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Assessment of the value of microgravity to estimate the principal directions of the anisotropic transmissivity of aquifers from pumping tests: A study using a Hough transform based automatic algorithm

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ABSTRACT

Estimation of the hydraulic parameters of an aquifer is usually performed via interpretation of pumping tests. This invasive method requires drilling both pumping and observation wells. As the process is expensive, only a single pumping well and one or two observation wells or piezometers are generally drilled, at most. The interpretation is done assuming aquifer isotropy and homogeneity. However, in many aquifers, horizontal anisotropy in hydraulic conductivity greatly affects the flow regime. Its disregard may lead to important misinterpretations, especially for environmental impact assessments. This paper studies the capabilities of gravity for the identification and determination of the principal directions of anisotropy. This has been automatized using a methodology based on the Hough Transform. The results show how a microgravity survey could be an adequate and relatively cheap monitoring tool for the identification of anisotropy. This is valuable information that can be used in the decision making process for performing or discarding additional studies. Even more, the presented methodology can be extended to other studies in which contour maps are used to identify directionality in any process or property.

1. Introduction

This work focuses on how microgravity can help identifying the presence of horizontal anisotropy in the hydraulic conductivity of unconfined aquifers subject to pumping tests. As pumping implies a change in the mass of water beneath the surface, the associated gravity anomaly on that surface contains relevant information regarding groundwater flow distribution, including anisotropy. When a pumping test is performed in an anisotropic aquifer, the drawdown cone shape differs from the radial symmetric pattern characteristic of isotropic conditions. Under this scenario the conventional configuration with one or two observation points is unable to capture precisely the shape of the depression cone. However, anisotropic conditions lead to a directional distribution of water in the subsurface that can be sensed by a geophysical technique sensitive to underground mass variations, as gravity is. The new gravity meters allow monitoring the changes caused by water being pumped from unconfined aquifers. This information can be extracted provided the signal to noise ratio is sufficiently high. In this article an automatic technique based on the Hough transform is used to estimate the horizontal principal directions of the permeability tensor.

Hydraulic conductivity, K (m/s) is defined as the flow per unit area produced by a hydraulic head gradient whose value is one. It quantifies the idea of resistance to the flow of groundwater through a porous medium. Transmissivity, T (m^2/s), is a related concept useful for horizontal aquifers. It is defined as $T = K \cdot b$, where b is the saturated thickness of the aquifer and conveys the idea that, for a producing well, it is important both the amount of water delivered specifically through each unit section (K) and the number of those vertical unit sections that are contributing, that is, b, the saturated thickness.

The hydraulic conductivity is meant to convey a linear relationship between the flow vector and the hydraulic gradient vector -what is called Darcy's law- and has, therefore, a tensorial character. The anisotropic case arises whenever certain directions are able to transmit different flow rates under the same hydraulic gradients.

Local vertical anisotropy ratios on the order of 100:1 have been reported to be common in the field (Freeze and Cherry, 1979). This article deals instead with horizontal anisotropy, for which ratios (K_{max}/K_{min}) can reach values of 20:1 (i.e. Kruseman and de Ridder, 1990). In case of passing unnoticed, this horizontal anisotropy can produce real environmental problems because, when pumping is performed in an anisotropic aquifer, the drawdown cone has an elongated shape and influences farther in the direction of higher transmissivity than it does in an isotropic aquifer (Ferré and Thomasson, 2010). So, saltwater intrusion problems in coastal aquifers, errors in the estimation of the time of migration for groundwater contaminants or issues from the poor design of capture zone networks may arise.

Horizontal anisotropy is widespread. Anisotropy is common in geological systems because they have been formed under natural

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processes characterized by directionality (e.g. water or wind flow, tectonic processes). Nevertheless, anisotropy can also emerge from smaller scale characteristics.

Rocks usually show structures spanning a broad range of scales, from the mm scale to the km scale and higher. It has been shown that sedimentary features at the smallest scales, such as mm thick laminations, can have a significant impact on the flow patterns established by a producing well at the scale of hundreds of meters (e.g. Pickup et al., 2005). Accordingly, the hydraulic conductivity inferred from a pumping test and defined, therefore, at the pumping well scale, depends on its values defined at smaller scales and should be consistent with them. There is a cross-talk between spatial scales (see Fig. 1).

To meet this consistency requirement, strategies to up-scale the permeability tensor from the smaller scales to the larger ones, like the pumping well scale, have been developed (Durlofsky, 1991; Wen and Gómez-Hernández, 1998; Renard and de Marsily, 1997; Farmer, 2002; Sanchez-Vila et al., 2006).

The underlying small scale features show up, in the up-scaled tensor, as non-zero non-diagonal cross-flow terms. These non-diagonal terms imply the existence of flows in directions perpendicular to those of the acting hydraulic gradients. Anisotropy, therefore, may also arise whenever large scale representative volumes are employed in practice using up-scaled permeabilities (Pickup and Hern, 2002) that involve the influence of the smaller scale geological structure (Weber, 1980; Van den Berg and De Vries, 2003).

The purpose of building accurate groundwater numerical models also supports the need to characterize the anisotropy at the pumping well scale. These models are fed with the hydraulic parameters obtained, for instance, from pumping tests and defined, therefore, at a spatial scale compatible with the characteristic length of the basic mesh elements spanning tens to hundreds of meters.

