Using Borehole Prospecting Technologies to Determine the Correlation between Fracture Properties and Hydraulic Conductivity: A Case Study in Taiwan

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ABSTRACT

This study conducted different borehole prospecting techniques for hydrogeological investigations of fractured rock at three active landslide sites in southern Taiwan. Borehole televiewer logging, flowmeter logging, and packer hydraulic tests were performed to quantify various hydrogeological parameters including fracture width, fracture angle, flow velocity and hydraulic conductivity. The dependence of hydraulic conductivity on fracture properties was evaluated by correlation analysis. While a high positive correlation was found between hydraulic conductivity and fracture width ($r = 0.89$), and flow velocity ($r = 0.87$), no correlation with fracture angle was observed. In addition, it is worthwhile to note that the product of fracture width and flow velocity showed a strong correlation with hydraulic conductivity ($r = 0.97$). The regression analysis also revealed that a power law relationship, with a coefficient of determination of 0.83, exists between the hydraulic conductivity and the product of fracture width and flow velocity. The rationality of this relationship was carefully verified by using another group of geophysical borehole measurements. The results demonstrated that it is capable of predicting the hydraulic conductivity of fractured rock based on borehole televiewer and flowmeter logging results.

Introduction

Taiwan is an island located in a tectonically active collision zone between the Eurasian Plate and the Pacific Plate. Climatically, the island is situated in a subtropical region with frequent typhoon events that are accompanied by intense rainfalls within a short period of time. These seismic and climatic elements frequently trigger, directly or indirectly, natural disasters such as landslides on the island that cause casualties and property damage. Prompted by the urge for minimizing the detrimental effects of such natural disasters, the Taiwanese government has funded a series of investigations and studies aiming to better understand the causes of the natural disasters, especially concerning the landslide problems.

Understanding the hydraulics of fractured rock has long been important when dealing with landslide problems. Many studies have indicated that hydraulic conductivity would appear to be affected by various fracture properties, including aperture width, frequency, geometric properties, connectivity, filling materials, and weathering degree of flow paths (Long *et al.,* 1985; Long and Witherspoon, 1985; Long and Billaux, 1987; Sahimi, 1995; Long and Ewing, 2004; Foyo *et al.,* 2005; Hamm *et al.,* 2007; Ku *et al.,* 2009). In recent years, many borehole hydrogeological investigations have been carried out to evaluate the relationship between hydraulic conductivity and fracture properties. Based on the field hydrological tests, Gustafson *et al.* (1991) described that 44% to 61% of fractures in granite are non-conductive. Tanaka and Miyakawa (1992) reported that highly conductive regions within a borehole are correlated with the appearance of high-density fracture zones. Their results were supported by data acquired through packer tests and borehole televiewer logging. By performing similar approaches, Hamm *et al.* (2007) demonstrated that the hydraulic conductivity has a stronger relationship to fracture aperture than fracture frequency, while they also found that the cubic fracture aperture model has a close relationship with transmissivity (with $r = 0.88$). In addition, Boadu (2000, 2003) suggested that seismic velocities, as well as the fractal properties of seismic waveforms, can both be considered as being a useful tool to predict the hydraulic properties of fractured rocks. By adapting the physically-based numerical

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experiments, his research provides a valuable and insightful guide for characterizing the hydraulic properties of fractured rocks (Boadu and Long, 1996) prior to conducting the field investigation.

Hydrogeological studies of fractured flow are rarely conducted on sedimentary fractured rock in Taiwan, particularly in piedmont landslide areas. In this study, a hydrogeological investigation, employing a series of subsurface exploration technologies, was conducted at three active landslide sites in southern Taiwan. Each site was initially investigated with borehole televiewer logging to identify the significant fracture features and fracturing degree at depth, and their hydrogeological implications. Flowmeter logging was then adopted to measure the distribution of highly conductive zones and fracture hydraulic connectivity along the borehole. It is considered, as indicated by Miyakawa *et al.* (2000), that the high conductive zone represents where the hydraulic conductivity is more than 10^{-7} m/s. Subsequently, hydraulic packer tests were carried out to further characterize the hydrogeologic system of the site and quantitatively determine the hydraulic properties of major hydrogeological units. Finally, correlation and regression analyses were performed to determine the dependence between different fracture properties and hydraulic conductivity. The obtained dependence was verified based on another group of geophysical borehole measurements, whereby its validity in predicting fractured rock hydraulic conductivity can be assessed.

Investigation Technologies

Methods and procedures for hydrogeological investigation on slopeland include, but is not limited to, field surficial geology investigations, borehole drilling and rock core sampling, landslide mapping with light detection and ranging (LIDAR), and resistivity image profiling (RIP), (Schulz, 2007; Lee *et al.,* 2008). This study focuses on the applications of borehole prospecting techniques and hydraulic packer tests, with the purpose of obtaining the relationship between fracture properties and their corresponding hydraulic conductivity. The techniques are described as follows.

