Advances in Water Resources 32 (2009) 1170–1179

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Insights from numerical modeling on the hydrodynamics of non-radial flow in faulted media

Silvain Rafini *, Marie Larocque

Centre de recherche pour l'Étude et la Simulation du Climat à l'Échelle Régionale, Département des sciences de la Terre et de l'atmosphère, Université du Québec à Montréal, Case postale 8888, Succursale Centre-ville, Montréal (Qc), Canada H3C 3P8

ARTICLE INFO

Article history:
Received 21 November 2008
Received in revised form 21 March 2009
Accepted 27 March 2009
Available online 5 April 2009

Keywords:
Faults
Flow
Aquifer
Groundwater
Numerical modeling
Pump test

ABSTRACT

The objective of this work is to explore the use of flow dimensions as a tool for characterizing hydraulic conditions in faulted media. Transient flow is numerically simulated in synthetic vertically-faulted reservoirs. Analysis of the obtained time series following the Generalized Radial Flow (GRF) model displays combined radial and fractional signals with a flow dimension $n = 1.5$. Investigating the transient geometry of the frontal equipotential surface shows that fractional flow occurrence is due to abnormal fault diffusion as a consequence of water supply from the matrix under specific conditions. An original hydrodynamical explanation for fractional flow in vertically faulted media is suggested, along with a reinterpretation of the bilinear regime. It is shown that the GRF theory remains valid in such discontinuum as the fundamental relationship between n and the cross-flow area is satisfied. These results provide insights in the use of the flow dimension as a hydraulic diagnostic tool in faulted media.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Investigating the hydrodynamic behaviour of naturally fractured and faulted reservoirs is a major challenge in several applied and fundamental research fields including prospection and exploitation of hydrological [3,37], geothermal [20,23], and petroleum [36] resources, radionuclide in-situ repository evaluation [17,28,31], and contaminant hydrology [19,24].

In discontinuous media, the stochastic or deterministic representation of geometrical properties of the hydraulically active structures and flow paths is a key point and a particularly hard task. It is nevertheless required for a proper determination of hydraulic parameters. The alternative and commonly adopted continuum approximation minimizes flow heterogeneity and neglects preferential pathways, resulting in underestimation of the flow abilities of the conductive structures and causing major errors in the evaluation of the potential of underground reservoirs.

Characterizing the hydraulic properties of natural reservoirs first requires knowledge of the flow geometry. A proper determination of the conceptual flow model allows adjustment of natural transient responses on adequate theoretical signals, which leads to a more realistic estimation of local and/or global hydraulic parameters. It has been reported since the late eighties that conventional models are inadequate in reproducing behaviours obtained from transient testing performed in discontinuous media [9]. This inadequacy has led authors to develop variations on the conventional approaches in their search for a proper representation of the natural data sets obtained in site characterization studies. Such extension was achieved in the GRF (Generalized Radial Flow) model introduced by Barker [5]. The GRF model is a continuum in which drawdown does not necessarily evolve in two dimensions during the transient test (pumping or injection). The flow dimension n, which can take any integer or non-integer value comprised between one and three, is defined as:

$$A(r) \sim r^{n-1} \tag{1}$$

where $A(r)$ is the cross-flow area (i.e., the frontal equipotential surface), and r the radial distance from the source. The case $n = 2$ corresponds to the conventional radial behaviour while flow conditions for which n is different from two are referred to as non-radial conditions.

Numerous field studies have reported that non-radial theoretical behaviours are efficient in representing flow conditions in complex hydrogeological media including discontinuous reservoirs [1,25–27,30,38]. However the GRF model is not widely used because (1) the physical significance of fractional flow conditions remains enigmatic; and (2) in practice, n is not constant during transient tests, which causes difficulties in the use of this model on larger-scale analyses as it involves the superposition of several continuum conceptualizations.

* Corresponding author. Tel.: +1 5149873000x1515.
E-mail addresses: rafini.silvain@courrier.uqam.ca, silraf@hotmail.com (S. Rafini).

0309-1708/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.advwatres.2009.03.009

The objective of this work is to explore the use of flow dimensions as a diagnostic tool for characterizing hydrodynamics in faulted media. This paper presents results from numerical simulations of three-dimensional transient flow within synthetic faulted reservoirs. Time-variant geometries of the frontal equipotential surface are analyzed along with the directional and mean diffusion behaviours. Results are compared to the flow dimensions determined in accordance with the GRF model, and fractional flow dimensions are interpreted in terms of hydrodynamic interrelationships between the fault and its surrounding conductive matrix.

2. Background

2.1. Non-radial flow behaviours

Analytical solutions for non-radial transient flow conditions were developed for faulted reservoirs (i.e., cross-cut by a major discontinuity) and fractured reservoirs (i.e., made up of variously sized fractures sets). Theoretical hydraulic responses for faulted reservoirs typically combine linear and bilinear behaviours [2,14,33,36]. For fractured reservoirs, available solutions include fractal network models [1,12] and channel networks formed by fractures intersections [13], which can be regarded as a fractal network according to Billaux [7] and Leveinen [29].

