Deducting from the total time (49 days = 1176 hours) the above value, the balance is 1027,6 hours. Dividing by this time the remaining distance: $426 - (40 + 140) = 246$ m, the average velocity is obtained as

$$v^{\mathrm{II}} = \frac{246}{1028} = 0{,}240 \text{ m/hour.}$$

Repeating the entire computation using this value, yields
$v^{\mathrm{III}} = 0{,}228$ metre/hour,
while, using v^{III}, the second repetition yields
$v^{\mathrm{IV}} = 0{,}2265$ metre/hour.

In view of the fact that the magnitude of v^{IV} hardly differs from that of v^{III}, the process of successive approximation may be finished. It may be concluded that velocities higher than v^{IV} develop over the end section only of the distance under consideration.

Discussion of results

Several simplifying assumptions have been introduced during the computation. The theoretical sphere in the vicinity of the feeding borehole is most probably distorted and assumes a shape resembling that of an ellipsoid elongated in the general direction of flow. The same conditions are likely to prevail also in the vicinity of the point of inrush, but with an opposite sign. The situation here is further complicated by the fact that the spherical surfaces pertaining to adjacent individual points of inrush intersect each other. In areas where several springs are located close together and belong to the same group, velocity distributions may be highly involved and flow directions may change within short distances.

From the relatively low velocities obtained it appears logical to conclude that in the test area flow velocities are little affected by tectonic lines. Low velocities similar to those obtained are in fact impossible unless the water introduced continuously after the dye solution spreads with a relatively large front, which is wider than the width of a single fault zone. The circumstance that springs within the mine are located along fault lines is a simple reflection of the fact that the impervious layer underlying the coal fields is weaker along the fault lines. Karstic water under a high piezometric head is capable of penetrating the thinned, farctured protection layer. For the development of the central core of the range with velocities higher than the average, opportunity is offered in the part of the fault zone reaching into the karstic base rock, where, as a result of the higher porosity, velocities up to several hundred metres per hour may occur.

Velocities lower than those estimated prevail certainly at greater distances from the points of water inrush, where the flow lines of the flow pattern diverge to greater distances. On the other hand, velocities are bound to be higher in the interior of the groups of springs, where the high-velocity ranges intersect.

For estimating the dimensions of the dye surge passing it has been taken into consideration that after the introduction of the dye solution the water was filled continuously into the borehole at the rate of 12 cu.m/hour. At the flow velocity v^{IV} this water volume proceeds along a surface of

$$F = \frac{Q}{v^{IV} \cdot 0{,}003} = 15\,800 \text{ sq.m}$$

area. The probable divergence of dyed water in the vertical and horizontal sense was estimated to show a ratio 1 : 1,5, on the basis of figure 3 obtained by vector construction. From this ratio a dye surge passing with 170 m width and at 110 m depth has been estimated in the vicinity of the feeding borehole.

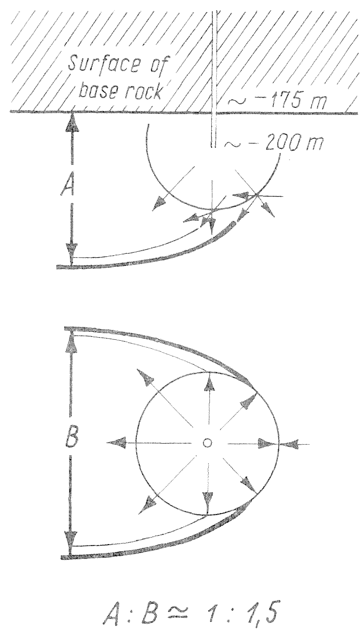

Fig. 3 — Ratio of divergence of the dye surge in the vicinity of the feeding well.

As will be seen from figure 4 a dye surge of these dimensions necessarily passed the surroundings of almost every water inrush observed. (For tracing the flow lines shown in the figure, data from observation wells in the wider environment of the test area were also used.)

About one-half of the total amount of fluorescein introduced into the formation is estimated to have appeared in the watersamples. Since the other half is likely to appear over an extended period at a concentration weaker than the observable threshold, to have been retained in areas of stagnation, or to have been absorbed finally, it is felt that most of the material introduced can be accounted for.

The velocities obtained by the test described above and the frontal passage of flow observed are characteristic primarily of karstic dolomite, which contains water under a high piezometric head. In limestone the fault lines are widened under the dissolving effect of water, to which limestone offers a reduced resistance, and the pattern of faults is then the factor governing the pattern of flow.

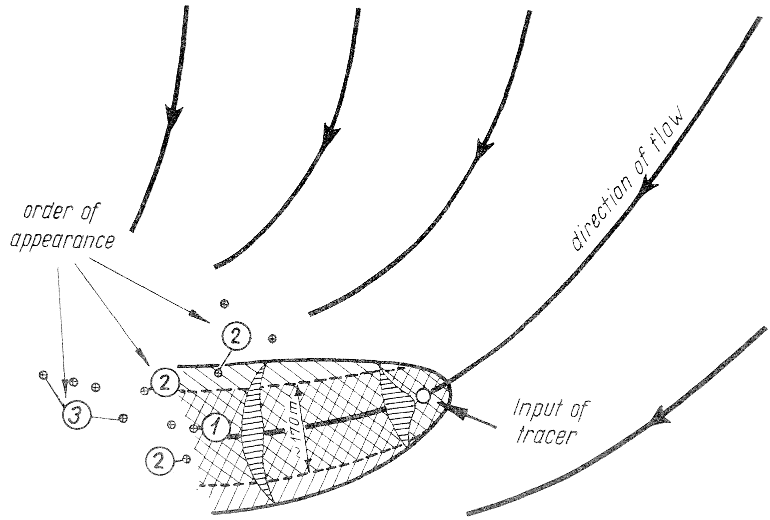

Fig. 4 — Passage of the fluorescein wave.

Shafts and boreholes sunk into karstic water bearing formations with the aim of obtaining water from them should be located in tectonically more active, more fractured and cavernous areas, since no high yield can be anticipated unless wide joints permitting the development of high-velocity ranges are present. The fractured, cavernous rock zone around the well sunk into a karstic formation performs the same function as the gravel filter around a well in a porous aquifer, or as the filter structure formed around the well by development.

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