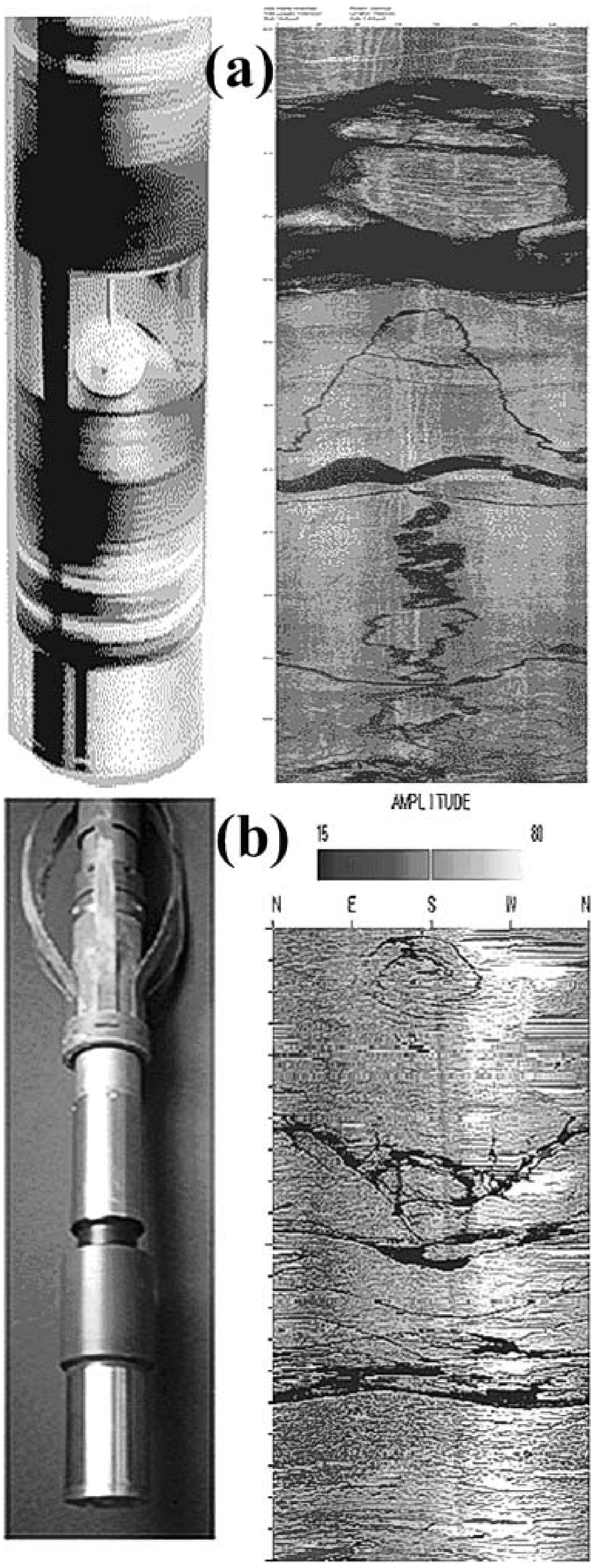

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Figure 1. The televiewer and scanned borehole image (Robertson Geologging Ltd) for the HiRAT (a) and OPTV (b).

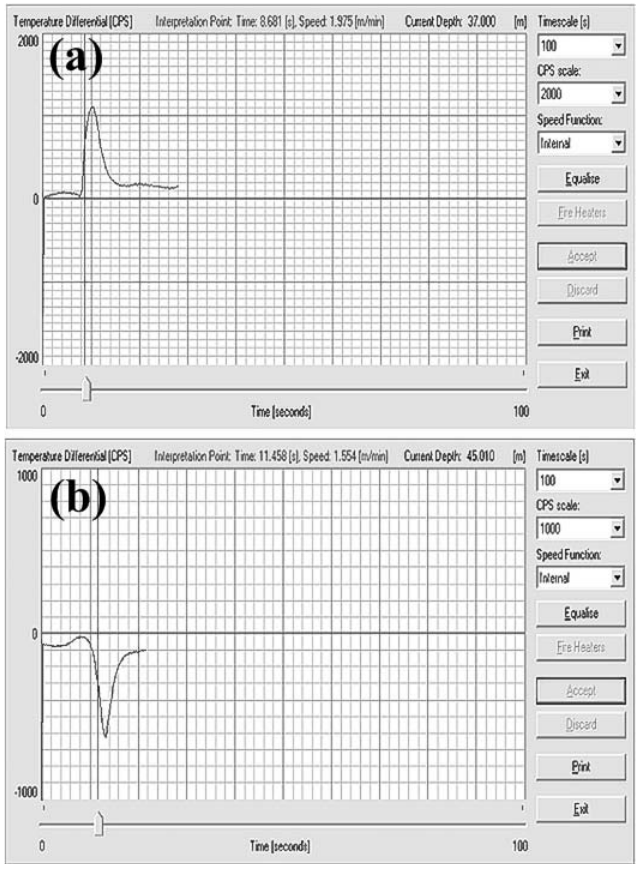

Figure 2. The heat-pulse curve (the elapsed time on the x-axis and the temperature difference measured by the thermistor on the y-axis). a) Upward flow heat-pulse curve; b) downward flow heat-pulse curve.

Borehole Televiewer Logging

The application of borehole televiewer to characterize the axial variations of fractured-rock properties has long been adopted in different fields (Kierstein 1984; Paillet *et al.,* 1990; Keys, 1989; Williams and Johnson, 2004; Hubbard *et al.,* 2008). This technique offers 360-degree borehole-wall imaging as it is lowered in a borehole. Relevant geologic appearances and structural discontinuities can be assessed in terms of the location, orientation, angle, width and infilling material of fractures, and the structural planar features. In addition, borehole imaging is capable of diminishing the uncertainties of conventional rock core drilling techniques, such as the retrieval of missing intervals and the dislocation of a rock core sample from its context because of inadequate recording (Williams and Johnson, 2004; Hsu *et al.,* 2007).

Generally, borehole televiewer devices are of two types: High resolution acoustic televiewer (HiRAT) and Optical televiewer (OPTV) (Fig. 1). The HiRAT probe comprises a fixed acoustic transducer and a rotating acoustic mirror system to acquire the acoustic signal reflected from the borehole wall. The amplitude and travel time of the reflected acoustic signal are recorded simultaneously as separate photographic-like images. The OPTV system consists of a ring of lights, a hyperboloidal mirror, and a video camera housing in the transparent window. The OPTV is capable of providing real-time borehole images (Keys, 1989; Williams and Johnson, 2004). Both devices have their own limitations and require proper care in their application. For example, HiRAT is commonly used in water or mud-filled boreholes, but cannot be used in a fluid-free borehole. Similarly, OPTV is typically applied in air or clean water-filled boreholes. However, the clarity of an OPTV image tends to deteriorate when non-flushed drilling mud, chemical precipitations, or bacterial growth is present in the borehole fluid (Williams and Johnson, 2004). Considering the limitations caused by borehole fluid conditions, both HiRAT and OPTV devices (Robertson Geologging, Ltd. UK) were adopted in this study.

