Estimation of Hydraulic Conductivity in Montane Regions of Taiwan

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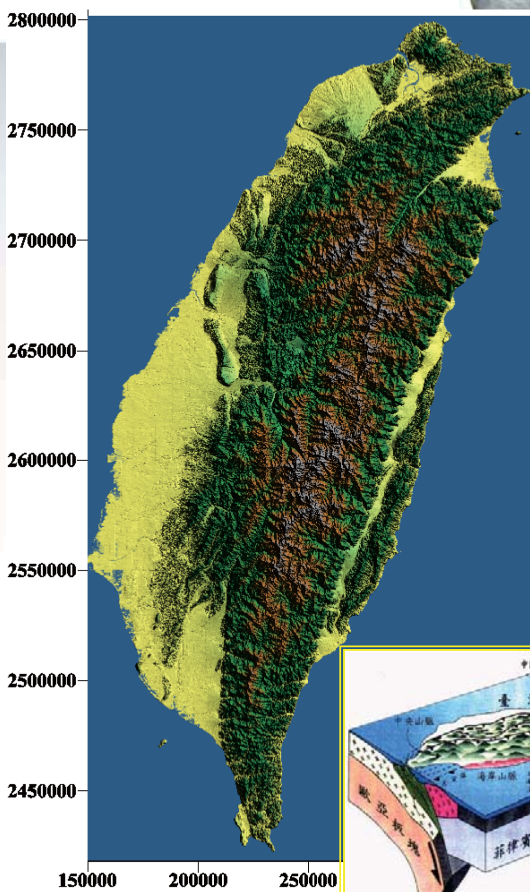
OUTLINES

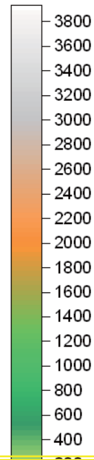
Estimation of Hydraulic Conductivity in Montane Regions of Taiwan

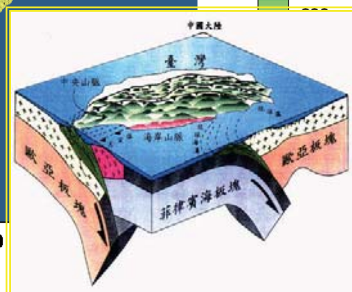
- Problem Significance
- Measurement of Rock Mass Hydraulic Conductivity
- Estimation of Hydraulic Conductivity
- Application of The HC Model
- Conclusions

Problem Significance

- Discontinuous Nature of Rock Masses in Taiwan
  - fissures, cleavages, beddings, joints, and faults are prominent
  - Thousands of earthquakes each years may induce faults movement
  - Highest precipitation reaches 6000 mm
    - Average rainfall is 2483 mm
    - Providing sufficient groundwater recharge
  - Rockmass is very young in geological time scale
- Groundwater Resource
  - With abundant recharge, groundwater may be one of most important water resources in Taiwan.







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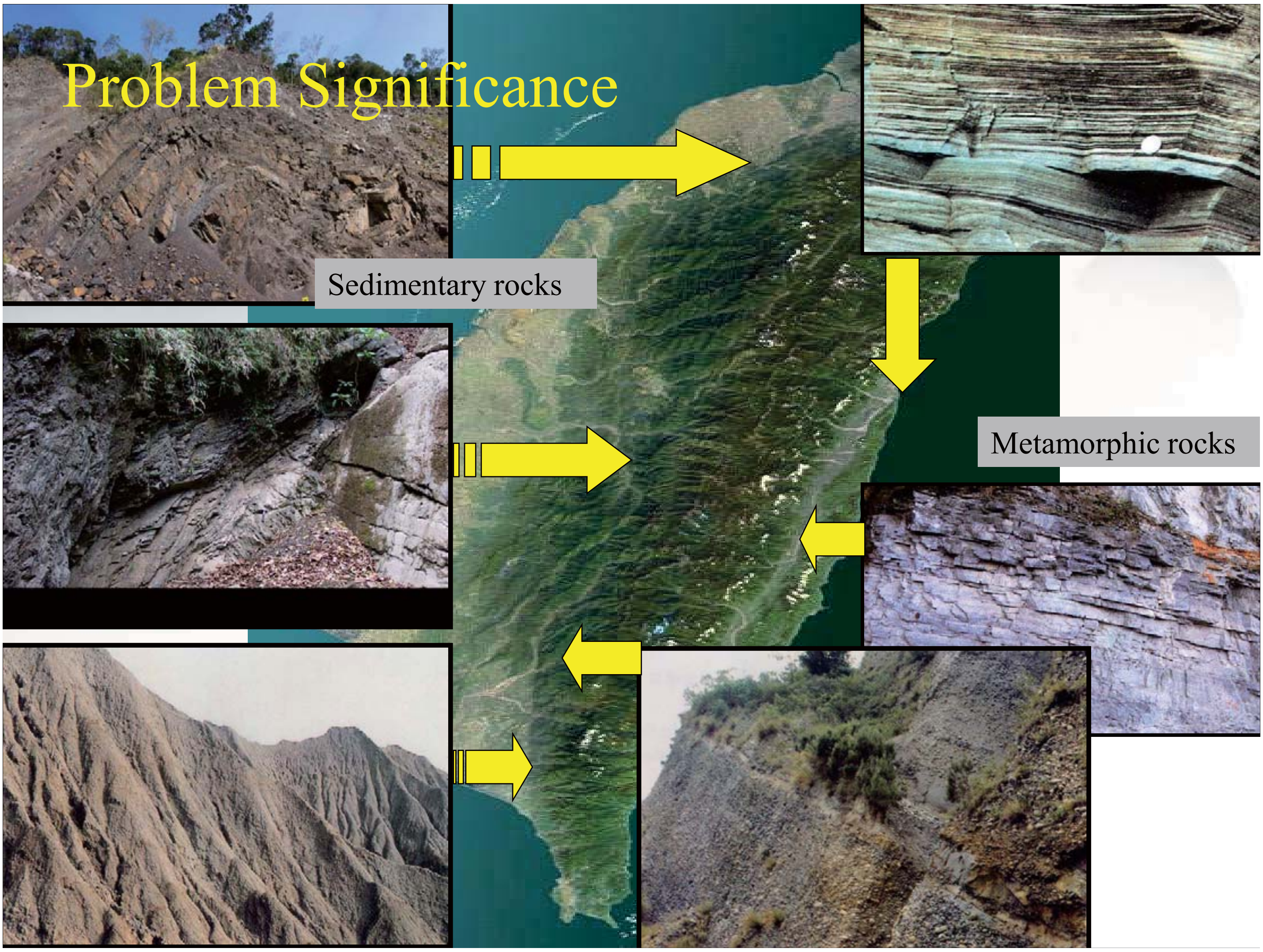

