Skibitzke and Robinson—DISPERSION IN GROUND WATER FLOWING THROUGH HETEROGENEOUS MATERIALS—Geological Survey Professional Paper 386-B

Dispersion in Ground Water Flowing Through Heterogeneous Materials

GEOLOGICAL SURVEY PROFESSIONAL PAPER 386-B

Prepared on behalf of the U.S. Atomic Energy Commission

Dispersion in Ground Water Flowing Through Heterogeneous Materials

By H. E. SKIBITZKE *and* G. M. ROBINSON

CONTRIBUTIONS TO PROBLEMS OF RADIOACTIVE WASTE DISPOSAL

GEOLOGICAL SURVEY PROFESSIONAL PAPER 386-B

Prepared on behalf of the U.S. Atomic Energy Commission

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1963

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

668729—63

DISPERSION IN GROUND WATER FLOWING THROUGH HETEROGENEOUS MATERIALS

By H. E. Skibitzke and G. M. Robinson

ABSTRACT

Laboratory studies of dispersion in water flowing through porous media show that the heterogeneity of the medium is the dominant dispersive factor. All other factors have insignificant effects on dispersion.

INTRODUCTION

Man has always discharged wastes on or in the ground, so contamination of ground water by wastes is not a new problem. The amount of wastes of all kinds, however, is increasing rapidly. This increase and the recent appearance of radioactive wastes, which are being disposed of directly or indirectly into ground-water systems, make it essential to learn in detail the nature of ground-water movement and the rates and directions of flow at specific locations.

The direction of ground-water flow, according to classical concepts, is perpendicular to the equipotential lines (lines connecting points of equal head) in an aquifer. This is literally correct, however, for only perfectly homogeneous granular, porous materials. In real aquifers, all of which contain inhomogeneities, the actual microscopic flow pattern is very complex in detail, and the directions of flow diverge from the hydraulic-potential gradients. This causes wide dispersion of water-soluble and -miscible liquids that enter an aquifer.

Determination of equipotential lines is relatively simple compared to the determination of real flow lines, because the principles by which equipotential values may be determined are much simpler than those which govern the direction of flow. Ground-water hydrologists generally have concerned themselves largely with lines of equal potential, but the advent of waste-disposal problems requires a change of emphasis.

DISPERSION PHENOMENA

Many investigators have used tracers to determine directions of ground-water flow. As early as 1899, Slichter (1899) reported experiments with tracers, but since then very little knowledge has been gained about relations between direction of flow and hydraulic gradient.

Recently, many investigators have studied dispersion in ground water. They have observed the spread of waste liquids in the vicinity of waste-disposal wells, for example, and have found that the spread far exceeds that which would be predicted by classical hydrodynamics. One notion is that chemical diffusion, compounded by flow around sand grains in an aquifer, causes dispersion. Experiments by the writers, however, show that such is not the case.

In many of the recent laboratory experiments the dispersion was much too great to be accounted for by diffusion and flow around sand grains. This conclusion necessitates analysis of the precise meaning of the permeability coefficient in Darcy's law. Many writers have noted that the permeability coefficient actually is a tensor quantity, though it is generally applied as a scalar. Permeability being a tensor, rather than a scalar, would account for a difference between the direction of flow and the direction of the maximum hydraulic gradient. However, the explanation of extensive dispersion is more involved because streamlines do more than simply bend; they also diverge. Divergence of streamlines is the principal concern in this discussion.

In most laboratory tests reported in the literature, observed dispersion in homogeneous media can be attributed to disturbing unnatural factors, such as differences in the chemical composition and physical characteristics of the tracer and the liquid, or to the physical and physico-chemical properties of the permeable material used in the experiments. Tracers having greater viscosity than the liquid (such as colored glycerin) or tracers of greater density (such as an aqueous solution of dye) seem to introduce excessively disturbing conditions in the experiments. To overcome difficulties of that sort, we used a radioactive-tracer solution which had the same viscosity, density, and other properties as the liquid (Skibitzke and others, 1961).

In the experiment, a dilute solution of nonradioactive phosphoric acid was allowed to flow through a porous block of artificially cemented homogeneous sandstone. Flow was maintained for about 1 month to bring the solution into ion-exchange equilibrium with the solid block. A tracer solution then was introduced through a small hollow needle near the input end of the block. The tracer was phosphoric acid which contained radioactive phosphorous but was otherwise physically and chemically identical with the liquid flowing through the block. By isotropic exchange along the filament of tracer solution downstream from the point of injection, radioactive phosphorus replaced some of the stable phosphorus which had been adsorbed on the sand grains. After 6 weeks of continuous flow with the tracer present, the block was cut into several slices and the distribution of radiophosphorus was determined. Analysis with radiographic film and with radiation counters showed that the sand grains actually retard diffusion rather than accelerate it. That is, diffusion was less than would be expected in a body of free water. Thus, strong dispersion in porous material does not seem to be caused by diffusion.