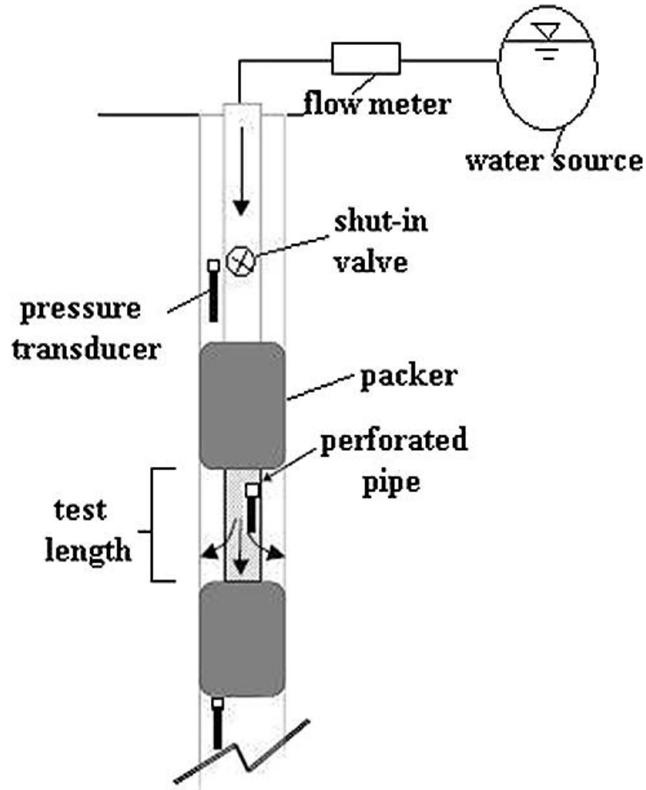

Figure 3. Schematic drawing of the double packer system.

Heat-pulse Flowmeter Logging

The heat-pulse flowmeter (HPFM) system (Robertson Geologging, Ltd. UK) used in this study consists of a wire-grid heating element and two sensitive thermistors (heat sensors) that are positioned above and

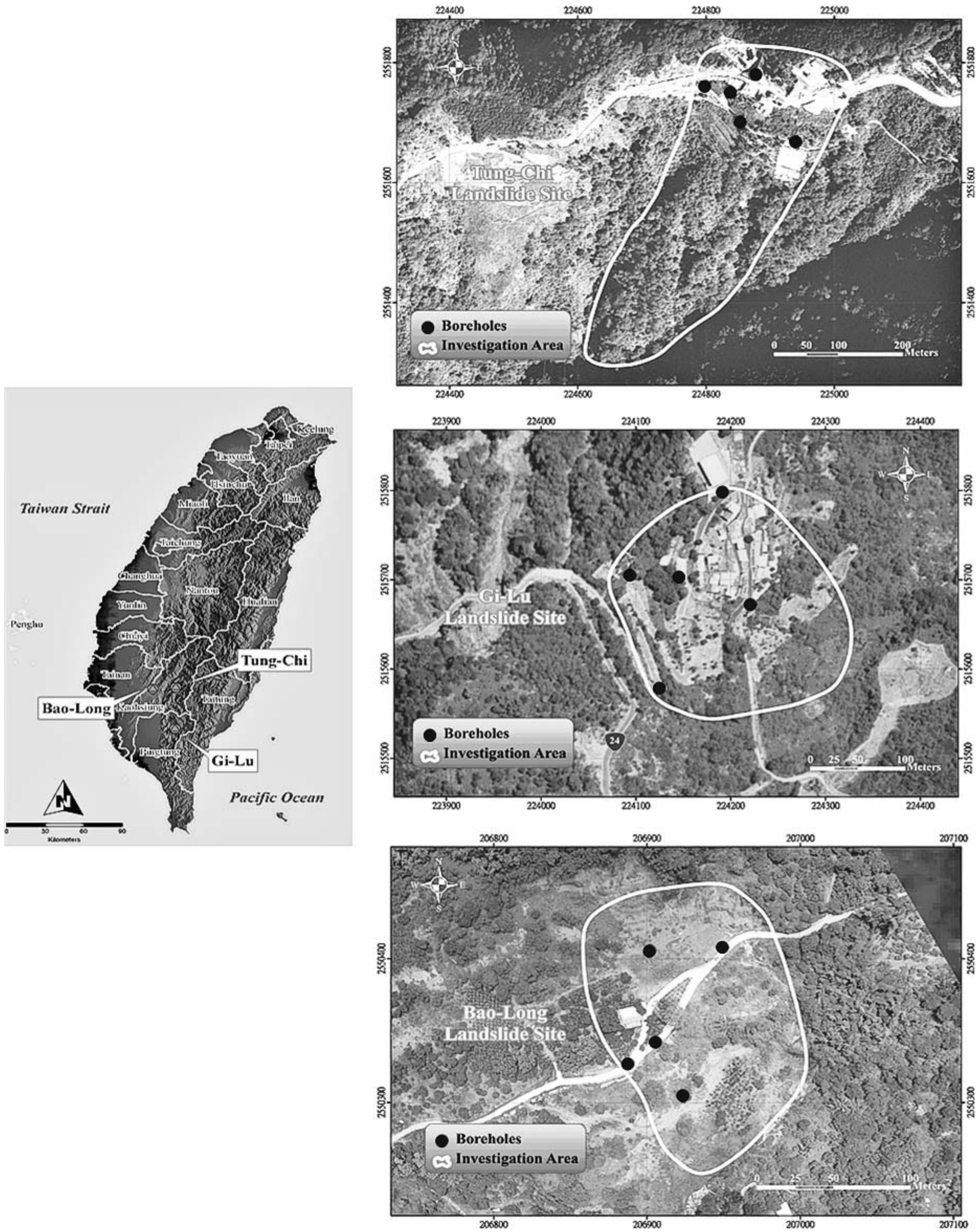

Figure 4. Site map of the three landslide sites.

