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ASSESSMENT OF THE GROUTABILITY USING SECONDARY PERMEABILITY INDEX IN AN ARID ZONE: A CASE STUDY IN SHITAB DAM SITE, SE IRAN

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EXTENDED ABSTRACT

L'acqua può filtrare attraverso le discontinuità dell'ammasso roccioso come le fratture, i giunti, i piani di stratificazione e le faglie. Ciò potrebbe essere estremamente pericoloso laddove si verificano infiltrazioni dall'invaso della diga attraverso la fondazione e le spalle della diga stessa. Le dighe in calcestruzzo sono generalmente suscettibili al cedimento della fondazione, ma infiltrazioni e fenomeni di piping affliggono le dighe in terra laddove sono fenomeni molto comuni. Tuttavia, i fattori di controllo delle infiltrazioni possono e devono essere gestiti, in quanto sono un problema critico che deve essere considerato durante la fase di progettazione della diga e la sua manutenzione. I fattori di controllo delle infiltrazioni possono essere classificati in due gruppi principali: 1) geologici e 2) tecnologici. L'infiltrazione può avvenire attraverso le spalle, la fondazione ed il corpo diga. Le infiltrazioni attraverso la fondazione della diga e le sue spalle sono generalmente controllate da fattori geologici. Le infiltrazioni incontrollate possono erodere materiale e causare instabilità dei versanti della diga. Per questo motivo, il controllo della velocità di infiltrazione (*rate*) attraverso le spalle e la fondazione della diga in terra è un argomento molto importante e richiede una conoscenza approfondita dei materiali affioranti alla base della diga, comprese le sue proprietà idrauliche, nonché dell'indice RQD (*Rock Quality Designation*). Questo studio è volto a valutare l'indice di permeabilità secondaria (SPI) e l'RQD in un'area con una complessità minima delle proprietà geologiche. Le osservazioni di terreno sono state condotte nel sito della diga di Shitab, nella provincia di Sistan e Balouchestan, nel sud dell'Iran (26°51′50.7″ N and 62°54′24.6″ E). Le spalle ed il basamento della diga di Shitab sono costituiti da rocce sedimentarie scistose con intercalazioni carbonatiche, a cui si sovraimpone alluvio di età quaternaria. Il clima nell'area di studio è arido ed i processi di erosione meccanica superano di gran lunga quelli chimici. La stratificazione è parallela all'asse della diga. Durante i sopralluoghi di sito non sono state rilevate faglie, pieghe o fenomeni carsici. Prove Lugeon sono state eseguite durante le operazioni di perforazione in sezioni di 5 metri composte da 5 pozzi (24 sezioni totali). Le qualità ingegneristiche dell'ammasso roccioso affiorante nel sito della diga di Shitab sono state attribuite con il metodo RQD utilizzando le informazioni ottenute da 5 pozzi.

L'ammasso roccioso nell'area di studio è stato classificato in base ai valori SPI come segue:

1) Livello poco profondo: include sezioni di pozzi di profondità inferiore a 15 metri, dove la classe A è il principale tipo di ammasso roccioso, forse a causa della presenza di strati di scisto grigio calcareo;
2) Livello intermedio: include sezioni di pozzi da 15 a 30 metri di profondità, dove è prevista una riduzione del livello di erosione meccanica dell'ammasso roccioso e della fratturazione. Tuttavia, vi è un aumento significativo della Classe C e della Classe D, mentre la Classe A è ancora il principale tipo di ammasso;
3) Livello profondo: include sezioni di pozzi più profondi di 30 metri, dove l'ammasso roccioso non è alterato. I tipi di ammasso di Classe C e Classe D sono assenti e la Classe A è prevalente. Tuttavia, è presente la classe B, forse a causa dell'esistenza di alcune fessure permeabili.

