Identification of conductible fractures at the upper- and mid- stream of the Jhuoshuei River Watershed (Taiwan)

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Abstract The movement and storage of ground water in the mountainous region has a significant impact on the dynamics of surface water flow. An adequate identification of the conductible fracture in the aquifer has thus received growing interest over the past decades. This paper summarizes the major findings from the first year of a hydrogeological investigation program initiated by the Central Geological Survey, Ministry of Economic Affairs (MOEA) of Taiwan since 2010, with a special focus on exploring in detail the fracture permeability. During the on-site investigation, geophysical logging was applied to delineate the lithostratigraphic characteristics of bedrock aquifers. The hydraulic conductivity of 67 observation segments was estimated by the constant head injection method. From the information gathered in this study, the hydraulic conductivities of the identified fractured medium above a depth of 40m are more than one order higher than that of the matrix. The occurrence of ground water in a fracture network, however, is found to be not solely governed by lithological composition, but more possibly by fracture porosity and spacing. A simple linear relationship was found by plotting the hydraulic conductivity against the product of total porosity and cubic aperture ratio (fracture spacing/sealed-off interval between the packers).

1 Introduction

Accompanying with the growing concern on the sustainability of available water resource, to gain more in-depth knowledge on the potential yield of aquifers is a crucial task. The movement of ground water within the mountainous region is either dominated by fracture continua, the porous medium, or even by both. The connectivity of discontinuities and the vector gradient of hydraulic heads are likely the most important factors determining the fracture/matrix permeability. Prior to evaluating whether a specific stratum of geometry is capable of yielding and

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storing a sufficient amount of ground water by means of any sophisticated numerical models, it is necessary to perform the downhole geophysical investigation to gain more insights into the lithologic composition of stratum unit.

The identification of conductible fracture in the mountainous-foothill region is often difficult. Within a fractured aquifer network, usually, not all the perceptible fractures will be hydrologically connected. The use of a combination of composite well logs and in-hole tracer tests could provide more than sufficient information regarding to the complex geometries and layering, however, especially when working with limited budget and time, a set of systematic and concise criteria for the quick in-situ identification of conductible fractures is indeed required.

The Central Geological Survey, Ministry of Economic Affairs (MOEA) of Taiwan has initiated a large-scale hydrogeological investigation program since 2010 that aimed at exploring in detail the hydraulic properties of bedrock aquifers in Taiwan mountainous-foothill region. This study presents estimates of hydraulic conductivity obtained by the constant head injection test and, further, to assess the relationship among hydraulic conductivity, fracture porosity and spacing.

2 Geological setting

The study area is located in the Western Foothills of Taiwan within the latitude and longitude of 23° 52' N and 120° 25' E, respectively. It covers the up- and middle-stream basin of the Jhuoshuei River with an area of 1,577 square kilometer. As shown in Fig. 1, the elevation lies between 142 and 1658 meters above sea level (m.a.s.l.). Owing to the collision of tectonic plates (Mouthereau and Lacombe 2006) a series of westward fold-and-thrust belts can be observed. The geological formation in this study area can be roughly separated from East to West into four regions by the orientation of faults. Region I at the most eastern side ranges in age from Eocene to Miocene, where the predominant lithology is massive slate rock accompanied with metasandstones and metasiltstones. Region II extends from Eocene to early Oligocene, the upper part is dominated by hard shale stone and the lower part is coarse quartz sandstone hosted. Region III, bounded by the Shuilikeng, Chelungpu and Tachienshan faults, is underlain by Miocene to Pleistocene sedimentary rocks. A distinct pattern of lithological distribution can be found in this region that closely related to the influence of folding, faulting and metamorphism. Region IV at the most western side is mainly consisted of unconsolidated alluvium and relatively young deposits from late Pliocene to Pleistocene. Topographic slopes in region I, II and III are from 30°-60°, relatively, more gentle topographic slopes (0-30°) are found in the region IV.