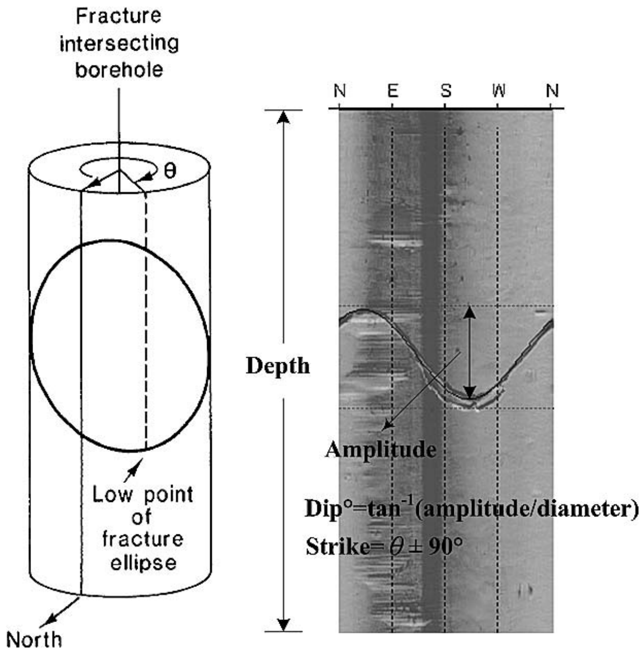

Figure 5. Fracture strike and dip determination from televiewer logging (after Paillet *et al.*, 1987).

below the wire-grid. A pulse of heat is generated at the wire-grid and migrates towards one of the thermistors, depending on the direction and rate of groundwater flow (Sloto and Grazul, 1989). The groundwater flux can be computed from the time required for the thermal pulse to pass the thermistors (Fig. 2). Since an equilibrium state of the groundwater system is assumed, the vertical distribution of the groundwater flow field can be obtained by consecutive measurements of water flux at different depths along the borehole when different hydraulic heads intersect (Keys, 1989). Borehole flowmeter logging not only provides useful information to characterize the aquifer permeability, but also aids in identifing the location of the water-producing/receiving zones, and fracture connectivity (Paillet, 1986; Muldoon *et al.,* 2001; Williams and Paillet, 2002). In addition, Miyakawa *et al.* (2000) pointed out that HPFM logging usually has to be carried out by either pumping water into or extracting water out from the borehole, because it is difficult to detect hydraulic pathways in a natural state because of low groundwater velocities.

Double Packer Hydraulic Test

The double packer hydraulic test is one of the most common approaches applied for determining the hydraulic conductivity and storage coefficient along discrete sections of a borehole. This approach allows investigating the spatial variability of flow in a borehole that is intersected by various hydrogeological units (Miyakawa *et al.,* 2000; Hamm *et al.,* 2007; Ku *et al.,* 2009). In this study, the double packer hydraulic test was conducted by isolating a 1.5 ~ 2.1 m long section within the borehole, and observing the variation of flow rate and/or pressure over a period of time. The system used consisted of two inflatable rubber packers, a shut-in valve, flow meters, a submersible pump, and three transducers for measuring the piezometric pressure in the isolated interval and in the areas above and below the packers. The rubber packers were inflated with nitrogen gas delivered from the gas cylinder. The shut-in valve was used to open and close the hydraulic connection between the pipe string and the test section. The pumping or injection rate was measured at the land surface by means of a flow meter (Fig. 3). Four types of hydraulic tests can be applied including pumping test, injection test, slug test, and pressure pulse test. A pumping test measures the changes in water levels during pumping, and can be conducted with either a constant or variable pumping rate. An injection test measures the flow rate during injection of water into the test interval at a known constant pressure head. A slug test is carried out by instantaneously adding a known amount of water to the test interval and to investigate the recession of the hydraulic head. A pressure pulse test involves applying an increment of pressure to the test interval and monitoring the pressure decay over time. Compared to the injection test, the representative volume of rock mass tested by the slug test and pressure pulse test is relatively small. Typically, the selection among these four types of hydraulic tests is based on the expected permeability of strata, the volume of rock to be sampled, and the availability of time and equipment.

Since the strata below the piedmont landslide areas are generally impermeable, the injection test was usually used instead of the pumping test, because the pumping test was considered too difficult to carry out in the study area. However, when the initial measured flow rate was far less than the minimum measurement of the flow meter (0.11 L/min) because of low strata permeability, the application of either the slug test or pressure pulse test was considered. The pressure pulse test was often applied because of the shorter time required. After acquisition of the relevant hydraulic data (piezometric pressure, time, flow rate, etc.) for each test was complete, the data were analyzed using the software AQTESOLV (HydroSOLVE Inc., Reston, Virginia), which allows both virtual and automatic type curve matching (Duffield, 2004). The quantitative evaluation of hydraulic parameters was carried out as an iterative process of the best-fit theoretical response curves based on the measured data of the hydraulic packer test (Hsu *et al.,* 2007; Ku *et al.,* 2009).

