Integrating Multiple Subsurface Exploration Technologies in Slope Hydrogeologic Investigation: A Case Study in Taiwan

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ABSTRACT

This study aims at presenting an integration of different downhole prospecting techniques for hydrogeologic investigation in an active landslide area. A series of subsurface exploration technologies were conducted, including borehole image scanning, electric logging, groundwater velocity measurements, and double packer testing. Both acoustic and optical borehole loggings as well as electric logging were applied to identify lithology, water bearing capacity and fracturing of the formation around the boring. Subsequently, borehole flow logs were used to indicate the distribution of permeability and hydraulic connectivity of fractures along the borehole. Based on the above prospecting results, test sections of hydraulic tests can be arranged. Finally, hydraulic packer tests were carried out to further characterize the hydrogeologic system of the site and quantitatively determine the hydraulic properties of major hydrogeologic units. Integrating multiple downhole prospecting techniques on slope hydrogeology investigation not only provides hydraulic properties for a study area, but also brings information to establish a hydrogeologic conceptual model and process the model simulation.

1. INTRODUCTION

Taiwan is an island located at a tectonically active collision zone between the Eurasian Plate and the Pacific Plate. Also, the island is in the subtropical climate region with frequent typhoon events that are always 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 with casualties and property damages. Prompted by the urge for minimizing the detrimental effects of such natural disasters, Taiwan government has initiated and funded a series of investigations and studies aimed at better understanding the causes of the natural disasters that may lead to the formulation of more effective disaster contingency plans and possibly some forecasts system.

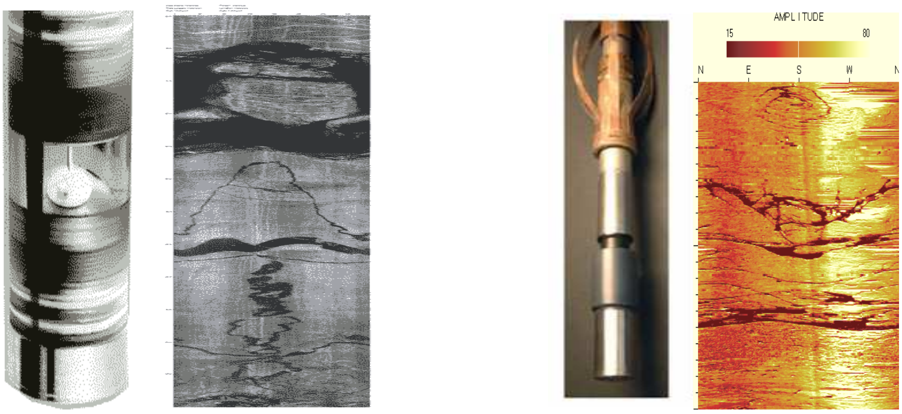
The hydrogeology of a landslide site can help unveil the detention condition of storm water entering the aquifer system of the slope as well as its groundwater condition which, in turn, plays a critical role in slope stability. In this study, a hydrogeologic investigation employing a series of subsurface exploration technologies was conducted at an active landslide site. The site was initially investigated with electrical logging in order to determine the lithology and possibly the water-bearing capacity of the geologic units beneath the slope surface. Subsequently, both acoustic and optical borehole image loggings were then applied to identify potentially significant fracture features at depth and their hydrogeologic implications. In addition, flowmeter loggings were conducted to indicate the distribution of permeability and hydraulic connectivity of fractures along the borehole. Integrating the aforementioned prospecting results, test sections of hydraulic tests can be arranged. Finally, hydraulic packer tests were carried out to further characterize the hydrogeologic system of the site and quantitatively determine the hydraulic properties of major hydrogeologic units. The entire investigation results were integrated to clarify the complexity of the subsurface environment and to establish the hydrogeologic conceptual model of the landslide site.