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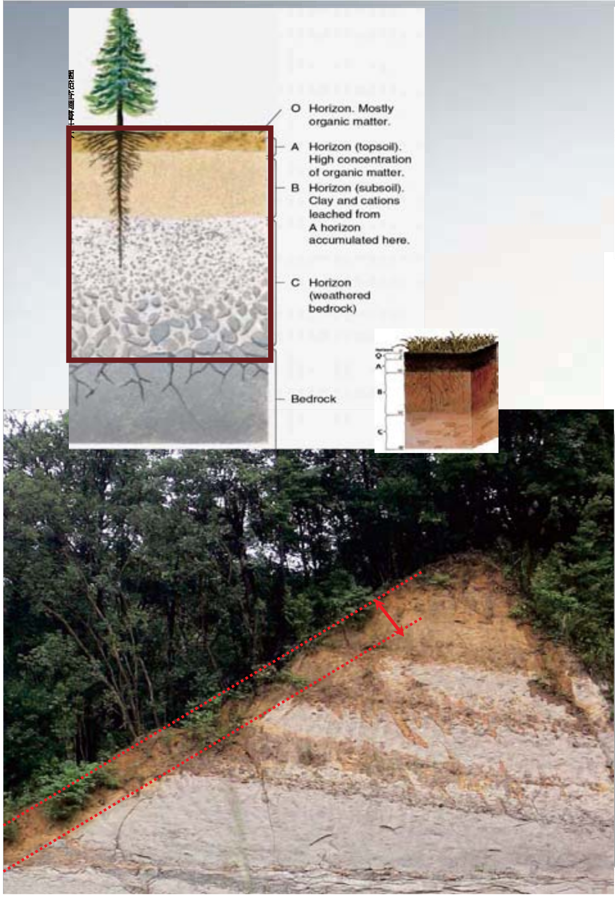
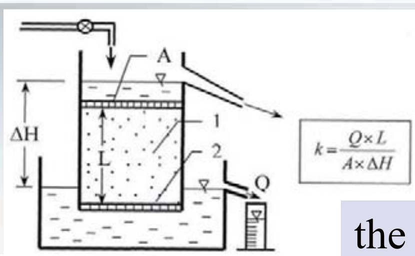
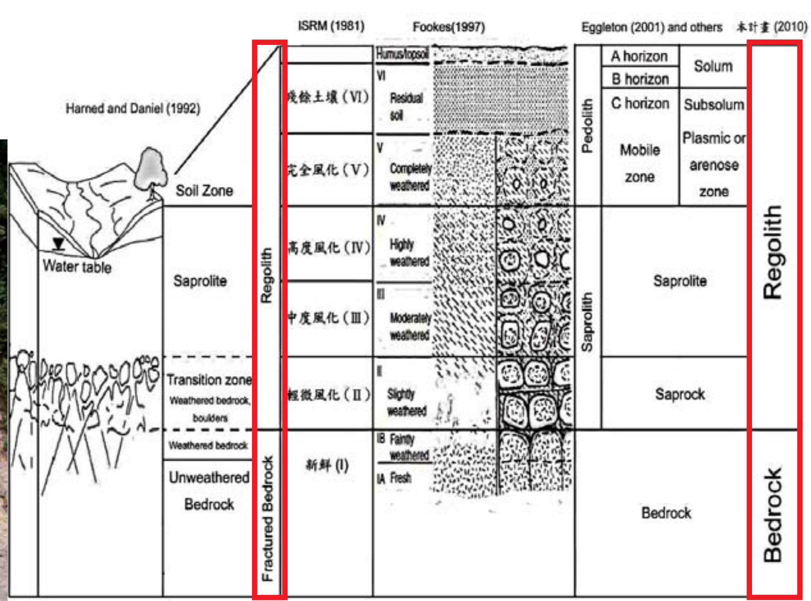