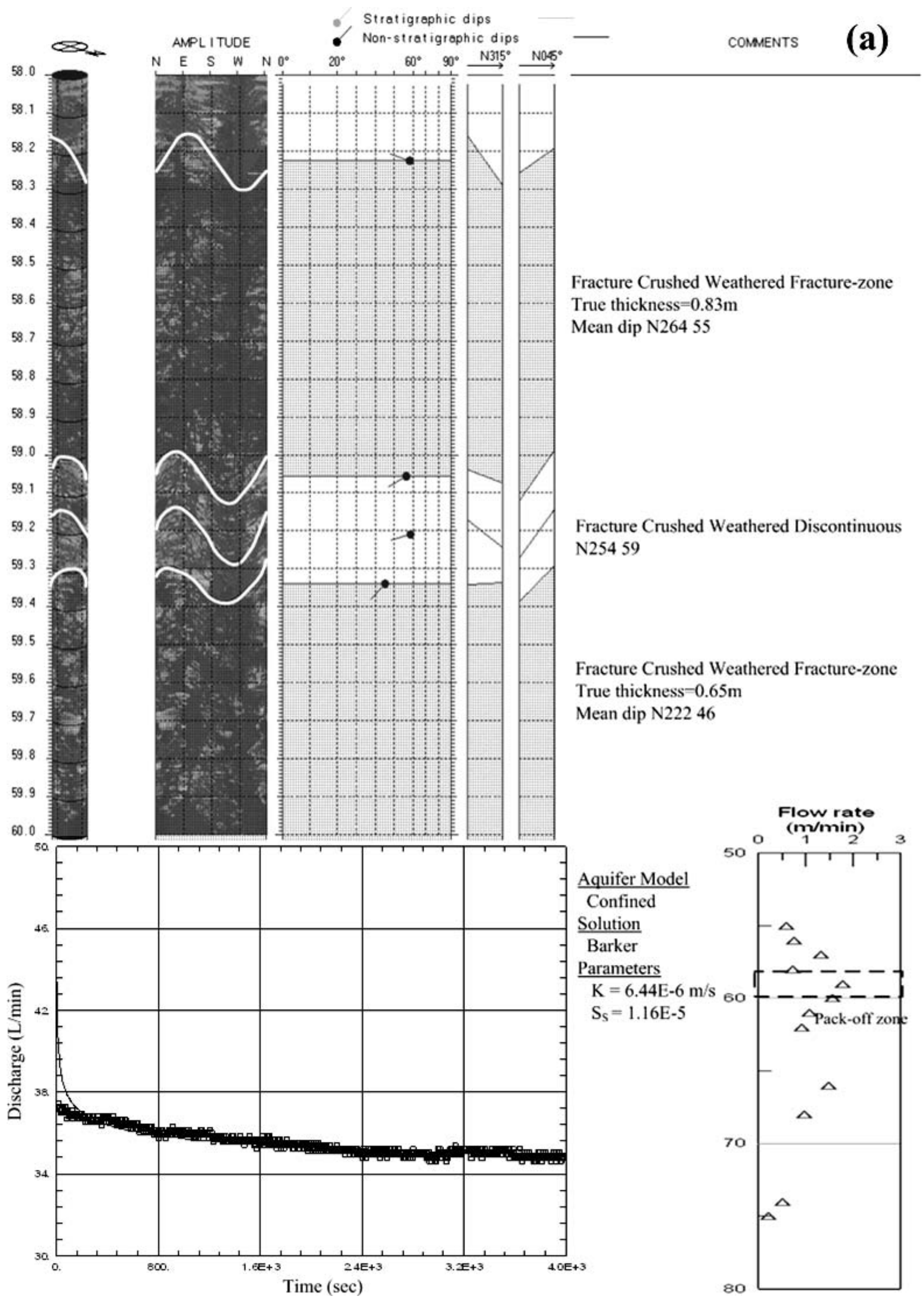

Figure 6. a) The packer test interval of 58.0–60.0 m from the Tung-Chi landslide site. The upper plot shows the computed angle and width of the fracture zone; the bottom plot shows the groundwater velocity log and hydraulic conductivity computed using AQTESOLVE. b) The packer test interval of 58.0–60.1 m from the Bao-Long landslide site. The upper plot shows the computed angle and width for a single fracture; the bottom plot shows the groundwater velocity log and hydraulic conductivity computed using AQTESOLVE.

