Vertical anisotropy of hydraulic conductivity in fissured layer of hard-rock aquifers due to the geological structure of weathering profiles

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Abstract – Pumping tests carried out in the fissured layer of a granitic hard-rock aquifer, interpreted at the observation wells by means of the analytical solution of Neuman and at the pumping wells with that of Gringarten show the existence of a strong vertical anisotropy of this layer of the aquifer; the horizontal permeability is clearly and systematically higher than the vertical permeability. These results agree perfectly with the geological observations, the fissured layer of the weathered granite profile showing the existence of many sub-horizontal fissures. It confirms that, within the fissured layer, the permeability of sub-horizontal fissures due to the weathering process dominates over that of sub-vertical fissures of tectonic origin.

Keywords: weathering, hard-rock, horizontal fracture, India, anisotropy, pumping test, granite

Abridged English Version

1. Introduction

Hard rock aquifers occupy the first 100 meters from the top [3, 14], that have been subjected to weathering process [18, 19]. The classical weathering profile comprises the following layers, which have specific hydrodynamic properties, from top to bottom (Fig. 1):

- Weathering cover with a thickness of 0 to 5 meters. This layer has high porosity and low permeability. When saturated, this layer constitutes the reserve of the aquifer;
- Fissured zone constituted by fractured hard rock, with a depth-decreasing density of fractures. These fractures result from the weathering process itself [18, 19]: the weathering of micaceous minerals induces expansion and cracks in the rock. In granite, for example, the fractures are parallel to the topography during the weathering phase. This layer assumes the transmissive function in the aquifer;
- Solid basement permeable only locally, where tectonic fractures are present.

When the spatial distribution of these layers with their hydrodynamic properties is understood, methodologies can be developed both for the assessment of groundwater resources and modelling of groundwater flows at the catchment scale [15, 16, 19].

The objective of this paper is to determine the coherence between geological observations and hydrodynamic properties of the aquifer, especially the anisotropy of permeability in the fissured zone.

2. Weathering profile

The Maheshwaram watershed located 30 kilometres South of Hyderabad in India is the main study area of the Indo-French Centre for Groundwater Research (French Geological Survey / National Geophysical Research Institute). Granites constitute the whole basin and the weathering profiles are easily observable through many dug wells used by the farmers for irrigation (Fig. 2). Under a few decimetres of red soils, the weathered layers with a thickness of 0 to 5 meters cover the fissured zone. A high density of horizontal fractures is observed in the fissured zone as illustrated by the picture in Fig. 2. Vertical fractures with a tectonic origin are also present. Due to the strong exploitation of groundwater resources, water levels are far below ground level and the weathered layers are dry while only the fissured zone is saturated. This allows us to test specifically this layer through pumping tests.

3. Vertical anisotropy of the fissured zone

Two pumping tests were carried out at constant discharge rates. Drawdowns in observations wells are interpreted by the Neuman [12] method while drawdowns in the pumping wells are analysed using the theory of the horizontal fracture developed by Gringarten [5].

3.1. Neuman method at observation wells

The theory initially developed by Boulton [1] to interpret some unusual drawdown curves obtained in the observation wells (see Fig. 3) takes into account the notion of « delayed yield from storage in unconfined aquifers » [2]. It was improved by Neuman [11, 12] who developed an analytical solution adapted to anisotropic unconfined aquifers where K_r is the radial permeability parallel to the aquifer extension and K_z is the vertical permeability. The Neuman solution, available as an abacus, gives reduced drawdowns in an observation well located at a radial distance *r* from the pumping well, $s_{DN} = \frac{4\pi T}{Q}$ as a function of :

- Reduced time $t_s = \frac{Tt}{Sr^2}$ for type A curves;

- Reduced time $t_y = \frac{Tt}{S_y r^2}$ for type B curves;

where T is the transmissivity of the aquifer, S the storage coefficient, Sy the specific yield, t the time since the start of pumping. The application of this method consists in fitting the observed drawdowns on the abacus constituted by two types of curves: type A curve for short times and type B curve for late times (Fig. 3). Both curves are characterised by the same parameter $\beta = \frac{r^2 K_D}{b^2}$, which is a function of the permeability anisotropy $K_D = \frac{K_Z}{K_r}$, the thickness of the aquifer b and the distance r between the observation and pumping wells.