In generale, l'indice SPI è direttamente proporzionale all'intensità della fratturazione d'ammasso. In altre parole, si prevede che l'SPI aumenti man mano che diminuiscono i valori RQD. Tuttavia, le aree con bassi valori di SPI (classe A e B) e RQD basso (molto scarso e scarso) possono essere causate dell'alta intensità delle fratture inter-connesse. La conduttività idraulica di un tale ammasso roccioso è molto bassa e l'eventuale trattamento migliorativo è inutile. I risultati di questo studio implicano, pertanto, che trattamenti migliorativi nelle aree di classe A del sito della diga di Shitab sono inutili. Opere di trattamento nelle aree classificate come classe B sono, invece, localmente necessari mentre risultano estremamente necessari nelle aree di classe C e D. Infine, trattamenti migliorativi del terreno devono essere orientati in una cortina di malta cementizia a motivi triangolari con distanza di 6 e 9 metri rispettivamente in ammassi rocciosi a bassa e alta permeabilità. I risultati di questo studio implicano che trattamenti del terreno sono necessari nel sito della diga di Shitab, specialmente nelle parti poco profonde (<15 m di profondità). I grafici SPI-RQD hanno rivelato una correlazione di quasi il 60% tra indice di permeabilità secondario e valori di RQD. Per concludere, l'analisi dei pozzi ha rivelato una grande complessità nelle caratteristiche ingegneristiche dell'ammasso roccioso del sito della diga di Shitab, specialmente in zone poco profonde. Sebbene la litologia sia molto semplice, i processi di alterazione meccanica hanno degradato le rocce poco profonde nelle zone aride. Di conseguenza, l'eterogeneità dell'ammasso roccioso dal punto di vista ingegneristico è probabilmente molto elevata. Questo studio dimostra che un approccio decisionale multi-parametrico è essenziale per progettare la strategia di trattamento dell'ammasso roccioso, anche quando la complessità litologica è minima.

ABSTRACT

The water seepage through dams' basement and abutments may result in catastrophic events at down-streams. Therefore, it is critical to seal dam foundation via reasonable methods. To decide a ground treatment strategy, one may not elaborate all necessary data-set especially in areas with very simple geologic properties. This study aims to evaluate the groutability in a very simple geologic condition. For this, the studies conducted along the Shitab Dam basement and abutments axis. The study area is located SE Iran, with an arid climate, where the mechanical weathering is extremely high. The investigation conducted through using 5 boreholes in the study area. The rock quality designation (RQD) index and Lugeon in-situ test were done. Additionally, the secondary permeability index (SPI) calculated using the field observations. The results revealed a serious complexity in engineering properties of the rock mass. Accordingly, the grout curtain pattern designed.

Keywords: Shitab Dam, secondary permeability index (SPI), rock quality designation (RQD)

INTRODUCTION

Water may seepage through the discontinuities of the rock mass such as fissures and joints, bedding planes, faults, etc. This might be extremely hazardous where the water seepage occurs from dam reservoir through the dam foundation and abutments. Therefore, it is essential to seal foundation and abutments with regard to the geological conditions of rock masses and their permeability. Ewert (1997b) suggested the Lugeon permeability test as the most useful and common approach to evaluate the rock mass permeability in geotechnical studies. Additionally, Ewert (1997c) discussed about the grout curtain installation based upon the water pressure tests (WPTs) results on the basis of the in-situ Lugeon permeability estimations. The Lugeon permeability approximation is strongly dependent on the level of the rock mass weathering as well as geometric characteristics (Karagüzel & Kiliç, 2000). Since then, there are many studies done on the dam site groutability using Lugeon permeability estimations (Kutzner, 1996; Nusier *et alii*, 2002; Turkmen, 2003; Ghobadi *et alii*, 2005; Uromeihy & Barzegari, 2007; Ajalloeian *et alii*, 2011; Gurocak & Alemdag, 2011; Sadeghiyeh *et alii*, 2012; Uromeihy & Farrokhi, 2011; Zeidabadi *et alii*, 2012).

Foyo *et alii* (2005) expressed that the RQD values obtained from the boreholes cores might be a useful tool "*... to predict the test section behavior under water pressure test*". Additionally, they suggested that the RQD must be in a direct relation with the water-absorbed quantity. However, the opposite situation might be possible. This study aims to evaluate the SPI and RQD relationship in an area with minimum geological properties complexity. The field observations were conducted in Shitab Dam site, Sistan & Balouchestan Province, SE Iran.

GEOLOGY SETTINGS

The Shitab Dam site is located at N 26º 51′ 50.7″ and E 62º 54′ 24.6″ (Fig. 1). Geologically, the Shitab Dam site is located in the East Iranian Flysch Zone with regard to Stöcklin *et alii* (1972) classification. Rocks with the age of Upper Eocene are the oldest lithologic exposures in the study area (Samimi-namin, 1983), and thick bedded sandstones with schist and conglomerate inter-beddings are abundant (Zayandab Consultant Engineering Company, 2013). However, the Shitab Dam abutments and basement are only consisting shale sedimentary rocks with limestone inter-beddings that are covered by quaternary alluvium. The climate in the study area is arid where the mechanical weathering outweighs the chemical weathering. The beddings direction is parallel to dam axis. There is no main fault, fold or any karstic phenomenon observed during the site explorations. The engineering geological characteristics of the site were evaluated using the data obtained from drilled boreholes along the dam axis.