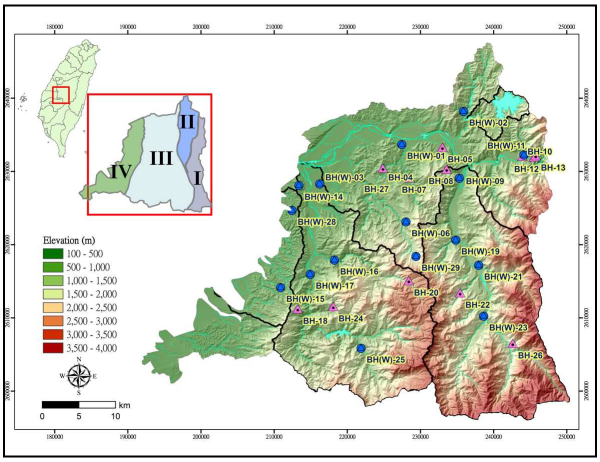

Fig. 1: Geological map of the study area.

A total of 29 vertical fully penetrating boreholes (see Table 1) were drilled to a depth of 100 meters (328ft.) below the land surface. The ground water level (m) from the earth surface was measured on-site during the test in the wet season. Rock samples were recovered and allowed for an initial on-site lithostratigraphic identification, as well as various laboratory analyses afterward.

Table 1: Boreholes description

Topographic region	**I**			**II**			**III**							
Borehole	B11	B12	B13	B02	B10	B21	B04	B05	B06	B08	B09	B16	B17	B18
Geometric height (m.a.s.l.)	391	472	468	431	357	638	409	295	764	633	403	280	227	631
Groundwater level beneath the surface (m)	14.0	77.0	86.1	4.5	9.0	36.5	4.5	11.0	10.0	4.0	16.5	14.3	4.0	23.0

Topographic region	**III**								**IV**						
Borehole	B19	B20	B22	B24	B25	B26	B27	B29	B01	B03	B07	B14	B15	B23	B28
Geometric height (m.a.s.l.)	476	1658	943	756	712	1172	191	1201	316	142	345	341	312	749	188
Groundwater level beneath the surface (m)	20.0	53.0	13.0	13.3	15.4	7.0	6.0	18.5	2.0	4.0	4.7	80.0	28.5	9.0	8.8

3. Methodology

In each borehole a series of borehole loggings were conducted in situ to identify the probable pathways of ground water. The electric log and the full waveform sonic log (from Robertson Geologging Ltd. UK) were adopted. These two sondes have long been used in the field of geosciences, a comprehensive overview has been provided in the study of Timur and Toksoz (1985), and Lau (1998). In this present research, the electric log was used to measure the spontaneous potential, electrical resistivity and natural gamma radiation, while the full waveform sonic log was applied to detect the sonic travel-time at a specific depth within the borehole. By using the acoustic-velocity logging, aquifer porosity can also be determined based on a time-average equation.

Borehole televiewer was performed to un-wrap the oriented circular borehole-wall images, which facilitated the interval of interest can be precisely straddled when performing packer tests. In addition, the fracture related characteristics such as the dip-azimuth, aperture width, and infilling material of fractures can also be quantified by further mapping efforts. The application of borehole televiewer on fracture identification has been adopted in earlier studies (Hartenbaum and Rawson 1980; Williams and Johnson 2004; Morin 2005; Hubbard et al. 2008). Two types of televiewer were adopted in this project to identify the appearance of fracture zones: the high resolution acoustic televiewer (HiRAT) and the optical televiewer (OPTV) (from Robertson Geologging Ltd. UK). The maximum pressure allowance of both types of televiewer is 20MPa.

Based on the geophysical log and televiewer profiles, four criteria were taken into consideration to identify the conductible fractures: (1) Reduced gamma-ray response; (2) Divergence of the short normal-resistivity log relatively to the long one; (3) Larger acoustic-velocity derived porosity; (4) Appearance of discernible spacing (>0.01m). Since after the conductible fractures in each borehole were identified, the hydraulic conductivity of the selected observation segments was determined by the constant head injection test (CHIT) with double packers system. This technique has been widely employed elsewhere to determine the hydraulic properties of a fractured stratum (e.g. Morin et al. 1988; Howard et al. 1992; Brown and Slater 1999; Niemi et al. 2000; Mejías et al. 2009). The detailed apparatus of the double packer assemblies employed in this study were described by Ku et al. (2009), and the procedures of testing were following the designation of American Society for Testing and Materials method (ASTM D4630-96 2002).