2. INVESTIGATION TECHNOLOGIES

A comprehensive hydrogeology investigation on slopeland may include surficial geology investigations, borehole drilling, testing of soil and rock properties from rock cores, landslide mapping with LIDAR, resistivity image profiling (RIP), double-ring infiltration test, borehole image scanning, electrical logging, flowmeter logging, and packer testing. This study focuses on describing downhole investigation techniques, and the purpose is to obtain hydraulic properties of borehole by integrating those techniques. The techniques are described as follows.

2.1 Borehole Image Scanning

Using borehole televiewers to characterize fractured-rock properties has been adopted for many years. The continuous, 360-degree images of the borehole wall are scanned while the probe moves up and down along the borehole, and the scanning result provides numerous geologic information, such as the location, orientation and angle of the fractures, aperture width, infilling material of fractures as well as the structural planar features. In addition, the borehole image is capable of clarifying the uncertainties of the traditional rock core drilling technique, including human errors for misplacing rock core samples from its original place, or interpretation for missing intervals (Williams and Johnson, 2004; Hsu et al., 2007). Considering the limitation caused by the borehole prospecting environments, both acoustic and optical televiewers were adopted in this study (Figure 1).



(a)Optical televiewer (b) Acoustic televiewer

Figure 1. The televiewer and scanned borehole image (Robertson Geologging Ltd).

2.2 Borehole Electrical Logging

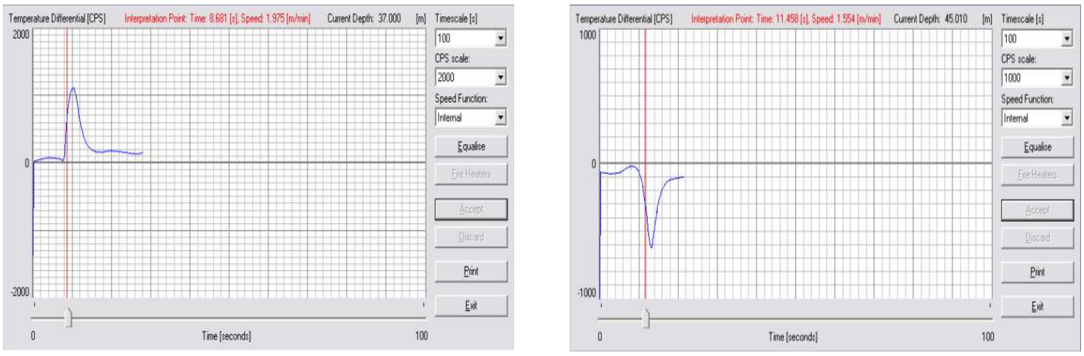
The borehole electrical logging is an ideal approach to determine various aquifer characteristics, such as the lithology, porosity, and water bearing capacity. The three major signals recorded from the electrical logging are spontaneous potential (SP), electrical resistivity, and natural gamma radiation (GR). The spontaneous potential measures the difference of electrical potential, which is caused by the exchange in saline concentration between the formation water and mud filtrate in the borehole. In an impermeable stratum (e.g., shale), the SP response usually shows slight change. In contrast, the SP shows negative deflection in a permeable stratum (e.g. sandstone). Therefore, aquifer lithology and their corresponding permeability can be classified from the SP response (Sloto and Grazul, 1989; Keys, 1990).

Since the electrical resistivity decreases with the degree of water existing in the rock formation and increases with the formation grain size, it is commonly utilized to distinguish the aquifer lithology and water bearing capacity (Keys, 1990). The electrical resistivity usually contains 64 inch normal (long) and 16 inch normal (short) resistivity depends on their prospecting distance surrounded the borehole. With higher mud filtrate in the invaded zone, the resistivity is generally larger than the uninvaded zone that contained more fresh water. Nerveless, in a permeable stratum, such as sandstone, usually shows greater separation between the short and long normal resistivity than a non-permeable stratum, such as the shale (Helm-Clark et al., 2004; Hsieh et al., 2005). It turned out that the separation between short and long normal resistivity is applicable to further determine aquifer permeability or transmissivity.

