Symposium on
The Problem of Shallow Water Table Rise (SWTR) in Urban Areas in the GCC Countries
September 17, 2023, Doha, State of Qatar



Estimation of Rock Mass Permeability – Current Practice and New Developments

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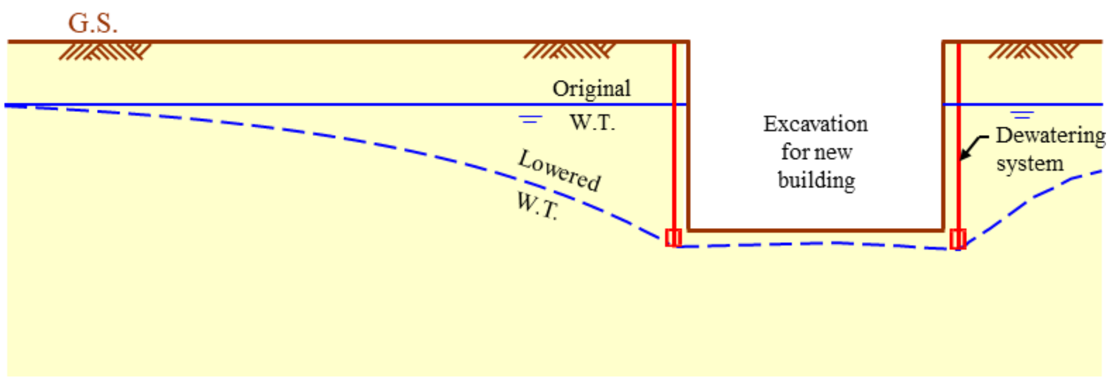
Introduction

Dewatering for Construction in Qatar

- Dewatering is the process of removing surface and subsurface water from a construction site.
- Construction dewatering is an essential activity for many civil engineering projects.
- The performance of such an activity mainly depends on:
  - Accuracy in estimating the permeability of the material to be dewatered.
  - Suitability of the dewatering system to the existing hydrogeological conditions.



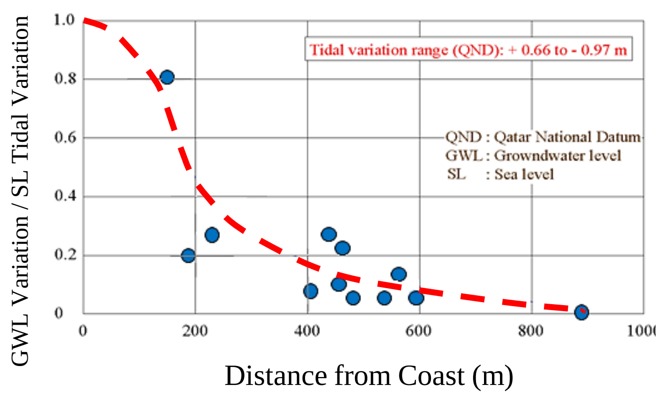
Dewatering for Construction in Qatar (Cont.)

High water table in most of the construction-active areas

The elevation of the groundwater level in most of the construction-active areas in Qatar is high. These areas are usually near the Gulf coast. As a result, construction dewatering is frequently required. For projects that are relatively far from the coast, dewatering may also be needed if they comprise deep excavation.

Reasons

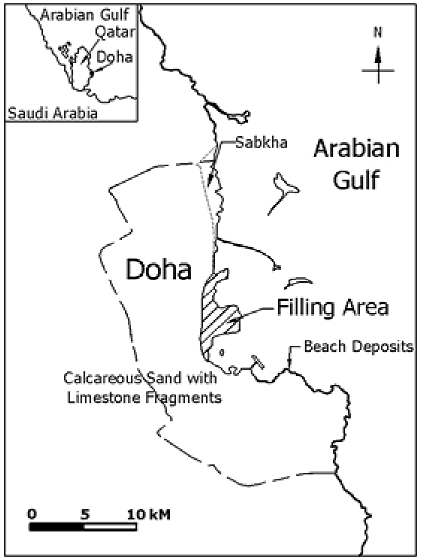
a. Proximity to the Gulf & Effect of Tidal Variation

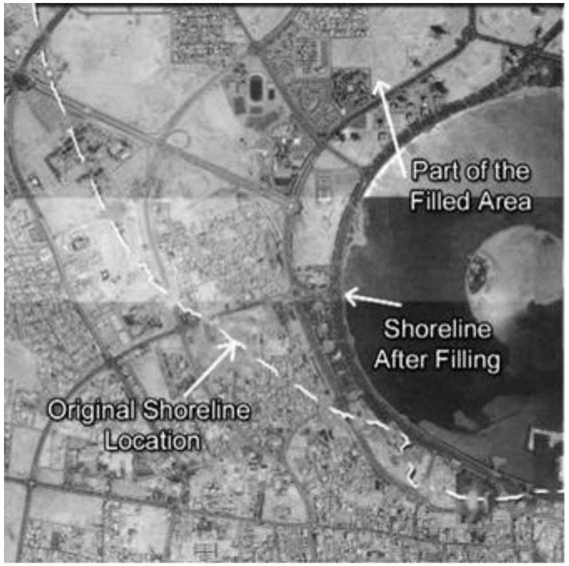


b. Water Leakage

Dewatering for Construction in Qatar (Cont.)

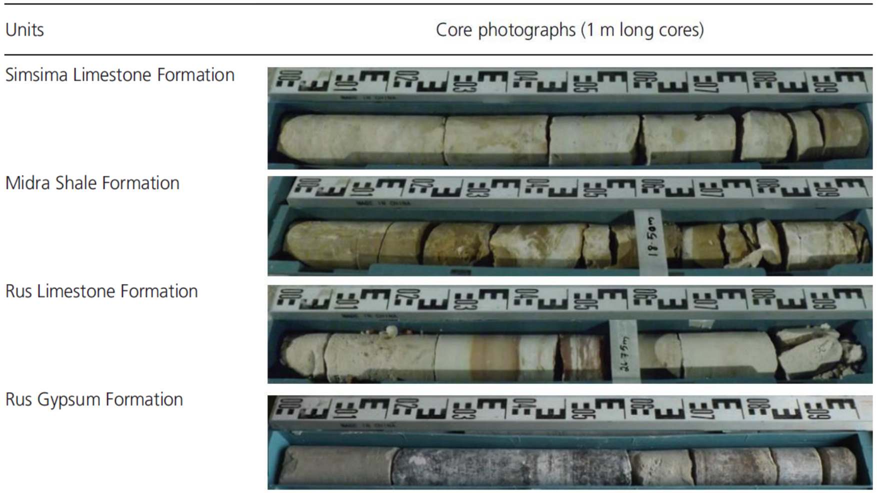
For example, one of the most construction-active areas in Doha is just a shallow bay along the city coast filled with calcareous sand, gravel, and limestone fragments (Dafna). The filling materials overlay sea-bed deposits (of silt and sand sizes) that is underlain by limestone. As a result, dewatering has been usually needed for construction of buildings and infrastructures in this area.





Typical Stratification of Qatar Geology

The typical stratification in areas near the gulf coast of Qatar usually consists of a man-made fill or coastal deposits underlain by an extended layer of randomly fractured limestone bedrocks occasionally interrupted by a near-horizontal layer of Midra shale. Limestone outcrops are dominant in the inland parts. In the south and central east of Qatar, an almost impermeable thick layer of Gypsum is usually encountered at a depth of 50 m or more.