The sealed-off interval was fixed at 1.5m. Water was injected with a constant pressure of 0.2Mpa or at least in excess of the ambient hydrostatic heads. At least two observation segments were specified in each borehole. To diminish the risk of failure due to borehole spalling, the packer testing was carried out from the observation segment located at the lowest position in the borehole and then moving upward to the next. Each test took at least three hours including rig transfer, quick calibration, packer inflation, data recording and pressure recovery. The variation of hydraulic head and injected flow rate within the testing section were recorded per second and stored in a data-logger developed by the Sinotech Inc.

4 Data analysis and interpretation

67 observation segments, including both fractured and non-fractured media (matrix) in consolidated bedrock, were tested by CHIT. Hydraulic conductivity was derived by the interpretation of injected flow rate with the software AQTESOLV, version 4.5 (HydroSOLVE Inc. Reston, VA). In this study, the generalized radial flow model proposed by Barker (1988) was adopted and written as:

$$S_s \frac{\partial h}{\partial t} = \frac{K}{r^{n-1}} \frac{\partial}{\partial r}\left(r^{n-1} \frac{\partial h}{\partial r} \right)$$

where S_s represents the specific storage of aquifer [L^{-1}]; $h(r, t)$ denotes the change in hydraulic head [L] with time, r represents the radial distance from the borehole [L]; K represents the hydraulic conductivity [LT^{-1}]; n denotes the flow dimension according to the distance from the borehole (1 for linear flow, 2 for cylindrical flow, 3 for spherical flow). The magnitudes of hydraulic conductivity are plotted on a logarithmic scale against the depth in borehole as shown in Fig. 2. The corresponding distribution of the magnitudes with respect to the occurrence of fractures as well as the type of rock is also presented.

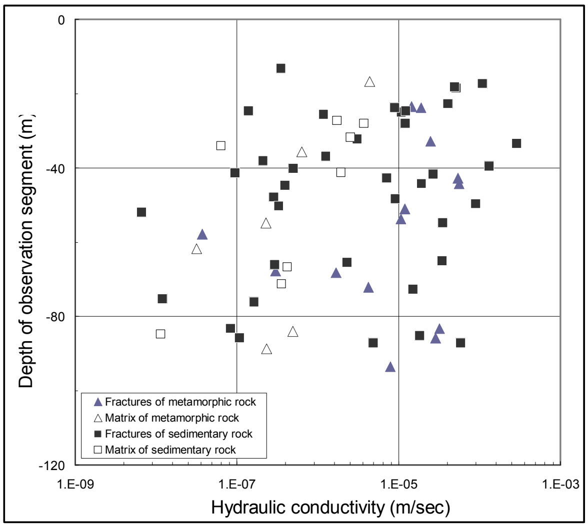

Fig. 2: Plot of the estimated hydraulic conductivity on a logarithmic scale with respect to different types of rock against depth in borehole.

The estimated hydraulic conductivity above a depth of 40m (*i.e.* the upper part of bedrock lying beneath the regolith layer) seems to show a slightly higher magnitude than at the greater depth, however, the overall hydraulic conductivities appear to be no significant depth correlation. With a view to evaluate the water-bearing capacity of fracture and matrix, a further subdivision can be made in terms of the magnitude of hydraulic conductivities as follows: (1) semi conductible medium: $10^{-5} < K < 10^{-3}$ m/s; (2) partial conductible medium: $10^{-7} < K < 10^{-5}$ m/s; (3) non-conductible medium: $K < 10^{-7}$ m/s. It is found that the identified fractures at the upper part of the bedrock possess semi-to-partial conductive capacity, while the fractures at the lower part of the bedrock exhibit a wider range of distribution pattern. Additionally, the occurrence of fractures in this study area shows approximately one order of higher hydraulic conductivity than of the matrix.

Fig. 3 attempts to further reveal the correlation of hydraulic conductivity (K) between total porosity (derived from acoustic velocity), and aperture ratio (fracture spacing/sealed-off interval between the packers, 1.5m). The open fractures with spacing less than 0.01m are not taken into account.