The application of this method (Table I) to the observation wells IFP-1/1, IFP-1/2 and IFP-9/1 leads to the evaluation of transmissivities, storage coefficients (S) and specific yields (Sy). The results are consistent with other observations and interpretations. The determination of K_D needs the knowledge of the aquifer thickness b. Flowmeter measurements during injection tests in eight wells of the basin have shown that the solid basement does not contain any conductive fracture (Fig. 4). Thus, the top of this layer was chosen as the bottom of the aquifer. Consequently, the degree of anisotropy and the permeability are computed in Table II. The results show an anisotropy with a horizontal permeability 2 to 30 times higher than the vertical one. This result is consistent with the observation of horizontal fractures in dug wells.

3.2. Gringarten method at pumping wells

Vertical flowmeter profiles in IFP-1 and IFP-9 (Fig. 4) show that a few fracture are conductive, respectively three in F1/1, F1/2 and F1/3 and one in F9/1. Actually, at IFP-1, only the deepest one was saturated during the whole pumping test. Similarly, the only conductive fracture crossed by IFP-9 was also saturated during the pumping test. Moreover, the analysis by the Neuman method shows the existence of anisotropy due to horizontal fractures. Thus, the method developed by Gringarten [6] for a vertical well crossing a horizontal fracture in an anisotropic aquifer, applicable to the pumping well, is well adapted to the hydrogeological context of the IFP-1 and IFP-9 wells.

The interpretation is done through the adjustment of observed drawdowns on theoretical curves of an abacus [5] giving the reduced drawdowns in a pumping well for a fracture located at the centre of the aquifer, as a function of reduced time. Knowing the geometry of the case (i.e. the thickness H of the aquifer), supposing the distance z_f between the bottom of the aquifer and the fracture equal to $0.5*H$ and using the value determined with the Neuman method for Ss, the hydrodynamic properties of the aquifer are evaluated (Table III): K_r the horizontal permeability, K_z the vertical permeability and the radius r_f of the horizontal fracture. It is observed that the anisotropy of the aquifer is also shown in the pumping wells with this method.

4. Conclusion

The geological observations on the granites of the Maheshwaram watershed (India) confirm the existence, as in many other areas of the World, of a high density of horizontal fractures in the fissured zone of the weathering profile. Measurements made with a flowmeter confirm that only a few of these fractures are conductive. The interpretation of pumping tests on several wells with observation wells systematically shows the existence of a vertical anisotropy of permeability: the horizontal permeability is 2 to 30 times higher than the vertical permeability. These results confirm the major influence of weathering-origin fissures on the hydraulic parameters of hard-rock aquifers, whereas tectonic-origin fissures have a less important role. The application of the Gringarten theory also makes it possible to determine the radius of horizontal fractures crossing the pumping wells.

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Figures captions

Figure 1 : Geological section of a typical weathering profile in a hard-rock aquifer (thickness corresponds to the case study).

Figure 2 : (a) photography of a dugwell in the Maheshwaram area, in biotite-bearing granite. (b) identification of various layers and horizontal fractures and diaclases

Figure 3 : Adjustment of drawdown in observation wells IFP-1/1 and IFP-1/2 using Neuman theoretical curves of types A and B.

Figure 4: Geological profile of wells IFP-1 and IFP-9 (1: soil and weathering cover, 2: weathered-fissured zone, 3: fresh basement) and vertical profiles of radial fluxes during an injection test. Identification of conductive fractures. (Q_{inj} : discharge rate during injection and flowmeter tests. Water table indicated on the figure corresponds to the level modified in the well by the injection).