MATERIALS AND METHODS

Lugeon Test

Lugeon test (sometimes named as packer test) is an in-situ test to quantify the bedrock water permeability and the

Lugeon Range	Classification	Hydraulic conductivity range (cm sec^{-1})	Condition of rock mass discontinuities	Reporting precision (Lu)
<1	Very Low	$<1\times10^{-5}$	Very Tight	<1
1-5	Low	1×10^{-5} - 6×10^{-5}	Tight	±0
5-15	Moderate	6×10^{-5} - 2×10^{-4}	Few Partly Open	±1
15-50	Medium	2×10^{-4} - 6×10^{-4}	Some Open	±5
50-100	High	6×10^{-4} - 1×10^{-3}	Many Open	±10
>100	Very High	1×10^{-3}	Open Closely Spaced or Voids	>100

Tab. 1 - Rock mass discontinuities classification according to Lugeon values (after Quiñones-Rozo, 2010) hydraulic conductivity resulted from the secondary permeability (Lancaster-Jones, 1975). The test is a constant-head type above the water table and is based upon measurements carried out at various depths of a borehole (Nappi *et alii*, 2005; Quiñones-Rozo, 2010). The results unit is Lugeon (L or Lu) that is defined as 1 liter water loss per minute per unit length of the test section in pressure of 1 MPa (Fell *et alii*, 2015). The permeability values obtained by Lugeon test give useful information about the rock discontinuities and fissures in the borehole test section (Tab. 1). The Lugeon Test was operated in 5 meter sections of 5 boreholes in Shitab Dam site (totally 24 sections). The tests were conducted during the boring operation.

Rock Quality Designation index (RQD)

Deere *et alii* (1966) suggested the Rock Quality Designation (RQD) as a useful tool to quantify the rock mass quality within drill core logs. The RQD is a rough measurement of the rock mass fissures and fractures as the percentage of intact pieces of the drill cores longer than 100 mm in total boring length. The RQD has some limitations, especially where low values of RQD may reflect the rock mass breakage during the drilling operations (Azimian & Ajalloeian, 2015). Deer (1968) presented the relationship between rock mass engineering quality and the RQD values (Tab. 2). The Shitab Dam site rock mass engineering qualities were designated by RQD method using the information obtained from 5 boreholes.

Secondary Permeability Index (SPI)

Foyo *et alii* (2005) demonstrated the secondary permeability index (SPI) as a useful method to convert the water pressure test (WPT) results into permeability values of the porous rock mass.

Rock quality description	*RQD value (%)*
Very poor	*0 - 25*
Poor	*25 - 50*
Medium	*50 - 75*
Good	*75 - 90*
Very good	*90 -100*

Tab. 2 - The relationship between RQD values and the rock mass engineering quality (after Deer, 1968)

