Application of Clustering System to Analyze Geological, Geotechnical and Hydrogeological Data Base according to HC-System Approach

Lilik Eko WIDODO^a, Tedy Agung CAHYADI^b, Sudarto NOTOSISWOYO^a, Eman WIDIJANTO^b

^a *Lecturer, Mining Engineering ITB, Indonesia*

^b *PhD Student, Mining Engineering ITB, Indonesia*

* tedyagungc.students.itb@gmail.com (*corresponding author's e-mail*)

Abstract

Highly fractured rocks at Grasberg Mining in PT Freeport Indonesia (PTFI) lead to fractured groundwater flow media. Hydraulic conductivity of fractured rock has more complexity than that of porous rocks media. In this study, hydraulic conductivity (K) has been estimated according to HC-System based on Rock Quality Designation (RQD), Lithology Permeability Index (LPI), Depth Index (DI) and Gouge Content Designation (GCD). Numerical model of HC-System at Grasberg Mining in general can be expressed by the equation $K = 2 \times 10^{-6} \times HC^{0.5571}$. The RQD data can be grouped into three ranges, i.e. first group that dominates over 80 % of the RQD data with K ranging between 1.9×10^{-8} – 2.3×10^{-7} m/s, second group that is within 40 – 80% of the RQD data with K falling between 2×10^{-8} – 7.2×10^{-7} m/s, and third group that takes part less than 40 % of RQD data with K ranging between 2.1×10^{-8} – 1.9×10^{-6} m/s. Based on the lithology, the hydraulic conductivity of rocks can be assigned as follows: igneous rock with K ranging 6.8×10^{-8} – 1.9×10^{-7} m/s, and sedimentary rock with K ranging 2.2×10^{-8} – 1.9×10^{-6} m/s. HC-System demonstrates good interpretation of hydraulic conductivity by means of clustering method, which uses geological and geotechnical data for hydrogeological characterization.

Keywords: clustering, hydraulic conductivity, HC-System, RQD, lithology

1. Introduction

The Grasberg mine of PTFI is one of the largest mines in the world. It is located between the confluence of several faults that lead to fractured rocks. In the Grasberg mine design process, it was required geological, geotechnical and hydrogeological data acquisition. Based on the results of drilling activities at Grasberg mine, a lot of information can be described for characterization of the hydrogeological conditions. Accordingly, by using HC-System (Hsu et al, 2011), 441 information from geotechnical drilling or as much as 4,850 points of data have been used to model hydraulic conductivity distribution based on RQD, LPI, DI, GCD data (Cahyadi et al, 2015).

Cluster analysis is a technique to divide the data into several groups with similar condition (Jain et al, 1999). Cluster analysis-based only describes a similar relationship, with the greater similarity (or homogeneity) within a group and greater the difference between group. The geological cluster analysis demonstrated relationship between intrusive contacts with increasing parameter hydraulic conductivity such as hydraulic conductivity in identifying hydrogeological characterization (Mayer et al, 2014).

The purpose of this study is to understand the relationship between hydrogeological and geological (lithology) as well as geotechnical (RQD) condition based on data from bore holes by means of clustering analysis.

2. Study Site

Data for this study were collected at Grasberg Mine. According Sapiie et al (1994), most of the faults in Grasberg Mine can be grouped as left lateral slip fault. The stratigraphy consists of 4 groups, such as Kembelangan Group (Jurassic – Cretaceous), New Guinea Limestone (Palaeocene-Miocene), Intrusion (Tertiary) and Glacial (Quaternary) on the top. The main fault includes Barat Laut, Merren Valley 1 & 2, Fairly Lake, Idenberg 1 & 2, Big Gossan and Hertzberg trending East - West (N 120° E - N 150° E and N 250° E), which can be classified as left lateral slip fault. Major faults are cut by faults trending N 050° E - N 070° E and N 350° E that consist of Grasberg, Cartenz Valley and New Zealand Pass. As a result of the intersection of faults, in Kembelangan Group and New Guinea Limestone occurred intrusion consisting of Dalam Intrusion, Main Grasberg Intrusion, Kali Intrusion. Stratigraphy in Grasberg and surrounding can be described from youngest to oldest age as follows: Alluvial (quaternary alluvial, colluvium, and glacial), Intrusion (Kali, Main Grasberg Intrusion, Dalam), Kais Formation (limestone

with low and high fracture as well as coarse fragmentation), Sirga Formation (sandstones with medium to coarse fragmentation), Faumai Formation (massive limestone), Waripi Formations (dolomite), Ekmai Formation (massive limestone), Piniya Formation (mudstone), Woniwogi Formation (sandstone) and Kopai Formation (sandstone).