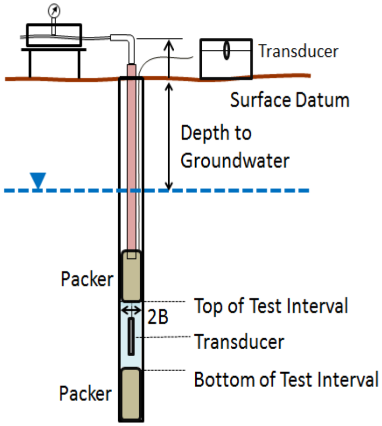


Core photographs examples of Doha geotechnical formations (after Karagkounis et. al 2016)

A Novel Data-driven Approach to Estimate Rock Permeability and Develop Guidelines for Design of Dewatering Systems

Goals

This research seized the unique opportunity of having the most extensive database ever available on the permeability of randomly fractured rock and the performance of dewatering systems to develop a novel and efficient approach for predicting the permeability of randomly fractured rock mass.



Challenges

1) Collection and documentation of case histories to be used in the analyses
2) Inherited wide range and difficulties in measurement of the coefficient of permeability (k) of rock

Collection and documentation of case histories

Out of several hundred cases that were made available and consequently documented, only the cases with complete information were considered.

These information were crucial for the research and include **having**:

i. **Complete geometrical description** of project setups

ii. **Complete geotechnical report** that comprises measured rock indices and results of field permeability tests in the dewatering zone

iii. **Flow rate charts**, for water pumped out of the dewatered excavation or pumping well

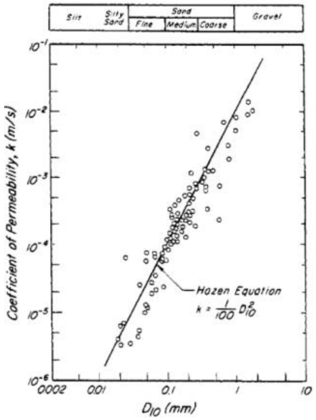
Difficulties in estimating *k* for rock mass

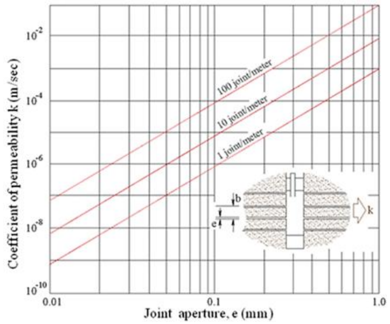
In geotechnical engineering, the rate at which water flows through ground material is represented by the coefficient of permeability (*k*) that is the property with the largest range of possible values. With respect to predicting the coefficient of permeability of rock mass, the following should be noted:

- It is not as direct as the case of granular soils.
- Related information available in the literature are mostly limited to estimating the directional permeability (i.e., permeability through one set of continuous joints) as a function of joint spacing and width (aperture).
- To describe the features of discontinuities, complicated numerical modelling and advanced geological survey are required. Such numerical modelling usually includes idealization.

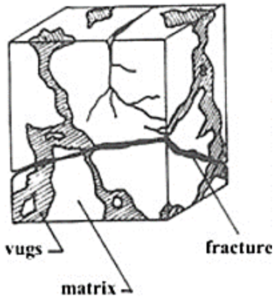
Classification of soils according to their coefficients of permeability (after Kulhawy and Mayne, 1990; and Terzaghi and Peck 1967).

Soil	Coefficient of Permeability, k (cm/s)	Degree of Permeability
Gravel	Over 10^{-1}	High
Sandy gravel, clean sand, fine sand	10^{-1} to 10^{-3}	Medium
Sand, dirty sand, silty sand	10^{-3} to 10^{-5}	Low
Silt, silty clay	10^{-5} to 10^{-7}	Very Low
Clay	Less than 10^{-7}	Practically impermeable

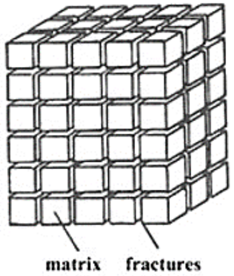




Effect of joint spacing and aperture on *k* (after Hoek and Bray 1974)



Actual grid block



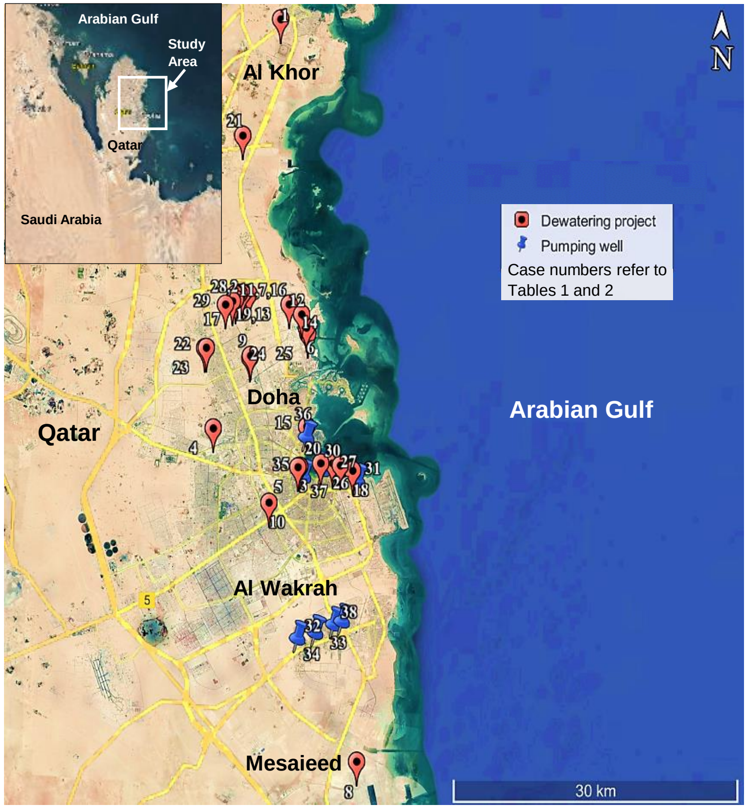
Idealized grid block

Predicting the Permeability of Rock Mass

The procedure of designing and executing the construction dewatering systems in randomly fractured rock masses using the **observation method** currently followed in practice leads to financial and environmental problems that can be avoided through a reliable prediction of the coefficient of permeability of rock mass (*k*).

The current practice is to design dewatering systems based on an average value for (*k*) measured using falling head, single packer, and/or double packer test results (i.e., $\boldsymbol{k}_{\mathbf{Test}}$).

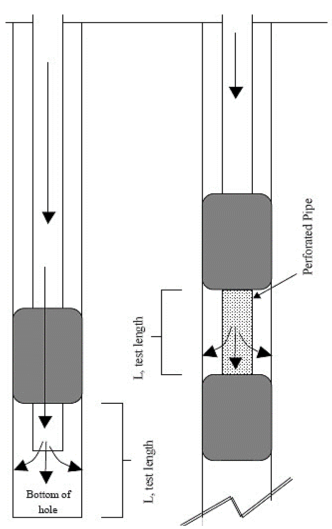
In this research, the actual permeability of rock masses has been represented by the coefficients of permeability estimated from results of pumping tests and back-calculated from the actual discharge pumped out of dewatering systems ($\boldsymbol{k}_{\mathbf{BC}}$).



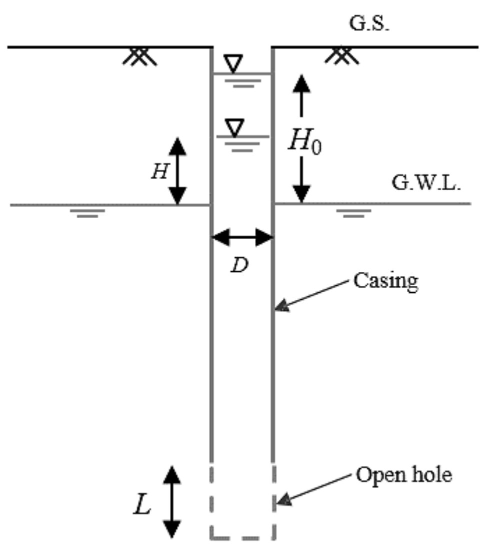
Predicting the Permeability of Rock Mass (Cont.)