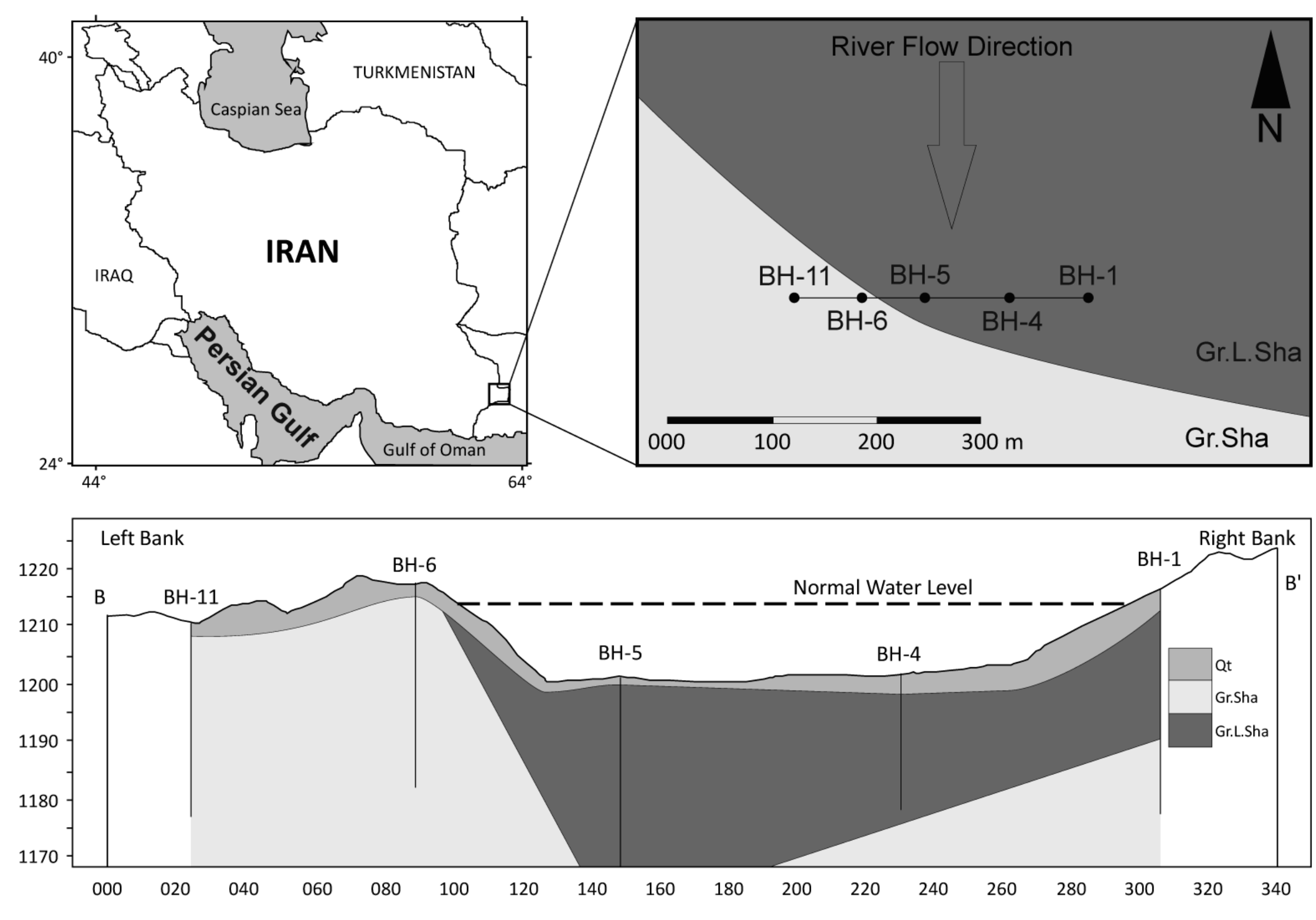


Fig. 1 - The simplified geological map of the Shitab Dam bedrock, and the dam axis geologic cross-section

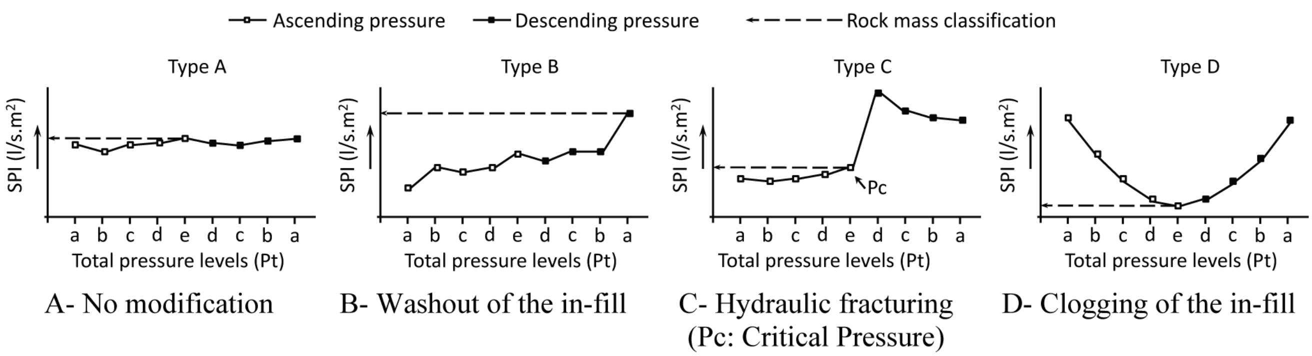


Fig. 2 - The Pt-SPI graphs to classify the rock mass (after Foyo et alii, 2005)

		Secondary Permeability Index (SPI in l/s m²)		
		2.16 10^{-14}	**1.72 10^{-13}**	**1.72 10^{-12}**
Rock mass	*Class A*	*Class B*	*Class C*	*Class D*
Classification	*Excellent*	*Good-Fair*	*Poor*	*Very poor*
Ground treatment	*Needless*	*Local*	*Required*	*Extensive*