Rainfall condition is high, of more than 4,000 mm/year, with 1,470 ha catchment area. The rainfall results in the quantity of precipitation of around 25,500 gpm, from which 55% runs off (Antoro et al, 2011). Groundwater flow is controlled by secondary aquifer, that is caused by interconnection of fractures. According to monitoring on January 2013, groundwater table position ranges between 8 m until 478 m from the surface.

3. Methodology

3.1 Hydrogeological data collection

Hydraulic conductivity data was collected using packer test and slug test. Packer test results are available from 2 boreholes and 18 target points. Moreover, slug test results are available from 31 boreholes. Model of isotropic hydraulic conductivity based on the information of Rock Quality Designation (RQD), Lithology Permeability Index (LPI), Depth Index (DI) and Gouge Content Index (GCI) can be resulted at 441 drill holes or 4,850 points. Data from 441 drill holes have been analysed in detail, so that it can be used to determine the relationship between hydrogeological, geological and geotechnical condition. Following Cahyadi et al (2015), hydraulic conductivity at drill holes were distributed by HC-System using equation $K = 2 \times 10^{-6} \times HC^{0.5571}$.

3.2 HC-System

HC-System approach (Hsu et al, 2011) was developed according to the packer test and slug test using geotechnical data from drilling, such as Rock Quality Designation (RQD), Lithology Permeability Index (LPI), Depth Index (DI), and Gouge Content Designation (GCD). HC-Index is an empirical method to estimate HC-Value (HC). In this study, it was put in a scatter plot along with hydraulic conductivity obtained from testing directly in the field using packer test and slug test. The HC-Value was expressed by using equation (1) below.

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

Where:

HC : HC-Value
RQD : rock quality designation
DI : depth index
GCD : gouge content designation
LPI : lithology permeability index

RQD value is an indicator of rock mass condition in term of fragmentation within it. From hydrogeological point of view, fractured rock mass ore later on known as fractured media has more ability to transmit water from and into the formation than ordinary porous media. Following Deere et al (1967), the RQD value was defined as the cumulative length of core pieces longer than 100 mm in a run (R_s) divided by the total length of the core run (R_T) and can be expressed in the equation (2). In geotechnical analysis, RQD is useful for defined Rock Mass Quality (Table 1 and Figure 1). In Grasberg Mine, aquifer is controlled by interconnection of fractures. RQD can be used to represent the secondary aquifer on site as it may contain significant groundwater.

Table 1. RQD classification index (Deere et al, 1989)

RQD	Rock mass quality
<25%	very poor
25-50%	Poor
50-75%	Fair
75-90%	Good
90-100%	Excellent

Figure 1. RQD value for various joint densities along drill cores (Deere et al, 1989)

$$RQD = \frac{\sum RS}{R_T} \times 100\% \quad (2)$$

The decrease in permeability with depth in fractured rocks is usually attributed to reduction in fracture aperture and fracture spacing. The depth may be considered as a factor in evaluating rock mass permeability (Lee et al, 1993). To assess the influence of the depth on permeability, a depth index, namely *DI*, was defined according Hsu et al (2011) as follows.

$$DI = 1 - \frac{L_c}{L_T} \quad (3)$$

in which 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 *RQD* value may decrease by increasing number of fractures in a core run. If the fractures contain infillings such as gouges, the hydraulic conductivity of the rock decreases because the cracked rock is blocked by filling material. GCD cannot be obtained from drill log. It means that GCD does not present on core run. It has been assumed to be proportional with *RQD* (Cahyadi et al, 2015). Accordingly, when *RQD* value is greater, 90%-100%, the permeability decreases then the GCD value is set to be within 0,9-1.

Lithology is an intrinsic character of a rock in terms of mineral composition and grain size. For an intact rock, the magnitude of permeability depends largely on the individual character of the rock matrices. It may be affected by the average size of the pores, which in turn is related to the distribution of particle sizes and particle shape. To assess the influence of lithology on permeability, a lithology permeability index (*LPI*) was defined as shown in Table 2 according Hsu et al (2011).