Considered field permeability tests

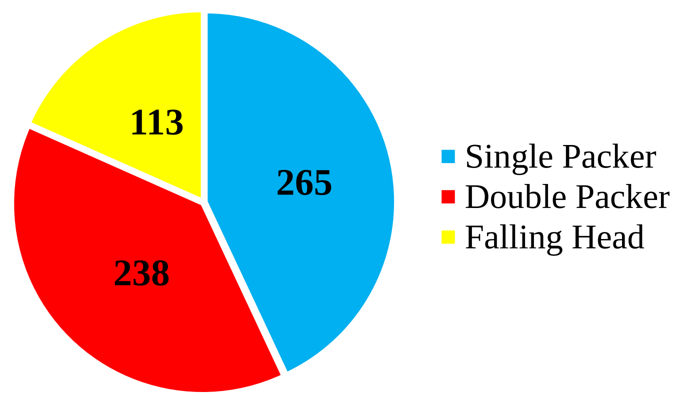
The rock coefficients of permeability measured through conducting the commonly used field tests (i.e., **falling head**, **single packer**, and **double packer tests**) were collected for the sites of considered dewatering projects and pumping wells.



Single Packer Test | Double Packer Test



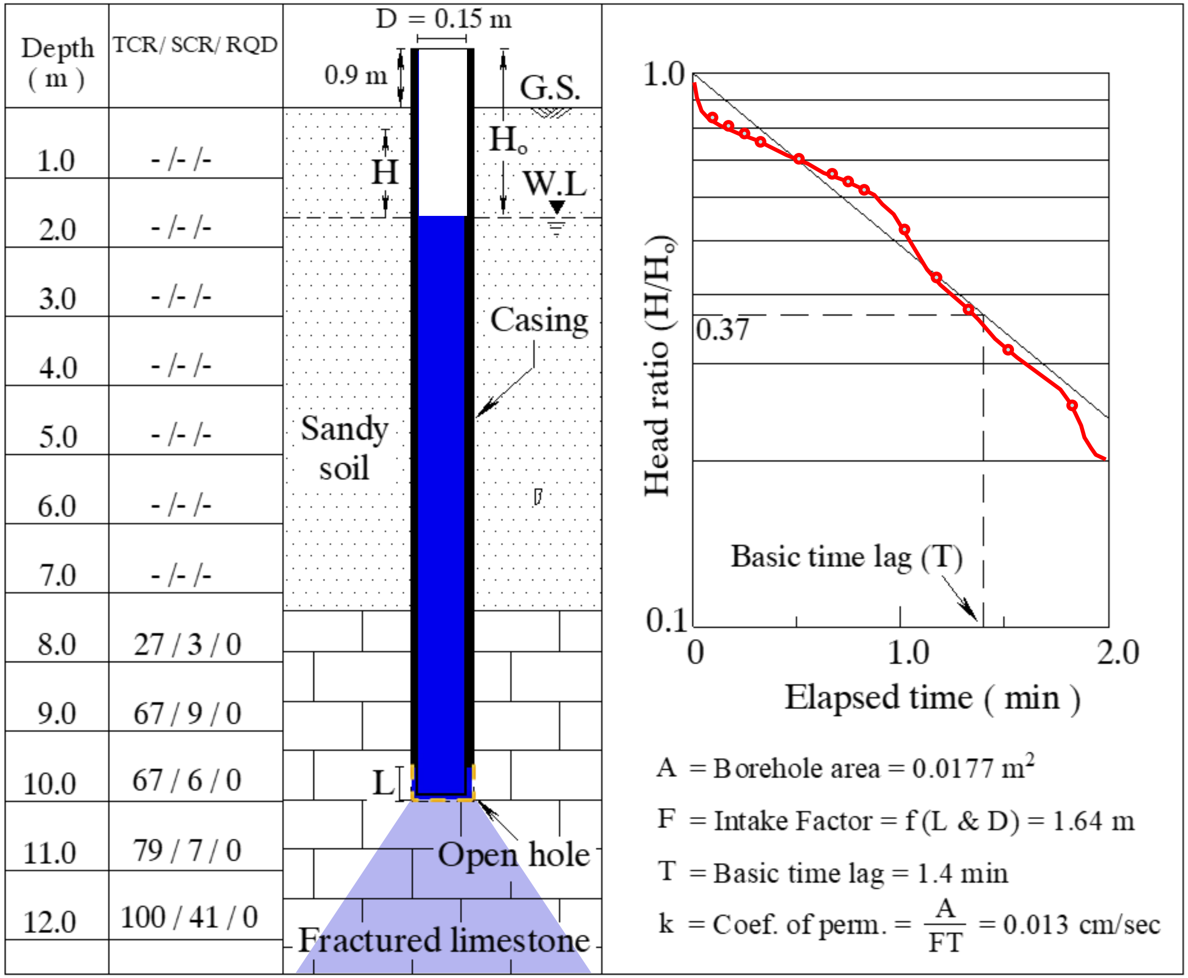
Falling Head Test



Total of 616 Field Tests

Predicting the Permeability of Rock Mass (Cont.)

Considered field permeability tests (Cont.)



Typical in-situ falling head permeability test setup and results used in the analysis

Predicting the Permeability of Rock Mass (Cont.)

Dewatering projects considered in the analyses

Table 1. Dewatering projects used in back-calculating the coefficient of permeability of the rock mass and developing its correlations to different fracturing indices.