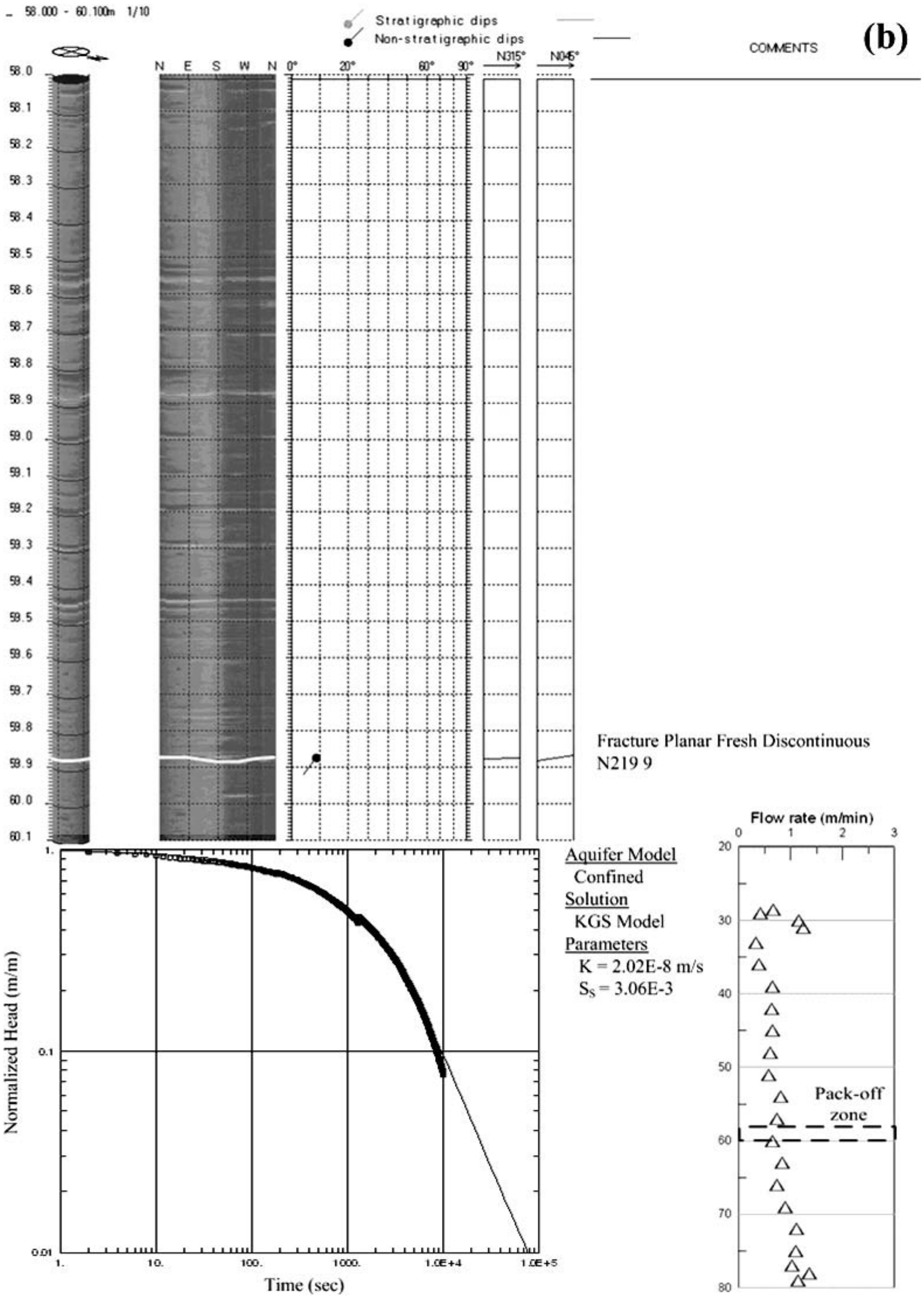
58.000 - 60.100m 1/10
Stratigraphic dips
Non-stratigraphic dips
(b)
COMMENTS
N E S W N
0° 20° 60° 90°
N315°
N045°
Fracture Planar Fresh Discontinuous
N219 9
Aquifer Model
Confined
Solution
KGS Model
Parameters
K = 2.02E-8 m/s
S_S = 3.06E-3
Normalized Head (m/m)
Time (sec)
Flow rate (m/min)
Pack-off zone

Table 1. Prospecting results of six boreholes.

Borehole	Test intervals (m)	Average fracture angle, FA (deg)	Fracture (zone) width, FW (m)	Flow velocity difference, ΔV (m/min)	Hydraulic conductivity, K (m/sec)	Product of fracture width and flow velocity difference (FW × ΔV, m^2/min)
FH-13	58.0–60.0	57.0	1.485	0.85	6.45E − 06	1.26E + 00
	61.0–63.0	35.0	0.845	0.96	9.57E − 06	8.11E − 01
	68.0–70.0	32.6	0.006	0.96	3.25E − 07	5.76E − 03
FH-15	45.5–47.5	29.5	1.430	2.55	1.59E − 05	3.65E + 00
	56.6–58.6	29.0	2.000	2.50	2.91E − 05	5.00E + 00
	65.8–67.8	32.3	0.032	0.66	1.67E − 06	2.11E − 02
FH-03	29.5–31.6	19.0	0.002	0.83	1.13E − 08	1.66E − 03
	39.0–41.1	11.0	0.002	0.02	1.98E − 10	4.00E − 05
	58.0–60.1	9.0	0.002	0.09	3.20E − 09	1.80E − 04
FH-05	34.0–36.1	38.0	0.022	0.09	1.68E − 07	1.98E − 03
	40.0–42.1	64.3	0.012	0.25	3.97 − E08	3.00E − 03
	50.0–52.1	31.2	0.014	0.21	4.10E − 07	2.94E − 03
	62.0–64.1	33.2	0.464	0.34	3.67E − 07	1.58E − 01
	65.0–67.1	22.3	0.062	0.63	6.60E − 08	3.91E − 02
FH-21	51.8–53.3	38.0	0.424	0.11	3.19E − 07	4.66E − 02
	63.8–65.3	40.0	0.522	0.79	4.88E − 07	4.12E − 01
FH-23	50.5–52.0	54.3	0.124	0.01	2.67E − 08	1.24E − 03
	57.0–58.5	38.2	0.080	0.07	1.12E − 07	5.60E − 03

Case Study and the Prospecting Results

The investigation was conducted at three landslide sites in the south central portion of Taiwan, as shown in Fig. 4, to assess the relationship between the hydraulic properties and the geological structures, and any correlation with the causes of the landslides. Borehole geophysical logging was conducted in six boreholes, each with a diameter of about 10 cm and depths ranging from 70 to 80 m. Two boreholes from each of the following three sites were investigated: Tung-Chi (borehole FH-13 and FH-15), Bao-Long (borehole FH-03 and FH-05), and Gi-Lu (borehole FH-21 and FH-23). The Tung-Chi and Bao-Long sites are located in Kaohsiung County. The primary lithological units of these two sites are weathered slate with clay-rich gouges and fresh shale with thin layered sandstone. The Gi-Lu site is located in Pingtung County, where the major lithological unit is composed of fresh slate with a minor amount of quartz and metamorphic sandstone.