The natural gamma logging measures the gamma radiation naturally emitted from the rock formation. In fine-grained sediment, such as shale, generally generates more gamma radiation because the layer contains large amount of adsorbed radioactive elements. Comparatively, the coarse-grained sediment, such as sandstone, emits little gamma radiation (Sloto and Grazul, 1989; Keys, 1990). Thus, the natural gamma logging is constructive for the aquifer lithologic and stratigraphic classification.

2.3 Heat-pulse Flowmeter Measurement

The heat-pulse flowmeter (HPFM) system consists of a wire-grid heating element and two sensitive thermistors (heat sensors) located above and below the wire-grid. The wire-grid generates a sheet of heat in the water and the heat may migrate toward one of the thermistors as the groundwater flow (Sloto and Grazul, 1989). The flow rate and the flow direction can be computed once the peak temperature was detected by the thermistor (Figure 2). When the stationary measurements were conducted at several depths along a borehole, the distribution of groundwater velocity can be obtained. This not only provides useful information to characterize the aquifer permeability, but also brings good indications to identify the location of the water-producing and receiving zones (Williams and Paillet, 2002).



Interpretation Point: Time: 8.681 [s], Speed: 1.975 [m/min]
Current Depth: 37.000 [m]
Timescale [s]: 100
CPS scale: 2000
Speed Function: Internal

Interpretation Point: Time: 11.458 [s], Speed: 1.554 [m/min]
Current Depth: 45.010 [m]
Timescale [s]: 100
CPS scale: 1000
Speed Function: Internal

(a) The upward flow heat-pulse curve (b) The downward flow heat-pulse curve

Figure 2. The heat-pulse curve (the elapsed time in X-axis and the temperature difference measured by the thermistor in Y-axis).

2.4 Double Packer Hydraulic Test

The double packer hydraulic test is the most common approach applied to determine the hydraulic conductivity and storage coefficient in a specific section of borehole using two inflatable packers. The double packer system adopted in this study contains 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 the areas above and below the packers (Figure 3). To conduct the test, the packers are inflated to isolate a section of borehole and the rate of flow and/or pressure in the test interval over a period of time can be measured. The data analysis was performed using a professional version of the test analysis software AQTESOLVE, which enables 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).

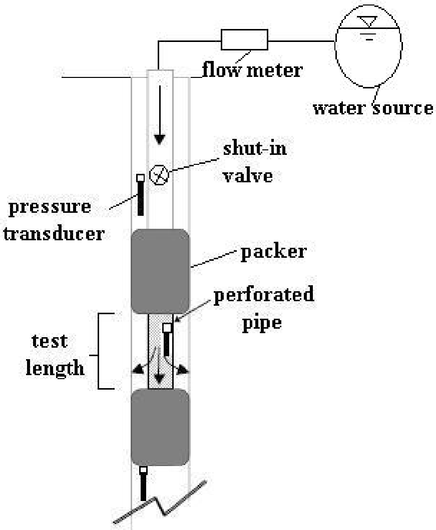


Figure 3. Schematic drawing of the double packer system.

3. CASE STUDY OF INTEGRATING THE LOGGING RESULTS

The investigation was conducted in the Hung-Tsai-Ping active landslide site in Nantou County, central Taiwan. After the Chi-chi earthquake took place in September 1999, several rainfall-triggered landslides events occurred in this area. In order to realize the subsurface hydrogeological conditions, three vertical boreholes to depths varying from 50m to 80m were drilled along a longitudinal profile of the landslide site. The above prospecting techniques were employed in one of boreholes due to the budget limit. The sequence of the investigation is to perform the electrical and borehole image logging to identify the lithology, water-bearing capacity, as well as the position and degree of the fracturing. The flowmeter logging was then applied to determine the transmissivity and the interconnectivity of fractures along the borehole. Based on the above results, the testing sections were selected for the packer test, which is conducted to determine the hydraulic parameters at different geologic unit.

Although each of prospecting tests has its own purpose, by integrating all results, the geologic and hydraulic conditions of the test site can be correlated. This is very useful to bring more precise subsurface information. Therefore, the data were finally integrated in this study. The interpretation of each test and integrated results are described below.