Case No.	Location	Drawdown (m)	Dewatering Method	GWL[b] (m)	Exc. Dim. (BxLxD)[c] (m)	Submersible Pump Depth BGS[d] (m)	Steady-state Discharge (m^3/s)	Formation (Thickness in Dewatering Zone)[f]	Average Rock Indices in Dewatering Zone (%)			Type of field Permeability Test (No. of tests)[g]
									RQD	SCR	TCR	
1	Al Khor	2.56	Sump & Trench	2.11	55x113x3.67	NA[e]	0.02	SL(1.02), RL(2.035)	32	49	76	SP(5)
2	Al kheesa	2.87	Sump & Trench	11.13	8x8x13.00	NA	0.015	RL(3.37)	12	28	73	SP(1)
3	Bin Mahmoud	2.89	Sump & Trench	4.61	15x15x6.50	NA	0.016	SL(3.39)	69	86	99	DP(10)
4	Education City	2.925	Sump & Trench	14.69	300x300x16.615	NA	0.040	SL(5.93)	22	46	85	DP(2)
5	Bin Mahmoud	2.98	Sump & Trench	4.52	14x32x6.50	NA	0.036	SL(3.48)	67	83	99	DP(10)
6	Lusail	4.00	Deep well & Trench	6.00	56x80x9.00	15.74	0.030	SL(9.74)	36	55	89	-
7	Al kheesa	4.87	Sump & Trench	11.13	8x8x15.00	NA	0.022	RL(5.37)	11	27	76	SP(1)
8	Mesaieed	6.25	Deep Well & Trench	4.00	74x78x9.25	12.00	0.042	SL(8.00)	7	14	64	FH(4)
9	Al Duhail	6.62	Deep Well & Trench	11.20	11x11x16.82	23.81	0.047	SL(0.7),MS(3.8),RL(7.81)	42	66	86	DP(2)
10	Al Maamoura	7.50	Deep Well	4.50	34x109x11.00	15.21	0.038	SL(10.71)	47	85	91	-
11	Al kheesa	8.50	Deep Well & Trench	13.50	12x19x21.00	26.00	0.028	RL(12.50)	16	29	77	SP(3)
12	Lusail	9.11	Deep Well & Trench	7.29	73x884x15.40	22.40	0.450	RL(15.11)	19	38	64	FH(20)
13	Al Kheesa	9.80	Deep Well & Trench	9.20	10x12x18.00	23.00	0.040	SL(1.525),RL(12.275)	19	32	75	SP(4)
14	Lusail	10.80	Deep Well & Trench	2.42	46x96x12.02	18.92	0.142	SL(13.03),MS(1.55),RL(1.92)	42	81	96	-
15	Corniche	11.40	Deep Well & Trench	4.000	65x122x14.80	21.80	0.053	SL(17.40)	33	44	85	-
16	Al kheesa	11.50	Deep Well & Trench	13.500	16x16x24.00	29.00	0.030	RL(15.50)	11	24	78	SP(3)
17	Al kheesa	13.43	Deep Well & Trench	14.372	16x16x27.00	32.00	0.030	RL(17.43)	30	46	94	SP(4)
18	Ras Abu Aboud	13.90	Sump & Trench	3.100	41x140x16.00	18.00	0.115	SL(14.90)	39	52	85	FH(5),SP(3),DP(4)
19	Al kheesa	14.35	Deep Well & Trench	16.65	16x18x30.00	35.00	0.030	RL(18.35)	11	23	76	SP(4)
20	Old Ghanim	14.70	Deep Well & Trench[a]	4.55	30x54x18.25	24.25	0.009	SL(11.15),MS(3.7),RL(4.85)	29	40	89	FH(1)
21	Al Dayaan	16.50	Deep Well & Trench	4.85	66x106x15.50	25.50	0.085	RL(20.65)	26	54	86	SP(2)
22	Bani Hajar	18.63	Deep Well & Trench	9.37	8x11x27.00	32.00	0.030	SL(0.73),MS(2.90),RL(19.00)	39	66	88	SP(4)
23	Bani Hajar	18.98	Deep Well & Trench	9.52	3.5x3.5x27.5	33.00	0.018	SL(1.68),RL(21.80)	43	68	88	SP(3)
24	Al Duahil	19.35	Deep Well & Trench	5.32	81x98x23.67	30.67	0.043	SL(7.5).MS(5.5),RL(12.35)	48	69	87	DP(3)
25	Lusail	20.15	Deep Well & Trench	2.35	51.2x88x21.50	28.50	0.023	SL(13.65),MS(2.30),RL(10.2)	18	30	83	-
26	Corniche	21.65	Deep Well & Trench[a]	8.31	19x145x28.96	35.96	0.033	SL(12.71),MS(5.00),RL(11.36)	57	67	87	SP(27),DP(12)
27	Al Sharq	22.31	Deep Well & Trench[a]	6.49	9.44x11.94x27.80	34.80	0.031	SL(9.81),MS(4.00),RL(14.50)	64	82	98	DP(14)
28	Al kheesa	23.20	Deep Well & Trench	16.73	16x18x30.50	36.00	0.025	RL(19.27)	30	46	95	SP(4)
29	Al kheesa	25.24	Deep Well & Trench	10.26	16x18x34.50	41.00	0.030	SL(2.94),RL(27.70)	37	55	97	SP(7)
30	Al Sharq	25.31	Deep Well & Trench[a]	6.49	9.6x11.5x30.80	37.65	0.031	SL(9.81),MS(5.00),RL(16.35)	65	83	98	DP(13)

[a]Retaining wall was used; [b]Water level below ground surface; [c] Dimensions: B = Width, L = Length, D = Depth; [d]Below ground surface; [e] Not Applicable; [f]Formations: SL = Simsima Limestone, MS = Midra Shale, RL = Rus Limestone ; [g]Permeability tests: FH = Falling Head, SP = Single Packer, DP = Double Packer.

Predicting the Permeability of Rock Mass (Cont.)

Pumping well cases considered in the analysis

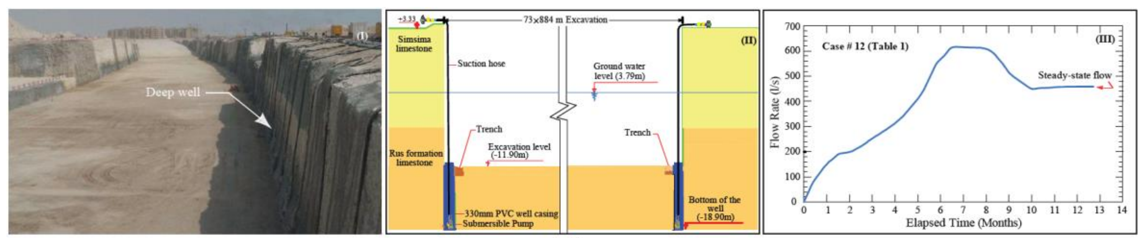
Table 2. Pumping tests used in measuring the coefficient of permeability of rock mass and developing its correlations to different fracturing indices.

Case No.	Location	Drawdown (m)	GWL[a] (m)	Depth of Pumping Well (m)	Distance of OW[b] from pumping well (m)	Pumping Discharge (m^3/s)	Formation (Thickness in Pumping Zone)[c]	Average Rock Indices in Pumping Zone (%)			Type of Field Permeability Test (No. of tests)[d]
								RQD	*SCR*	*TCR*	
31	Ras Abu Aboud	0.14	6.15	15	79&13	0.00129	SL(8.85)	34	47	82	SP(3), DP(1), FH(1)
32	Meshaaf	0.40	12.250	45	25&10	0.0058	SL(9.75), MS(7.5), RL(15.5)	76	83	98	FH(2)
33	Meshaaf	0.50	9.64	45	25&10	0.0209	SL(17.36), MS(5.12), RL(12.88)	74	79	95	FH(2)
34	Meshaaf	0.89	10.63	45	20&10	0.0058	SL(17.37), MS(6.35), RL(10.65)	77	81	97	FH(2)
35	Bin Mahmoud	1.06	5.473	25	25&9.26	0.008	SL(10.527), MS(4.5), RL(4.5)	70	86	98	DP(34)
36	Dafna	1.14	2.00	22	5&15	0.0126	19 (SL)	26	35	76	SP (8), FH(7)
37	Souq Waqif	1.63	3.26	25	24.9&2.97	0.0095	SL(12.19), MS(3), RL(6.55)	41	49	78	SP(14), DP(4), FH(2)
38	Meshaaf	8.48	9.77	45	25&10	0.025	SL(17.23), MS(6), RL(12)	80	88	98	FH(3)

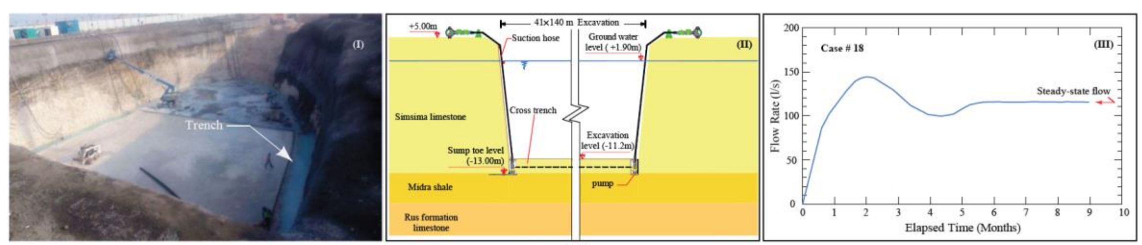
[a]Water level below ground surface; [b]Observation well; [c]Formations: SL= Simsima Limestone, MS = Midra Shale, RL= Rus Limestone; [d]Permeability tests: FH = Falling Head, SP = Single Packer, DP = Double Packer.

Examples of the analyzed dewatering projects: (A) Using deep wells; (B) Using sump & trench system

I. Excavation of the project site;
II. Schematic drawing for the excavation and the employed dewatering system;
III. Change of flow rate with time.