the constant-head method



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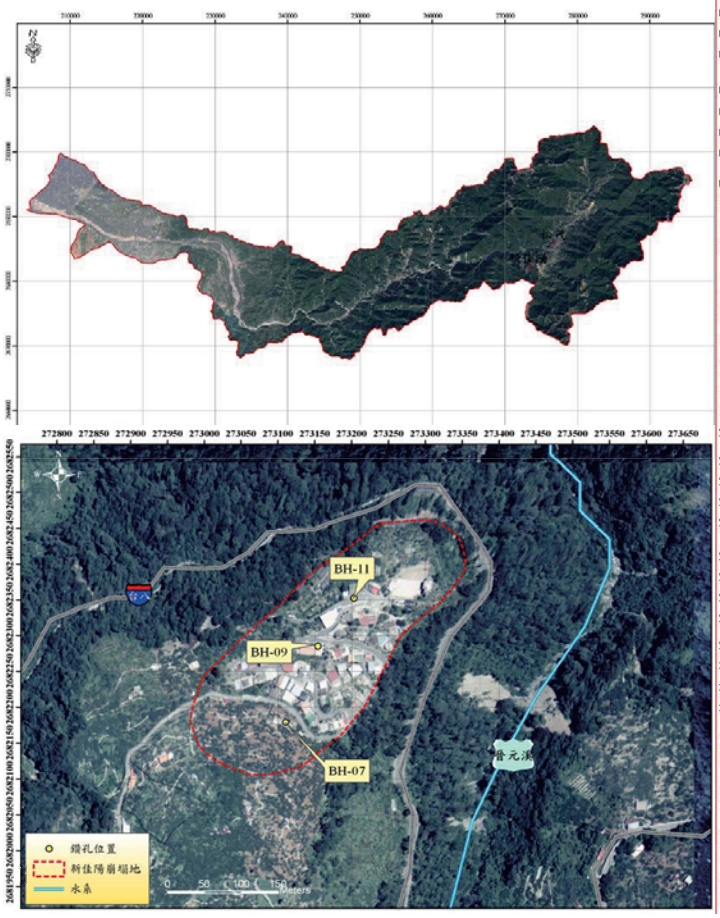
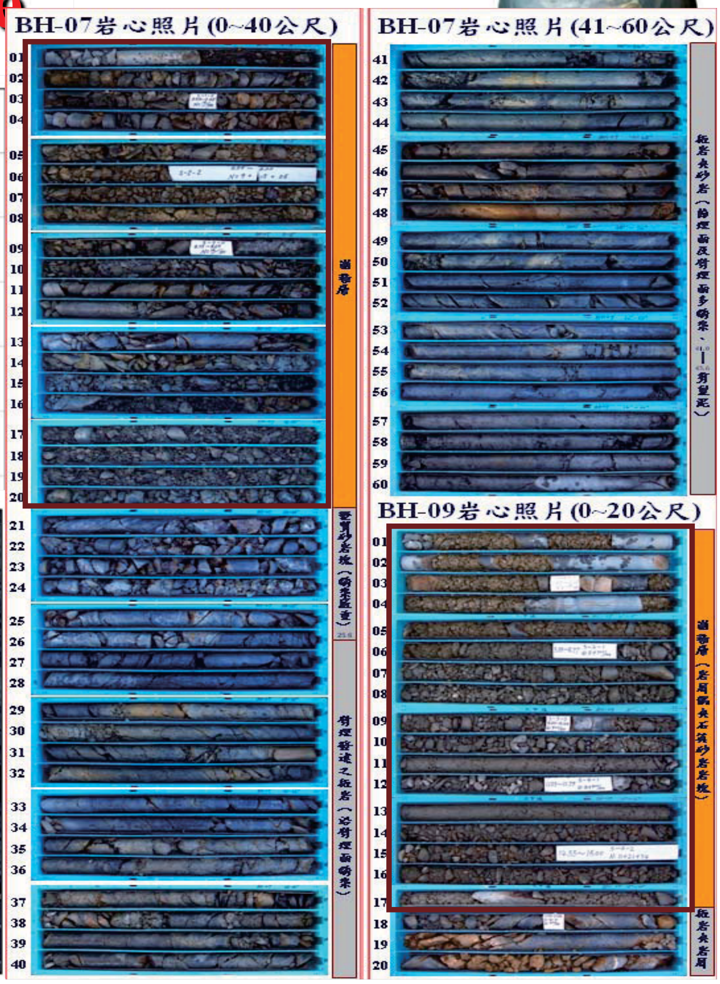
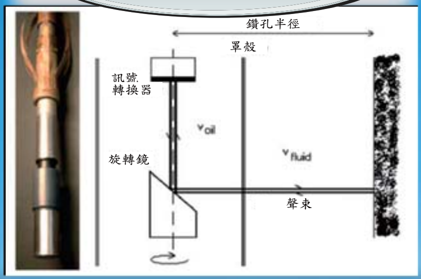




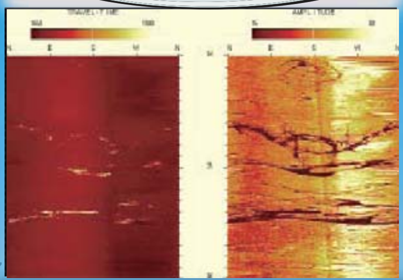
Measurement of rock mass hydraulic conductivity

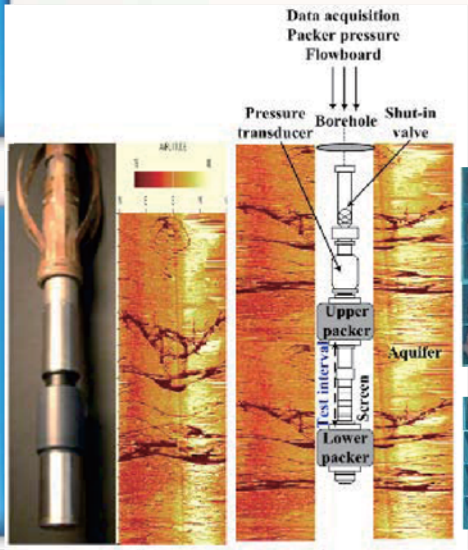
- The information gathered from BHTV was used to characterize lithology and fractures for the borehole and was essential to the proper design of the hydrogeological program.

