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Jean-Christophe Maréchal, Robert Wyns, Patrick Lachassagne, K. Subrahmanyam. Vertical anisotropy of hydraulic conductivity in the fissured layer of hard-rock aquifers due to the geological structure of weathering profiles. *Journal of the Geological Society of India*, 2004, 63 (5), pp.545-550. hal-00466718

HAL Id: hal-00466718

<https://hal.science/hal-00466718>

Submitted on 24 Mar 2010

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Vertical anisotropy of hydraulic conductivity in the 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 using that one of Gringarten show the vertical anisotropy of this layer of the aquifer; the horizontal permeability being clearly and systematically higher than the vertical permeability. These results perfectly agree with the geological observations, the fissured layer of the weathered granite profile showing the existence of many sub-horizontal fractures. It confirms dominating role, within the fissured layer, of the permeability of fractures due to the weathering process over that one of fissures with a tectonic origin.

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

INTRODUCTION

Hard rock aquifers occupy the first 100 meters from the top (Detay et al. 1989; Taylor and Howard, 2000), that was subject to weathering process (Wyns et al. 2002). The classical weathering profile comprises the following layers, which have specific hydrodynamic properties, from the top to the bottom (Fig. 1):

- Alterites or weathering cover with a negligible thickness (where this layer is eroded) to a few tens of meters. This layer has a high porosity and a low permeability. When it is saturated, this layer constitutes the reserve of the aquifer;
- Fissured zone is constituted by fractured hard rock, with a depth-decreasing density of fractures. It is now demonstrated that these fractures, a long time associated to decompression process, result from the weathering process itself (Wyns et al. 2002). Their genesis is mainly due to the weathering of micaceous minerals (particularly biotite) whose expansion induces cracks in the rock. In rocks with an isotropic texture (granite for example), the fractures are parallel to the topography during the weathering phase. In anisotropic rocks (gneiss, foliated granites), fissuration is planar and its orientation and intensity are determined by the angle between the foliation and topographic surface. This layer assumes the transmissive function in the aquifer and is pumped by most of the wells drilled in hard-rock areas;
- Fresh basement is permeable only locally, where tectonic fractures are present.

These (paleo) weathering profiles are well known in numerous areas across the World (Tardy and Roquin, 1998): Northern America, Southern America, India, China, Korea, Japan, Australia, Europe, comprising Northern Europe (Migon and Lidmar-Bergström, 2002 ; Migon, and Thomas, 2002 ; Wyns, 2002).

The understanding of the spatial distribution of these layers with their hydrodynamic properties allows developing methodologies both for the assessment of groundwater resources and the modelling of groundwater flows at the catchment scale (Wyns, 1991; Wyns et al. 2002).

For this purpose, alterites can easily be assumed as porous media. Some investigations are moreover necessary to characterise hydrodynamic properties of the fissured layer, with the object to take into account the heterogeneity and anisotropy of its properties at the scale of the mesh in a hydrogeological model. The objective of this paper is to determine the coherence between geological observations (existence of many horizontal fractures) and hydrodynamic properties (permeability anisotropy) of the aquifer.

WEATHERING PROFILE

The Maheshwaram watershed located in India is the main study area of the Indo-French Centre for Groundwater Research (French Geological Survey / National Geophysical Research Institute). The watershed, located around the village of Maheshwaram 30 kilometres away from Hyderabad, with an extent of about 55 km², is mainly constituted by Archean granites with isotropic texture. The weathering profiles are easily observable through many dugwells used by the farmers for irrigation (Fig. 2). The profiles are generally truncated by erosion: under a few decimetres of red soils, the alterites are thick of less than 5 meters. A high density of horizontal fractures is observed in the fissured zone as illustrated on the picture of Fig. 2. Vertical fractures with a tectonic origin are also present. Their hydraulic role at greater depths has been shown in India by several studies of the Central Ground Water Board (1979).

Due to the overexploitation of groundwater resources, water levels are far below ground level and the alterites are dry while only the fissured zone is saturated. This specificity was used to realise pumping tests with the object to characterise hydrodynamic properties of the fissured layer only. A focus was put to determine if analogies exist between the geological structure of this layer (fissuration with dominating horizontal component) and its hydrodynamic properties (anisotropy of permeability).

VERTICAL ANISOTROPY OF THE FISSURED ZONE

Two pumping tests of medium duration (17 and 12 hours) have been carried out at constant discharge rates with measurements of drawdown both in observation and pumping wells. Drawdowns in observation wells are interpreted by Neuman (1975) method while drawdowns in the pumping wells are analysed using the theory of the horizontal fracture developed by Gringarten and Witherspoon (1972).