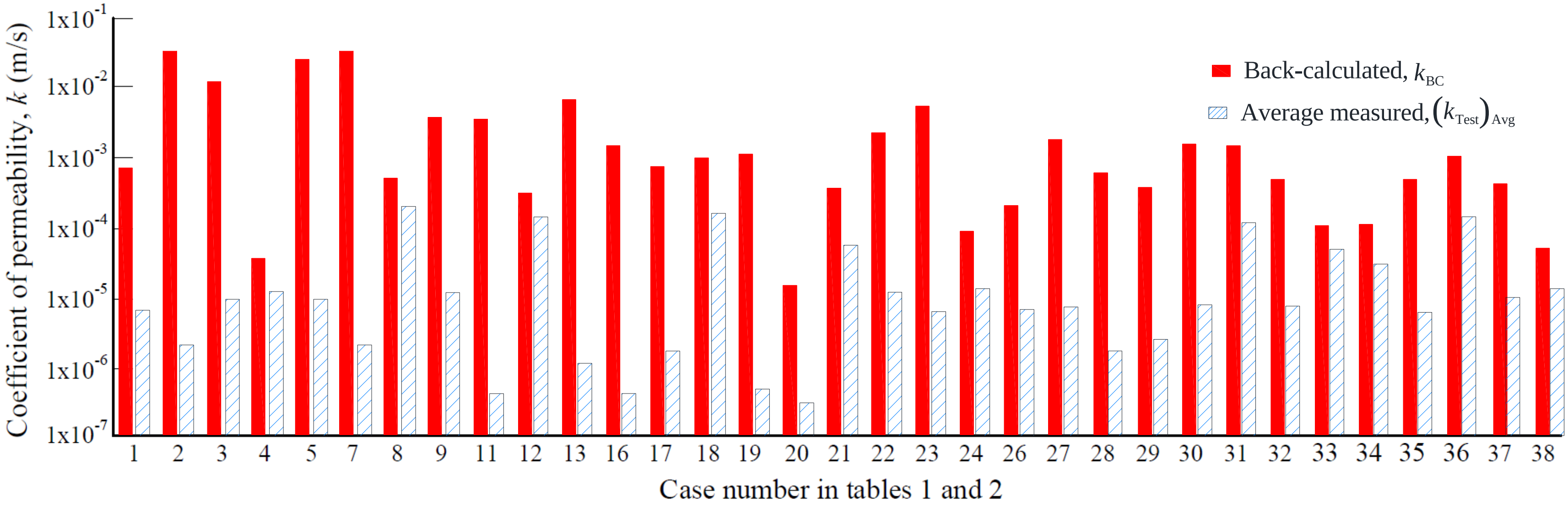
(A)



(B)

Predicting the Permeability of Rock Mass (Cont.)

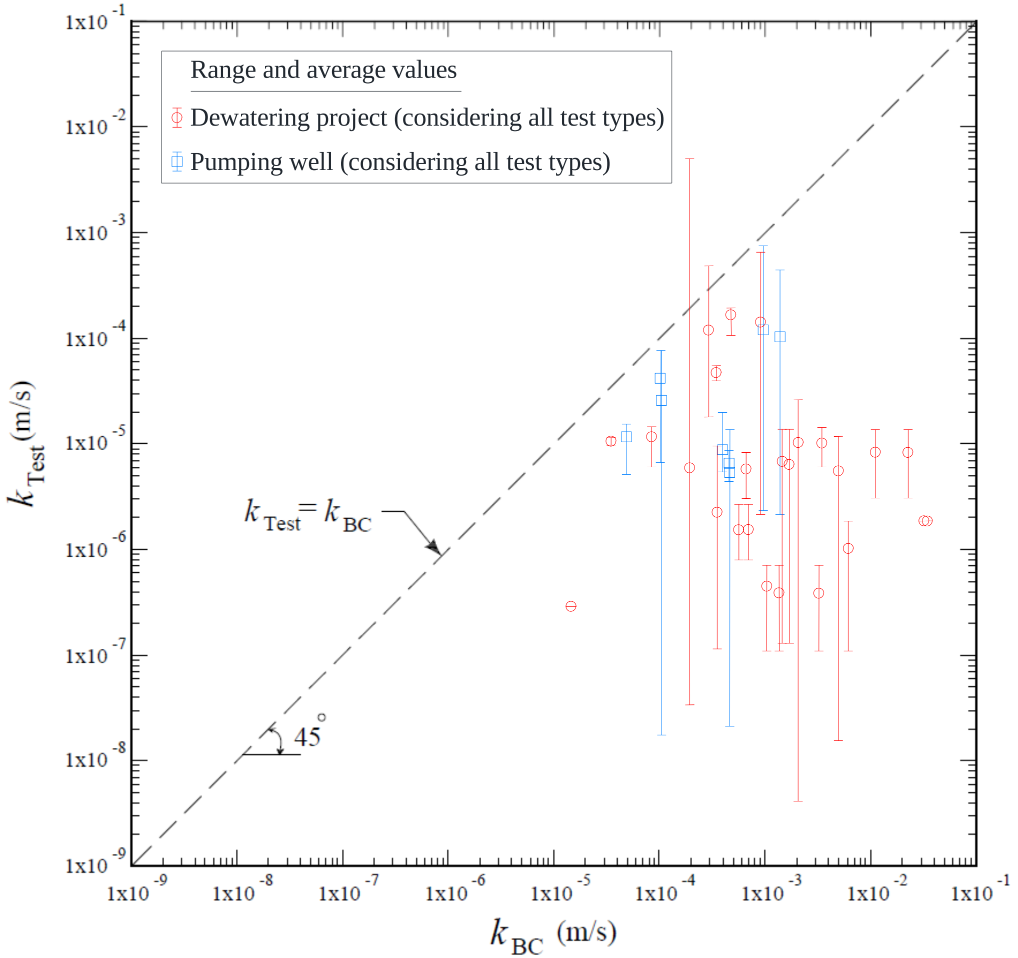
Comparison between $(k_{\text{Test}})_{\text{Avg}}$ and k_{BC}



Comparison between the average measured permeability values [$(k_{\text{Test}})_{\text{Avg}}$] and the corresponding back-calculated permeability (k_{BC}) values for fractured rock masses in the studied dewatering cases.

Predicting the Permeability of Rock Mass (Cont.)

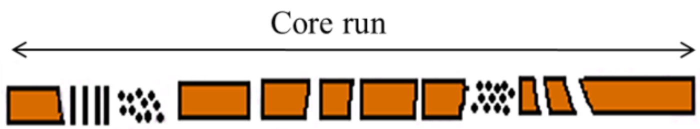
Comparison between k_{Test} and k_{BC}



Comparison between the measured permeability (k_{Test}) values and the corresponding back-calculated permeability (k_{BC}) values for fractured rock masses in the studied cases.

Predicting the Permeability of Rock Mass (Cont.)