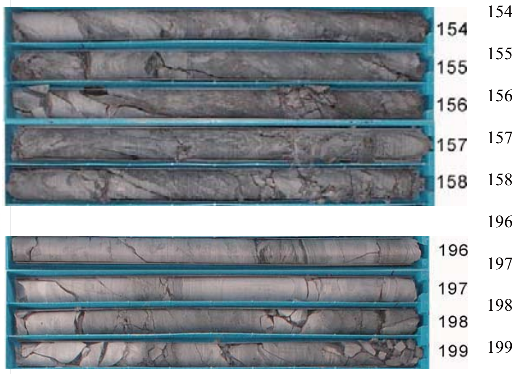
BHTV



BHTV image





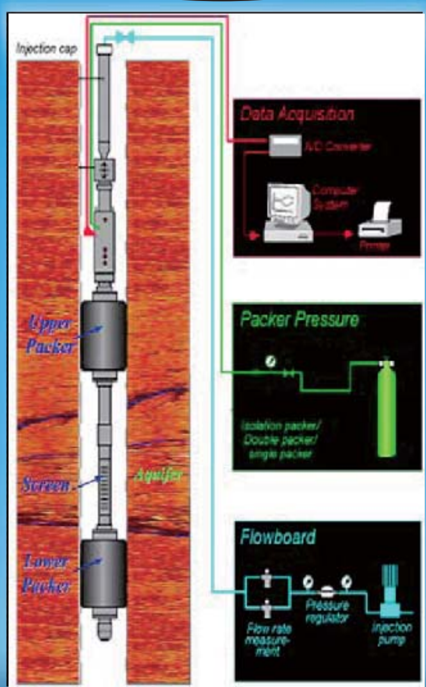


Measurement of rock mass hydraulic conductivity

- **Hydrogeology:**
  - Piezometric mapping
  - Aquifer testing
    - Conductivity, etc.
  - →Hydrogeologic Model

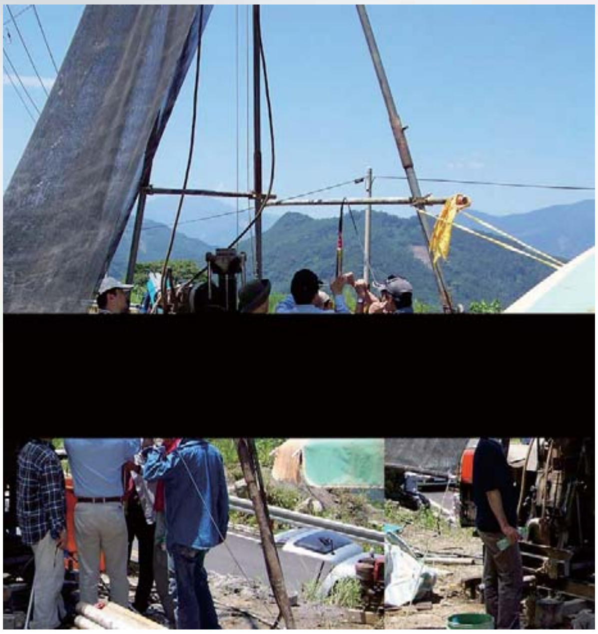
- **Double packer systems are the most commonly used tools for hydrogeological testing in boreholes for fracture rocks.**
- **They can be used to determine the hydraulic property in a section of borehole based on two inflatable packers. It is now recognized that this approach is appropriate to investigate the variability of a borehole as it intersects various hydrogeological units.**

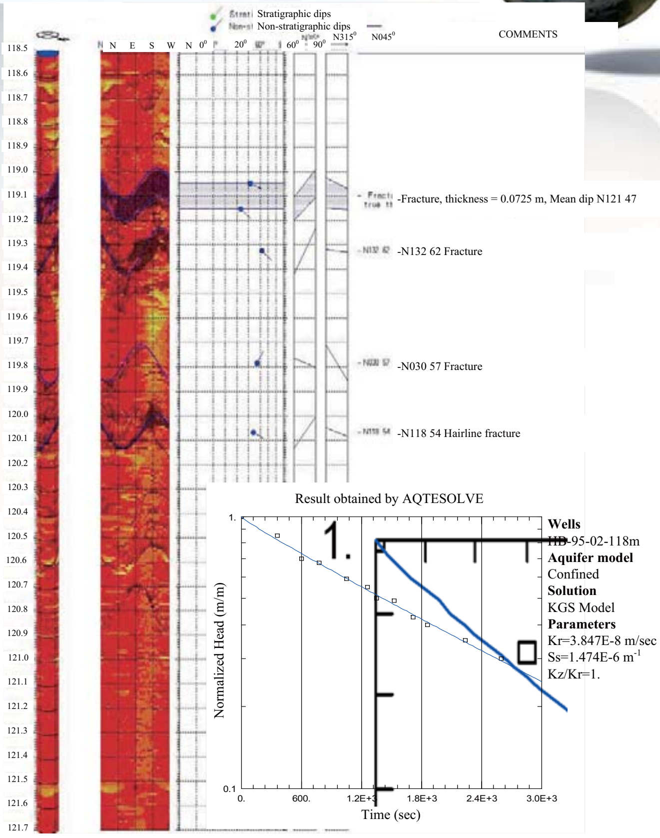
Double packer test



Measurement of rock mass hydraulic conductivity

- Evaluation of hydraulic parameters and BHTV images at pack-off zones 118.5 m to 121.7 m in Borehole HB-95-02.

