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Impact of highly permeable sediment units with inclined bedding on solute transport in aquifers

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Abstract

Investigations in outcrops of non-homogeneous gravel deposits in north-eastern Switzerland by Jussel et al. [Jussel P, Stauffer F, Dracos T. Transport modeling in heterogeneous aquifers: 1. Statistical description and numerical generation of gravel deposits. Water Resour Res 1994;30:1803–17] revealed distinct sedimentary structures or facies elements appearing as more or less horizontal lenses and layers embedded in extended patches of background gravel material. One of the observed sediment units consists of highly permeable inclined sequences of gravel layers. This inclination manifests itself as a strong anisotropy of the hydraulic conductivity with inclined principal directions. In this paper, the role of highly conductive sediment units with inclined bedding is investigated by a series of three-dimensional numerical flow and advective transport experiments. A typical single lens with inclined principal axes of the hydraulic conductivity tensor is investigated, which is embedded in homogeneous background matrix material. Particle tracking shows pronounced lateral (horizontal and vertical) distortions of the flow path depending on the angles of the bedding of the lens. The results allow better understanding of the flow and transport phenomena that are finally responsible for macrodispersion effects in similar gravel aquifers.

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1. Introduction

The topic of this paper is the investigation of the role of one class of sediment units on the transport of solutes in aquifers. Sedimentary structures of natural sandy gravel deposits in north-eastern Switzerland were described and statistically analyzed by Jussel et al. [6]. Freshly excavated outcrops in gravel pits revealed distinct sedimentary structures appearing as lenses and layers, mostly embedded in a background gravel matrix. Hydraulic properties of the different components of the sedimentary structures (hydraulic conductivity and porosity) were determined in the laboratory from disturbed and undisturbed samples. The data showed large differences in hydraulic conductivity among the different components of up to five orders of magnitude. The gravel material mainly consisted of sandy gravel without silt (grey gravel) and with silt (brown gravel), well sorted sand, little silt, and well sorted extremely permeable coarse gravel (open framework gravel). Two sediment units consisted of alternate layers of different materials. One of them is formed by inclined alternating sequences of open framework/bimodal gravel layers forming couplets. The layer thickness of these sequences was of the order 0.1 m. Bimodal gravel material is characterized by its distinctly bimodal grain size distribution. The other sediment unit with alternating layers consisted of horizontal or inclined brown and grey gravel layers forming extended patches. Fig. 1 shows an example of the detected sedimentary structures from the Huentwangen gravel pit (Rhine valley near Zurich, Switzerland). All sediment units were specified by statistical parameters (mean and variance) defining the lens

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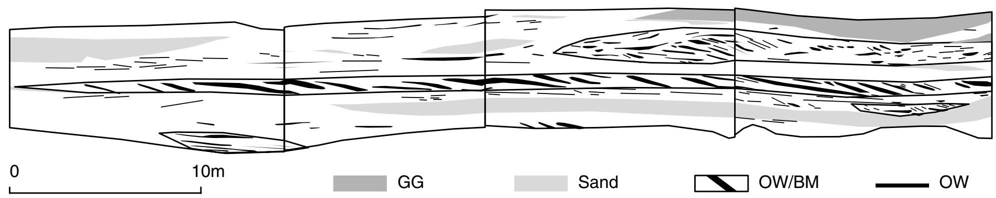

Fig. 1. Sedimentary structures detected in the Huentwangen gravel pit (Rhine valley near Zurich, Switzerland); OW: open framework gravel; BM: bimodal gravel; GG: grey gravel; the background gravel consist of GG/BM and BG (brown gravel) structures, which are not distinguished in the graph (after [8]).

length, the lens height, the direction of the principal axis of the lens with respect to the former flow direction of the sedimenting river, the hydraulic conductivity tensor, the porosity, the local dispersivity, and geostatistical parameters. A weak spatial variability of hydraulic conductivity was present within each single lens of a given type of the sediment unit. A much higher variability was found between different lenses of the same type. Finally, an even wider variability was present between different types of sediment units. The open framework gravel material caused the probability density function of log-hydraulic conductivity in the overall gravel material to be bimodal [6]. All other gravel material together approximately fitted a log-normal distribution. Open framework gravel is present as relatively short and thin, horizontal or inclined single lenses or appears in groups of inclined open alternating framework/bimodal gravel layers.

Jussel et al. [7] and Stauffer and Rauber [8] used the detailed statistical information on sediment units geometry and the hydraulic parameters to numerically generate unconditional realizations of synthetic block-shaped facies type aquifers. The procedure is briefly reviewed here since it represents the starting point for this paper. It was assumed that the sediment units 'grey gravel', 'brown gravel' and mixtures of both (layered or not) represent the matrix, in which lens-type elements (single open framework gravel lenses, sand lenses, inclined alternating sequences of open framework-bimodal gravel layers [OW/BM couplets], inclined alternating sequences of grey gravel/brown gravel layers [GG/BG couplets], and silt lenses) are embedded. Layered sequences like the OW/BM couplets were modeled as anisotropic media. A lens shape was approximated in their model by an ellipse in the plan view and by a power function in the vertical cross-section. The sediment units were generated as follows:

(1) Generation of the matrix-type sediment units, starting with the background matrix. While the grey gravel/brown gravel structure was considered as the background matrix, pure grey gravel and brown gravel lenses were treated as matrix-type lenses, thus embedded in the background matrix. They were generated by defining the position and the size of each lens. These elements were randomly set allowing no overlapping of lenses.
(2) Generation of the lens-type sediment units by defining the position and the size of each lens. Again these lenses were set at random, excluding any overlapping regions.
(3) The geometric mean hydraulic conductivity values of the lenses of a given sediment unit type were randomly chosen according to the corresponding global mean and variance. Porosity and local dispersivity values were assigned for a given sediment unit.
(4) Assignment of a correlated field of log-hydraulic conductivity within each sediment unit according to the selected mean and the variance.

The model for three-dimensional saturated steady-state flow is based on the flow continuity equation and Darcy's law:

$$\nabla \cdot (\mathbf{K}\nabla h) = 0 \tag{1}$$

where $\mathbf{K}$ is the hydraulic conductivity tensor and h is the piezometric head. Boundary conditions taken into account were either prescribed head or impermeable boundary. Stauffer and Rauber [8] integrated the flow equation by using the Finite Element method. The flow calculation yielded the specific flux field in the entire model domain. The three-dimensional transport model was based on the mass balance equation for a conservative solute, which accounted for the effect of advection and dispersion. The equation was numerically integrated by an adapted Random Walk technique. Stauffer and Rauber [8] performed unconditional stochastic numerical flow and transport experiments using 100 different synthetic block-shaped gravel aquifers of the size $110\ \mathrm{m} \times 35\ \mathrm{m} \times 6\ \mathrm{m}$. The tracer transport problem consisted of observing the evolution of the moments of a tracer cloud represented by 2000 mass particles, initially located in a small area. Apparent macrodispersivity values (longitudinal, transversal horizontal, and transversal vertical) were estimated by analyzing the moments and the breakthrough curves of the tracer cloud at different locations along the mean flow path according to the method as described by Jussel et al. [7]. Results are shown in Fig. 2.

The statistical parameters of the sediment units were used by Stauffer and Rauber [8] to characterize the overall gravel deposit by a single variance and a single horizontal and vertical correlation length of log-hydraulic conductiv-