3.1 The borehole image logging and stereographic projection analysis

The continuous borehole images were used to correct the missing depths produced from the rock core drilling. For example, around 0.3 m shift in depth was found in the section between 25.4m and 26.9 m (Figure 4). In addition, by adopting the post processing software, the orientations of the fractures were calculated, and they were collected to perform a stereographic projection analysis. According to the 45 stereo plots delineated from the borehole fractures, the major fracture orientation was determined, which the dip direction is 32° and the dip is 53° (Figure 4). The stereographic projection analysis can be used to further identify the failure type of the slope (Hoek and Bray, 1981). However, no typical failure type was found in the study area.

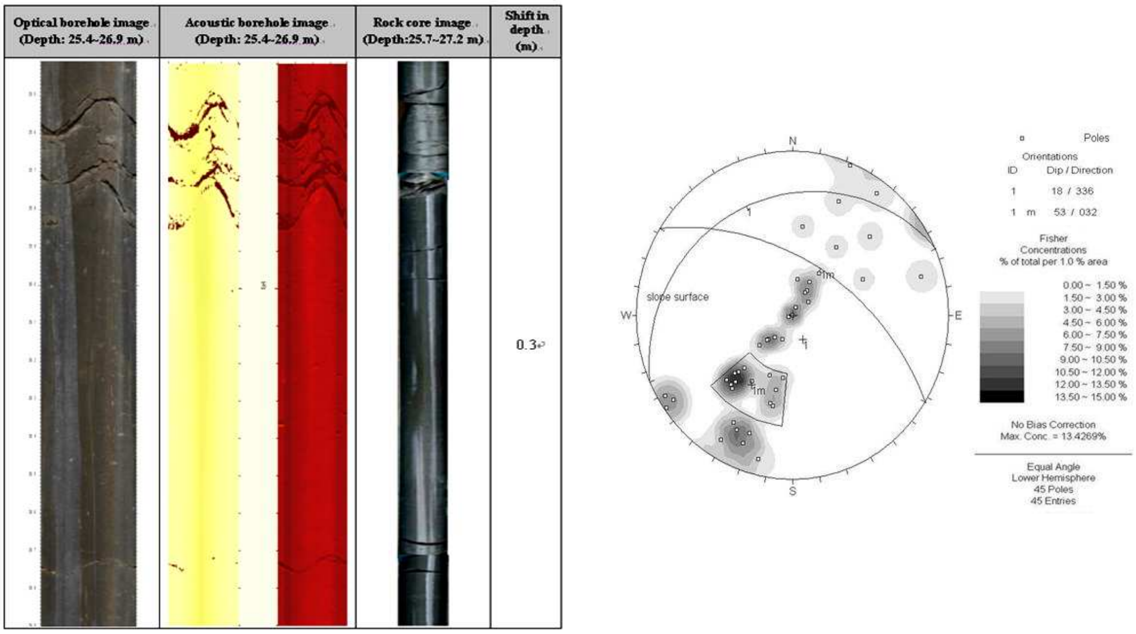


Figure 4. The comparison of image logging and rock core data (left); and the result of the stereographic projection analysis (right).

3.2 The borehole electrical logging

The results of borehole electrical logging are shown in Figure 5. Testing response demonstrated that the aquifer was mainly consisted of shale, except for the sections at 32~33 m and 34~38m, where the two sections can be characterized as the sandstone. This lithologic interpretation is fairly consistent with that from the rock core samples. Besides, the spontaneous potential exhibited a significant negative deflection in the sandstone. This is due to the high permeability of the layer that engendered greater saline exchange. The similar phenomena can be found from the response of electrical resistivity, which an apparent difference between short and long electrical resistance was displayed at the same depth.