Tab. 3 - Rock mass classification based on SPI and ground treatment considerations (Foyo et alii, 2005)

Secondary permeability index is defined as follows:

$$SPI=C\ Ln(2le/r+1)/2\pi le\times Q/Ht$$

where *SPI* is Secondary permeability index (l/s·m² of borehole test surface), *C* is constant that depends on viscosity when the rock temperature is 10°C (C=1.49×10^{-10}) (Snow, 1968), *le* is the test section length (m), *r* is the borehole radius (m), *Q* is water volume absorbed by jointed rock mass (liter), *t* is each pressure level duration (seconds) and *H* is the total pressure (as meter of the water column, m). Typically, the SPI results can be applied to divide the rock mass into different quality zones (Tab. 3) as a basis to designate the ground treatments and dam foundation grouting extends (Foyo *et alii*, 2005). Additionally, Foyo *et alii* (2005) recognized four types of Pressure-SPI graphs including types A, B, C, and D (Fig. 2). Then, they developed an approach as a guideline for the ground treatment (Fig. 3).

RESULTS AND DISCUSSION

The results from the field observations and studies are presented in table 4. Regarding the obtained data; we correlated the SPI values with boreholes depths. Then, the relationship between SPI and RQD values studied. Finally, the grouting quality and extend was decided for any boreholes sections.

The relationship between SPI and boreholes depths

The rock mass classified in the study area based upon SPI values with regard to Foyo *et alii* (2005) guideline (Tab. 3) as follows:

Shallow level: includes boreholes sections shallower than 15 meters, where Class A is the major rock mass type (Fig. 4), maybe due to presence of limy gray shale strata.

Intermediate level: includes boreholes sections between 15 to 30 meters deep, where decrease in rock mass weathering level and fractures is expected. However, there is a significant

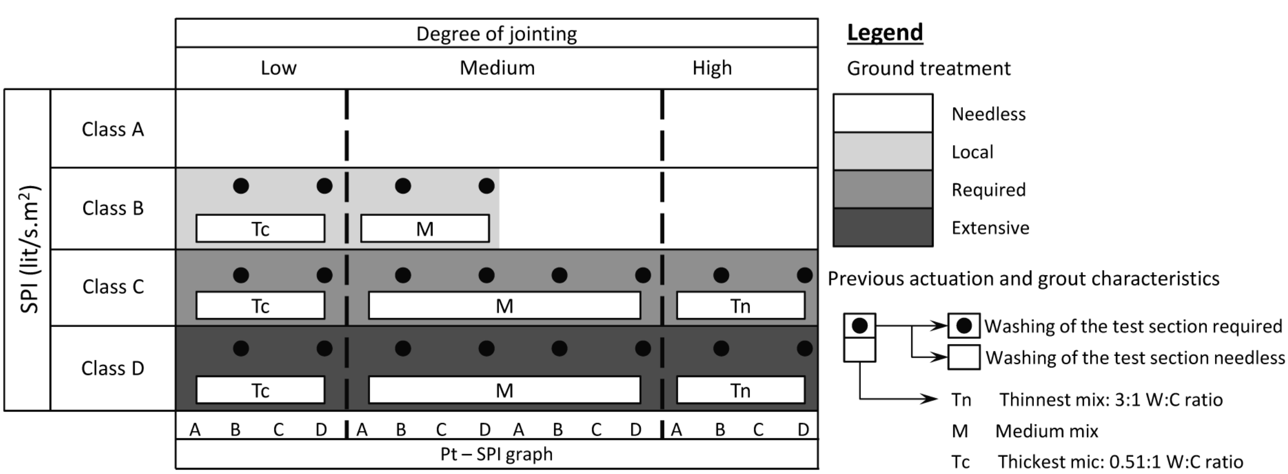


Fig. 3 - The ground treatment quality according to SPI values (after Foyo et alii, 2005)

