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Research paper

Evaluating permeability and groutability of Souk Tleta dam site based on Lugeon tests, RQD, SPI and trial grouting

Ryma Afiri [a,b,*], *Smail Gabi* [a,b], *Karima Bouzelha* [b], *Rachid Tabou* [c]

[a] *Geomaterials, Environment and Development Laboratory, Mouloud Mammeri University, Tizi Ouzou, Algeria*

[b] *Department of Civil Engineering, Mouloud Mammeri University, Tizi Ouzou, Algeria*

[c] *Tractebel - ENGIE Group, France*

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ABSTRACT

This study is conducted mainly to evaluate the permeability and the groutability at Souk Tleta dam site. It is an embankment dam with a height of 95 m and a crest length of 200m located in the Tizi-Ouzou province in Northern Algeria. The foundation of the dam consists of thick deposits of pervious alluvium of about 21 m and Burdigalian sandstone formations. The main problem of this dam is that the bedding plains of Burdigalian sandstone in the dam site are parallel to the flow direction. To conduct this study, permeability of formations is evaluated by Lugeon test and secondary permeability index. Rock quality is evaluated by geological assessment and RQD values. Results indicate that the overall permeability of the foundation rock mass before trial grouting in more than 54% of the Lugeon tests is high and requires treatment. To investigate effect of grouting in reducing permeability of rock mass and to evaluate the grout take in rock masses, two trial grouting programs are carried out on dam foundation and left abutment of dam site up to maximum depths of 70 m and 67 m, respectively.

1 Introduction

Dams have been constructed for thousands of years to control floods, produce hydroelectricity, provide drinking water, supply industry, and irrigate agricultural fields. A large number of dams were built as populations increased and national economies grew. Dams are among the most complex and sensitive artificial civil engineering structures, both in terms of project design and construction. The safety of such structures depends largely on their foundations stability, which requires a detailed geological study.

There are some well-known worldwide dam failures due to lack of geological and engineering geological information on dam site. For instance the Malpasset dam which remains a textbook case collapsed in 1959 due to existence of a low shear

* *Corresponding author. Tel.: +213 665651963.*
E-mail address: r.afiri@hotmail.fr

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strength zone in the left abutment associated with excessive water pressure on discontinuities [1, 2]. The Teton earth dam was located on fissured rhyolite abutments allowed water to seep around dam led to internal erosion that eventually caused the dam's collapse in 1976 [3]; and the Austin dam was constructed on porous sedimentary rock, where heavy seepage had taken place through the porous material caused the failure of the dam in 1911 [2, 4]. Dam failure episodes also occurred due to internal erosion problems [5-7], to poor quality of the foundation rock and / or lack of information on the latter [8] and because of seepage problems [9]. In Algeria, the Fergoug dam has experienced numerous failures over the past years. The dam failed in 1881due weaknesses in rock formation of right abutment composed of an alternation of sandstone and clay with a strong dip toward downstream [10]. The landslide of the right abutment caused the failure of Cheurfa dam in 1885, where weaknesses in the foundation, unidentified at design step are at issue.

The geological complexity of the foundation rocks, in particular in certain sites involving fault and fracture zones, and the presence of fragile intermediate layers is an important issue for large-scale projects where permeability is one of the most difficult parameters to study [11-13]. The evaluation of the geological and geotechnical properties of dam sites has always attracted the attention of many researchers to understand the behaviour of the rock at different filling levels of the dam [14]. Failures due to water seepage is the most common failure cause, when the retained water seeks paths through the dam, foundations and banks of the dam; they represent 30% of total failures [15].

The problems of seepage through the foundations of a dam and its considerable effects depend on the rock conditions (geological, geotechnical and hydrogeological). Uromeihy et al. [16] studied the effect of the geological properties of the rock foundation on seepage problems at the Kamal-Saleh dam. Hu and Ma [15] conducted a case study to solve seepage problems through the dam foundations where the cause of seepage is due to outcrops of permeable Neogene conglomerates in both abutments. On the other hand, Barzegari [17] evaluated the permeability of a dam rock mass foundation based on water pressure tests (Lugeon test) results and secondary permeability index (SPI) proposed by Foyo [18]. Therefore, to improve the safety of these hydraulic projects when their rock foundations are cracked, their permeability should be decreased by using methods such as grout injection [19].