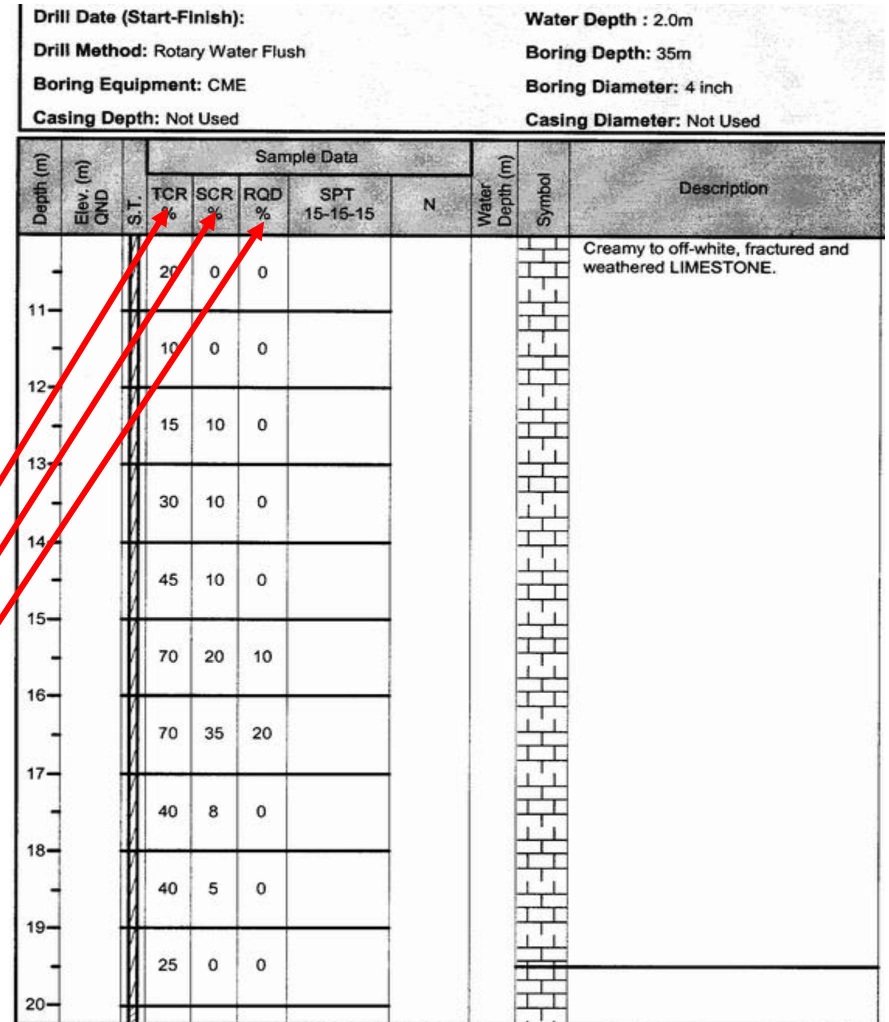
Rock fracturing indices that may be related to its mass permeability (Cont.)



Total Core Recovery (*TCR*)

Solid Core Recovery (*SCR*)

Rock Quality Designation (*RQD*)



Drill Date (Start-Finish):
Drill Method: Rotary Water Flush
Boring Equipment: CME
Casing Depth: Not Used
Water Depth : 2.0m
Boring Depth: 35m
Boring Diameter: 4 inch
Casing Diameter: Not Used

Depth (m)	Elev. (m) QND	S.T.	TCR %	SCR %	RQD %	SPT 15-15-15	N	Water Depth (m)	Symbol	Description
			20	0	0					Creamy to off-white, fractured and weathered LIMESTONE.
11			10	0	0					
12			15	10	0					
13			30	10	0					
14			45	10	0					
15			70	20	10					
16			70	35	20					
17			40	8	0					
18			40	5	0					
19			25	0	0					
20										

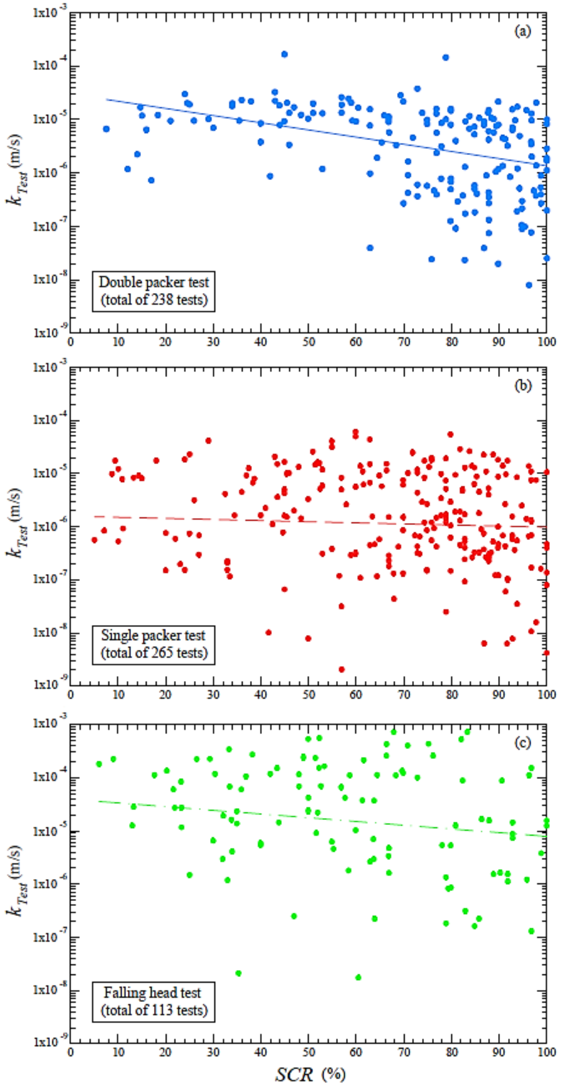
$$RQD = \frac{\text{The sum length of all core pieces that are 4 inches (10 cm) or larger}}{\text{The length of core run}} \times 100\%$$

$$SCR = \frac{\text{The length of core recovered as a solid cylinder}}{\text{The length of core run}} \times 100\%$$

$$TCR = \frac{\text{The length of the total amout of core samples recovered}}{\text{The length of core run}} \times 100\%$$

Predicting the Permeability of Rock Mass (Cont.)

Field permeability test results (k_{Test}) and general trend lines as related to *SCR*



$$k_{\text{Test}} = 3x10^{-5} * \ e^{-0.03(SCR)}$$

Double packer test results, with SCR

$$k_{\text{Test}} = 2x10^{-6} * \ e^{-0.005(SCR)}$$

Single packer test results, with SCR

$$k_{\text{Test}} = 9x10^{-5} * \ e^{-0.026(SCR)}$$

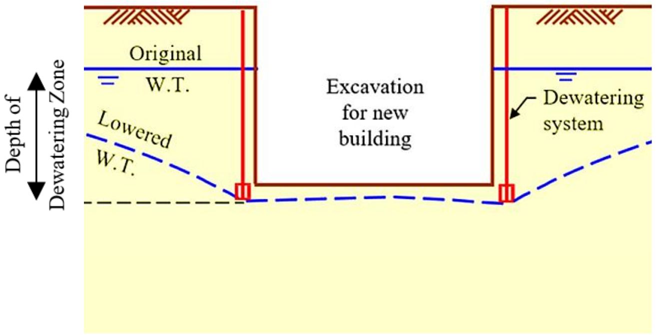
Falling head test results, with SCR

Predicting the Permeability of Rock Mass (Cont.)

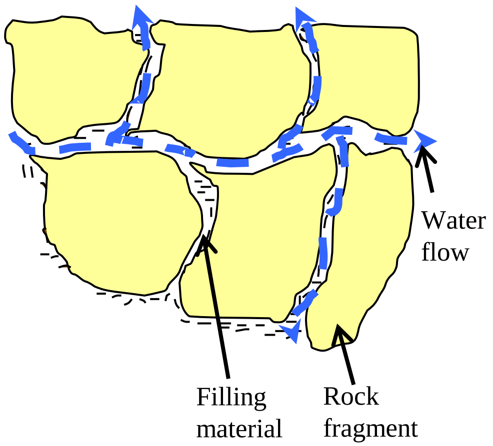
Factors to be used for better prediction

Considering the following influences helps in better prediction of permeability of rock mass:

a. Difference between the degree of fracturing at the tested rock and that of the rock mass in the dewatering zone [e.g., difference between **(SCR)**$_{\mathbf{Test}}$ and **(SCR)**$_{\mathbf{DZ}}$]. Such an effect is addressed in this study using the *SCR* adjustment factor (**F**$_{SCR}$).