The position and degree of the fracturing were first identified based on the HiRAT or OPTV loggings. From the continuous and oriented 360° views of the borehole wall, the orientation and width of a fracture or fracture zone were calculated by using the post-processing software Rgldip 6.0 (Robertson Geologging, Ltd. UK) (Fig. 5). The stationary groundwater velocity measurement was then carried out every 2 m along the borehole. The obvious permeable and high-connectivity openings were identified at the depth/position where significant velocity difference was observed. This is attributed to the fact that the vertical flow potential at the fractured or highly permeable sections was likely to be disturbed by the transverse flow (*i.e.,* recharge or

Table 2. Results of correlation analysis.

	Correlation Coefficient, r			
	Average fracture angle, FA (deg)	Fracture (zone) width, FW (m)	Flow velocity difference, ΔV (m/min)	Product of fracture width and flow velocity difference (FW × ΔV, m^2/min)
Hydraulic conductivity, K (m/sec)	−0.04	0.89	0.87	0.97

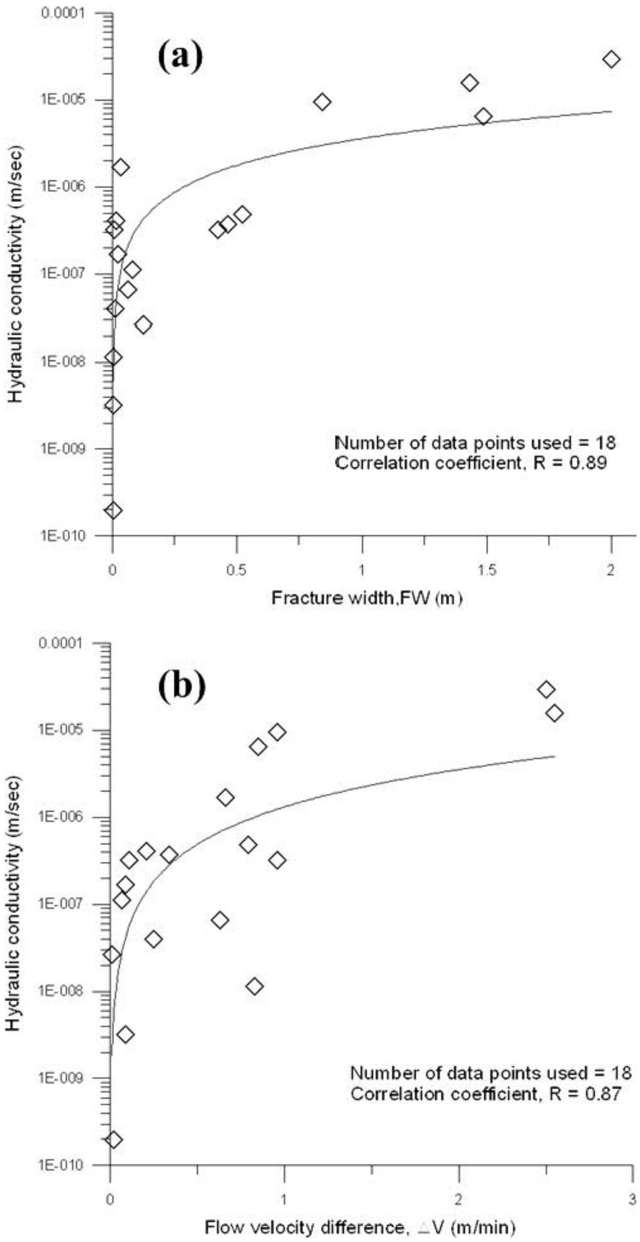

Figure 7. Correlation between a) fracture width (FW) and hydraulic conductivity, and b) flow velocity difference (ΔV) and hydraulic conductivity.

discharge flow) towards the borehole, thus a sharp change in vertical flow velocity occurred.

Based on the preliminary geophysical logging results, different test intervals were selected for the double packer hydraulic test, and the results were used to determine the hydraulic conductivity of different geological structures (Fig. 6). A total of 18 test sections were selected for packer hydraulic tests in this study. The test section logging results, including fracture angle, fracture (or fracture zone) width, flow velocity difference, and hydraulic conductivity, are summarized in Table 1.

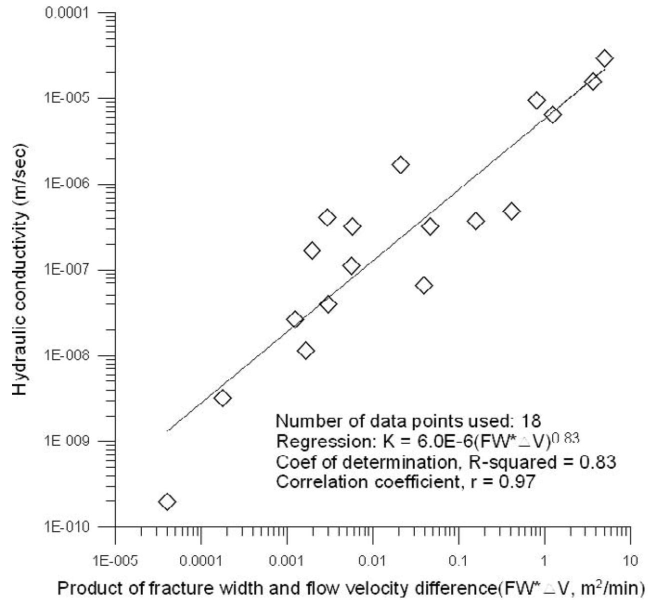

Figure 8. Correlation between hydraulic conductivity and product of fracture width and flow velocity difference.

