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

Jean-Christophe Maréchal, Robert Wyns, Patrick Lachassagne, K. Subrahmanyam, Frédéric Touchard

► To cite this version:

Jean-Christophe Maréchal, Robert Wyns, Patrick Lachassagne, K. Subrahmanyam, Frédéric Touchard. Vertical anisotropy of hydraulic conductivity in fissured layer of hard-rock aquifers due to the geological structure of weathering profiles. *Comptes Rendus Géoscience*, 2003, 335 (5), pp.451-460. 10.1016/S1631-0713(03)00082-8 . hal-00458972

HAL Id: hal-00458972

<https://hal.science/hal-00458972>

Submitted on 22 Feb 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Jean-Christophe Maréchal^{a,*}, Robert Wynn^b, Patrick Lachassagne^c, Kambhampati Subrahmanyam^d, Frédéric Touchard^a

^a BRGM, Service EAU, Unité « Ressources en eau, Milieux Discontinus », Centre Franco-Indien de Recherche sur les Eaux Souterraines, NGRI, Uppal Road, 500 007 Hyderabad, India

^b BRGM, Service CDG/MA, 3 avenue Claude Guillemin, 45060 Orléans, France

^c BRGM, Service EAU, Unité « Ressources en eau, Milieux Discontinus » 1039 rue de Pinville, 34000 Montpellier, France

^d National Geophysical Research Institute, Centre Franco-Indien de Recherche sur les Eaux Souterraines, Uppal Road, 500 007 Hyderabad, India

* Correspondance : Indo-French Centre for Groundwater Research, National Geophysical Research Institute, Uppal Road, 500 007 Hyderabad, India, Tel: + 91 40 715 80 90, Fax: + 91 40 717 15 64, marechal@ngri.res.in

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 observation 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, S_y 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 (S_y). 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 $0.5 \cdot H$ and using the value determined with the Neuman method for S_s , 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.

6. Références

- [1] N.S. Boulton, Analysis of data from pumping tests in unconfined anisotropic aquifers, *J. Hydrol.* 10 (1970) 369-378.
- [2] N.S. Boulton, J.M.A. Pontin, An extended theory of delayed yield from storage applied to pumping tests in unconfined anisotropic aquifers, *J. Hydrol.* 14 (1971) 53-65.
- [3] M. Detay, P. Poyet, Y. Emsellem, A. Bernardi, G. Aubrac, Development of the saprolite reservoir and its state of saturation: influence on the hydrodynamic characteristics of drillings in crystalline basement (in French), *C. R. Acad. Sci. Paris II* 309 (1989) 429-436.
- [4] C. Engerrand, Hydrogéologie des socles cristallins fissures a fort recouvrement d'altérites en régime de mousson : étude hydrogéologique de deux bassins versants situés en Andhra-Pradesh (Inde), Thèse de doctorat Université Paris VI, 2002.
- [5] A.C. Gringarten, P.A. Witherspoon, A method of analysing pump test data from fractured aquifers, in: I.A.o.R. Mehan. (Ed.), *Percolation through fissured rock*, Deutsche Gesellschaft fur Red and Grundbau, Stuttgart, 1972, pp. T3B1-T3B8.
- [6] A.C. Gringarten, H.J. Ramey, Unsteady-state pressure distribution created by a well with a single horizontal fracture, partially penetrating or restricted entry, *Trans. Am. Inst. Min. Eng.* 257 (1974) 413-426.
- [7] P. Lachassagne, S. Ahmed, C. Golaz, J.C. Maréchal, D. Thiery, F. Touchard, R. Wyns, A methodology for the mathematical modelling of hard-rock aquifers at catchment scale based on the geological structure and the hydrogeological functioning of the aquifer, XXXI IAH Congress, Munich, in: K.-P. Seiler and S. Wohnlich (Ed.), *New approaches characterising groundwater flow*, A.A. Balkema Publishers, 2001, pp.367-370.
- [8] P. Lachassagne, R. Wyns, P. Bérard, T. Bruel, L. Chéry, T. Coutand, J.F. Desprats, P. Le Strat, Exploitation of high-yield in hard-rock aquifers: Downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones, *Ground Water* 39(4) (2001) 568-581.
- [9] P. Migon, K. Lidmar-Bergström, Deep weathering trough time in central and northwestern Europe: problems of dating and interpretation of geological record, *Catena* 49 (2002) 25-40.
- [10] P. Migon, M.F. Thomas, Grus weathering mantles-problems of interpretation, *Catena* 49 (2002) 5-24.
- [11] S.P. Neuman, Theory of flow in unconfined aquifers considering delayed response of the water table, *Water Resources Research* 8(4) (1972) 1031-1045.
- [12] S.P. Neuman, Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response, *Water Resources Research* 11(2) (1975) 329-342.
- [13] Y. Tardy, C. Roquin, *Dérive de continents, paléoclimats et altérations tropicales*. Editions du BRGM, Orléans, 1998.
- [14] R. Taylor, K. Howard, A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda, *Hydrogeology Journal* 8(3) (2000) 279-294.
- [15] R. Wyns, L'utilisation des paléosurfaces continentale en cartographie probabiliste, *Géologie de la France* 3 (1991) 1-10.
- [16] R. Wyns. PRD324. Hydrogéologie des aquifères discontinus. Ressources en eau Margeride Ouest. Modélisation de la géométrie (altitude, épaisseur) des arènes granitiques du bassin versant lozérien de la Truyère (Lozère, Massif Central), in : *Rapport BRGM R40191* (1998), Orléans, France, 18 p., 9 figures, 4 planches.

[17] R. Wyns, Climat, eustatisme, tectonique : quels contrôles pour l'altération continentale ? Exemple des séquences d'altération cénozoïques en France, Bull. Inf. Géol. Bass. Paris 39(2) (2002) 5-16.

[18] R. Wyns, J.C. Gourry, J.M. Baltassat, F. Lebert, Caractérisation multiparamètres des horizons de subsurface (0-100 m) en contexte de socle altéré, 2ème Colloque GEOFCAN, BRGM, IRD, UPMC, (1999) 105-110.

[19] R. Wyns, J.M. Baltassat, P. Lachassagne, A. Legchenko, J. Vairon, F. Mathieu, Application of Magnetic Resonance Soundings to Groundwater Reserves Mapping in Weathered Basement Rocks (Brittany, France), Bull. Soc. géol. France, sous presse.

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) 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

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 (-)	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 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)	<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 III : 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).