

# AN EMPIRICAL MODEL TO CORRELATE ROCK MASS CLASSIFICATION AND HYDRAULIC CONDUCTIVITY, GEOTECHNICAL ENGINEERING DATA ACQUISITION AND REDUCTION PERSPECTIVE

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## ABSTRACT

This paper presents an empirical model for estimating rock mass hydraulic conductivity of fractured Hawkesbury Sandstone in the Sydney basin. The hydraulic conductivity of a fractured crystalline rock mass can be a critical factor in tunnelling projects and dewatering designs. The Lugeon test (commonly known as the “packer test”) is a common test used to estimate the in-situ permeability of a rock mass.

The Packer test is carried out over a specific length (typically 3-6 m) within a borehole to reduce the range of variation of the affecting parameters. To construct a detailed profile of hydraulic conductivity through the rock mass a relatively large number of Packer tests are often required which can be costly and time consuming.

The new rock mass classification system called the “HC system” was proposed by Hsu et al. (2011). The HC-system assists with the hydraulic modelling of a rock mass and is based on 4 parameters which can be readily assessed from borehole logs and borehole Televiewer data, namely Rock Quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD) and Lithology Permeability Index (LPI). A modified new rock mass classification system called the "HC-system" or HC model has been specifically developed for Hawkesbury Sandstone in the Sydney basin.

Regression analysis was conducted to assess the correlation between the calculated HC value (using the HC model) and the corresponding hydraulic conductivity from the in-situ packer tests.

To confirm the feasibility of the proposed empirical HC model, the model was subsequently used to estimate the hydraulic conductivity of similar Hawkesbury Sandstone boreholes from a range of projects that also have corresponding Packer test data for comparison.

This empirical HC model may assist with two important hydrogeological applications. The first application is to estimate hydraulic conductivity of fractured sandstone of similar geological set up based on HC-values. By using this approach, hydraulic conductivity data in a given site can be estimated from borehole data, which increases the reliability and confidence of the packer testing. Secondly, for in-situ aquifer tests the HC-system is a valuable new rock mass classification system for estimating the degree of permeability of a borehole. The results obtained confirm the validity and flexibility of the empirical approach to handle cases of onshore and offshore data sets, in relation to data acquisition and data reduction (optimisation).

Keywords: Lugeon, hydraulic conductivity, Rock Quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD), Lithology Permeability Index (LPI), Regression analysis.

## 1 INTRODUCTION

Triassic Hawkesbury Sandstone occupies an area of some 12,500 square kilometres in the Sydney basin (Geological Society Australia, 1969). Sydney is currently undertaking several major transportation tunnelling projects through Hawkesbury Sandstone. In this paper, data from different projects in Hawkesbury Sandstone within the Sydney basin are considered.

Engineering tasks such as tunnel construction, slope stabilisation, dam construction, mine development and petroleum abstraction require the estimation of hydraulic conductivity of fractured rock mass. The understanding of hydraulic properties of fractured rock mass, which involves the fluid flow behaviour in fractured consolidated media, is a critical step in support of these tasks. To obtain hydraulic properties of fractured rock mass, packer testing can be adopted. Although this type of test can directly measure the hydraulic conductivity, costs of the testing can be relatively high. The precision of the packer test and reporting depends on a number of factors from the beginning to the end of the testing and interpretation. Several studies (Snow, 1970; Louis, 1974; Carlsson & Olsson, 1977; Burgess, 1977; Black, 1987; Wei et al., 1995; Yihdego 2016) have proposed the estimation of rock mass hydraulic conductivity using different empirical equations, which were based on the concept that rock mass permeability decreases with depth, however hydraulic properties of rock mass may also vary with other factors including; geostatic stress, lithology, fracture properties and filling materials.

The use of empirical methods is a common practice in the geotechnical community. This paper proposes an empirical model to estimate hydraulic conductivity (K) of fractured sandstone rock mass based on the Rock Mass Classification (RMC) concept. The new rock mass classification system called the “HC system” was proposed by Hsu et al. (2011). It is based on the following four parameters: Rock Quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD) and Lithology Permeability Index (LPI). HC index can be calculated from borehole image data and rock core data. Hydrogeological studies are typically piggy-backed onto geotechnical investigations to reduce design and construction costs; cross correlation between data sets can provide additional insights.

Regression analysis was done to evaluate the dependence of HC-Values on measured hydraulic conductivity from Packer tests. As a result, an empirical formula was constructed to estimate the hydraulic conductivity. The details and the rating approach of each of the parameters are discussed. The feasibility of using HC-System on this study area is analysed.

In this case study a realistic and improved correlation (between RMC and K) was carried out in Sydney basin by integrating and maximising existing data and turning to useful information via data fusion, interpolation and interpretation. The results obtained confirm the validity and flexibility of the empirical approach to handle cases of onshore and offshore data sets, in relation to data acquisition and data reduction (optimisation). However, they may not provide fundamentally new insights as to the overall application of correlation indicated by the empirical model.

The purpose of this empirical model is; to reduce the cost on hydraulic testing, increase the confidence in data retrieved from packer testing and for the preliminary assessment of the degree of permeability of fractured sandstone.

## 2 STUDY AREA

The geology of study area is comprised of Permo-Triassic sedimentary rocks overlain by Quaternary aged sediments. Within the depth of investigation the geological sequence along the project alignment used for this assessment comprises a thick sequence of Hawkesbury Sandstone. In the more elevated areas, for example at North Sydney, Ashfield Shale of the Wianamatta Group overlies the Hawkesbury Sandstone (although it was not encountered in boreholes used for this assessment). The Hawkesbury Sandstone comprises three main facies:

- Sheet facies.
- Massive facies.
- Mudstone facies.

The sheet and massive facies make up about 95% of the total thickness of Hawkesbury Sandstone. The sheet facies comprise cross-bedded strata bounded by near horizontal bedding planes. The massive facies is composed of poorly sorted sand, and often contains clasts and flakes of mudstone (or siltstone). The mudstone facies can form strata up to about 10m thick, with interlaminated dark grey siltstone and sandstone.