EFFECTS OF HETEROGENEITY

In additional experiments, we observed dispersion in models of heterogeneous media. Several hydraulic models, having various sizes and width-to-length ratios, were built by cementing sand with epoxy resin to form an artificial sandstone. All the finished models were less than 4 feet long and 2 feet wide and were about 2 inches thick. Heterogeneity was introduced before cementing the blocks by embedding bodies of coarse sand in a matrix of fine sand or by embedding bodies of fine sand in a matrix of coarse sand. Most of the embedments were sinuous channels, U-shaped in cross section, and with depths less than one-third the thickness of the model (fig. 1). Glass plates, cemented along the top and bottom of the sandstone model, permitted direct observation of saturated flow. By cementing the glass to the sand, we avoided the boundary effects that have distorted the flow patterns in many experiments. Liquid was permitted to flow through the completed model, and small streams of dye were injected in the flow field at upstream points. Although physical properties of a dye may cause some dispersion, dye tracer permits visual comparison of phenomena in homogeneous and heterogeneous materials. Flow velocities approximating 20 feet per day were within the range of velocity of ground water under average natural conditions in similar materials.

A typical example of wide dispersion caused by heterogeneity is shown in plate 1. The model was about 4 feet long and about 1 foot wide. In cross section, the shape of the embedments was much like those illustrated in figure 1, and they were much higher in permeability than the matrix. The two dye-injection points were near the inflow edge of the model. Red dye was introduced at one point and green at the other. During the experiment, dye spread through nearly the whole width of the model by the time it reached the downstream end.

The process by which the dye spreads is analogous to the process by which an influent stream recharges an aquifer, or by which effluent ground water feeds a stream (fig. 2). The position of the streamline which separates recharge flow from through flow (represented by the heavy line in figure 2) depends on the rate of recharge or discharge in the region of high permeability compared to the rate of flow in the part of the matrix with through flow. The curve representing any streamline is asymptotic to a straight line parallel to the direction of through flow. Highly permeable channels in the model shown in figure 1 carried liquid at a much higher velocity than did the adjoining less permeable

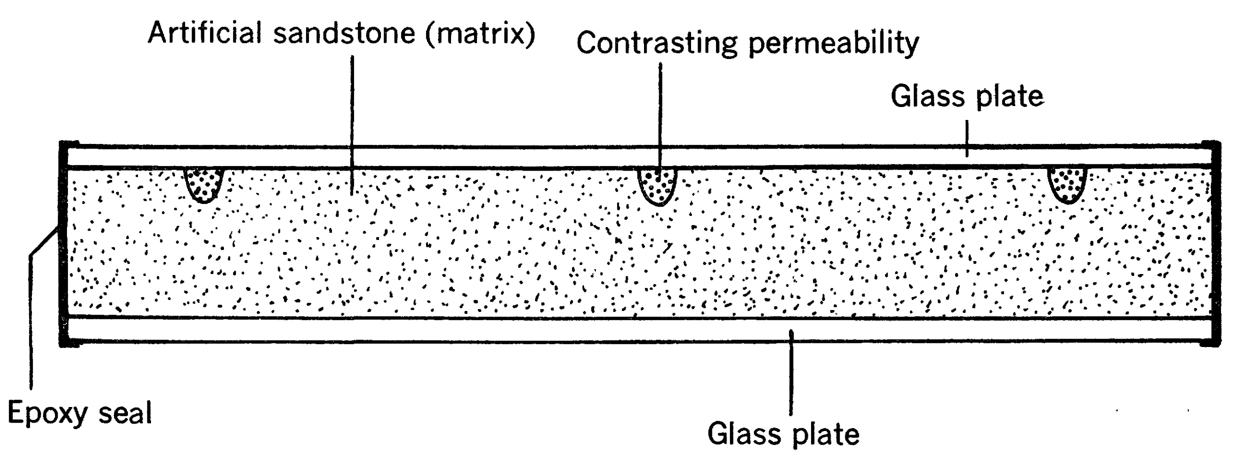
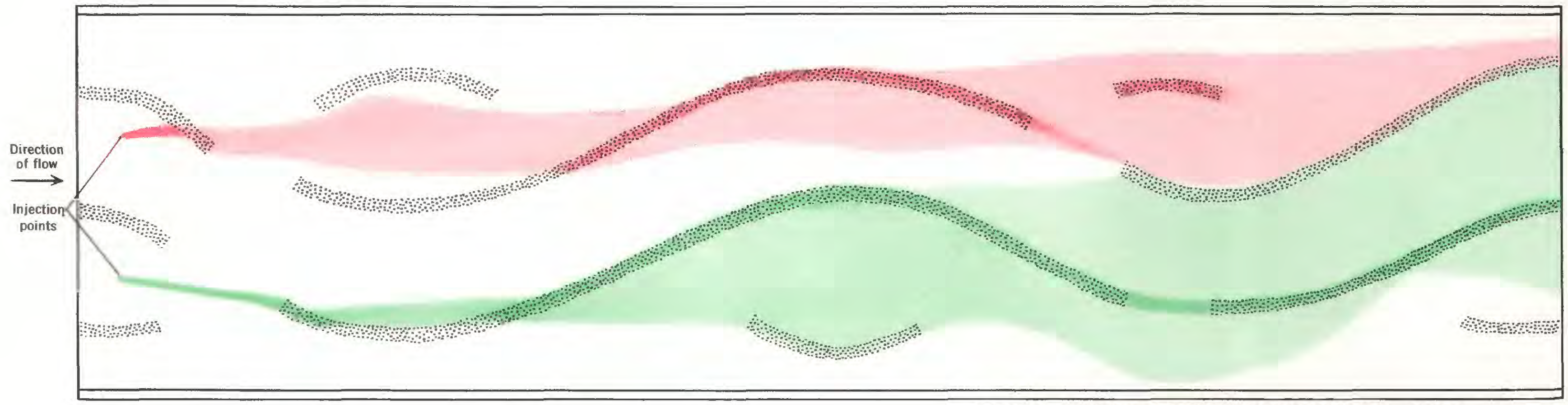