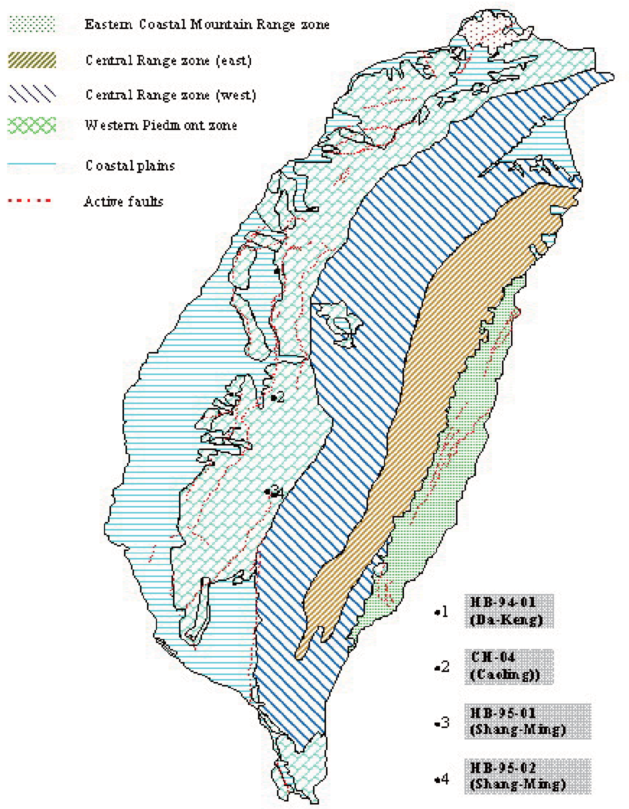




Problem Significance

Fig. 2(a). Rock core photos of borehole HB-95-2 with fault influence.

Fig. 2(b). Rock core photos of borehole CH-04 without fault influence.



Location of major faults and four boreholes for this study in Taiwan

Estimation of Hydraulic Conductivity

Empirical equations

- An empirical relation proposed by Louis (1967) from field measurements indicates that the rock mass hydraulic conductivity **decreases with the depth by an exponential formula**.
- A numerical study conducted by Wei and others based on rock fracture network simulation (Wei and Hudson, 1988;Wei et al., 1995) suggested that the hydraulic conductivity **decreases with depth and is proportional to the depth cubed**.

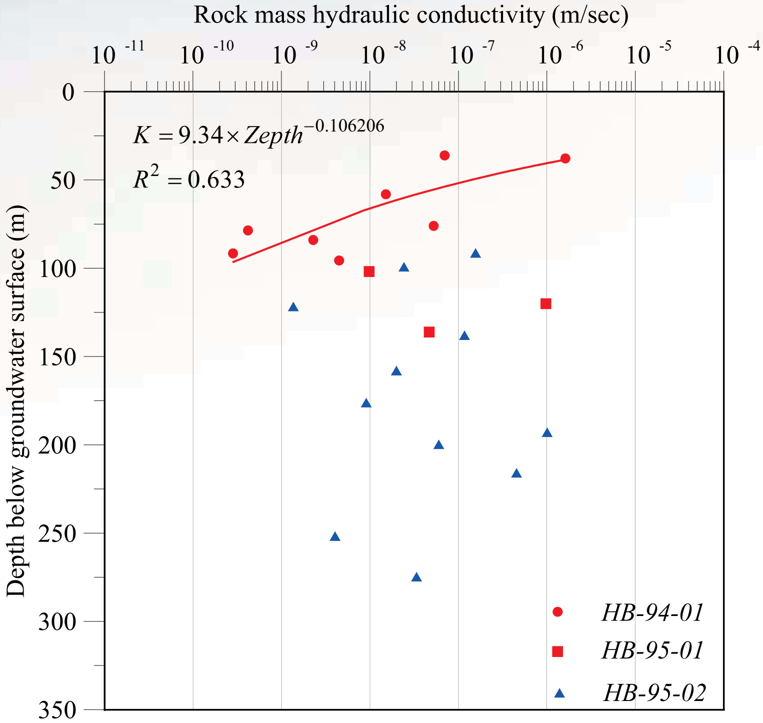
Equation	Reference
$k = az^{-b}$	Black (1987) a and b are constants, z is the vertical depth below the groundwater surface.
$\log K = -8.9 - 1.671 \log Z$	Snow (1970) K (ft^2) is the permeability. z (ft) is the depth.
$K = 10^{-(1.6 \log z + 4)}$	Carlson and Olsson (1977) K (m/s) is the hydraulic conductivity. z (m) is the depth.
$K = K_s e^{(-Ah)}$	Louis (1974) K (m/s) is the hydraulic conductivity. K_s is the hydraulic conductivity near ground surface. h (m) is the depth. A is the hydraulic gradient.
$\log K = 5.57 + 0.352 \log Z - 0.978(\log Z)^2 + 0.167(\log Z)^3$	Burgess (1977) K (m/s) is the hydraulic conductivity. Z (m) is the depth.
$K = K_i[1 - Z/(58.0 + 1.02Z)]^3$	Wei et al. (1995) Z is the depth. K is the hydraulic conductivity. K_s (m/s) is the hydraulic conductivity near ground surface.

Table 1 Diverse approximations for estimating rock mass hydraulic conductivity

Estimation of Hydraulic Conductivity

Empirical equations

- Relationship between hydraulic conductivity and depth



22 hydraulic test data

Estimation of Hydraulic Conductivity

Empirical equations

- The empirical model for estimating hydraulic conductivity of highly disturbed clastic sedimentary rocks in Taiwan
  - **An attempt to find the decrease in permeability with depth was conducted. The results, however, are very scatterd.**
  - **Potential factors**
    - Rock Quality Designation (RQD)
    - Depth Index (DI)
    - Gouge Content Designation (GCD)
    - Lithology Permeability Index (LPI)
      - that may affect the degree of permeability should be considered.

$$\text{RQD} = \frac{\sum \text{Length of Intact and Sound Core Pieces} > 100\text{ mm}}{\text{Total Length of Core Run, mm}} \times 100\%$$

$$= \frac{R_S}{R_T} \times 100\%$$

Estimation of Hydraulic Conductivity

Empirical equations

- **Depth Index (DI)**

$$\text{DI} = 1 - \frac{L_c}{L_T}$$

  - L_T is the total length of a borehole;
  - L_c is a depth which is located at the middle of a double packer test interval in the borehole.
  - The value of DI is always greater than zero and less than one. The greater the DI value, the higher the permeability
- **Gouge Content Designation (GCD)**

$$\text{GCD} = \frac{R_G}{R_T - R_S}$$

  - R_G is the total length of gouge content.
  - The value of GCD is always greater than zero and less than one.
  - The greater GCD value stands for the more gouge content in a core run, and thereby it will reduce the permeability.