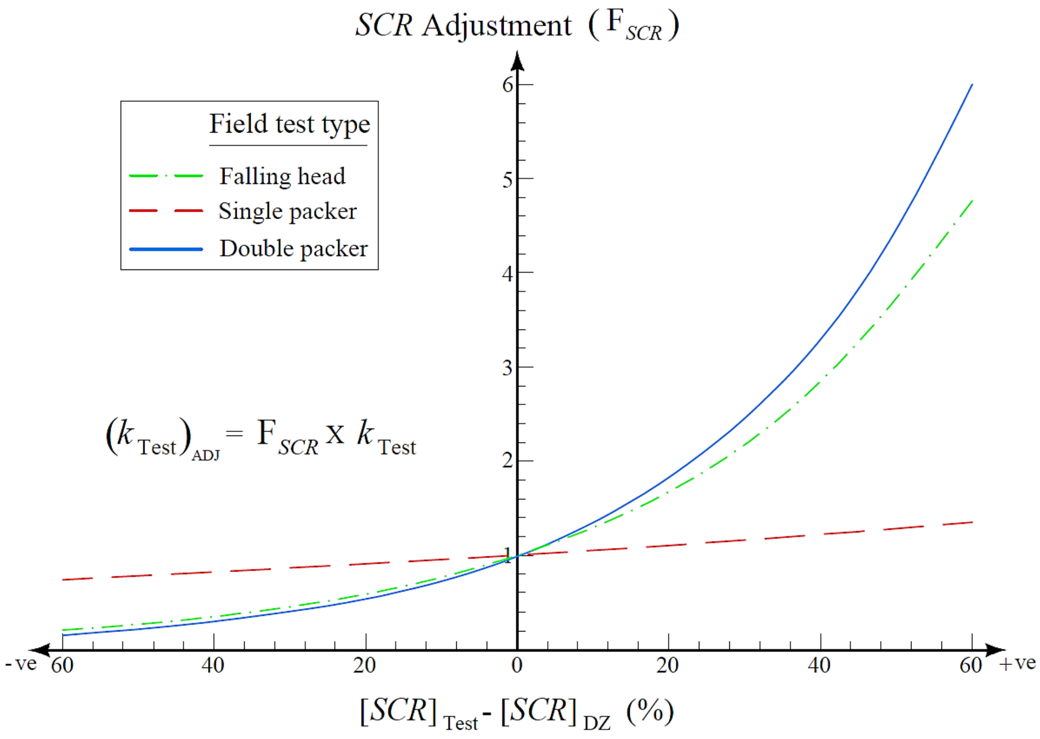
b. Cracks multi-directional connectivity and other crack surface and filling material properties that may not be reflected in the results of the frequently conducted field permeability tests. Such an effect is addressed in this study using the connectivity factor (**F**$_{\mathbf{CON}}$).



Predicting the Permeability of Rock Mass (Cont.)

Determining the *SCR* adjustment factor (F_{SCR})

F_{SCR} can be determined as a function of the test type and the difference between $(SCR)_{Test}$ and $(SCR)_{DZ}$ using chart or equation.



Change of *SCR* adjustment factor with the difference between the *SCR* values of the test $(SCR)_{Test}$ and the dewatering zone $(SCR)_{DZ}$.

For Falling head test:

$$F_{SCR} = e^{0.026[(SCR)_{Test} - (SCR)_{DZ}]}$$

For Single packer test:

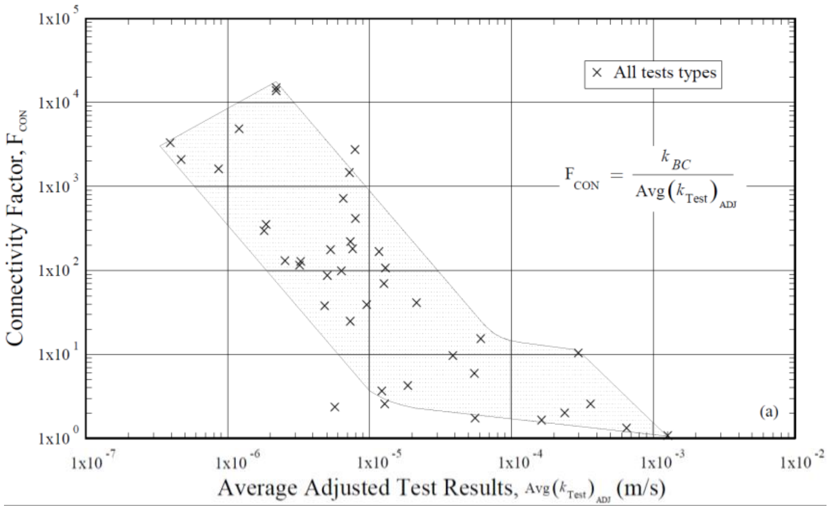
$$F_{SCR} = e^{0.005[(SCR)_{Test} - (SCR)_{DZ}]}$$

For Double packer test:

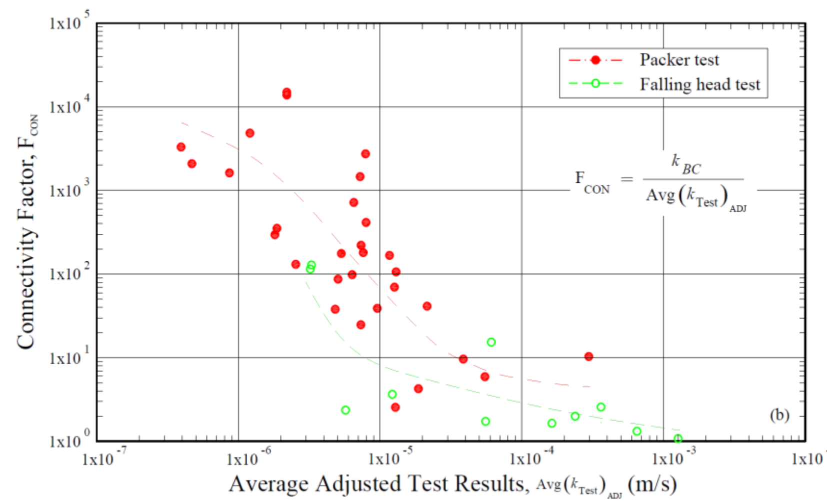
$$F_{SCR} = e^{0.03[(SCR)_{Test} - (SCR)_{DZ}]}$$

Predicting the Permeability of Rock Mass (Cont.)

Determining the connectivity factor (F_{CON})



Relation between the average adjusted test results of the dewatering zone and the connectivity factor.



Relation between the average adjusted test results of the dewatering zone and the connectivity factor based on test type.

Predicting the Permeability of Rock Mass (Cont.)

Numerical example I

Given data of double packer tests in dewatering site:

$(SCR)_{\text{Test}}$ = 65%, 80%, 70%, 75%.

$k_{\text{Test}} = 1.0 \times 10^{-6}, 2.0 \times 10^{-7}, 3.0 \times 10^{-6}, 5.0 \times 10^{-7}$ m/s.

$(SCR)_{\text{DZ}}$ = 50%.

Prediction Steps:

Using the equation $F_{SCR} = e^{0.03[(SCR)_{\text{Test}} - (SCR)_{\text{DZ}}]}$
or chart, we get $F_{SCR} \approx$ 1.57, 2.46, 1.82, 2.12

$\because (k_{\text{Test}})_{\text{ADJ}} = F_{\text{SCR}} \times k_{\text{Test}}$

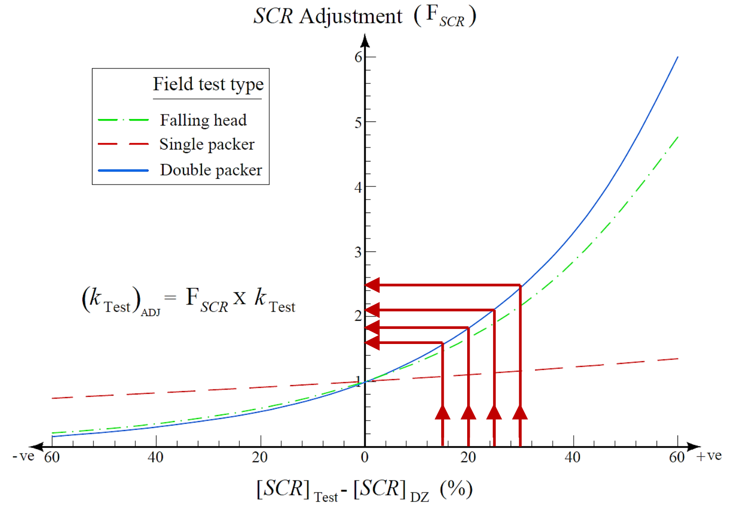
$\therefore (k_{\text{Test}})_{\text{ADJ}} = 1.6 \times 10^{-6}, 5.0 \times 10^{-7}, 5.4 \times 10^{-6}, 1.0 \times 10^{-6}$ m/s