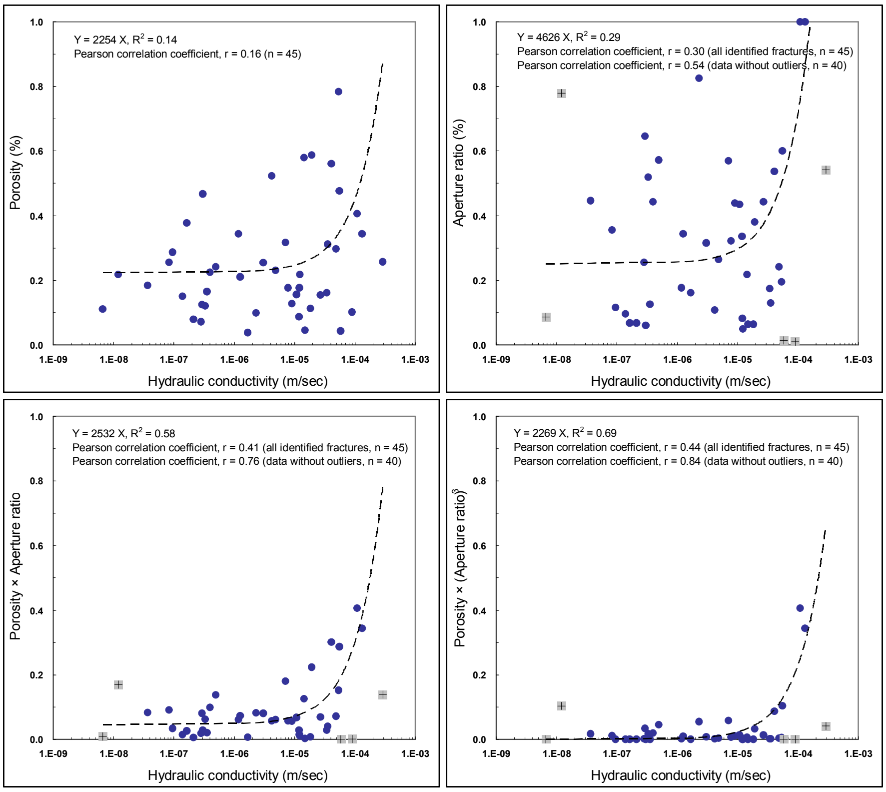

Fig. 3: Hydraulic conductivity in the logarithm scale versus total porosity (up-left), aperture ratio (up-right), product of total porosity and aperture ratio (down-left), and product of total porosity and cubic aperture ratio (down-right).

As shown in Fig. 3, when considered individually, there is only a weak positive correlation found between hydraulic conductivity and the total porosity (Pearson's r = 0.16), while a moderate correlation is found with respect to the aperture ratio (Pearson's r = 0.30, all data included; Pearson's r = 0.54, excluding outliers). Interestingly, a slightly stronger correlation (Pearson's r = 0.41, all data included; Pearson's r = 0.76, excluding outliers) is shown when plotting the product of total porosity and aperture ratio versus the hydraulic conductivities. It indicates that the transport of ground water does not controlled by either the intra-aggregate pores, or the inter-aggregate spacing alone, but regulated by both proportionally. After exploring various possible relations, a simple linear relationship (Hydraulic conductivity K = 0.00044[Porosity × (Aperture ratio) ^{3}], coefficient of determination R^2 = 0.69) was identified by plotting the hydraulic conductivity against the product of total porosity and cubic aperture ratio. Note that this relationship has not taken the fracture orientation into account. A further testing of this relation with respect to three-dimensional fracture orientation is recommended.

5 Discussions and recommendations

This paper reports the summary of a just-completed project aiming toward understanding the fracture permeability in mid-Taiwan mountainous-foothill region. It is also the purpose of this study to provide a theoretical and empirical based guideline for quick identification of conductible fractures. On the basis of 29 vertical boreholes at the upper- and mid-stream site of Jhuoshuei River basin, the conjunctive use of geophysical logging and televiewer imaging was carried out and used for determining the lithologic characteristics. Four hypothesized criteria were proposed which are applicable to identify the presence of permeable zone. The hydraulic conductivity at the predetermined depths was estimated by the constant head injection method.

According to the data collected during the first year, it is found that the majority of the identified fractured medium, especially above a depth of 40m, shows more than one order of higher hydraulic conductivity than of the non-fractured medium. However, the transport of ground water in the mountainous region does not independently controlled by either the inter-aggregate spacing, or the intra-aggregate pores alone, but, possibly, regulated by both proportionally. A simple linear relationship was identified by plotting the hydraulic conductivity against the product of total porosity and cubic aperture ratio. This relation could provide as an initial guide in assessing the potential yield of aquifer with the help from a drilling borehole. More systematic research is needed to formulate this relation with respect to fracture orientation.

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