Estimation of Hydraulic Conductivity

Empirical equations

- Rock mass permeability index, called the HC index

  $$HC = (1 - RQD)(DI)(1 - GCD)(LPI)$$

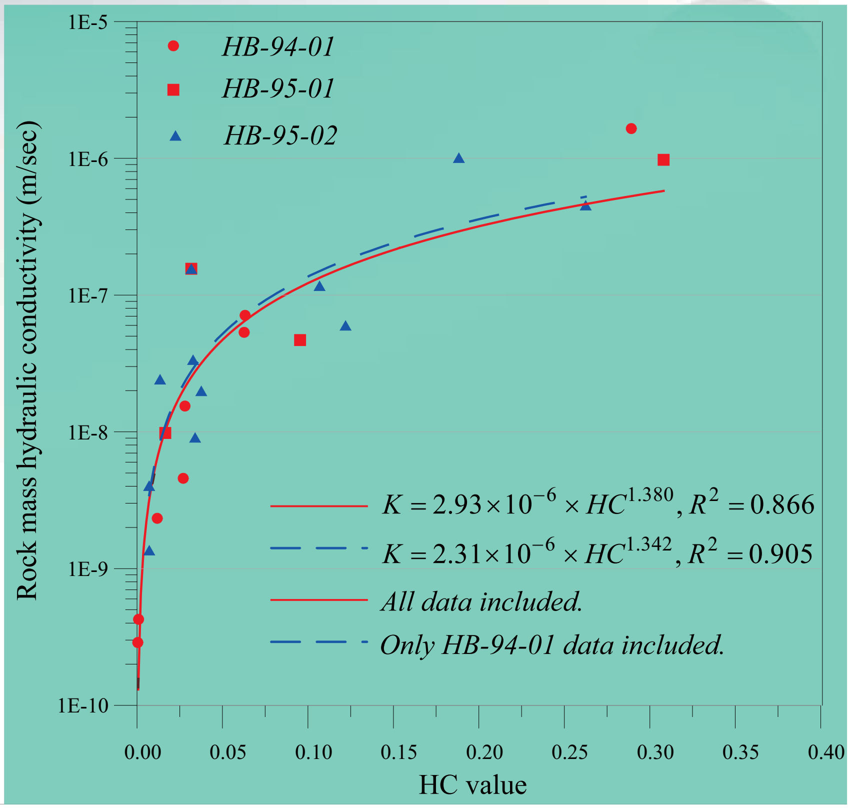
- **HC-value based on 22 hydraulic test data**

Boreholes	Test intervals (m)	1-RQD	DI	1-GCD	LPI	HC	K (m/s)
HB-94-01	34.7-36.3	0.094	0.677	1.000	1.000	0.0635	7.06E-08
	36.4-38.0	0.438	0.662	1.000	1.000	0.2895	1.64E-06
	56.7-58.3	0.063	0.477	1.000	0.950	0.0283	1.53E-08
	74.6-76.2	0.500	0.315	1.000	0.400	0.0629	5.3E-08
	77.2-78.8	0.010	0.291	1.000	0.400	0.0012	4.22E-10
	82.6-84.2	0.125	0.242	1.000	0.400	0.0121	2.31E-09
	90.2-91.8	0.010	0.173	1.000	0.400	0.0007	2.86E-10
	94.2-95.8	0.500	0.136	1.000	0.400	0.0273	4.53E-09
HB-95-01	99.0-101.9	0.345	0.598	0.200	0.400	0.0165	9.8E-09
	117.2-120.1	0.690	0.526	1.000	0.850	0.3081	9.76E-07
	133.2-136.1	0.724	0.461	0.286	1.000	0.0954	4.68E-08
HB-95-02	88.6-91.4	0.071	0.743	1.000	0.600	0.0318	1.56E-07
	96.0-99.2	0.031	0.721	1.000	0.600	0.0135	2.42E-08
	118.5-121.7	0.219	0.657	0.071	0.700	0.0072	1.36E-09
	134.8-138.0	0.344	0.610	0.727	0.700	0.1068	1.17E-07
	154.8-158.0	0.938	0.553	0.103	0.700	0.0376	1.99E-08
	173.0-176.2	0.938	0.501	0.103	0.700	0.0340	9.08E-09
	189.8-193.0	0.594	0.453	1.000	0.700	0.1883	1.01E-06
	196.6-199.8	0.563	0.434	0.500	1.000	0.1220	6.00E-08
	213.2-216.0	0.679	0.387	1.000	1.000	0.2625	4.54E-07
	249.0-251.8	0.393	0.285	0.091	0.700	0.0071	4.03E-09
	272.0-274.8	0.214	0.219	1.000	0.700	0.0328	3.36E-08