Table 2 Rating for *LPI* values based on lithology in the study area (Cahyadi et al, 2015)

Lithology	Suggest Rating	Lithology	Suggest Rating
Andesite	0.15	Sandy dolomite	0.95
Trachyandesite	0.15	Silty dolomitey	0.95
Hydrothermal breccia	0.1	Gravel	1
Intrusive breccia	0.1	Limestone	0.7
Diorite	0.15	Limestone breccia	1
Porphyritic diorite	0.15	Dolomitic limestone	0.7
Monzonite	0.15	Sandy limestone	0.4
Porphyritic monzonite	0.1	Silty limestone	0.3
Quartz diorite	0.15	Mudstone	0.3
Quartz diorite porphyritic	0.15	Shale	0.5
Quartz monzonite	0.15	Shale carbonaceous	0.75
Quartz monzonite porphyritic	0.15	Shale limey	0.6
Tuff	1	Sandstone	1
Alluvium	1	Limestone sandstone	0.95
Colluvium	1	Sandstone breccia	1
Rehandle Material	1	Sandstone breccia	1

Lithology	Suggest Rating	Lithology	Suggest Rating
Sedimentary breccia	1	Limey sandstone	0.3
Tectonic breccia	1	Silty sandstone	0.3
Conglomerate	1	Siltstone	0.3
Clay	0.3	Dolomitic siltstone	0.2
Dolomite	0.7	Limey siltstone	0.3
Dolomite breccia	0.85	Sandy siltstone	0.2
Limey dolomite	0.7		

3.3 Clustering

The method of clustering can be classified between two primary group of clusters: hierarchical and partitional method. A partitional clustering is simply division of set of data object into non overlapping subsets (cluster) such that each data object is in exactly one subset (Jain et al, 1999), for example, any distribution lithology at some place. Different physic shape can be clustered to 3 clusters such us igneous rock, sediment rock and metamorphic rock. It is simple way for clustering method that was called partitional method.

In this study, the clusters were used to identify relationship between hydraulic conductivity between geological such us lithology, and geotechnical such us RQD. Based on HC-System, hydraulic conductivity at drill holes can be estimated (Cahyadi et al, 2015). Two partitional clusters method were performed in this study. The first (geotechnical cluster) was used to cluster the hydraulic conductivity based on the Rock Quality Designation (RQD). From hydrogeological view point, any relationship exists between fracture and hydraulic conductivity. The greater the value of RQD will decrease permeability values and otherwise. The second cluster (geological cluster) was used to cluster the hydraulic based on the geological log for the boreholes (lithology).

All clusters were completed using filtering method on EXCEL spreadsheet program. Hydraulic conductivity from slug test and packer test were modeled to get HC-System equation, then hydraulic conductivity of every point in borehole can estimated. The RQD and lithology data from boreholes for slug and packer tests were then captured for clustering of hydraulic conductivity using partition method.

4. Result and Discussion

4.1 Hydraulic Conductivity Model based on the HC-System

From boreholes data, type of lithology, mineral, RQD and the position of core can be identified. Cahyadi et al (2015) have modeled values of hydraulic conductivity in the Grasberg open pit using the equation $K = 2 \times 10^{-6} \times HC^{0.5571}$ according to HC-System. The equation was then used to predict the value of hydraulic conductivity along 441 drilling points or 4,850 points of cores. The corresponding relationship between RQD, GCD, DI, HC-Index and hydraulic conductivity is shown at Table 2.

Figure 2 shows scatter plot of RQD, LPI and DI against measured hydraulic conductivity. From figure 2, it can be seen that RQD and hydraulic conductivity are closely correlated with value determination coefficient of 0.82 or correlation coefficient of 0.91. LPI and hydraulic conductivity have a coefficient of determination of 0.52 or correlation coefficient of 0.72. From both correlation, it can be concluded that RQD have more dominant effect on the flow of groundwater in the fractured rock, while the DI is poorly correlated to the hydraulic conductivity with determination coefficient of 0.02 and correlation coefficient of 0.14. It is possibly due to the geological structures or forces that may alter the compacted rocks to become the fractured rock.