Figures

Figure 1

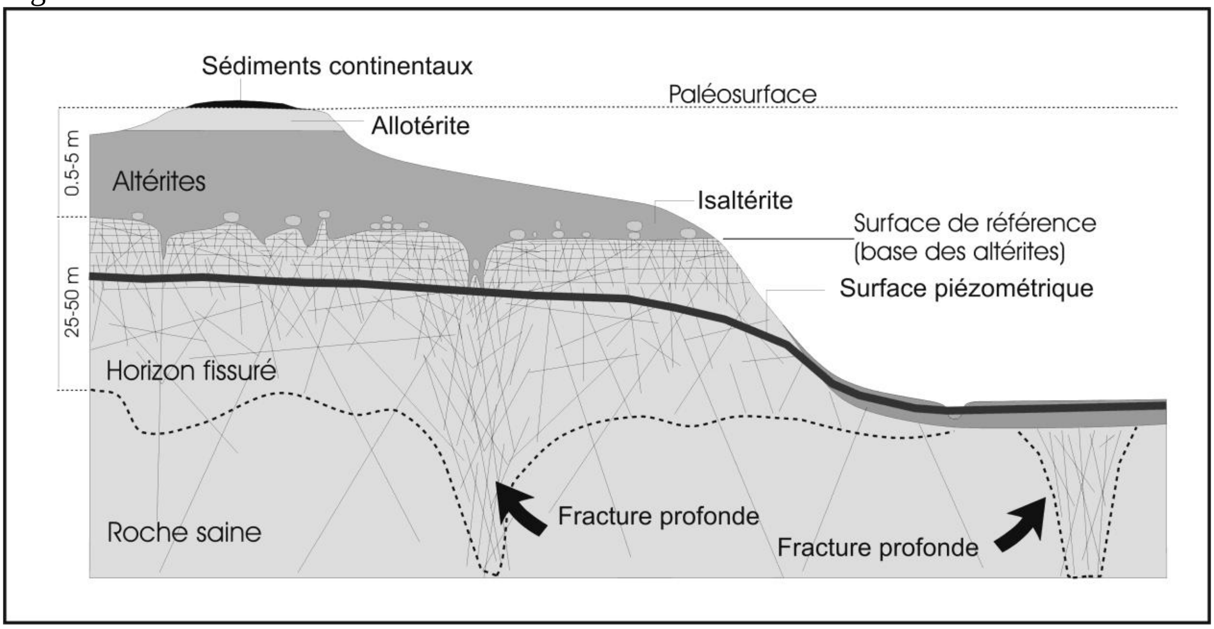


Figure 2

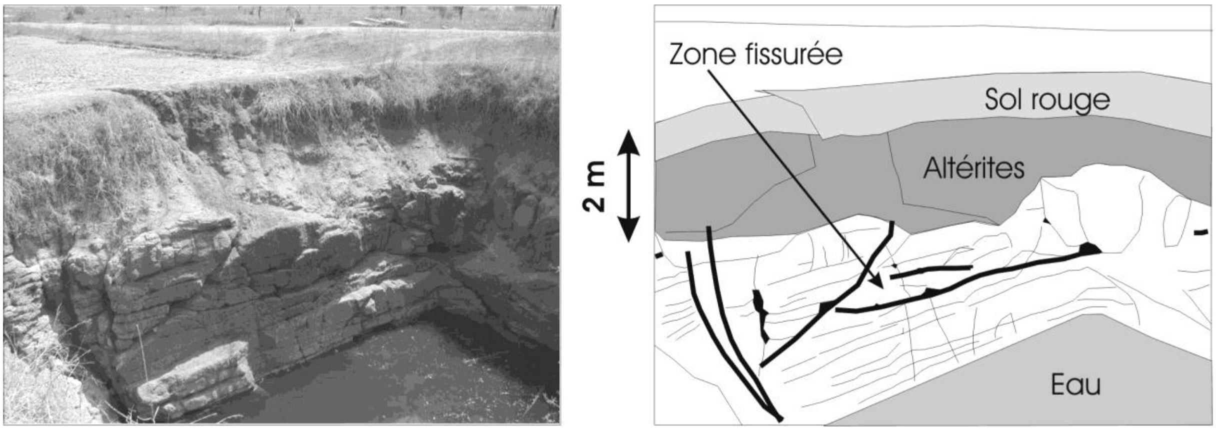


Figure 3

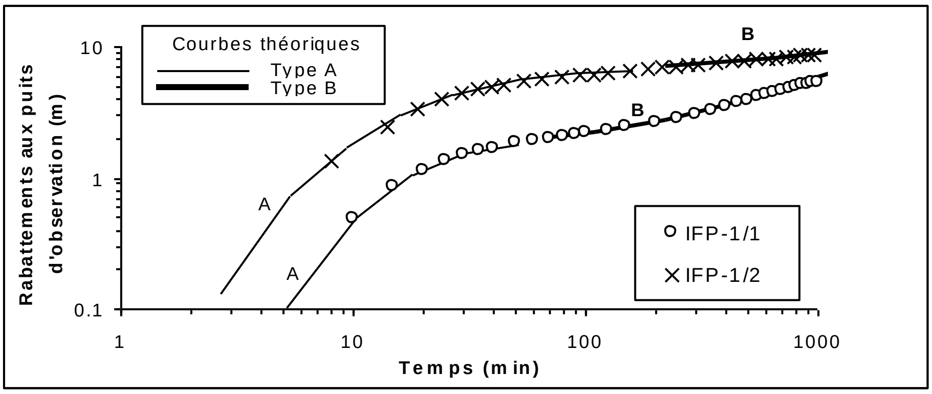
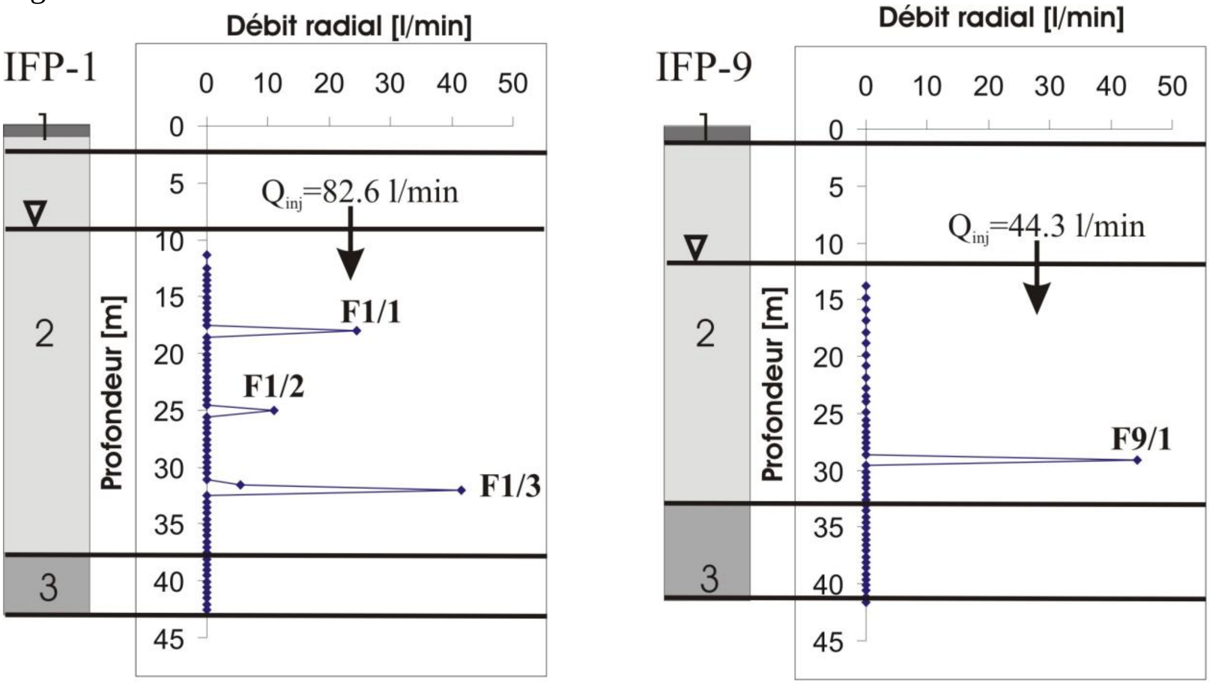


Figure 4



Tables

Puits d'observation	Puits de pompage	r (m)	T_A (m^2/s)	T_B (m^2/s)	T_A/T_B (-)	T_{AB} (m^2/s)	S (-)	Sy (-)
IFP-1/1	IFP-1	28	1.76E-05	1.96^{E}-05	0.90	1.86E-05	7.0E-05	1.7E-03
IFP-1/2	IFP-1	27.5	1.71E-05	1.76^{E}-05	0.97	1.74E-05	3.7E-05	1.5E-03
IFP-9/1	IFP-9	30.7	5.55E-04	7.65^{E}-04	0.73	6.51E-04	7.1E-04	3.4E-03

Table I : transmissivity and storage parameters obtained by adjustment of drawdown ((T_A : transmissivity obtained by adjustment on type A curve, T_B : transmissivity obtained by adjustment on type B curve, T_{AB} : average of T_A and T_B).

Puits d'observation	β (-)	r (m)	b (m)	K_r (m/s)	K_Z (m/s)	K_D (-)	$1/K_D$ (-)
IFP-1/1	1.00	28	21.8	8.5E-07	5.2E-07	0.606	1.7
IFP-1/2	0.20	27.5	21.8	8.0E-07	1.0E-07	0.126	8.0
IFP-9/1	0.60	30.7	7.3	9.0E-05	3.0E-06	0.034	29.5

Table II : permeability and anisotropy degree determined at observation wells using Neuman method

Paramètres connus						Paramètres déterminés par l'ajustement				
Puits	H (m)	*Fissure*	z_f (m)	z_f/H (-)	S_s * (1/m)	H_{DG} (-)	r_f (m)	K_r (m/s)	K_z (m/s)	K_r/K_z (-)
IFP-1	21.8	F1/3	6.0	0.28	2.5E-06	3	30.4	3.5E-06	1.9E-07	18.7
IFP-9	7.3	F9/1	4.0	0.55	9.7E-05	5	3.4	2.9E-05	5.2E-06	5.5

Table III : permeability, anisotropy degree and radius of the horizontal fracture determined at pumping wells using Gringarten method (* : *Ss* is the average of specific storage coefficient determined for each site using Neuman method at observation wells).