3.3 The heat-pulse flowmeter measurement

The distribution of the heat-pulse flowmeter measurement under non-pumping conditions is shown in Figure 5. The upward flow was detected at 19.0, 21.0, 32.5, 34.0, 36.0, 38.0 and 43.8 m, where the flow rate is 0.16, 0.50, 1.23, 0.60, 0.69, 0.28 and 0.26m/min, respectively. The measurements showed that the relatively high flow rate was mainly located in the sandstone layer (around 32~38 m), while it is not easily detected in the shale layer. Furthermore, a sharp change of flow rate was found at 32.0 m. It indicated that a recharge flow could appear at this location.

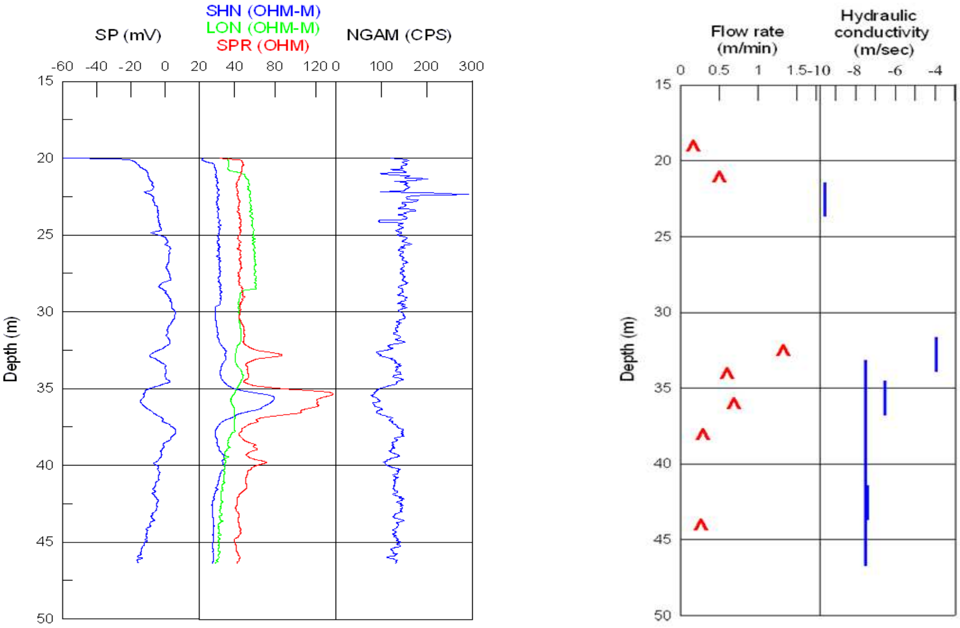


Figure 5. The results of electrical logging (left); flowmeter measurement and packer test (right).

3.4 The hydraulic packer test

Both single packer and double packer tests were conducted in this study. The single packer was performed to determine hydraulic properties in large sections of the rock formation which can represent different geologic unit, while the double packer test was adopted to explore hydraulic properties in specific intervals that have the existence of different geologic structures. According to the results as shown in Figure 5 and Table 1, a wide range in hydraulic conductivity from the order of 10^{-4} to 10^{-10}m/s was found. The maximum and minimum hydraulic conductivity were 1.10×10^{-4} m/s at depth 32.0~33.5m and 2.81×10^{-10}m/s at depth 21.8~23.3m, respectively. In addition, the hydraulic conductivity obtained from the single packer test was 3.07×10^{-8}m/s in the section from 33.5m to 50.0m. The above results provide critical information to establish a hydrogeological conceptual model when modeling the landslide problem.