Data Analysis

To define the dependence between the rock mass hydraulic conductivity and fracture angle, fracture width, and the flow velocity, a univariate correlation analysis was performed. The correlation coefficient between the different values can be computed using the following equation:

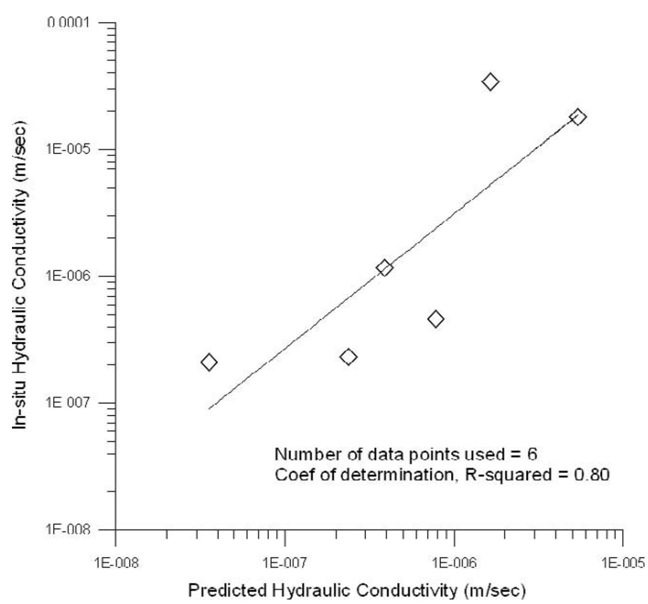

Figure 9. Verification of Eq. 3 using borehole data from a different site, but having similar lithologic conditions as the Bao-Long site.

Table 3. Verification of equation.

Borehole	Test intervals (m)	Fracture (zone) width, FW (m)	Flow velocity difference ΔV (m/min)	Product of fracture width and flow velocity difference (FW × ΔV, m^2/min)	Predicted hydraulic conductivity, $K_{equation}$(m/sec)	Measured hydraulic conductivity, $K_{in\text{-}situ}$(m/sec)
BH-37	65.5–67.0	0.080	0.460	0.037	3.91E − 07	1.17E − 06
	73.5–75.0	0.065	0.310	0.020	2.37E − 07	2.31E − 07
BH-43	9.6–11.1	0.386	0.220	0.085	7.80E − 07	4.61E − 07
	28.0–29.5	0.070	2.970	0.208	1.64E − 06	3.44E − 05
	43.0–44.5	0.006	0.340	0.002	3.57E − 08	2.10E − 07
	54.0–55.5	2.000	0.440	0.880	5.40E − 06	1.81E − 05

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{S_x S_y}, \quad (1)$$

where $\bar{x}$ and $\bar{y}$ are the sample means of x and y, and S_x and S_y are the sample standard deviations of x and y, which are defined as:

$$S_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})}{n}}, \ S_y = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})}{n}}. \quad (2)$$

The results of the correlation analysis are shown in Table 2. It was found that both fracture width and flow velocity difference show close correlation with hydraulic conductivity, with a correlation coefficient of 0.89 and 0.87, respectively (Fig. 7). However, the fracture angle and hydraulic conductivity show little correlation ($r = -0.04$). Most noticeably, the product of fracture width and flow velocity are highly correlated with the hydraulic conductivity, having a correlation coefficient of 0.97. This strong correlation is attributed to the fact that the flow velocity difference is connectivity-dependent. Accordingly, after exploring several possibilities, a power law relationship ($R^2 = 0.83$) was obtained by plotting on a log-log scale the hydraulic conductivity against the product of fracture zone width and flow velocity difference, as shown in Fig. 8. The following equation fits the data in our study:

$$K = 6.0E - 6(FW \times \Delta V)^{0.83}, \quad (3)$$

where FW represents the fracture (or fracture zone) width in the test interval, ΔV is the measured water flow velocity difference in the test interval, and K represents the hydraulic conductivity.

To validate this power law relationship, a verification was conducted using two other groups of in situ geophysical borehole measurements, which were obtained near the site of a nuclear power plant. The geologic unit of the site is mainly composed of shale and thin layered sandstone. Both televiewer and flowmeter loggings were performed, and six intervals were selected for the packer test. The quantitative evaluation of hydraulic conductivity was applied using AQTESOLV. The comparison of rock mass hydraulic conductivities measured from in situ test data and those calculated using Eq. 3 is shown in Table 3. A coefficient of determination between in situ hydraulic conductivity and that predicted from Eq. 3 is 0.80 (Fig. 9). Equation 3 can be used to provide an initial reasonable estimate of hydraulic conductivity prior to conducting a hydraulic packer test, thus substantially reducing both survey time and costs.

Conclusions

This study performed different borehole techniques to explore various hydrogeologic characteristics such as fracture angle, fracture or fracture zone width, groundwater velocity, and hydraulic conductivity, at three landslide sites. By adopting a correlation analysis, the dependence between hydraulic conductivity and other prospecting data can be identified. The results of analysis revealed a good correlation of the hydraulic conductivity with fracture width and flow velocity. In addition, the product of the fracture width and differential flow velocity was strongly correlated with the hydraulic conductivity, in which a correlation coefficient of 0.97 was obtained. Because the flow velocity is dependent on the fracture connectivity, borehole tests revealed that the rock mass hydraulic conductivity is not only related to fracture width, but also possesses a strong relationship with its corresponding connectivity. As a result, a power law relationship between the hydraulic conductivity and product of the fracture zone width and flow velocity difference was established. This relationship was validated using geophysical borehole measurements acquired at different locations. A high coefficient of determination predicted from the established relationship (0.80) indicates that quick and accurate predictions can be made. This equation provides an easy, but reasonable estimate of hydraulic conductivity at sites with similar lithologic conditions as in the study area. Consequently, it is concluded that such an approach is constructive for subsurface hydrogeologic assessment, particularly in the absence of packer test data caused by budget restraints.

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