### 3 ASSESSMENT OF AQUIFER PERMEABILITY

#### 3.1 PREVIOUS ASSESSMENT

McKibbin and Smith (2000) quote a hydraulic conductivity range for the Hawkesbury Sandstone between 0.01 and 1 m/day (1 and 100 uL) and note that values in excess of 0.1 m/day (>10uL) are probably associated with fracture permeability.

Interpretation of the in-situ water pressure test results (packer tests) yielded a range of Lugeon rock mass permeability values from <1uL to >100uL. The permeability of the rock mass can vary rapidly with the influence of local features. The unscaled geometric mean hydraulic conductivity within Hawkesbury Sandstone may generally vary between  $10^{-6}$  m/s to  $10^{-7}$  m/sec (as determined by discrete borehole “packer” testing). However, individual tests in a single borehole can vary between the lower and upper bound capabilities of the test apparatus (effectively ranging from less than  $10^{-8}$  m/sec to greater than  $10^{-5}$  m/sec). Hewitt (2004).

#### 3.2 CURRENT ASSESSMENT

As indicated in Table 1, assessment of 441 successful five stage Packer test results from 95 boreholes in Hawkesbury Sandstone within the Sydney area was carried out which indicates Lugeon values in the range <1uL to >100uL. Out of the total 441 packer tests 295 of the tests (67%) recorded Lugeon values < 1uL (very tight discontinuity) and were therefore excluded from this assessment. Data with the same Lugeon values were also excluded to minimise repetition. This resulted in 65 representative Packer tests used for the development of the empirical model.

**Table 1: The rock mass permeability based on the packer test results (Lugeon values)**

Lugeon Values	Relative Permeability	No. of Packer Tests		Percentage of Tests
		Offshore	Onshore	
<1	Low	86	209	67%
1-5	Moderate	36	23	13%
5-20	High	27	16	10%
20-50	Verv High	28	4	7%
>50	Extremelv High	12	0	3%
Total		189	252	100%

The field test results (Packer and slug tests) indicated that the rock mass in the study area has a hydraulic conductivity between the order of  $10^{-5}$  m/s and  $10^{-8}$  m/s at depth between 5m and 144m BGL.

The higher Lugeon values (>20uL or  $> 2 \times 10^{-6}$  m/s) are recorded at offshore tests and close to the harbour foreshore. This is attributed to a higher incidence of open (highly permeable) rock structure induced by stress relief in the steeper topography and possibly more weathering, associated with palaeovalley. Due to these variations separate analyses were carried out for offshore and onshore investigations.

### 4 COMPONENTS OF NEW ROCK MASS CLASSIFICATION SYSTEM HC INDEX

The new rock mass classification system potential factors, including Rock Quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD) and Lithology Permeability Index (LPI), that may affect the degree of permeability are considered. The rating approach for each factor that represents the magnitude of permeability is described.

Since these parameters are typically assessed during geotechnical investigations, the quality of the investigation and testing (Jemberere and Yihdego 2016) can affect the correlations of the new rock mass classification system with hydraulic conductivity. Figure 1 shows the strategy used for assessing these parameters from core photos and imaging.