Neuman method at observation wells

On a bi-logarithmic diagram (Fig. 3), the drawdown curves at observation wells IFP-1/1 and IFP-1/2 during pumping tests at IFP-1 well have a complex shape, difficult to interpret with classical methods (Theis for example, even considering an impermeable boundary). Drawdown curves are composed by three parts: the first one, at short times, with strong

slopes, is followed by an intermediate period during which a level stabilisation occurs; a third part for long times shows a new increase of slopes.

The theory initially developed by Boulton (1970) to interpret some special curves obtained in the observation wells takes into account the notion of « delayed yield from storage in unconfined aquifers » (Boulton and Pontin, 1971). It was improved by Neuman (1972, 1975) 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. Neuman considers an unconfined and infinite aquifer. When a fully penetrating well is pumped with constant discharge rate, the water comes for one part from the storage in the aquifer and for the other part from gravitational drainage at the free surface. The Neuman solution, under 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, S_y the specific yield, t the time since the starting of pumping. The application of this method consists in matching 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 1) 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 (S_y). Very similar values obtained in each observation wells for T_A and T_B show the coherence of the interpretation of this pumping test using Neuman method. The values obtained for specific yields are consistent with other ones deduced both from indirect methods by Magnetic Resonance soundings (Wyns et al. 2002) and from direct methods by adjustment of water levels fluctuations using a global model (Engerrand, 2002).

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 fresh basement does not contain any conductive fracture (Fig. 4). It is namely the case in pumping wells IFP-1 and IFP-9 (Fig. 4). Thus, the top of this layer was chosen as the bottom of the aquifer. As for classical methods, the uncertainty on the value of r makes difficult any interpretation of drawdown in pumping wells. The results of the interpretation at observation wells, included in Table 2, show an anisotropy of the permeability tensor, in accordance with geological observations: horizontal permeability is systematically higher than vertical one. This result is consistent with the observation of many horizontal fractures in dugwells.

Gringarten method at pumping wells

Flowmeter vertical profiles in IFP-1 and IFP-9 (Fig. 4) show that a few fractures are conductive, respectively three (F1/1, F1/2 and F1/3) and one (F9/1). Actually, at IFP-1, only the deepest fracture (F1/3 at 31.5 meters depth) was saturated during the whole pumping test. Similarly, the only conductive fracture intersected by IFP-9 (F9/1 at 29 meters depth) was also saturated during the whole pumping test. Moreover, the analysis by Neuman method

arises the existence of hydraulic anisotropy due to the presence of horizontal fractures. Thus, the method developed by Gringarten and Ramey (1974) for a vertical well intersecting a horizontal fracture in an anisotropic aquifer, applicable to the pumping well, is well adapted to the hydrogeological context of IFP-1 and IFP-9 wells.

The complexity of the analytical solution necessitates an interpretation through the adjustment of observed drawdowns on theoretical curves of an abacus (Gringarten and Witherspoon, 1972) giving the reduced drawdowns in a pumping well as a function of reduced time for various geometrical configurations represented by the parameter H_{DG} , when the fracture is

located at the centre of the aquifer ($z_f/H = 0.5$), with $t_{DG} = \frac{K_r t}{S_s r_f^2}$, $s_{DG} = \frac{4\pi \sqrt{K_r K_z} r_f s}{Q}$

$$\text{and } H_{DG} = \frac{H}{r_f} \sqrt{\frac{K_r}{K_z}},$$

where z_f is the distance between the fracture and the bottom of the aquifer, H the aquifer thickness. K_r , the permeability along the radial direction parallel to the fracture, can be interpreted as the permeability increased by the existence of the horizontal fracture. K_z , the vertical permeability, represents the matrix permeability, S_s the specific storage coefficient, t the time since the pumping starting, r_f the radius of the horizontal fracture, s the drawdown and Q the pumping discharge rate.

Adjustments of observed drawdowns by Gringarten theoretical curves leads to high values of H_{DG} , suggesting a high permeability anisotropy. 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 $0.5 \cdot H$ and using the value determined previously by Neuman method for S_s (average of $2.5 \cdot 10^{-6}$ 1/m at IFP-1/1 and IFP-1/2 and $9.7 \cdot 10^{-5}$ 1/m at IFP-9), the hydrodynamic properties of the aquifer are evaluated (Table 3): K_r the horizontal permeability, K_z the vertical permeability and the radius r_f of the horizontal fracture. It is observed that in both cases the anisotropy of the aquifer is shown in the pumping wells while estimated fracture radius (from 3 to 30 meters) are coherent with field observations.

CONCLUSIONS

The geological observations done 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 layer of the weathering profile. They show also the existence of a few vertical fractures. Measurements done using flowmeter confirm that only a few of these fractures are conductive in the wells.

The interpretation of pumping tests on several wells with observation wells shows systematically the existence of a vertical anisotropy of permeability: the horizontal permeability is 2 to 30 times higher than vertical permeability. The application of Gringarten theory also allows determining the radius of horizontal fractures intersecting the pumping wells.