In terms of flow geometry, radial behaviour conventionally relates to conditions where the relationship $A(r) \sim r$ is satisfied anytime during the transient test. This implies that the transient flow geometry evolves in two dimensions. In homogeneous isotropic media, this refers to cylindrical equipotential surfaces. In less ideal media (anisotropic, heterogeneous), it relates to any irregular shape of equipotential surfaces as long as this shape remains unchanged during the hydraulic test. For instance, pumping tests in an anisotropic homogeneous reservoir will lead to radial flow since the eccentricity of the elliptic cross-flow area remains constant. Finally, in Euclidean geometry a fractional flow dimension necessarily implies a time-changing shape of the frontal equipotential surface during the transient test.

Integrating Eq. (1) in the range $[0,r]$ leads to the power-law relationship between the cumulative length of hydraulic structures (i.e., the mass) and the observation scale, with the exponent equal to n. For fractional values of n, dividing the mass by the embedding volume leads to the scale effect that is characteristic of fractal media [12]: density decreases as investigation scale increases. Fractional dimension behaviours are thus frequently associated to fractal hydraulic properties of the reservoir [6,12,17,26], although the fractal approximation on natural deformation patterns is still controversial [32]. The use of fractal models is restricted by the limited number of magnitude orders over which it can be applied to real networks. Chang and Yortsos [12] showed that these finite size effects rapidly mask the fractal hydraulic response. In real conditions, this statistical distribution could be efficient only within a short range of domain sizes [21], such that lower and upper cut-off sizes may be practically too close to allow fractal responses to occur.

Chilès and de Marsily [13] and Leveinen [28] suggest that the fractional dimension of flow relates to a deficit or excess of connections into the channel network formed by fracture intersections. This interpretation actually lies into the frame of fractal theory since the density of such a channel network is linked by a decreasing power law relationship with r.

Following the analogy with linear heat flow problems, Doe [16] suggests that the variable-flow area conditions introduced by Barker [5] in the GRF model lead to a flow problem similar to that of a constant-flow area medium with conductivity changing as a power function of the radial distance r. This property actually meets the fractal theory. Alternatively, Doe [16] emphasizes that fractional flow behaviours can be induced by any hydraulic structure with geometric properties generating a time-variant cross-flow area with respect to Eq. (1), regardless of the fact that the source is cylindrical. This behaviour is illustrated in Fig. 1 through conveniently shaped theoretical conduits, which hence form the most basic conception of flow structures assuming a non-conductive matrix. This figure displays the linear ($n = 1$), radial ($n = 2$), spherical ($n = 3$) and fractional ($n = 1.5$; this is a particular non-radial regime) flow cases. Barker's model actually refers to any system in which the shape of the frontal equipotential surface varies during the hydraulic test according to a power-law relationship, regardless of the exponent. Cases with an exponent lower than unity (sublinear) or higher than three (hyperspherical) are conceptually possible [16].

2.2. Faulted media models

After the pioneering work of Bixel et al. [8], Gringarten et al. [18] analytically described linear flow within the conductive matrix surrounding an infinitely conductive vertical fault connected to the pumping well. In this particular case, representation of the fault as a planar source leads to a flow dimension equal to one. Cinco-Ley et al. [14] later introduced the concept of bilinear flow, which supposedly occurs in a similar geometrical system accounting for finite fault conductivity. Abbaszadeh and Cinco-Ley [2] extended this concept to systems where the vertical fault is not connected to the source and is pseudo-anisotropic (i.e., distinct but interdependent transversal and longitudinal hydraulic properties). The analysis of Cinco-Ley's theoretical curves accord-

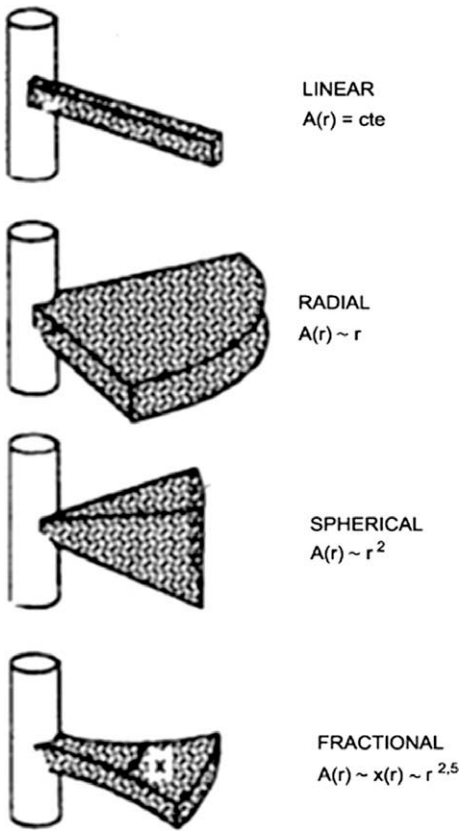

Fig. 1. Interpretation of flow dimensions in terms of flow geometry, from Doe [16]. In this theoretical model, changing cross-flow area directly relates to a specific, and unrealistic, geometry of the conceptual hydraulic conduit.

Download English Version:

https://daneshyari.com/en/article/4526716

Download Persian Version:

https://daneshyari.com/article/4526716

Daneshyari.com