3.5 The integrated logging results

The results acquired from the aforementioned tests were finally integrated (Figure 6 and Table 1). The response of the electrical logging indicated that the aquifer mainly consists of shale except for the sections at 32~33m and 34~38m, where the two sections can be identified as the sandstone unit. Meanwhile, the electrical logging indicated that the sandstone yielded high transmissivity. This can be verified from the flowmeter measurement which the most apparent flow was detected in the sandstone layer. The flowmeter measurement also demonstrated that a major flow path existed at the depth of 32.0 m, where the water-receiving zone can be also delineated at this place. The results of the packer tests revealed coincident phenomena, which the maximum hydraulic conductivity in the sandstone was three orders of magnitude greater than the hydraulic conductivity in the shale. Furthermore, when the borehole images were took into account, the various fracture properties (e.g. dips, fracture number and aperture width) can further recognize the above phenomena efficiently. Therefore, it can be noted that the five high-angle (mean dip: 49.2 degree) fractures in the 32.0~33.5m section yield high interconnectivity based on the large flow rate and hydraulic conductivity. Conversely, it can also be concluded the fractures containing clayey fillings in the section of 21.8~23.3 m produce relatively low interconnectivity.

Based on the above borehole prospecting and other exploration results such as rock core data from the other two boreholes, RIP, and double-ring infiltration test, a two-dimensional hydrogeological conceptual model at the Hung-Tsai-Ping landslide site was finally established (Figure 7). The model was divided into three hydrogeologic units including colluvial cover, weathered bedrock (sandstone) and bedrock (shale), in which the hydraulic conductivity for three units ranges from 10^{-6}~10^{-7}m/s, 10^{-4}~10^{-7}m/s and 10^{-8}~10^{-10}m/s, respectively. The model is capable to perform the seepage and slope stability analysis to simulate the landslide problem in the study area.

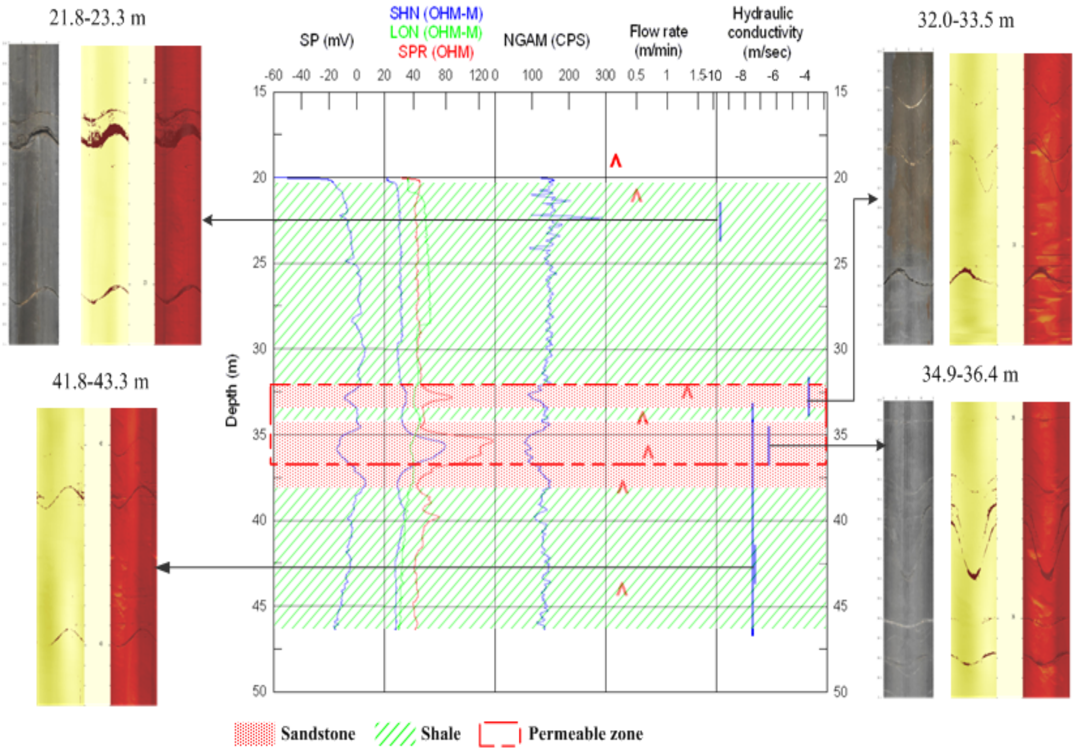


Figure 6. The integrated prospecting results.