These results confirm the major role of weathering-origin fissures on the hydraulic parameters of hard-rock aquifers at shallow depths. The role of tectonic-origin fissures becomes comparatively more important at greater depths, beyond 70-90 meters.

Acknowledgements: This work has been achieved by the scientists belonging to the Indo-French Centre for Groundwater Research (BRGM-NGRI). The authors thank the French Ministry of External Affairs and the Service of Cooperation and Cultural Action of the French Embassy in New Delhi, which has supported the travel of French experts in India. The Indo-

French Centre for Groundwater Research received also a funding from CNRS (French National Centre for Scientific Research) in the ACI Program « Water and Environment ».

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Figures legends

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

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

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

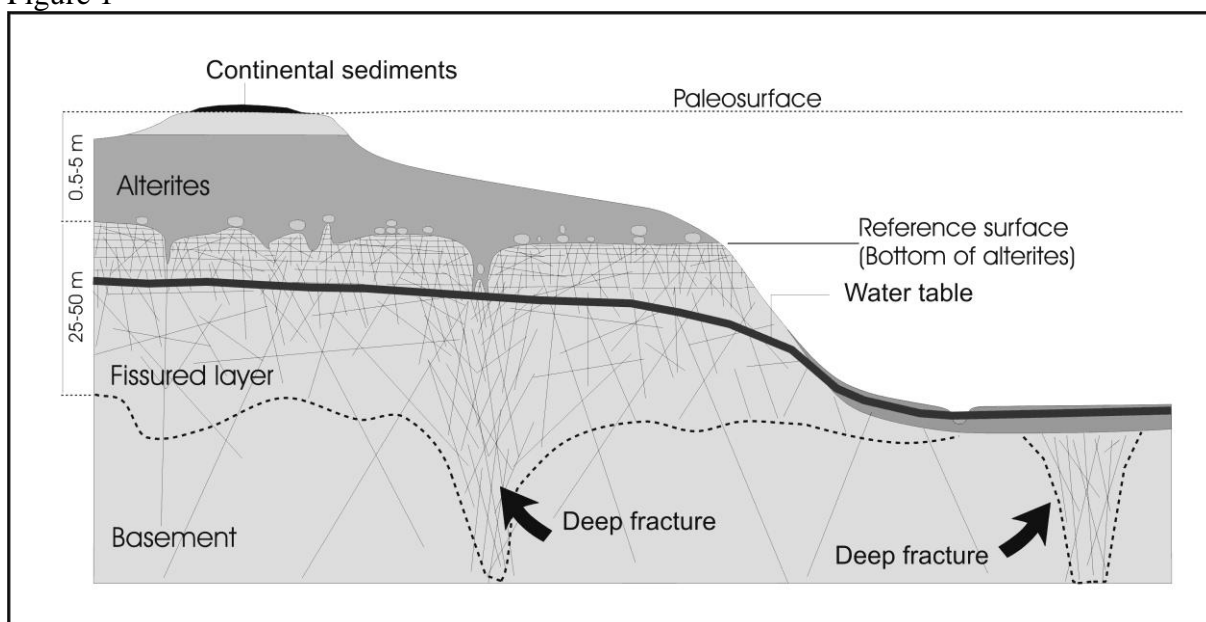


Figure 2

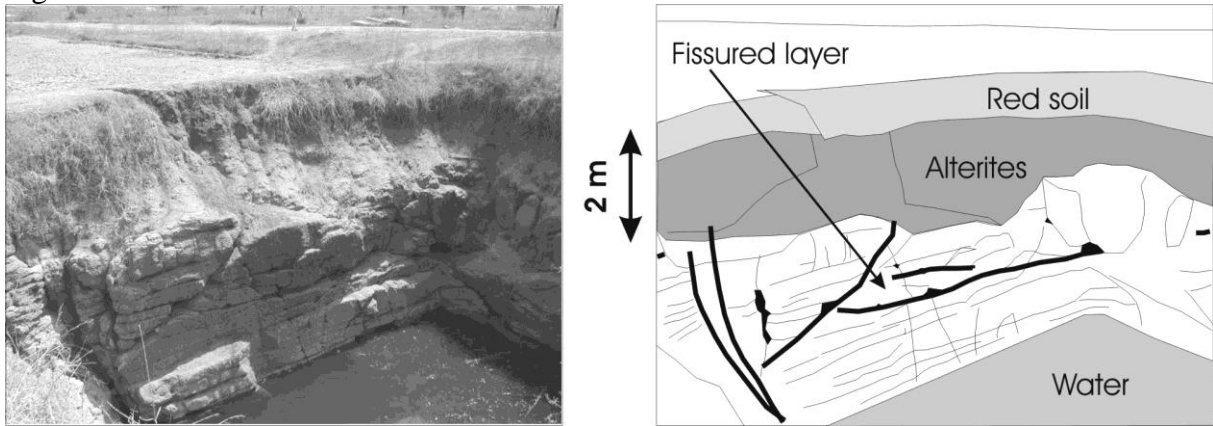


Figure 3

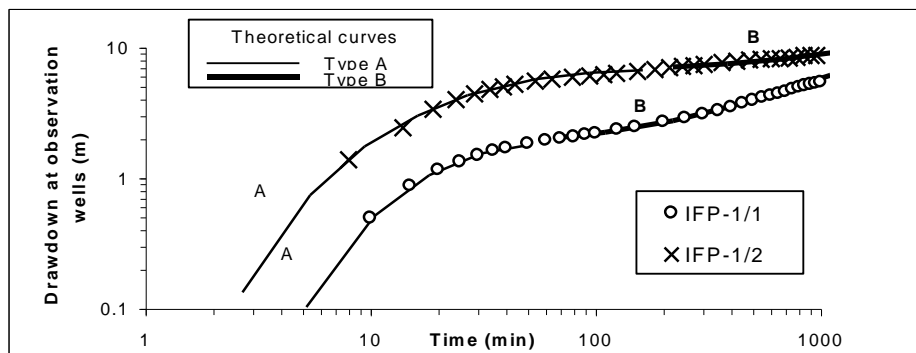
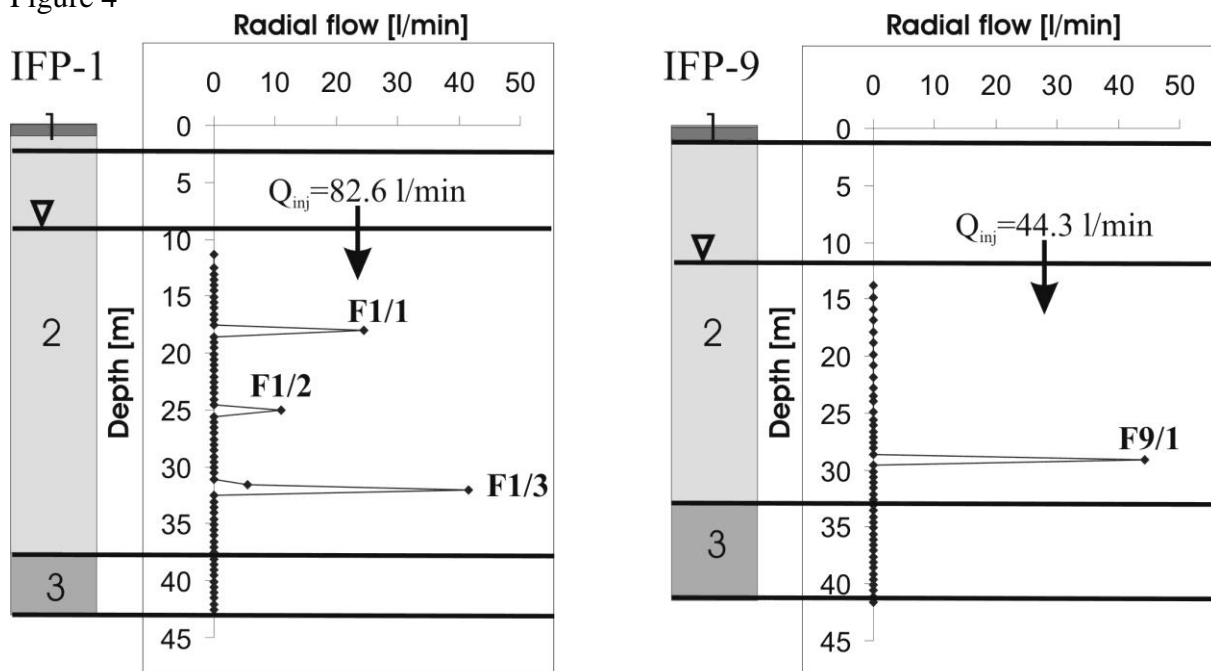


Figure 4



Tables

Observation well	Pumping well	r (m)	T_A (m ² /s)	T_B (m ² /s)	T_A/T_B (-)	T_{AB} (m ² /s)	S (-)	S_y (-)
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 1 : 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).

Observation well	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 2 : permeability and anisotropy degree determined at observation wells using Neuman method

Pumping Well	Known parameters					Parameters determined by adjustment				
	H (m)	<i>Fissure</i>	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 3 : permeability, anisotropy degree and radius of the horizontal fracture determined at pumping wells using Gringarten method (* : S_s is the average of specific storage coefficient determined for each site using Neuman method at observation wells).