Figure 2. Relationship between hydraulic conductivity and RQD, LPI, DI

Table 2. Result of calculation of HC-Values in each packer and slug test zone (Cahyadi et al, 2015)

Hole ID	Lithology	K Packer & Slug Test (m/s)	Point Test	Total Depth (m)	1-(RQD/100)	DI	1-GCD	LPI	HC
VZW-094	Hornblende Trachyandesite	5.79E-06	23.25	300	0.9	0.92	0.9	0.8	0.59778
VZW-094	Volcanic Breccia	4.73E-07	69.85	300	0.6	0.76	0.6	0.1	0.02762
VZW-094	Volcanic Breccia	2.16E-07	95.5	300	0.6	0.68	0.6	0.1	0.02454
VZW-094	Volcanic Breccia	7.78E-08	120.5	300	0.4	0.59	0.4	0.1	0.00957
VZW-094	Volcanic Breccia	1.63E-07	145.5	300	0.4	0.52	0.4	0.1	0.00824
VZW-094	Volcanic Breccia	4.54E-08	170.5	300	0.2	0.43	0.2	0.1	0.00173
VZW-094	Skarn	1.50E-06	196.5	300	0.8	0.34	0.8	0.8	0.17664
VZW-094	Limestone	4.27E-08	221.5	300	0.2	0.26	0.2	0.5	0.00523
VZW-094	Limestone	3.37E-07	250	300	0.5	0.16	0.5	0.5	0.02083
VZW-094	Limestone	1.51E-07	283.5	300	0.4	0.05	0.4	0.5	0.0044
GHD-3885-26	Volcanic Breccia	1.08E-06	29.95	200	0.9	0.85	0.9	0.3	0.20661
GHD-3885-26	Volcanic Breccia	1.43E-06	77.75	200	0.9	0.61	0.9	0.3	0.14853
GHD-3885-26	Volcanic Breccia	2.06E-06	113.2	200	0.9	0.43	0.9	0.3	0.10546
GHD-3885-26	Hornblende Trachyandesite	9.64E-07	132.2	200	0.9	0.33	0.9	0.8	0.21967
GHD-3885-26	Hornblende Trachyandesite	1.79E-06	147.75	200	0.9	0.26	0.9	0.8	0.16929
GHD-3885-26	Hornblende Trachyandesite	2.11E-06	166	200	0.9	0.17	0.9	0.8	0.11016
GHD-3885-26	Hornblende Trachyandesite	1.23E-06	179.2	200	0.9	0.10	0.9	0.8	0.06739
GHD-3885-26	Hornblende Trachyandesite	9.97E-07	192.5	200	0.9	0.03	0.9	0.8	0.0243
CSTG-01	Alluvium	3.98E-07	17.05	137.5	0.6	0.87	0.6	0.8	0.25229
CSTG-02B	Alluvium	1.75E-06	29.71	108.5	0.9	0.72	0.9	0.8	0.47056
VZW-17S	Alluvium	1.52E-06	23.76	121.7	0.9	0.80	0.9	0.8	0.52149
OHS-21	Overburden	8.79E-07	12.36	205.1	1	0.93	1	1	0.93974
VZW-25A	Overburden	2.71E-06	3.12	74	1	0.95	1	1	0.95784
VZW-31	Quartz Monzonite	9.57E-07	118.59	347.9	0.5	0.65	0.5	0.2	0.03296

Hole ID	Lithology	K Packer & Slug Test (m/s)	Point Test	Total Depth (m)	1-(RQD/100)	DI	1-GCD	LPI	HC
VZW-58	Quartz Monzonite	1.38E-06	329.09	700	1	0.52	1	0.7	0.37091
VZW-74	Quartz Monzonite	3.97E-08	28.5	500	0.2	0.94	0.2	0.2	0.00754
VZW-50	Quartz Monzodiorite	3.76E-07	277	399.6	0.4	0.30	0.4	0.1	0.00491
VZW-55	Quartz Monzodiorite	2.55E-07	28.51	132.8	0.4	0.78	0.4	0.1	0.01257
VZW-62	Quartz Monzodiorite	1.74E-08	87.14	200.2	0.5	0.56	0.5	0.1	0.01412
VZW-17	Granodiorite	1.17E-07	280.5	432.5	0.1	0.35	0.1	0.1	0.00035
VZW-76	Trachyandesite	4.13E-08	94.18	300	0.1	0.68	0.1	0.1	0.00069
VZW-51	Volcanic Breccia	7.36E-07	18.7	101.5	0.8	0.81	0.8	0.3	0.15663
VZW-29	Limestone	7.53E-09	305.85	408.61	0.1	0.25	0.1	0.1	0.00025
VZW-29S	Limestone	5.46E-08	6.46	27.5	0.2	0.76	0.2	0.1	0.00306
VZW-40	Limestone	1.59E-06	11.73	400	0.9	0.97	0.9	1	0.78625
VZW-49D	Limestone	7.52E-07	14.6	550	0.6	0.97	0.6	0.5	0.17522
VZW-52	Limestone	1.09E-06	11.4	267.45	0.9	0.95	0.9	1	0.77547
VZW-53A	Limestone	2.82E-06	27.5	489.8	0.9	0.94	0.9	1	0.76452
VZW-59	Limestone	7.05E-07	227.02	401	0.6	0.43	0.6	0.5	0.0781
VZW-63	Limestone	3.38E-06	46.97	500	1	0.90	1	1	0.90606
VZW-68	Limestone	2.27E-06	288.2	400	1	0.27	1	1	0.2795
VZW-69	Limestone	1.21E-06	210.42	400	1	0.47	1	1	0.47395
VZW-71	Sandstone	2.06E-07	307.58	351	0.3	0.12	0.3	0.9	0.01002
VZW-75	Limestone	3.01E-07	164.61	350	0.5	0.52	0.5	0.5	0.06621
VZW-39	Limestone	2.04E-08	152.62	300.8	0.2	0.49	0.2	0.1	0.00197
VZW-61	Limestone	7.36E-08	87.8	375.2	0.2	0.76	0.2	0.1	0.00306
VZW-73	Limestone	5.29E-08	71.65	450	0.2	0.84	0.2	0.1	0.00336
VZW-245	Volcanic Breccia	1.14E-08	94.91	120	0.5	0.20	0.5	0.1	0.00523
VZW-244	Limestone	1.46E-07	66.37	150	0.5	0.55	0.5	0.1	0.01394