FIGURE 1.—Typical cross section of sandstone models used for studying effects of heterogeneity on dispersion. Section transverse to direction of fluid movement.



INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—62293

TYPICAL DISPERSION OF DYES IN A MODEL WITH HETEROGENEITY

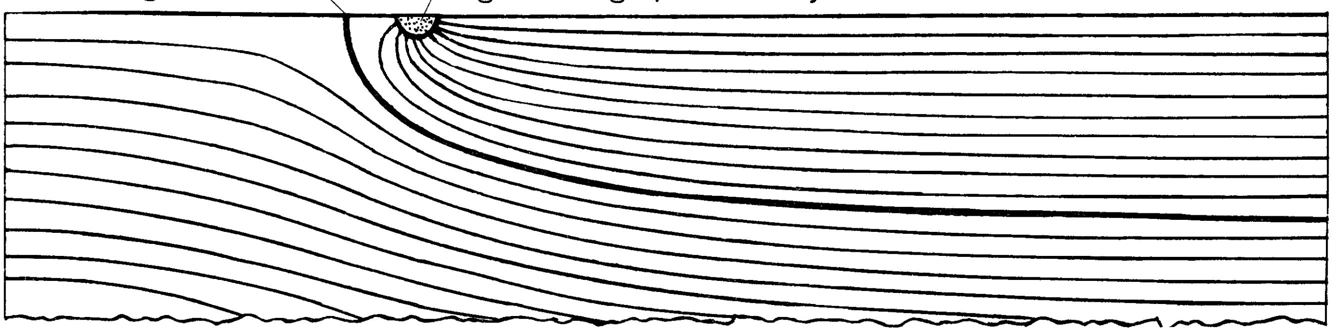


FIGURE 2.—Section showing theoretical flow lines near a region of high permeability. General direction is to the right if head is relatively high or to the left if relatively low in the region of high permeability.

matrix. Liquid flowed from the model matrix into the channel and from the channel into the matrix. Thus, dyed liquid that had entered the channel recharged the less permeable matrix along much of the channel length, thereby spreading dye through most of the matrix.

Figure 1 shows dispersion created by long sinuous zones of high permeability which are alined with the general direction of flow. Further studies are in progress with models having highly permeable zones of shorter length, different shapes, and various orientations with respect to the direction of flow.

Flow lines are known to refract at heterogeneity boundaries; and in tests in which refraction alone was analyzed it was shown that a large angle of refraction at the boundary between materials of contrasting permeability accelerated spreading of the dye. In all our experiments the effect was always the same: once the dye entered a region of contrasting permeability, dispersion was widespread.

The experiments are being continued, and the observations made to date are being analyzed to determine the quantitative relations among the degree of dispersion, the hydraulic characteristics of the matrix and of the imposed heterogeneities, and the rates of flow in the system. Quantitative knowledge is prerequisite to forecasting the spread of waste materials which enter the zone of saturation.

REFERENCES CITED

Skibitzke, H. E., Chapman, H. T., Robinson, G. M., and McCullough, R. A., 1961, Radiotracer techniques for the study of flow in saturated porous materials: Internat. Jour. Appl. Radiation and Isotopes, v. 10, no. 1, p. 38–46.

Slichter, C. S., 1899, Theoretical investigation of the motion of ground waters: U.S. Geol. Survey 19th Ann. Rept., pt. 2, p. 285–394.

O