Estimation of Hydraulic Conductivity

Empirical equations

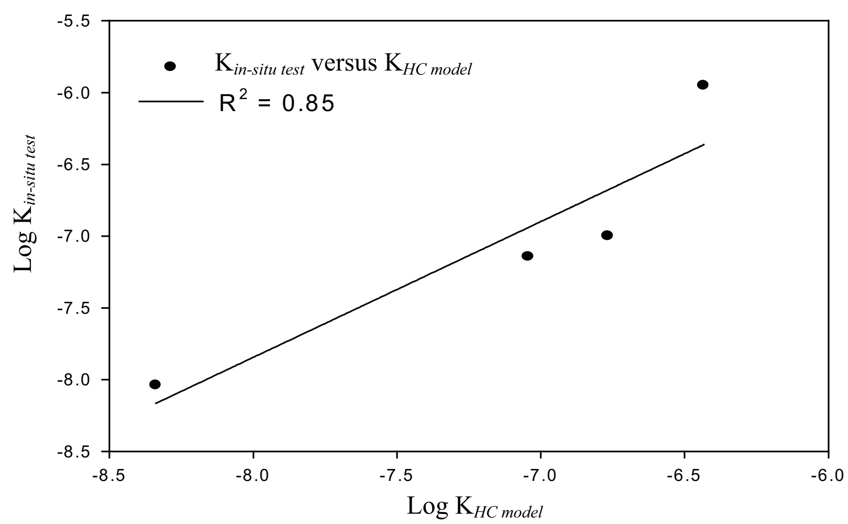
- An empirical model for estimating hydraulic conductivity of highly disturbed clastic sedimentary rocks in Taiwan



Estimation of Hydraulic Conductivity

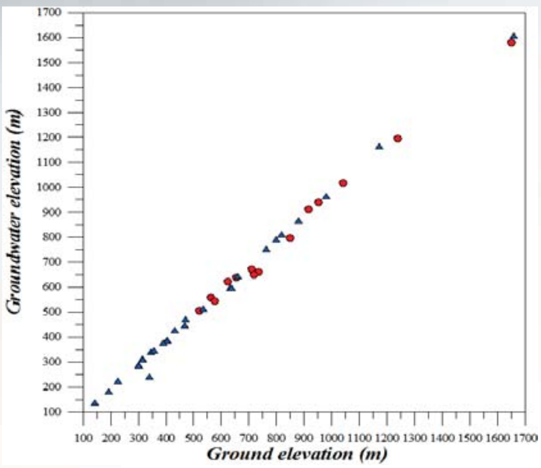
Empirical equations

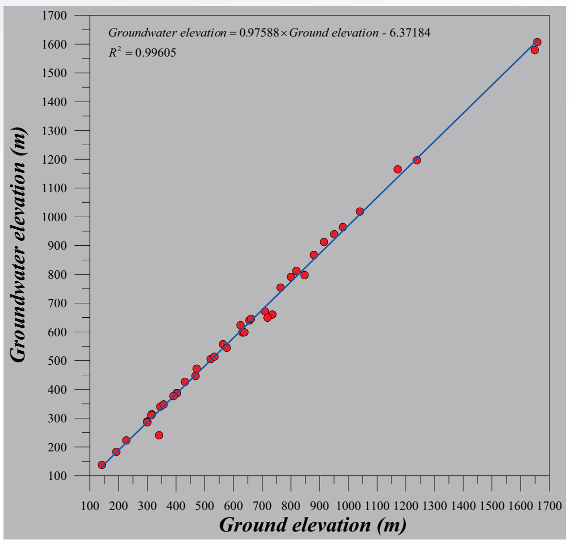
- **Correlation between $K_{in\text{-}situ}$ and K_{HC} *model***
  - Another borehole data with the drilling depth of 120 m is adopted to verify the empirical HC model. The principal lithologic units of the borehole, namely CH-04, are mainly sandstone, shale, and sandstone with some thin shale