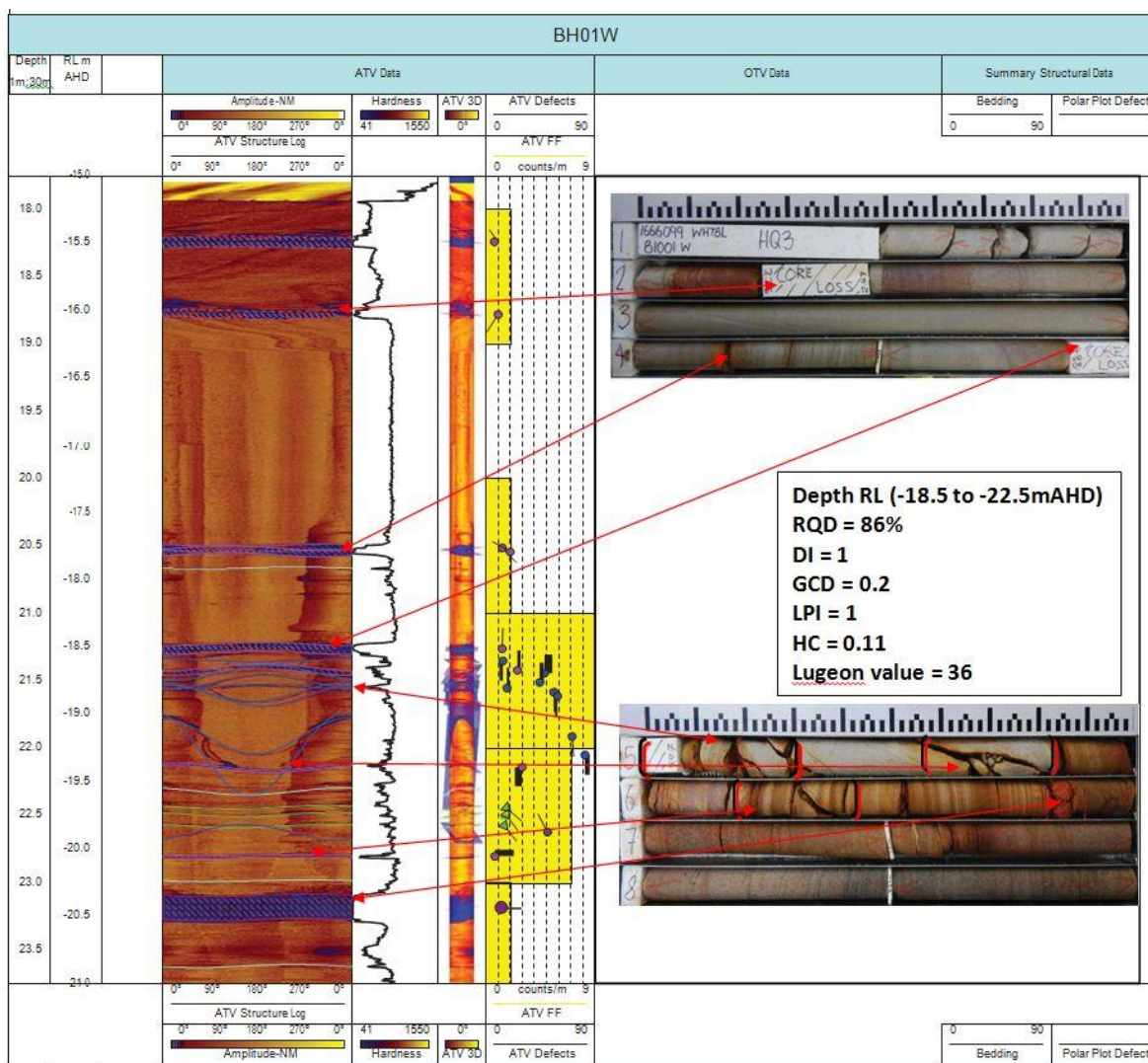


Figure 1: Identification of fractures and crushed zones from ATV image and core photo

#### 4.1 ROCK QUALITY DESIGNATION (RQD)

The degree of fracturing may be regarded as a factor in evaluating rock mass permeability. RQD is an index to evaluate and quantify the rock mass quality developed by Deere et al. in 1967. It can be used to assess the influence of the fracture characteristic on permeability.

$$RQD = \frac{\sum RS \times 100}{RT} \tag{1}$$

RS – Length of core pieces longer than 100mm in a run.

RT – Total length of the core run.

The HC-Value is calculated from the inverse relationship of RQD ( $1 - RQD/100$ ). The result of the equation will give a HC-Value between 0 and 1. The greater the RQD, the lower the HC-Value. If the RQD is 100%, ( $1 - RQD/100$ ) will become zero. To avoid this situation, the term ( $1 - RQD/100$ ) should be taken as 0.01 or less depending on the overall RQD values (Hsu et al., 2011).

#### 4.2 DEPTH INDEX (DI)

Many researchers (for example Lee & Farmer, 1993; Singhal & Gupta, 1999) have indicated that rock mass permeability may decrease systematically with depth. The decrease in permeability with depth in fractured rocks is usually attributed to a reduction in fracture aperture and fracture spacing (Ku et al., 2009). The reduction is due to the effect of geostatic stresses, and therefore the permeability of fractured rocks will reduce. The depth may be considered as a factor in evaluating rock mass permeability. To assess the influence of the depth on permeability, a depth index called DI was defined as the following equation.

$$DI = 1 - \frac{LC}{LT} \tag{2}$$

LC – A depth which is located at the mid-point of hydraulic test (middle of a packer test interval in the borehole).

LT – Total length of a borehole.

The term  $(1-LC/LT)$  with a number ranging from 0 to 1 is used so that a deeper depth will give a lower HC-Value.

#### 4.2.1 Use of Depth Index in the HC value equation

The term Depth Index (DI) is calculated by equation 2, where LC is the depth at the middle of a packer test interval in the borehole and LT is the total depth of the borehole. It is the ratio of the Packer Test depth compared to the total depth of that particular borehole. It is meaningful only when all the Packer tests are done in one single borehole. For instance, if two boreholes were drilled, Borehole A is 100m deep and Borehole B is 200m deep. Two Packer tests were done at the same depth (50m) in both boreholes. Depth Index (DI) at 50m of Borehole A will be  $1-50/100 = 0.5$  while at 50m of Borehole B will be  $1-50/200 = 0.75$ . However, the Depth Index (DI) is developed based on the presumption that the permeability of a rock mass decreases with depth due to the reduction in fracture aperture and spacing (Ku et al., 2009), they should therefore have the same value of DI for the same depth of 50m. Hence, unless the results of DI are normalized for holes with different total length, they cannot be used directly for comparison.

The study area was subjected to tectonic deformations mainly near the harbour and resulted in fractured rocks; this means that the fracture aperture and spacing of rock mass is not only controlled by depth.

To evaluate the relationship between vertical depth and hydraulic conductivity in Hawkesbury Sandstone, the mid-depth of the Packer test section and the corresponding hydraulic conductivity are plotted as shown in Figure 2 (Hewitt 2004). The plot shows that although the zones with higher permeability tend to be found in shallower depths, there is no obvious correlation between the depth and the hydraulic conductivity which does not make it a good indicator of hydraulic conductivity. It is concluded that the depth is not a significant factor on the hydraulic conductivity of this project, so the Depth Index (DI) is taken to be 1.