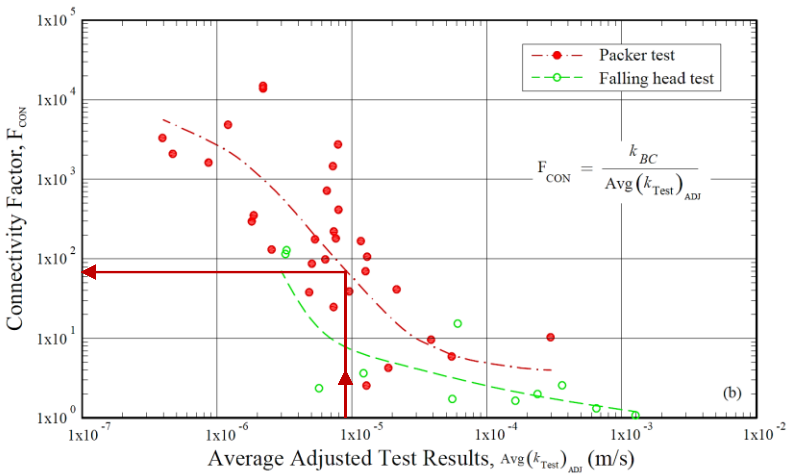
Avg $(k_{\text{Test}})_{\text{ADJ}} = 8.5 \times 10^{-6}$ m/s

Using the equation $F_{\text{CON}} = 2 \times 10^{-8} * [\text{Avg } (k_{\text{Test}})_{\text{ADJ}}]^{-1.882}$
or chart, we get $F_{\text{CON}} \approx$ 70

$\because k_{\text{PR}} = F_{\text{CON}} \times \text{Avg } (k_{\text{Test}})_{\text{ADJ}}$

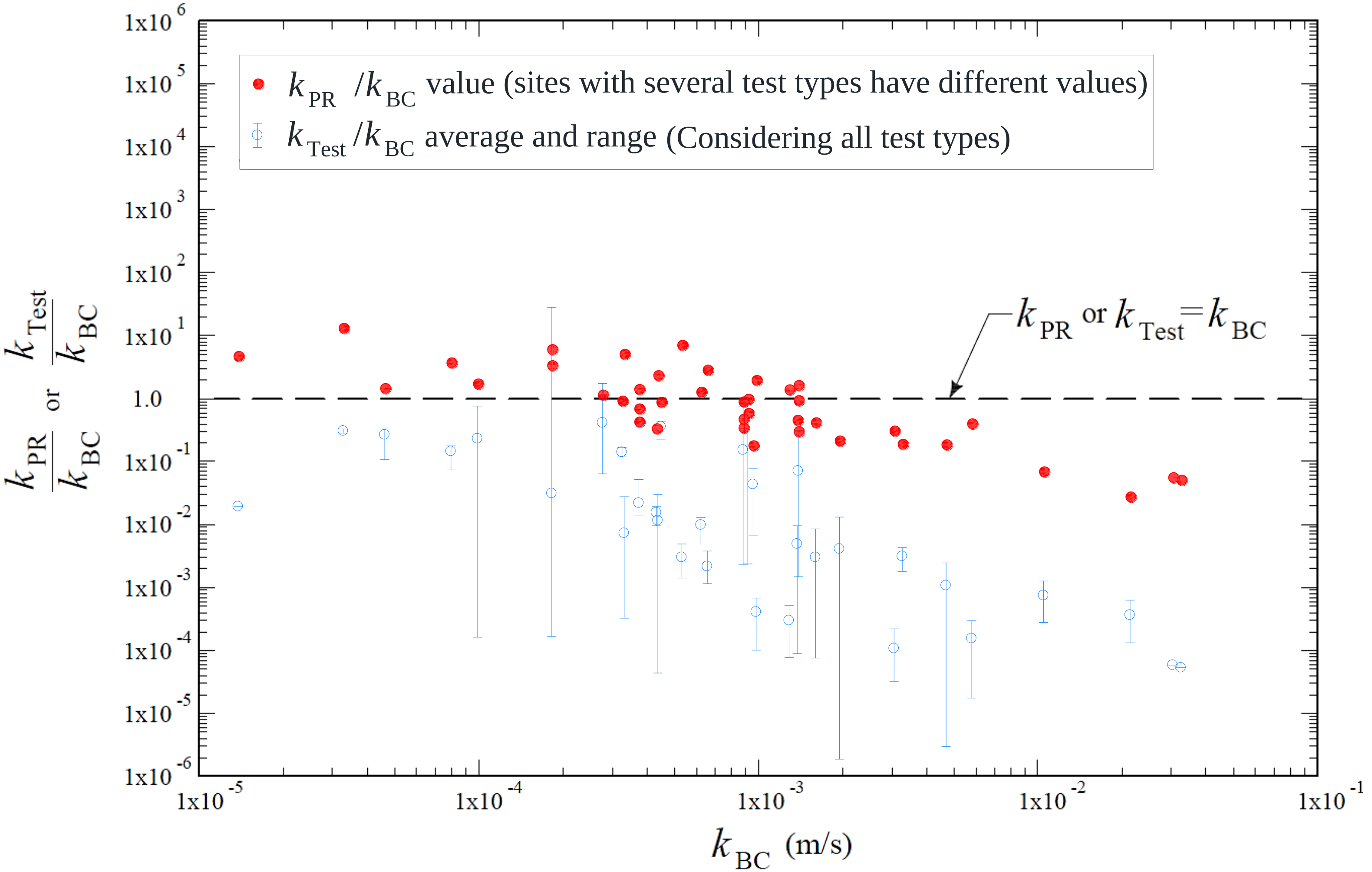
$\therefore k_{\text{PR}} = (70)(8.5 \times 10^{-6}) \approx$ **6.0×10^{-4} m/s**





Predicting the Permeability of Rock Mass (Cont.)

Ratios of k_{PR} and k_{Test} to k_{BC}



Ratios of the predicted (k_{PR}) and measured coefficient of permeability (k_{Test}) to corresponding back-calculated (k_{BC}) values.

Main Conclusions

1. There is a **significant discrepancy between the average k measured from the field permeability tests** (double packer, single packer and falling head) and the back-calculated one (true permeability).
2. *SCR* is more indicative than *RQD* in expressing the degree of fracturing for permeability estimation.
3. Results of the double packer test have better correlation with *SCR* than those yielded from the other two tests (Single packer and falling head).
4. Values of the measured *k* are not sensitive to the vertical stress at test elevation in the depth range usually encountered in dewatering activities.
5. *SCR* adjustment factor should be applied to the results of permeability tests. The value of such factor differs based on each test type.
6. Adjusted test results (that reflect the effect of density, size, and infillings of fractures) can be correlated to the true permeability that is additionally affected by the fractures interconnection as well

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Acknowledgment

The funding provided for this research work by the Qatar National Research Fund (QNRF), Qatar, under Project No. NPRP 12S-0314-190366, is deeply appreciated. Furthermore, the research team would like to thank Qatar University for furnishing the human resources needed for this study. Special thanks go to the industrial collaborators (Hydroserv Qatar and Fugro Qatar) for providing the information and raw data utilized in this study.

Thanks for Your Time

Questions?