In many field studies and for modeling purposes it is common the use of the concept of hydrofacies (Anderson, 1989; Poeter and Gaylord, 1990) defined as a homogeneous but anisotropic geological unit that is hydrogeologically meaningful. Fractured media, also, can behave like an equivalent anisotropic porous media when satisfying some characteristics (Long et al., 1982; Smith and Schwartz, 1984; Lebbe and De Breuck, 1997).

Due to the above reasons prior knowledge of the principal directions of permeability for adequate (at least approximated) orientation of the model is extremely relevant.

In real field practice, pumping tests are the most common field technique to estimate transmissivity. Usually, isotropy and radial symmetry are assumed for interpretation. However, as explained above, horizontal anisotropy is very relevant.

Solutions for analyzing pumping tests in aquifers with horizontal anisotropy have been developed in the past (Papadopulos, 1965; Hantush, 1966a, 1966b; Hantush and Thomas, 1966; Way and McKee, 1982; Neuman et al., 1984; Hsieh and Neuman, 1985; Hsieh et al., 1985; Mutch, 2005; Heilweil and Hsieh, 2006; Fitts, 2006; Mathias and Butler, 2007). These solutions require a number of observation wells or piezometers that cannot be accomplished in many practical field studies due to economic or logistic reasons. In addition of being expensive, wells are intrusive and destructive, disturb the textural characteristics of the geological media and can create a preferential flow path for contaminant transport and communicate multilayer aquifers.

Prior knowledge of the existence of anisotropy and of its approximate principal directions is important to reduce the number of wells needed and to correctly place them. This goal can be approached by direct geological observation but, when direct access is not possible, data from geophysical surveys (e.g. Ritzi and Andolsek, 1992; Sandberg et al., 2002) may constitute valuable additional sources of information. In this article, microgravity is used for that purpose.

The use of geophysical techniques to provide quantitative information on hydrogeological parameters and processes developed swiftly during the last twenty years (e.g. Rubin and Hubbard, 2005; Binley

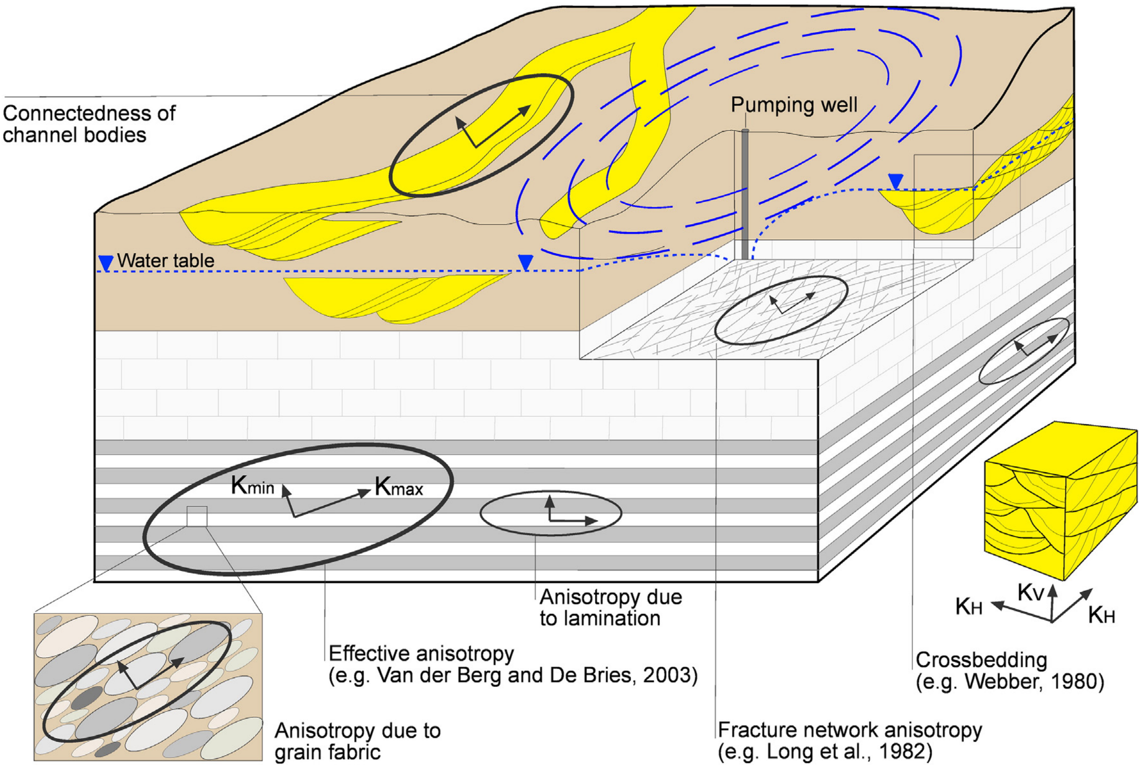

Fig. 1. This figure illustrates how anisotropy is present at different scales. The anisotropy at the pumping well scale (blue elliptic isolines) may capture the presence of palaeochannels well-connected in one direction or of a fracture network with a preferential orientation. Also, in an otherwise homogeneous environment, anisotropy emerges from the smaller scale directional behaviors (grain fabric anisotropy; laminations, crossbedding). The problem here studied is, therefore, widespread in real applications. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)