Borehole N°.	Section depth (m)	Rock type	RQD (%)	Lugeon[1]	Behavior[2]	SPI[3]	Description
1	5-10	Gr. Sha.[4]	ND[5]	100	Total Pert	ND	Unconsolidated layers thickness from ground surface[6]: 3.5 m.
	10-15	Gr. Sha.	78.84	0	Impermeable	1×10^{-16}	
	15-20	Gr. Sha.	56.44	0	Impermeable	1×10^{-16}	
	20-25	Gr. Sha.	20.96	0	Impermeable	1×10^{-16}	
	25-30	Gr. L. Sha.[7]	48.98	5	Turbulent	1.2×10^{-14}	
	30-35	Gr. L. Sha.	67.32	0	Impermeable	1×10^{-16}	
4	3-8	Gr. Sha.	15	0	Impermeable	1.29×10^{-14}	Unconsolidated layers thickness from ground surface: 2.3 m.
	8-13	Gr. Sha.	38.37	0	Impermeable	1×10^{-16}	
	13-18	Gr. Sha.	28.68	0	Impermeable	1×10^{-16}	
	18-23	Gr. Sha.	36.5	0	Impermeable	1×10^{-16}	
5	7-12	Gr. Sha.	9.02	0	Impermeable	1×10^{-16}	Unconsolidated layers thickness from ground surface: 1 m.
	12-17	Gr. Sha.	10.36	0.4	Impermeable	1.18×10^{-15}	
	17-22	Gr. Sha.	5.68	0	Impermeable	1×10^{-16}	
	22-27	Gr. Sha.	6.09	0.2	Impermeable	8.42×10^{-16}	
	27-32	Gr. Sha.	ND	0	Impermeable	ND	
6	2-7	Gr. L. Sha.	37.46	10.2	Wash Out	3.16×10^{-14}	Unconsolidated layers thickness from ground surface: 1 m.
	7-12	Gr. L. Sha.	60.67	19.8	Wash Out	5.61×10^{-14}	
	12-17	Gr. L. Sha.	58.09	5	Laminar	1.54×10^{-15}	
	17-22	Gr. L. Sha.	51.96	5.4	Wash Out	1.6×10^{-14}	
	22-27	Gr. L. Sha.	31.26	8.4	Void Filling	2.45×10^{-14}	
	27-32	Gr. L. Sha.	ND	0	Impermeable	ND	
	32-35	Gr. L. Sha.	ND	0	Impermeable	ND	
11	3-8	Gr. L. Sha.	49.22	0.4	Impermeable	4.22×10^{-16}	Unconsolidated layers thickness from ground surface: 2 m.
	8-13	Gr. L. Sha.	76.82	4.3	Void Filling	1.21×10^{-14}	
	13-18	Gr. L. Sha.	57.19	2.2	Wash Out	6.35×10^{-15}	
	18-23	Gr. L. Sha.	47.96	0	Impermeable	1×10^{-16}	
	23-28	Gr. L. Sha.	76.96	0.8	Impermeable	2.4×10^{-15}	
	28-33	Gr. L. Sha.	14	0.3	Impermeable	8.77×10^{-16}	

[1] Water absorption measured in l/m of test-stage per minute at a pressure of 10 kg/cm^2
[2] According to Houlsby (1990) suggestions
[3] l/s m^2 of borehole test surface
[4] Gray Shale
[5] No data because of operational errors and/or instrumental failures
[6] Including alluvium layer and weathered horizon
[7] Gray Limy Shale

Tab. 4 - The results obtained during field studies and observations

increase in Class C and Class D, while the Class A is still the major rock mass type (Fig. 4).

Deep level: includes boreholes sections deeper than 30 meters, where the rock mass is not weathered. Therefore, the Class C and Class D rock mass types are absent and Class A is the majority. However, Class B is present, maybe due to existence of some permeable fissures (Fig. 4).

The relationship between RQD and SPI values

Generally, the SPI is directly proportional to the rock mass fractures intensity. In other words, it is expected that the SPI increase as the RQD values decrease. However, areas with low SPI values (Class A and Class B), and low RQD (Very Poor, and

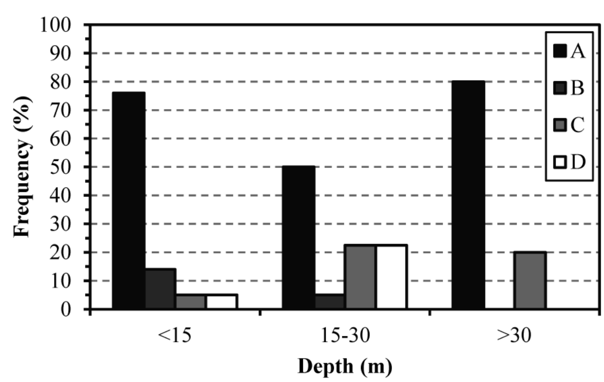
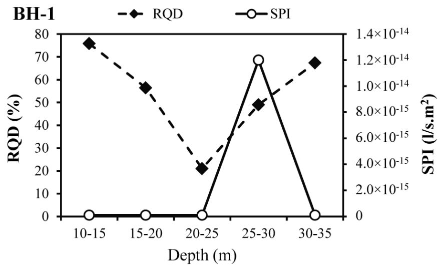
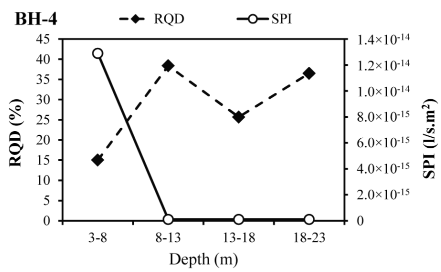