Correlation between Groundwater Elevation and Ground elevation

Initial groundwater level

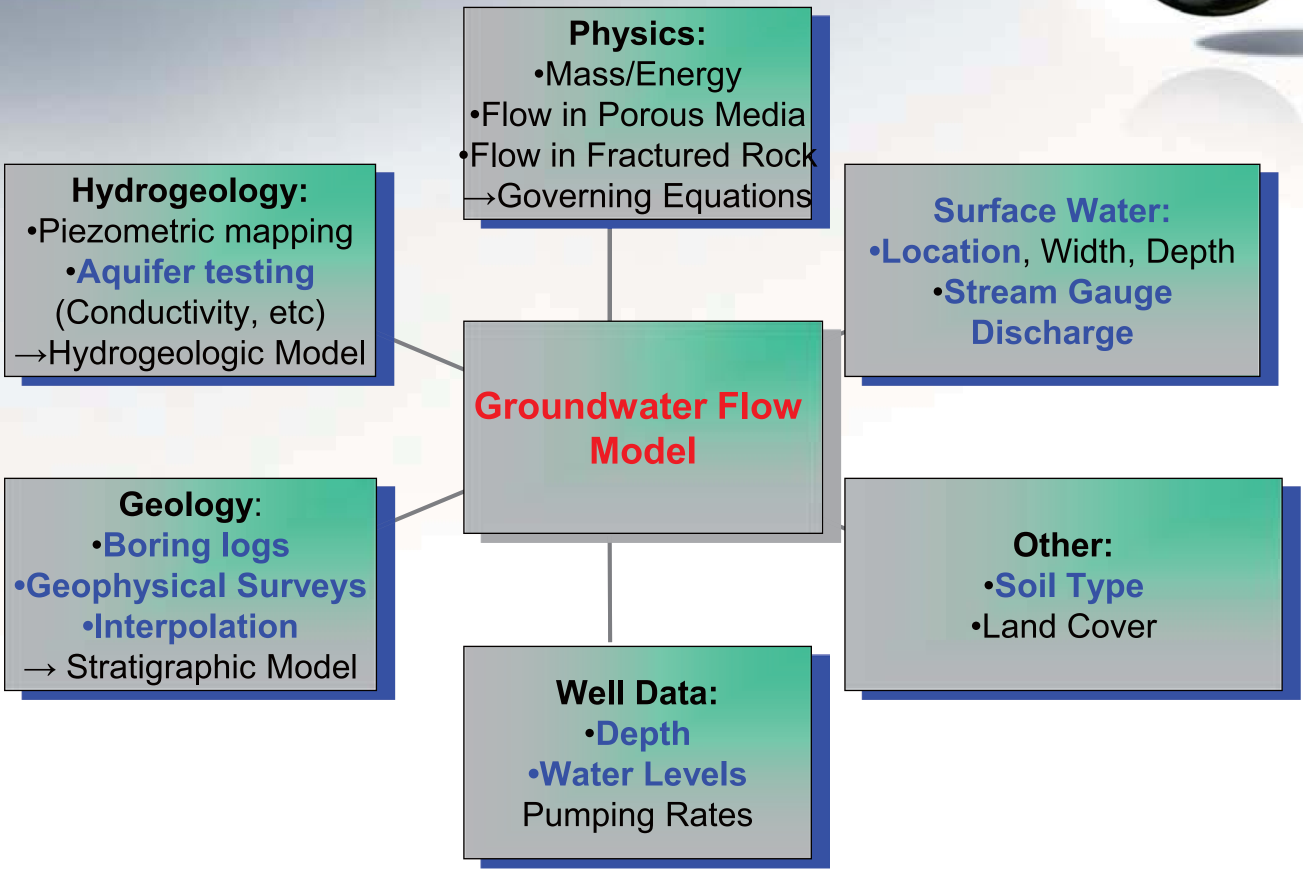




$$Groundwater\ elevation = 0.97588 \times Ground\ elevation - 6.37184$$

$$R^2 = 0.99605$$

Application of the HC Model



Application of the HC Model

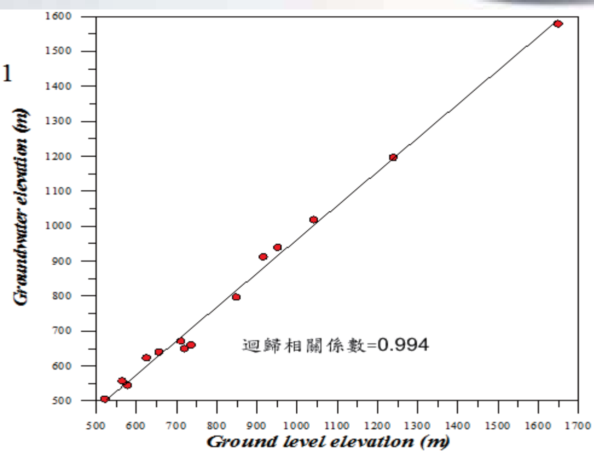
- Initial Groundwater Table

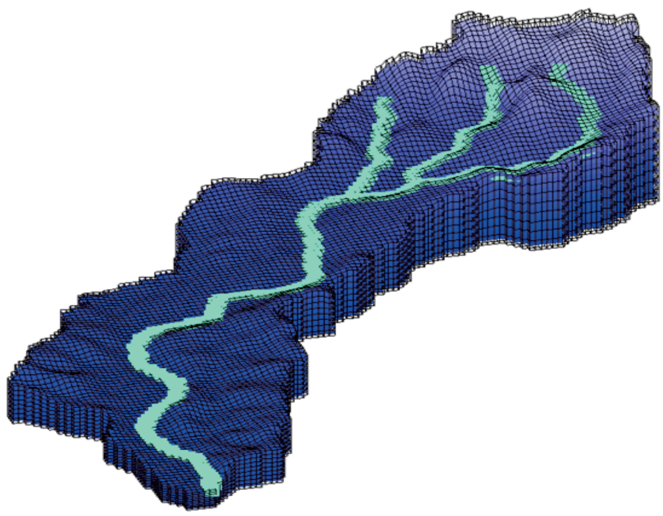
Relationship of initial groundwater level to the ground elevation

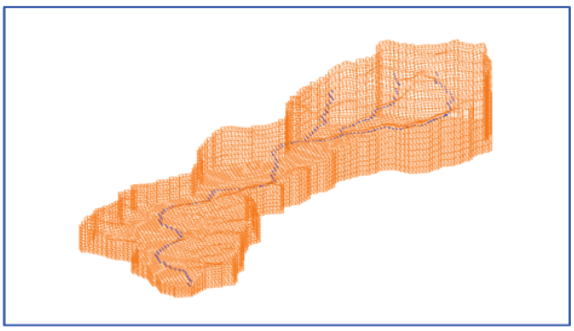
$$Groundwater\_elevation = 0.9672 \times Ground\_elevation - 4.781$$

Groundwater_elevation : initial groundwater level

Ground_elevation : ground elevation







Conclusions

- This study proposes an empirical model for estimating rock mass hydraulic conductivity using data collected for highly disturbed clastic sedimentary rocks in Taiwan.
  - The measurement of rock mass hydraulic conductivity of highly disturbed clastic sedimentary rocks in Taiwan has be successfully performed using the data of BHTV and double packer hydraulic tests.
  - The field results indicated that the rock mass in the study area has the conductivity between the order 10^{-10} and 10^{-6} m/s at the depth between 34 m and 275 m below ground surface.
  - The results demonstrate that the rock mass hydraulic conductivity of highly disturbed clastic sedimentary rocks in Taiwan mainly depends on the following four parameters: RQD, DI, GCD, and LPI.