4.2 Cluster of RQD and Lithology in Relation Cluster of Hydraulic Conductivity

The primary objective of this study is to understand the relationship between the characteristics of the hydrogeological conditions in the field in relation to geological condition (lithology) and geotechnical condition (RQD) based on data from drilling. The results of hydraulic conductivity modeling according to Cahyadi et al (2015) were clustered in this study into two parts, namely the cluster based on the geotechnical data and the cluster based on the geological data.

Clustering of hydraulic conductivity based on the geotechnical data relies on the RQD. This is very important as the correlation of hydraulic permeability and the RQD is very high. Cluster partition was set up for 10 divisions with RQD value interval of 10 % for each division. Table 3 shows the results of cluster of hydraulic conductivity based on geotechnical data.

Table 3. Results of clustering of hydraulic conductivity based on the geotechnical data (RQD)

CLUSTER	RQD (%)	K MAX (m/s)	K MIN (m/s)
A	0-10	1.97762E-06	2.17989E-08
B	11-20	1.6449E-06	6.21718E-08
C	21-30	1.44909E-06	2.40253E-08
D	31-40	1.12814E-06	3.76736E-08
E	41-50	4.6015E-07	1.88798E-07
F	51-60	7.19233E-07	2.07084E-08
G	61-70	*	*
H	71-80	*	*
I	81-90	2.3493E-07	1.92339E-08
J	91-100	*	*

* there were no data log bore holes

In this study, cluster analysis was based on the data along the Grasberg mine drill holes that have been recorded in the database. Accordingly, the value of RQD written in terms of the range of values. For example, in one of the holes of a depth of 0 m to of 31.6 m was defined as limestone breccia, with RQD values of 30-50%, so that the value of RQD used for calculation of HC-System relies on the average RQD value of corresponding RQD range in the database. For example, the RQD value of a depth from 0 m to 31.6 m is 40%. This condition leads to the unallocated RQD value in the cluster G, H, and J. However, if the modeling hydraulic conductivity was based on block model then the entire cluster will be allocated. Result clusters were shown in the Table 3 representing the distribution of maximum and minimum value of hydraulic conductivity. According to distribution of each cluster it can be analyzed how the distribution of hydraulic conductivity values at each cluster.

Figure 3. Hydraulic Conductivity Distribution

The RQD data can be grouped into three ranges, i.e. first group that dominates over 80 % of the RQD data with K ranging between 1.9×10^{-8} – 2.3×10^{-7} m/s, second group that is within 40 – 80 % of the RQD data with K falling between 2×10^{-8} – 7.2×10^{-7} m/s, and third group that takes part less than 40 % of RQD data with K ranging between 2.1×10^{-8} – 1.9×10^{-6} m/s. Table 2 and Table 3 show hydraulic conductivity and RQD from field investigation and HC-System Model, which resume bigger RQD with decreasing hydraulic conductivity.