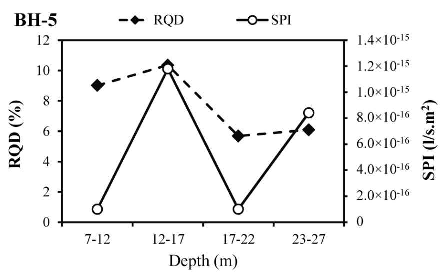
Fig. 4 - The boreholes depth-SPI relationship in the Shitab Dam basement and abutments



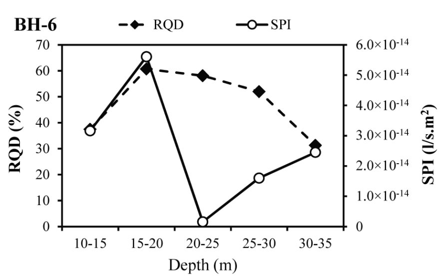
A- The RQD and SPI-depth plot in BH-1



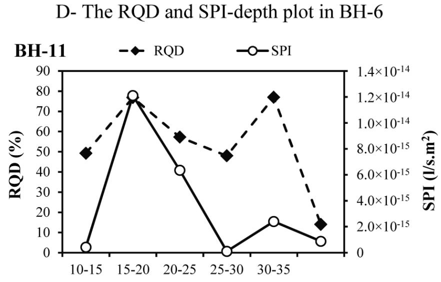
B- The RQD and SPI-depth plot in BH-4



C- The RQD and SPI-depth plot in BH-5



D- The RQD and SPI-depth plot in BH-6



E- The RQD and SPI-depth plot in BH-11

Fig. 5 - The RQD-depth and SPI-depth plots for boreholes in Shitab Dam site

Poor) may be because of high inter-locked fractures intensity. The hydraulic conductivity of such a rock mass is very low and ground treatment is needless. It may happen in shaly or schisty rock masses. Hereafter, we name areas with these sorts of properties as "Type Z" in this research. Regarding the information in tables 2, 3 and 4, the relationship between RQD values and SPI classes in the studied boreholes are as follows.

Borehole 1 (BH-1): The SPI and RQD variations of the BH-1 plotted as a function of depth (Fig. 5A). It is clear that the SPI is very low (Class A), but RQD is Good in shallow parts (10-15 m deep). Therefore, there is no need for ground treatment in shallow parts of the BH-1. In deeper parts of the BH-1 (15-20 and 30-35 m), the SPI is Class A but the RQD is at Medium (Fig. 5A). This means that there are few fractures with wide aperture size, and then thick mix of grout is needed for ground treatment procedure. The Class A SPI and Poor RQD at depths between 20-25 meters revealed a Type Z section. In depths 25-30 meters, the Class D SPI and Poor RQD might be resulted by few fractures with wide aperture size. Under this condition, it is necessary to treat the ground using thick grout mixtures.

Borehole 4 (BH-4): The SPI and RQD variations of the BH-4 plotted as a function of depth (Fig. 5B). In depths 3-8 meters, the Class D SPI and Very Poor RQD suggest that the ground treatment is extremely needed. Furthermore, the Class A SPI and Poor RQD in other parts of the BH-4 may be because of Type Z rock mass, where ground treatment is needless.

Borehole 5 (BH-5): The Class C SPI in depths between 17 to 22 m (Fig. 5C), where the RQD is Very Poor, indicates that the ground treatment must be conducted using thin grout mix. The Class A SPIs and Very Poor RQDs in other sections of the BH-5 suggest the existence of Type Z rock mass.

Borehole 6 (BH-6): The Very Poor and Poor RQDs, and Class A SPI values in BH-6 in depths 2-7 and 22-27 meters (Fig. 5D) show that there are Type Z rock mass where ground treatment is needless. The Class A SPI and Medium RQD at depths between 12 to 22 meters represent that ground must treated by using medium mix grout. The SPIs are Class B and RQDs are Poor and Medium in other sections of the BH-6 (2-12 and 22-27 m). Therefore, although they are not in the ranges determined for Type Z rock mass, they are very close and ground treatment shall be conducted in very local scale by using medium to thin grout.