Table 1. The results of the electrical logging, flowmeter measurement, fracture properties, and hydraulic conductivity (the test interval of the packer test)

Test interval (m)	Response of the electrical logging	Flow rate (m/min)	Fracture numbers	Mean dip (degree)	Type of packer test	Solution	Type of aquifer	Hydraulic conductivity K (m/s)
21.8~23.3	- Spontaneous potential: -5 ~ -12 (mV) - Short normal resistivity: 22 (Ohm-m) - Long normal resistivity: 50 (Ohm-m) - Natural gamma radiation: abnormal signal	around 0.50	Discontinuous: 1 Fracture zone: 1	32.0	double packer	KGS Model	Confined	2.81×10^{-10}
32.0~33.5	- Spontaneous potential: 2 ~ -10 (mV) - Short normal resistivity: 22~30 (Ohm-m) - Long normal resistivity: 38~43 (Ohm-m) - Natural gamma radiation: 90~150 (CPS)	around 1.23	Discontinuous: 5	49.2	double packer	Baker	Confined	1.10×10^{-4}
34.9~36.4	- Spontaneous potential: 2 ~ -15 (mV) - Short normal resistivity: 25~80 (Ohm-m) - Long normal resistivity: 35~39 (Ohm-m) - Natural gamma radiation: 80~150 (CPS)	around 0.60	Discontinuous: 6	40.6	double packer	Baker	Confined	3.11×10^{-7}
41.8~43.3	- Spontaneous potential: -5 ~ -9 (mV) - Short normal resistivity: 19 (Ohm-m) - Long normal resistivity: 22 (Ohm-m) - Natural gamma radiation: 150 (CPS)	around 0.28	Discontinuous: 3	44.0	double packer	KGS Model with skin	Confined	4.16×10^{-8}
33.5~50.0	- Spontaneous potential: 6 ~ -15 (mV) - Short normal resistivity: 19~80 (Ohm-m) - Long normal resistivity: 22~48 (Ohm-m) - Natural gamma radiation: 90~150 (CPS)	around 0.28~0.50	Discontinuous: 23	39.7	Single packer	Dougherty-Babu	Confined	3.07×10^{-8}

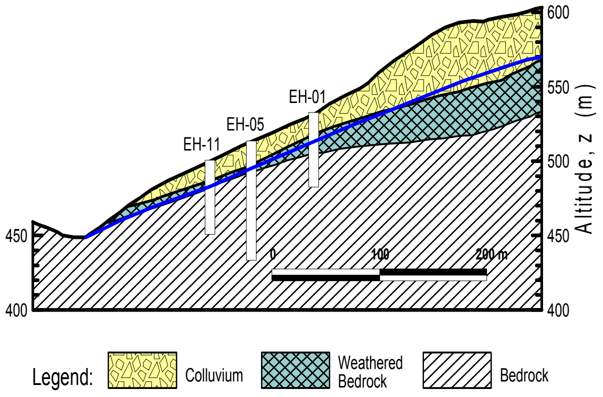


Figure 7. The hydrological conceptual model of the Hung-Tsai-Ping landslide site.

4. CONCLUSIONS

The use of different subsurface prospecting approaches is very helpful in clarifying the complexity of the subsurface hydrogeologic conditions. In this study, four subsurface exploration technologies, including borehole image logging, electrical logging, flowmeter logging and double packer tests, were conducted at an active landslide site. Although each of the approach has its own investigation purpose, by integrating the results, the geologic and hydraulic conditions of the study area can be better understood, such as the permeable zone at different lithologic units, the correlation of the fracture features and their interconnectivity, location of the water-receiving or producing zone, the water-bearing zone and their corresponding fracturing degree, as well as the hydraulic properties at the intervals that are particularly interesting. Owing to project budget limit, the techniques illustrated in this paper were only conducted in one borehole. The hydrogeologic model with higher spatial resolution and better accuracy of the project site for sure is determined through investigation results from multiple wells. Such multiple wells investigations are desired to perform in future study.

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