The second cluster of hydraulic conductivity relies on geologic parameters. Based on Figure 2, lithology was converted to LPI and becomes the secondary parameter that influences the hydraulic conductivity. Clustering by the method of partition using the spread sheet EXCEL was based on the formula: VLOOKUP (COLUMNX-CODE-LPI ; COLUMNX-CODE-LPI : COUNMX-WEIGHT-LPI ; 2 ; FALSE). If clustering of hydraulic conductivity was based on the lithology, there will be 26 clusters since there are 26 type of rocks in the database. By using filtering, the hydraulic conductivity of specific rock or lithology can be requested by inputting the corresponding rock or lithology, for example, hydraulic conductivity of andesite can requested by giving the andisite as the type of rock. Distribution of hydraulic conductivity based on the geology (lithology) can be seen in Table 4.

Table 4. Results of clustering of hydraulic conductivity values based on the lithology

CLUSTER	K MAX (m/s)	K MIN (m/s)
Andesite	6.85633E-07	1.92339E-08
Trachyandesite	2.5424E-07	1.96979E-07
Intrusive breccia	2.86698E-07	3.09222E-08
Diorite	6.38344E-07	2.00356E-08
Quartz diorite	4.686E-07	4.95415E-08
Quartz diorite porphyritic	2.25776E-07	1.04837E-07
Quartz monzonite	1.25622E-07	1.25622E-07
Tuff	9.08473E-07	9.08473E-07
Alluvium	1.91982E-06	1.12049E-07
Colluvium	1.93375E-06	4.51454E-07
Rehandle Material	1.97762E-06	2.17989E-08
Sedimentary breccia	6.36111E-07	4.22845E-07
Tectonic breccia	1.07434E-06	4.30392E-07
Conglomerate	1.00346E-06	9.07384E-07
Clay	7.55858E-07	7.06612E-07
Dolomite	7.7066E-07	7.7066E-07
Gravel	1.45366E-06	8.90272E-08
Limestone	1.63791E-06	4.08755E-08
Limestone breccia	1.97312E-06	6.0957E-08
Dolomitic limestone	1.14824E-06	1.9447E-07
Sandy limestone	1.06672E-06	5.54575E-07
Shale	4.11499E-07	4.11499E-07
Sandstone	1.90922E-06	1.89878E-07
Limestone sandstone	9.68645E-07	9.68645E-07
Sandstone breccia	8.2061E-07	7.34794E-07
Limey sandstone	1.06672E-06	5.54575E-07

Based on the geological structure, Grasberg main rock is sedimentary rocks that is intruded by igneous intrusions. The intersection of several faults in the sedimentary rocks lead to fractured rock conditions. The presence of groundwater in horizontal drilling indicates the variation of lithologies, but the groundwater is mainly controlled by fractured limestone of Kais Formation. By comparing the observed and modeled measured hydraulic conductivity according HC-System, it can be showed that the distribution of hydraulic conductivity values in sedimentary rocks have a range of values ranging from 10^{-8} - 10^{-6} m/s. It is clear that the hydraulic conductivity modeled according to HC-System is closely matched to the observed value. It is different from sedimentary rock, igneous rock has a different range of observation value compared with that according to HC-System. Observation value indicates that the distribution of hydraulic conductivity of igneous rock ranges from 10^{-8} to 10^{-6} m/s, whereas the results according to HC-System varies between 10^{-8} - 10^{-7} m/s. This is due to very low weight of LPI value used in the modeling, i.e. only around 0.1 – 0.15. Since the RQD values has greatest influence on the hydraulic conductivity then the modeled hydraulic conductivity value are more proportional to RQD value as indicated by Table 2. This condition gives the sense that the flow of water in locations is affected by fractured media, instead of porous media.

5. Conclusions

The result of the study demonstrate that:

- HC-System approach can be used to demonstrate relationship between hydrogeological (hydraulic conductivity), geological condition (lithology) and geotechnical condition (RQD).
- Based on the RQD data, the hydraulic conductivity can be grouped into three groups, i.e. first group that dominates over 80 % of the RQD data with K ranging between 1.9×10^{-8} – 2.3×10^{-7} m/s, second group that is within 40 – 80% of the RQD data with K falling between 2×10^{-8} – 7.2×10^{-7} m/s, and third group that takes part less than 40 % of RQD data with K ranging between 2.1×10^{-8} – 1.9×10^{-6} m/s.

- Based on the lithology, the hydraulic conductivity of rocks can be assigned as follows: igneous rock with K ranging $6.8 \times 10^{-8} - 1.9 \times 10^{-7}$ m/s, and sedimentary rock with K ranging $2.2 \times 10^{-8} - 1.9 \times 10^{-6}$ m/s.

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