Borehole 11 (BH-11): The Class A SPIs, and Very Poor and Poor RQDs in depths 3-8 and 28-33 m reveal the Type Z rock mass (Fig. 5E). The Class A SPI and Good RQD at depths between 8 to 13 m suggests that there might be very few fractures but with wide apertures. Under this condition, it is necessary to conduct the ground treatment procedure by using thick mix grout. In other parts of the BH-11, there is no specific relationship between RQD and SPI values.

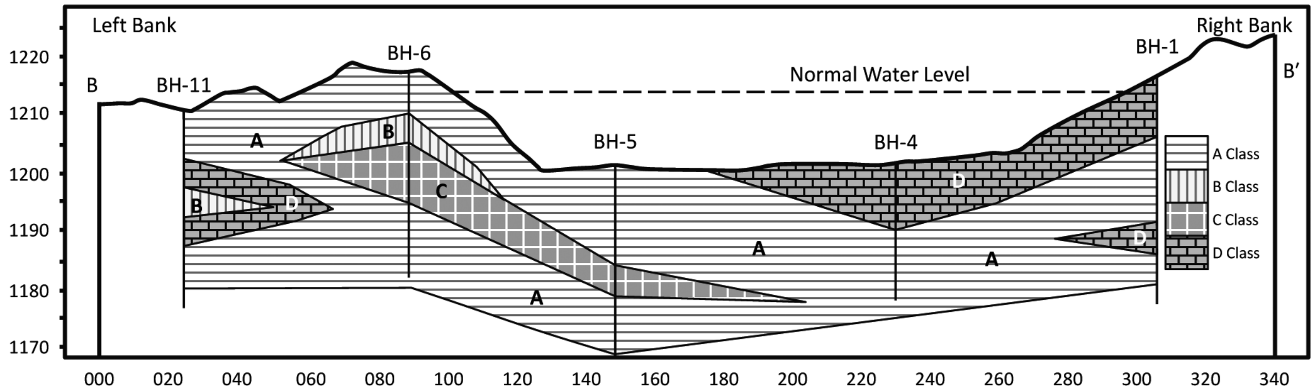


Fig. 6 - The grout curtain pattern designed for the Shitab Dam site

Ground treatment

Regarding the rock mass RQD and SPI specifications of the boreholes, the ground treatment designed (Fig. 6). The results imply that ground treatment in A Class areas of the Shitab Dam site is needless. The ground treatment in areas classified as B Class is necessary locally with regard to RQD values and jointing level. The ground treatment in C and D Class areas is extremely necessary (Fig. 6). The figure 6 reveals that:

Generally, the ground treatment is needless in areas deeper than 30 meters. This is due to that the rock mass is not altered by weathering processes in deeper zones.

The grout curtain is necessary in surficial shallow zones (<13 m) of BH-1 and BH-4.

Considering the SPI and RQD values in BH-11, ground treatment is necessary in depths between 8 to 13 meters by using thin mixed grout.

Finally, the ground treatment must be oriented in a triangular pattern grout curtain with 6 and 9 meters spacing respectively in low and high permeability rock masses. However, alternate rows of grouting might be needed according to future test boreholes, unless the optimal rock mass characteristics' are achieved.

CONCLUSION

The results imply that the ground treatment is necessary in Shitab Dam site, especially in shallow parts (<15 m deep). Additionally, the grout curtain is needless within rock mass deeper than 20 m. The SPI-RQD plots revealed almost a 60 percent correlation between secondary permeability index and RQD values. Accordingly, the grout curtain pattern designed based upon field observations, Lugeon tests data, SPI, and RQD estimations in shallow zones.

To conclude, the analysis of the boreholes revealed a great complexity in engineering characteristics of the Shitab Dam site rock mass, especially at shallow zones. Although the rock mass lithology is very simple, mechanical weathering processes have altered the shallow rocks in arid zones. Consequently, the rock mass heterogeneity from the engineering view point is likely to be very high. This study shows that a multi-parameter decision making approach is essential to design the ground treatment strategy, even where the lithologic complexity is minimum. In other words, considering the in-situ tests carried out in Shitab Dam site, it is apparent that one cannot delimit the field observations with regard to the geologic features simplicity.

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