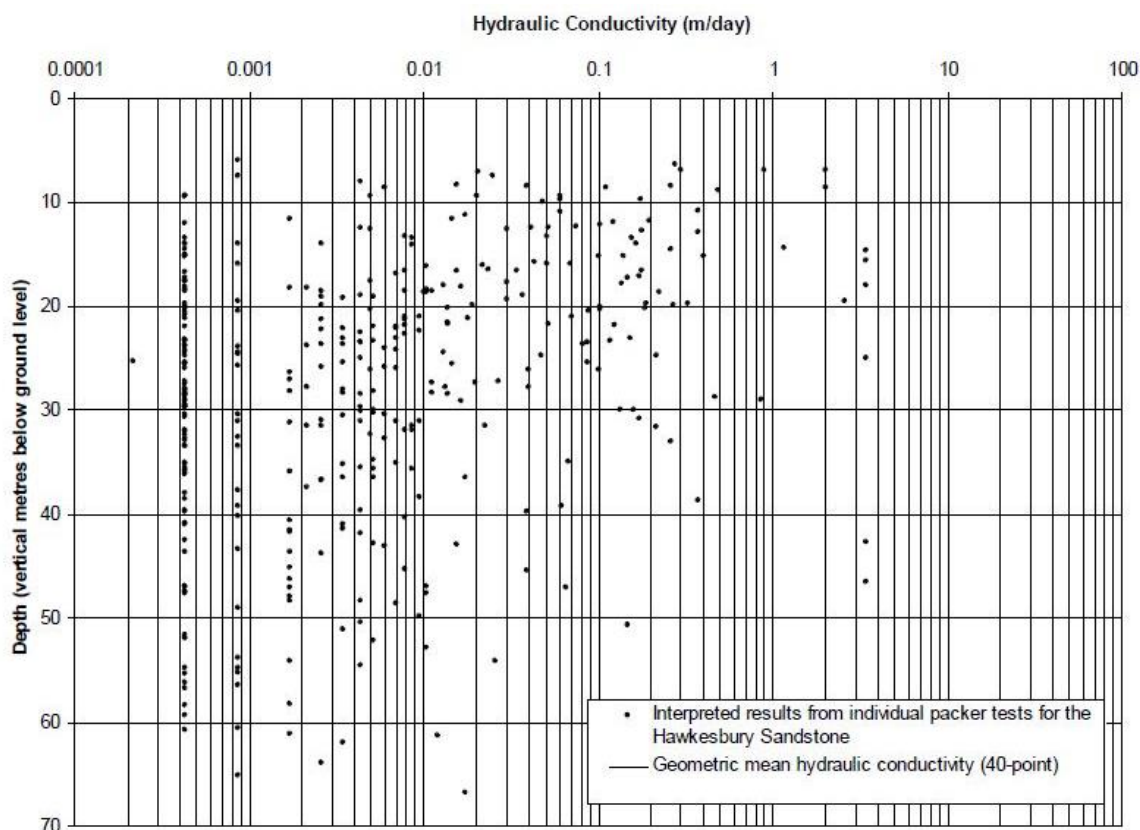


Figure 2: Hydraulic conductivity interpreted from packer tests Hewitt 2004)

#### 4.3 GOUGE CONTENT DESIGNATION (GCD)

In general, the permeability of clay-rich gouges has extremely low values (Singhal & Gupta, 1999). The RQD value may decrease by an increase of fractures in a core run. If the fractures contain infillings such as gouges, permeability of the fractures will reduce. To assess the influence of the gouge materials on permeability, a gouge content designation index called as GCD was defined as the following equation:

$$GCD = \frac{RG}{RT-Rs} \quad (3)$$

RG – Total length of gouge content from the total of core run.

RT – Total length of the core run.

RS – Length of core pieces longer than 100mm in a run.

GCD has a value between 0 and 1. With the greater length of gouge content RG, the value of GCD will be smaller and thus a lower permeability and a smaller HC value.

#### 4.4 LITHOLOGY PERMEABILITY INDEX (LPI)

The previous three parameters, RQD, DI and GCD are factors related to fracture properties (RQD and DI: fracture aperture and spacing; GCD: infilling materials). Apart from fracture properties, the rock matrix lithology also affects the permeability. Lithology of a rock mass refers to the mineral composition, texture, grain sized and so forth (Hsu et al., 2011). The porosity of the intact rock is controlled by the size, shape and degree of sorting of the composing particles. Especially for sedimentary rocks, the particle properties greatly affect the permeability. Sandstone with larger grain size will have a higher permeability than siltstone which has smaller grain size.

To evaluate the permeability of different rock types, an index called Lithology Permeability Index (LPI) is defined (Hsu et al., 2011) with some suggested values for different lithology as shown in Table 2. Since all of the rocks tested in this study are sandstone, the LPI is taken as 1.

**Table 2: Rating for LPI values based on lithology**

Lithology	Hydraulic Conductivity (m/s)				Range of Rating	Suggested Rating
	Reference <sup>a</sup>	Reference <sup>b</sup>	Reference <sup>c</sup>	K average		
Sandstone	10 <sup>-6</sup> -10 <sup>-9</sup>	10 <sup>-7</sup> -10 <sup>-9</sup>	10 <sup>-7</sup> -10 <sup>-9</sup>	10 <sup>-7.5</sup>	0.8 – 1.0	1.00
Shale	10 <sup>-10</sup> -10 <sup>-12</sup>	10 <sup>-10</sup> -10 <sup>-13</sup>	-	10 <sup>-10.5</sup>	0.4 – 0.6	0.50
Siltstone	10 <sup>-10</sup> -10 <sup>-12</sup>	-	-	10 <sup>-11</sup>	0.2 – 0.4	0.30
Sandy Siltstone	-	-	-	-	0.3 – 0.4	0.40

<sup>a</sup>B.B.S. Singhal and Gupta (1999). <sup>b</sup>Karlbeinz Spitz and Joanna Moreno (1996) <sup>c</sup>Bear (1972)

## 5 ROCK MASS PERMEABILITY AND EMPIRICAL HC MODEL

### 5.1 HC INDEX

As stated in Section 4, the rock mass permeability may be dependent on the following four parameters: Rock quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD), and Lithology Permeability Index (LPI). The permeability is possibly affected by any two factors, three factors or even all four factors. Thus, a rock mass classification scheme was applied to establish the rock mass permeability system. The new rock mass classification scheme is the product of the four parameters. It can account for the synthetic effect from the four parameters on permeability.

The new rock mass classification system called the “HC-system” is given by the following equation Hsu et al. (2011).

$$HC = \left(1 - \frac{RQD}{100}\right) \times DI \times (1 - GCD) \times LPI \quad (4)$$

Where:

HC – HC Value.

RQD – Rock Quality Designation.

DI – Depth Index.

GCD – Gouge Content Designation.

LPI – Lithology Permeability Index.

The value of each parenthesis at the right hand side of Equation (4) is always greater than zero and less than one depending on the values assigned to the four parameters. The greater the value of each parenthesis, the higher the permeability. Thus, the system performs a numerical assessment of the rock mass permeability using the four parameters. However, it should be noted that if (1-RQD) is zero, a value of 0.01 (or lower) in the term of (1-RQD) should be used to avoid the HC-value being zero. The rationality of Equation (4) must be verified by observed data through in-situ hydraulic tests.

## 5.2 RELATIONSHIP OF HYDRAULIC CONDUCTIVITY AND HC-SYSTEM FOR ONSHORE AND OFFSHORE TESTS

To verify rationality of Equation (4), the study collected in situ hydraulic test data (30 onshore and 35 offshore tests) to determine the relationship between hydraulic conductivity and HC-index. The HC values were plotted in a scatter plot with hydraulic conductivity from packer tests for both onshore and offshore. Borehole Id with “W” shows that tests are carried out in offshore areas and plotted separately in Figure 3.

