VERTICAL ANISOTROPY OF HYDRAULIC CONDUCTIVITY IN THE FISSURED LAYER OF HARD-ROCK AQUIFERS DUE TO THE GEOLOGICAL PATTERNS OF WEATHERING PROFILES

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Pumping tests carried out at the Maheshwaram watershed area near Hyderabad in the fissured layer of a granitic hard-rock aquifer and interpreted at the observation wells by means of the analytical solution of Neuman (1975) and at the pumping wells using the theory of Gringarten (1972), 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 observation that the fissured layer of the weathered granite profile shows the existence of many sub-horizontal fractures. It confirms the dominant role, within the fissured layer, of the permeability of fractures due to the weathering process over that of fissures with a tectonic origin.

Introduction

Hard rock aquifers occupy the first 100 metres from the top (Detay et al. 1989; Taylor and Howard, 2000) and are subjected to the 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 metres. 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 (gneisses, foliated granites), fissuring 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 (palaeo) weathering profiles are well known in numerous areas across the world in Northern America, Southern America, India, China, Korea, Japan, Australia, and Europe (Tardy and Roquin, 1998; 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



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

Hyderabad, with an extent of about 55 km², is mainly constituted by Archaean 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 centimetres/decimetres of red soils, the alterites are less than 5 m thick. A high density of horizontal fractures is observed in the fissured zone as illustrated in the field photo (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. The aim was to determine if analogies exist between the geological structure of this layer (fissuring 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) were carried out at constant discharge rates with measurements of drawdown both in observation and



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

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pumping wells. Drawdowns in observation wells are interpreted by the method of Neuman (1975) 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 even considering an impermeable boundary. Drawdown curves are composed by three parts: the first one, at short periods, with strong slopes, is followed by an intermediate period during which a level stabilisation occurs; a third part for long periods shows a new increase of the slope.

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 a part from the storage in the aquifer and for another part from the 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, Sy 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 periods and type B curve for long periods (Fig. 3). Both the curves are characterised by the same parameter

$$\beta = \frac{r^2 K_D}{b^2}$$

which is a function of the permeability anisotropy

$$K_{p} = \frac{K_{z}}{K_{r}}$$

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 (Sy). 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 level fluctuations using a global model (Engerrand, 2002).

The determination of K_p needs the knowledge of the



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

Table 1. Transmissivity and storage parameters obtained by adjustment of drawdown ($(T_A : \text{transmissivity obtained})$ by adjustment on type A curve, $T_B : \text{transmissivity obtained}$ by adjustment on type B curve, $T_{AB} : \text{average of}$ $T_A \text{ and } T_B$)

Observation well	Pumping well	<i>r</i> (m)	$\frac{T_A}{(m^2/s)}$	T_B (m ² /s)	T_{A}/T_{B}	$\frac{T_{AB}}{(m^2/s)}$	S	Sy
IFP-1/1	IFP-1	28	1.76E-05	1.96E-05	0.90	1.86E-05	7.0E-05	1.7E-03
IFP-1/2	IFP-1	27.5	1.71E-05	1.76E-05	0.97	1.74E-05	3.7E-05	1.5E-03
IFP-9/1	IFP-9	30.7	5.55E-04	7.65E-04	0.73	6.51E-04	7.1E-04	3.4E-03

Table 2. Permeability and anisotropy degree determined at observation wells using Neuman method

Observation well	β	<i>r</i> (m)	<i>b</i> (m)	<i>K</i> , (m/s)	<i>K</i> _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

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). Such is 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 any interpretation of drawdown in pumping wells difficult. The results of the interpretation at

observation wells, included in Table 2, show an anisotropy of the permeability tensor, in accordance with the geological observations: horizontal permeability is systematically higher than vertical one. This results are consistent with the observations of many horizontal fractures in dugwells.

Gringarten Method at Pumping Wells

Flowmeter vertical profiles in IFP-1 and IFP-9 (Fig. 4)



Fig.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).

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	Known parameters					Parameters determined by adjustment				
Pumping well	<i>Н</i> (m)	Fissure	<i>Z_f</i> (m)	<i>Z/H</i>	Ss* (1/m)	H _{DG}	r _f (m)	<i>K</i> , (m/s)	<i>K</i> . (m/s)	K,/K
IFP-1	21.8	F1/3	6.0	0.28	2.5E-06	3	30.4	3.5E-06	1.9E-07	18.7

9.7E-05

5

3.4

 Table 3. 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)

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 from 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.

F9/1

4.0

0.55

IFP-9

7.3

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
 $t_{DG} = \frac{K_r t}{S_s r_f^2}$, $s_{DG} = \frac{4\pi \sqrt{K_r K_z} r_f s}{Q}$ 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 starting of pumping, 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^*H and using the value determined previously by Neuman method for Ss (average of 2.5 10⁻⁶ 1/m at IFP-1/1 and IFP-1/2 and 9.7 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 m) are coherent with the field observations.

2.9E-05

5.2E-06

5.5

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

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