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Negative correlation between porosity and hydraulic conductivity in sand-and-gravel aquifers at Cape Cod, Massachusetts, USA

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Abstract

Although it may be intuitive to think of the hydraulic conductivity K of unconsolidated, coarse-grained sediments as increasing monotonically with increasing porosity Φ, studies have documented a negative correlation between these two parameters under certain grain-size distributions and packing arrangements. This is confirmed at two sites on Cape Cod, Massachusetts, USA, where groundwater investigations were conducted in sand-and-gravel aquifers specifically to examine the interdependency of several aquifer properties using measurements from four geophysical well logs. Along with K and Φ, the electrical resistivity R_0 and the natural gamma activity γ of saturated deposits were determined as functions of depth. Qualitative examination of results from the first site implies a negative correlation between K and Φ that is substantiated by a rigorous multivariate analysis of log data collected from the second site. A principal components analysis describes an over-determined system of inversion equations, with approximately 92% of the cumulative proportion of the total variance being accounted for by only three of the four eigenvectors. A subsequent R-mode factor analysis projects directional trends among the four variables (K, Φ, R_0 and γ), and a negative correlation between K and Φ emerges as the primary result.

Keywords: Geophysical logs; Porosity; Hydraulic conductivity; Granular deposits

1. Introduction

The hydraulic conductivity of granular deposits is generally considered as being dependent upon porosity and sorting. As porosity increases or decreases, the hydraulic conductivity of coarse-grained sediments is thought to monotonically follow the same trend (e.g. Nelson, 1994). Other factors such as grain size and shape, tortuosity, packing arrangement, and pore shape also affect the hydraulic conductivity of these materials. Vukovic and Soro (1992) present an extensive compilation of empirical formulas that consider both porosity and sorting in the computation of hydraulic conductivity. These investigators recommend using the Zunker formula for fine and medium grain-size sand, and the Zamarin formula for large grain sands.

The Zunker empirical formula takes the form

$$K = \frac{g}{\upsilon}\beta_Z\left[\frac{\Phi}{1-\Phi}\right]d_e^2 \tag{1}$$

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and the Zamarin formula is represented by the relation

$$K = \frac{g}{\upsilon}\beta_{ZN}\left[\frac{\Phi^3}{(1-\Phi)^2}\right]d_e^2 \qquad (2)$$

In Eqs. (1) and (2), K, hydraulic conductivity (L/T); g, gravitational constant (L/T^2); ν, kinematic viscosity (L^2/T); Φ, total porosity (dimensionless); β_Z, empirical coefficient based on sorting and grain shape (dimensionless); β_{ZN}, empirical coefficient based on porosity (dimensionless); and d_e, effective grain diameter (L). Other empirical investigations have shown that grain size is the fundamental independent parameter that controls hydraulic conductivity in unconsolidated sediments (e.g. Hazen, 1911; Pryor, 1973). Shepherd (1989) summarizes this work with the expression

$$P = Cd^2 \qquad (3)$$

where P is the permeability (L^2), d is a representative grain size (L), and C is a dimensionless proportionality constant. This constant may encompass a variety of factors, including path tortuosity and particle shape.

Experimental studies of grain packing (Fraser, 1935) and grain-packing models based on mixed grain-size populations (Marion et al., 1992; Kolterman and Gorelick, 1995) have demonstrated that the porosity of a granular material varies with the volume fraction of fines (Fig. 1) and that it reaches a minimum value, Φ_{min}, when the volume of fine-grained particles equals the porosity of the coarse-grained particles. At this stage, the fines fill much of the void space produced by the packed coarse grains. As the fines content continues to increase to the right of the inflection point, Φ_{min} (Fig. 1), the larger grains become suspended in the accumulating mix of fines. At this subsequent stage, the representative grain diameter, d, decreases but the porosity increases. Moreover, this decrease in d occurs at a faster rate than does the corresponding increase in Φ. Consequently, if the hydraulic conductivity of a granular material is based predominantly on grain size (Eq. (3)), K may decrease with increasing porosity under changes in grain-packing schemes. Although the relation presented in Fig. 1 was developed for a mixture of two distinct grain sizes, it has been recognized in real field samples (Graton and Fraser, 1935; Beard and Weyl, 1973; Clarke, 1979).

In the work reported herein, this negative correlation between porosity and hydraulic conductivity in granular deposits is examined through the multivariate analysis of geophysical log data. Logs were obtained in shallow wells at two sites on Cape Cod, Massachusetts, to help characterize the local sand-and-gravel aquifers prevalent throughout the

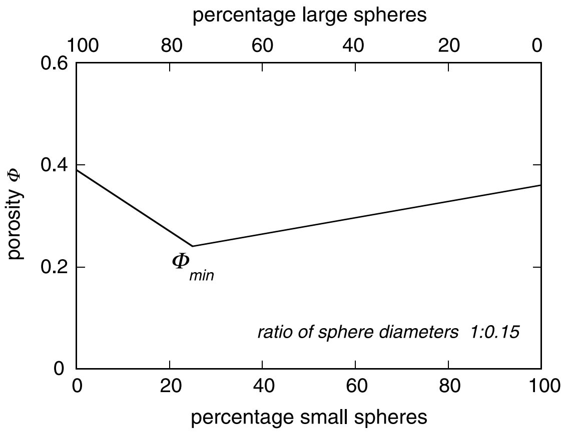

Fig. 1. Illustration of packing effect on porosity (modified from Fraser, 1935).

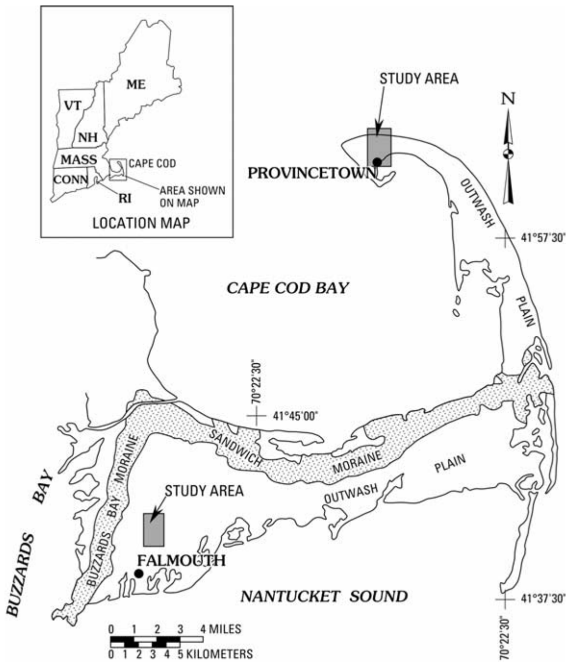

Fig. 2. Location of two study sites on Cape Cod, Massachusetts.