Based on packer test results, the hydraulic conductivity (K values) in the study area was heterogeneous. The K values generally ranged from  $10^{-8}$  to  $10^{-6}$  m/s. The contributions of each of the four parameters are summarized in an HC index-empirical approach shown in Table 3.

To evaluate the relationship between variables and to determine how well a model fits the data, a statistical method called Regression Analysis was undertaken to estimate the dependence of HC Value on hydraulic conductivity. A total of 65 Packer tests were applied to the study. HC-values can be calculated from borehole image data and rock core data, in which the values of RQD and GCD at each test interval with Equations (1) and (3), respectively. The value of DI is not a significant factor on hydraulic conductivity for the current investigation, so the Depth Index is taken to be 1. The value of LPI for each test zone can be obtained from rock core data and Table 2.

Table 3 shows the calculated results for the HC-system based on the validated 65 Packer test data. The regression results indicate that a power law relationship exists between the hydraulic conductivity from the Packer Tests and HC values with a coefficient of determination of  $R^2$  equals 0.95 for both onshore and offshore tests, which means 95% of test data points can be explained by the line as shown in Figure 3. The empirical HC model is shown in Equation 5 & 6.

$$K = 1 \times 10^{-5} \times (HC)^{0.85}, R^2 = 0.95 \text{ for onshore tests.} \quad (5)$$

$$K = 4 \times 10^{-5} \times (HC)^{1.12}, R^2 = 0.95 \text{ for offshore tests.} \quad (6)$$

**Table 3: The calculated HC values compared to the 65 Packer Tests results, ID's with “W” are offshore tests.**

Hole ID	Test intervals(m)	Total Depth(m)	1-(RQD/100)	DI	1 - GCD	LPI	HC Value	K (m/s) from Packer Test
B10	45.5 - 54.4	57	0.04	1	0.50	1	0.022	3.7E-07
B10	51.5 - 54.4	57	0.10	1	0.33	1	0.034	7.2E-07
B28	05 - 11.0	19	0.08	1	0.20	1	0.017	3.8E-07
B28	15 - 19.0	19	0.10	1	0.25	1	0.025	5.5E-07
B32	65.2 - 70.5	104	0.01	1	1.00	1	0.009	2.0E-07
B38	59 - 68.0	137	0.02	1	0.75	1	0.017	2.9E-07
B40	66.4 - 75.4	113	0.01	1	1.00	1	0.010	3.4E-07
B40	101.3 - 106	113	0.05	1	1.00	1	0.049	1.01E-06
B41	33.4 - 39.4	113	0.01	1	1.00	1	0.008	1.70E-07
B77	30.5 - 38.2	79	0.05	1	0.78	1	0.039	7.4E-07
B77	33.1 - 38.2	79	0.04	1	1.00	1	0.023	6.9E-07
B77	39.9 - 42.4	79	0.15	1	1.00	1	0.15	3.4E-06
B65	20.5 - 26.5	56	0.01	1	1.00	1	0.009	2.3E-07
B6	14.09 - 25.5	86	0.005	1	1.00	1	0.005	1.9E-07
B6	47.47 - 53.27	86	0.01	1	1.00	1	0.013	3.2E-07
B34	41.5 - 48	76	0.01	1	1.00	1	0.009	2.4E-07
B210	33.2 - 39.42	53	0.06	1	1.00	1	0.065	1.5E-06
B210	39.2 - 45.4	53	0.01	1	1.00	1	0.006	2.3E-07
B211	10.4 - 15.7	57	0.04	1	0.35	1	0.013	3.0E-07
B211	14.3 - 18.3	57	0.10	1	0.57	1	0.056	9.2E-07
B211	24.9 - 28.7	57	0.07	1	0.50	1	0.034	7.7E-07
B211	33.26 - 38.8	57	0.11	1	0.79	1	0.085	1.6E-06
B211	36.1 - 41.7	57	0.05	1	0.22	1	0.011	2.3E-07
B21	10.35 - 15.59	43	0.12	1	0.44	1	0.053	1.0E-06
B221	12.3 - 15.59	43	0.19	1	0.44	1	0.082	1.5E-06
B221	15.16 - 26.02	43	0.005	1	1.00	1	0.005	1.4E-07
B233	12.5 - 20.5	53	0.01	1	1.00	1	0.005	1.7E-07
B233	35.9 - 41.8	53	0.09	1	0.17	1	0.015	4.0E-07
B238	58.5 - 69.7	144	0.01	1	1.00	1	0.005	1.4E-07
B13	51.6 - 57.6	120	0.03	1	0.25	1	0.007	2.7E-07
B02W	18 - 23	29	0.32	1	1.00	1	0.320	1.15E-05
B02W	13 - 20	29	0.15	1	1.00	1	0.150	4.3E-06
B02W	24 - 29	29	0.02	1	1.00	1	0.02	2.2E-07

Hole ID	Test intervals(m)	Total Depth(m)	1-(RQD/100)	DI	1 - GCD	LPI	HC Value	K (m/s) from Packer Test
B01W	4.85 - 8.5	23	0.14	1	0.80	1	0.112	3.6E-06
B01W	9 - 13.3	23	0.37	1	1.00	1	0.370	1.4E-05
B04W	8-15.18	26	0.097	1	0.71	1	0.069	2.3E-06
B05W	4.7 - 10.95	27	0.18	1	1.00	1	0.179	7.7E-06
B06W	18.5 - 24.5	31	0.23	1	1.00	1	0.230	1.15E-05
B08W	14.0 - 21.6	21	0.02	1	0.33	1	0.007	1.6E-07
B09W	16.5 - 22.5	79	0.01	1	1.00	1	0.005	2.7E-07
B10W	11.5 - 17.5	21	0.15	1	1.00	1	0.150	4.7E-06
B11W	28 - 32.6	70	0.11	1	0.33	1	0.043	1.1E-06
B16W	17.5 - 27	27	0.004	1	1.00	1	0.004	1.15E-07
B16W	9.5 - 12.5	27	0.03	1	0.44	1	0.013	2.3E-07
B21W	7.7 - 12.6	23	0.03	1	1.00	1	0.027	8.2E-07
B23W	6.3 - 12.2	17	0.04	1	1.00	1	0.039	1.2E-06
B24W	9.1 - 11.94	31	0.09	1	0.40	1	0.035	6.7E-07
B24W	10.8 - 17.93	31	0.05	1	0.43	1	0.021	3.9E-07
B68W	13.8 - 20	20	0.10	1	1.00	1	0.100	3.3E-06
B69W	3.7 - 9.05	15	0.08	1	1.00	1	0.079	2.4E-06
B71W	3.5 - 10.8	22	0.13	1	0.89	1	0.115	3.4E-06
B212W	32.1 - 40.53	84	0.02	1	0.50	1	0.012	3.1E-07
B212W	39.5 - 51.53	84	0.01	1	1.00	1	0.008	1.2E-07
B214W	7 - 11.5	71	0.13	1	0.66	1	0.084	2.3E-06
B214W	11 - 17.5	71	0.19	1	0.76	1	0.143	4.3E-06
B214W	47.3 - 53.5	71	0.05	1	0.50	1	0.024	3.7E-07
B215W	18 - 25	33	0.10	1	0.71	1	0.071	1.8E-06
B215W	21.3 - 25	33	0.16	1	0.75	1	0.119	4.1E-06
B215W	27 - 33	33	0.17	1	1.00	1	0.170	4.8E-06
B218W	25 - 30.3	70	0.10	1	0.27	1	0.028	6.5E-07
B108W	11.75 - 18.65	32	0.14	1	1.00	1	0.139	4.3E-06
B117W	8.8 - 15	96	0.05	1	0.50	1	0.024	7.8E-07
B117W	14.8 - 21	96	0.05	1	0.67	1	0.032	7.7E-07
B118W	21.0 - 29.8	73	0.08	1	0.43	1	0.034	7.5E-07
B118W	29.5 - 35.67	73	0.03	1	0.50	1	0.016	4.6E-07

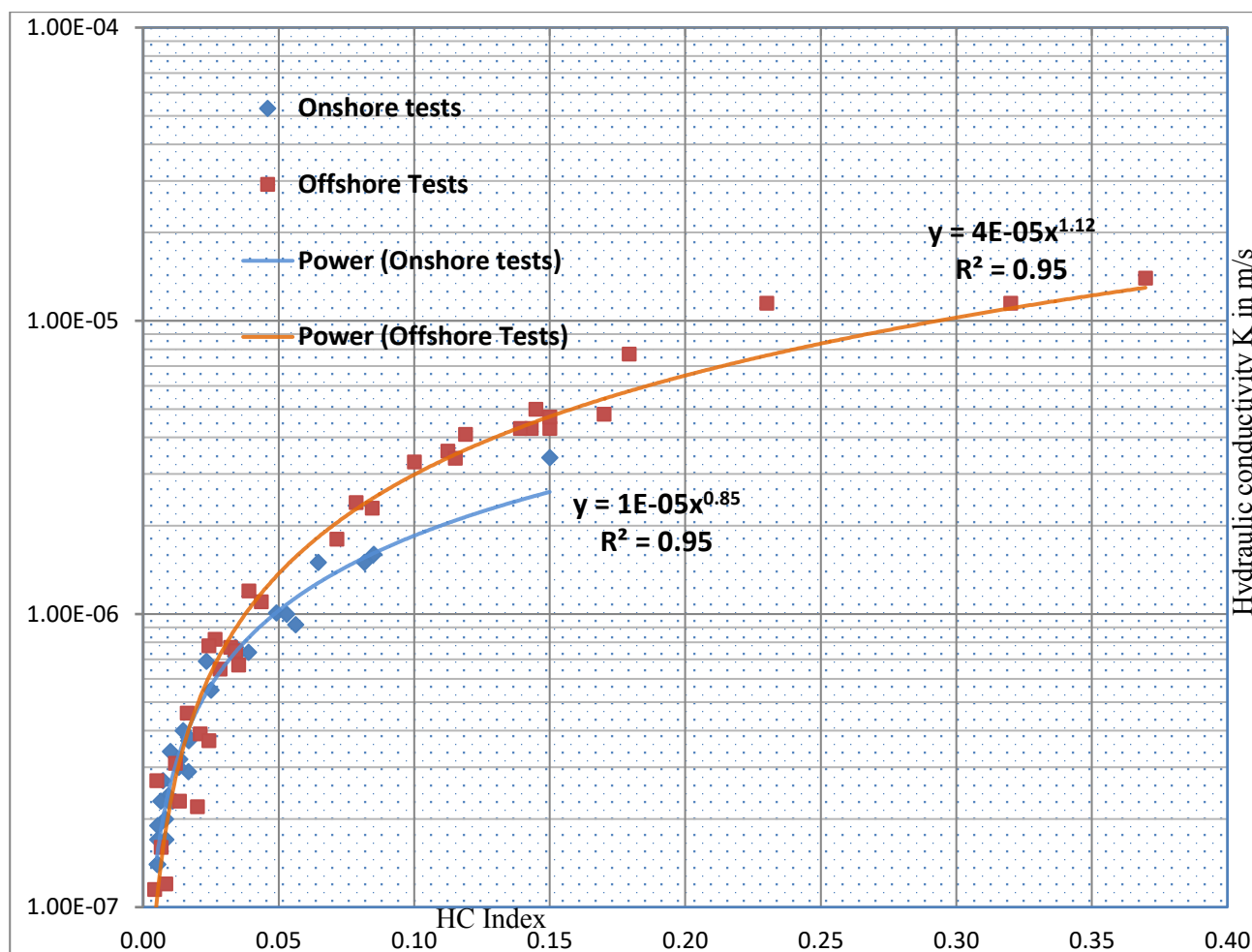


Figure 3: Correlation between HC index and Hydraulic Conductivity from Packer Test, onshore & offshore tests

### 5.3 THE EMPIRICAL HC MODEL VERIFICATION

To further verify the feasibility of the proposed empirical HC model, model verification has been undertaken. 14 onshore and 9 offshore hydraulic test data from different tunnel projects with similar sandstone units were used to verify the HC model. Table 4 shows 14 onshore and 9 offshore hydraulic test data for the model verification, in which  $K_{HC-model}$  and  $K_{in-situ}$  are represented. Borehole Id with “W” shows that tests are carried out in offshore area. The verification regression results indicated that  $K_{HC-model}$  and  $K_{in-situ}$  are well correlated with a coefficient of determination of  $R^2$  equals 0.97 for both on onshore and offshore tests.

Figures 4 and 5 show the correlation between the rock mass hydraulic conductivity obtained from in situ testing and that from the estimation of the empirical HC model for onshore and offshore tests respectively. This verification example demonstrates that the empirical HC model is able to determine the rock mass hydraulic conductivity for different sites in which the lithologic conditions and geographic locations are similar.

Table 4: Result of verification borehole tests for Sandstone unit

Hole ID	Test intervals (m)	Total Depth (m)	RQD (%)	DI	1-GCD	LPI	HC	$K_{HC-Model}$ (m/s)	$K_{in-situ}$ (m/s)
SRT BH8	13.6 - 20.3	42	94.0	1	1.00	1	0.06	9.11E-07	1.20E-06
SRT BH9	21 - 27.2	35	95.2	1	1.00	1	0.05	7.62E-07	8.00E-07
SRT BH10	14.9 - 21.1	36	98.1	1	1.00	1	0.02	3.50E-07	4.00E-07
EP_BH01	7.5 - 14	40	92.0	1	0.90	1	0.07	1.07E-06	1.50E-06
EP_BH03	11.0 - 20.0	50	96.1	1	0.71	1	0.03	4.75E-07	5.00E-07
EP_BH05	16 - 21.0	50	99.2	1	1.00	1	0.01	1.65E-07	2.00E-07
EP_BH05	7.0 - 12.0	50	99.0	1	1.00	1	0.01	2.06E-07	3.00E-07
RZ_BH62	54 - 61	70	95.7	1	0.67	1	0.03	4.87E-07	5.00E-07

RZ_BH69	19 - 24	50	95.0	1	1.00	1	0.05	7.84E-07	9.00E-07
RZ_BH69	29 - 34	50	97.0	1	1.00	1	0.03	5.08E-07	5.00E-07
BHF05	38 - 42.4	65	99.1	1	1.00	1	0.01	1.85E-07	2.30E-07
BHF13	45 - 51	60	87.0	1	1.00	1	0.13	1.8E-06	2.50E-06
BHF13	50 - 56	60	91.7	1	0.70	1	0.06	8.93E-07	9.00E-07
BHF20	37.6 - 42.4	72	99.5	1	1.00	1	0.01	1.18E-07	1.20E-07
SRT BH202W	31.2 - 39	46	98.8	1	1.00	1	0.01	2.70E-07	2.00E-07
SRT BH204W	22 - 29.1	29	89.0	1	1.00	1	0.11	3.37E-06	3.40E-06
SRT BH205W	38 - 44.5	49	89.1	1	1.00	1	0.11	3.35E-06	2.70E-06
SRT BH206W	30.2 - 37.3	45	98.3	1	0.58	1	0.01	2.27E-07	2.00E-07
SRT BH211W	39.8 - 45.9	64	94.1	1	1.00	1	0.06	1.67E-06	1.60E-06
SRT BH211W	45.8 - 51.8	64	90.0	1	0.83	1	0.08	2.47E-06	2.00E-06
SRT BH213W	31.7 - 39	39	94.5	1	0.50	1	0.03	7.12E-07	5.50E-07
SRT BH214W	33.8 - 41	46	98.0	1	1.00	1	0.02	5.04E-07	5.00E-07
SRT BH215W	27.7 - 34.5	46	95.6	1	0.50	1	0.02	5.58E-07	5.50E-07

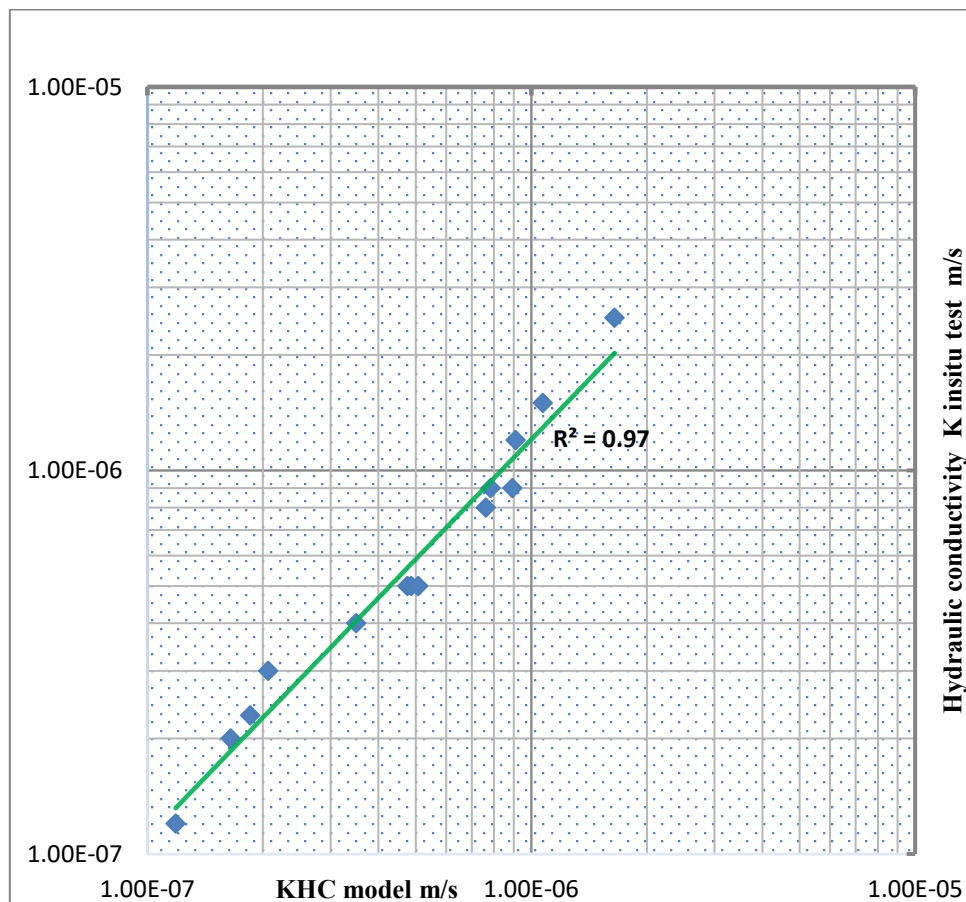


Figure 4: Correlation between  $K_{HC}$  model and  $K_{in-situ}$  onshore tests

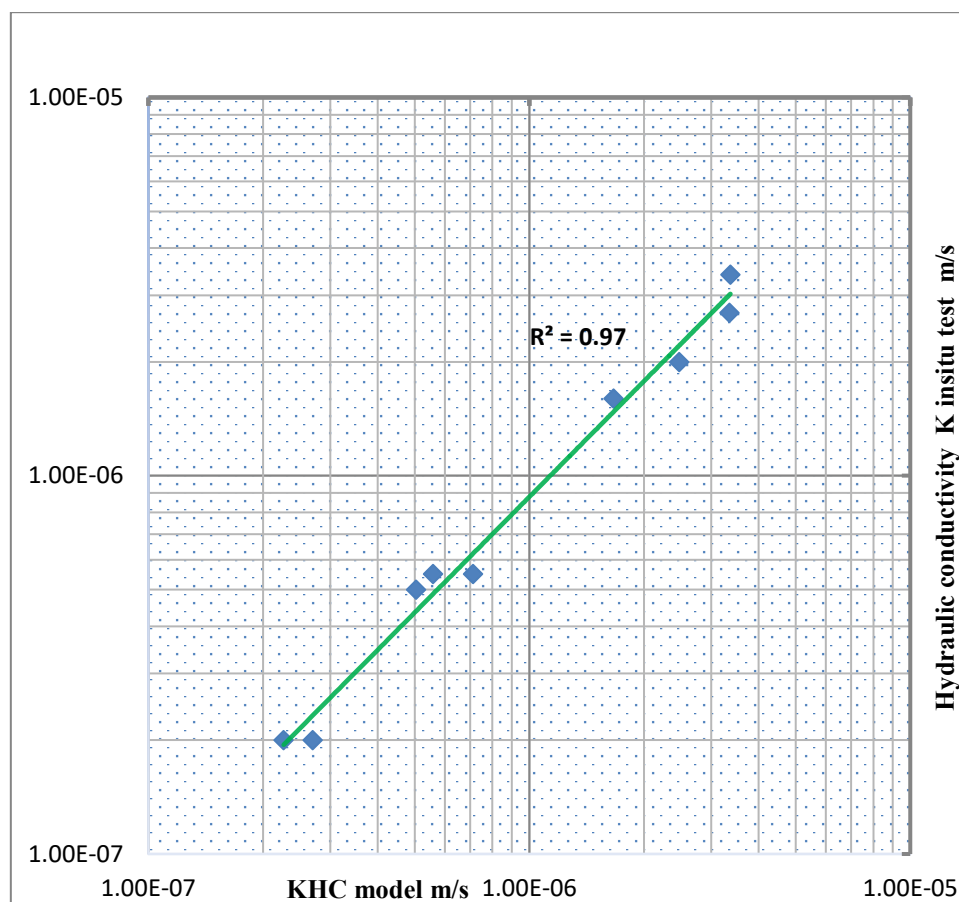


Figure 5: Correlation between  $K_{HC \text{ model}}$  and  $K_{in-situ}$  offshore tests

## 6 CONCLUSIONS

The estimation of rock mass hydraulic conductivity using empirical equations has great advantages. As discussed in this paper, the dependence of the measured hydraulic conductivity on the section depth, RQD, gouge content and lithology was evaluated. Based on this study the following conclusions are made:

- A modified new rock mass classification system called the "HC-system" or HC model has been developed to estimate the hydraulic conductivity of Hawkesbury Sandstone in Sydney basin based on the proposed Hsu et al. 2011 empirical model.
- There is no obvious correlation between depth and hydraulic conductivity in this investigation. It is concluded that the depth is not a significant factor on the hydraulic conductivity, so the Depth Index (DI) is taken to be 1.
- Hydraulic conductivity values of Hawkesbury Sandstone generally vary from  $10^{-6}$  to  $10^{-8}$  m/s and are predominantly controlled by fracture properties.
- The regression results indicate that a power law relationship exists between the hydraulic conductivity and HC values with a coefficient of determination of 0.95 for both offshore and onshore tests.
- The verification regression results indicate that a power law relationship exists between the  $K_{HC\text{-model}}$  and  $K_{in-situ}$  with a coefficient of determination of  $R^2$  equal to 0.97 for both offshore and onshore tests.
- Regression equation (Equation (5)) is capable of providing a useful tool to predict hydraulic conductivity of fractured sandstone based on measured HC-values.
- By using this empirical method hydraulic conductivity data in a given site can be estimated, which reduces the cost on hydraulic testing and increases the reliability and quality of the packer tests.
- HC-system is a valuable new rock mass classification system for preliminary assessment of the degree of permeability of a borehole.
- The correlation between RMC and K of this study is appropriate for the geological conditions in the Sydney basin. The results obtained confirm the validity and flexibility of the empirical approach to handle cases of onshore and offshore data sets, in relation to data acquisition and data reduction (optimisation).

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## 8 DISCLAIMER

The views, opinions, considerations and conclusions expressed in this presentation are strictly those of authors and do not necessarily reflect the views of Roads and Maritime Services.

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