Since every dam foundation is unique, geological and geotechnical investigations on dam sites, namely, permeability measurements rock mass quality assessment, seepage control, grouting process study as well as treatment of foundation were the main subjects that caught the attention of researchers. Uromeihy et al [20] and Sissakian et al [21] studied respectively the geological properties and the problem of foundation seepage of Chapar-Abad and Mosul Dams, composed mainly and respectively of limestone and gypsum-limestone. Similarly, Barzegari [17] evaluated the geotechnical characteristics of the fractured basaltic andesite of the Peygham-chay dam rock foundation by emphasizing on its permeability. Based on foundation rock quality and Lugeon tests results, Azimian et Ajalloeian [22] assessed the permeability and the groutability of conglomerates of the Nargesi dam. Khaleghi Esfahani et al [23] studied a dam Axis Selection on Soft Rocks Based on Geomechanical Characteristics; permeability and quality (RQD) of the rock mass. Wang et al. [24]; Ye et al. [25]; Gao et al [19] used methods such as grouting to decrease the permeability of the fractured rocks and to improve the safety of a dam when cracks in the rock mass foundation and abutments occurred. For their part, Rastegar Nia et al. [26] assessed the relationship between the calculated grout values from rock mass properties and the Grouted Values in the Bazoft Dam Site composed mainly of marly limestone and limestone ; the results show that grout takes can be predicted based on the calculated grout values. On the other hand, Høien and Nilsen [27] argued that complex geological conditions contribute to the unpredictability of the grouting process, hence the need for grouting tests.

In this paper, we are interested by evaluation of permeability and groutability at Souk Tleta dam site located in Tizi-Ouzou department (Algeria).This dam is found on a sedimentary formation composed mainly of a large part of weathered sandstone, interstratified with thinly cemented conglomerates. One of the main problems with these sandstones is that the orientation of their sedimentation is parallel to the direction of the river flow; creating potential flow path that could threaten the dam stability. In this regard, and taking into consideration this complex geological structure of the sandstones of the study region, a detailed evaluation of the geological characteristics of the rock masses exposed on the dam site is necessary to assess its permeability and to consider sealing solutions. The permeability of rock masses is determined and analyzed using data from 148 Lugeon water pressure tests in 23 boreholes of different diameters. In addition, by providing RQD (Rock Quality Designation) obtained from the exploratory investigation boreholes, considerable information on the rock mass quality are specified, and then a detailed mapping of the proposed treatment using the secondary permeability index is established.

The secondary permeability index (SPI) proposed by Foyo et al. [18] resulting from the conversion of the water pressure test into permeability, allows defining fissured rock mass quality according to different quality classes and determine different aspects concerning ground treatment.

To predict and assess the efficiency of grouting process in reducing permeability, it is essential to carry out a trial grouting survey before grout curtain and dam construction. The aim of the trial grouting is to compare the ratio of permeability before and after grouting, and to provide excellent information about grout take for each injection stage. In this way, maximum spacing between grout boreholes and injection pressure can be estimated, the permeability is measured before and after grouting tests, and the results will be discussed and compared in this study.

2 Dam Location and Geological Characteristics of Dam Site

The Souk Tleta earth dam is an embankment dam with a central impermeable clay core located at the confluence of two rivers, 20 km west of the Tizi-Ouzou province in Northern Algeria (Fig.1). At the dam site, the river Bougdoura flows northward from the south. The purpose of the dam is to provide water supply for domestic uses and irrigation. The dam is under construction since 2014. It will be constructed with a crest length of about 200 m, a height of 95 m at the highest section above the riverbed level, and a storage capacity of almost 96 x 106 m3 at the normal water level [28].

The dam is situated in a valley with a moderate steep on the right abutment, with slopes of about 35° and a steep on the left abutment with a slope of almost 51°. The dam and its reservoir area are located on the southern edge of the Miocene sedimentary basin of Tizi-Ouzou.

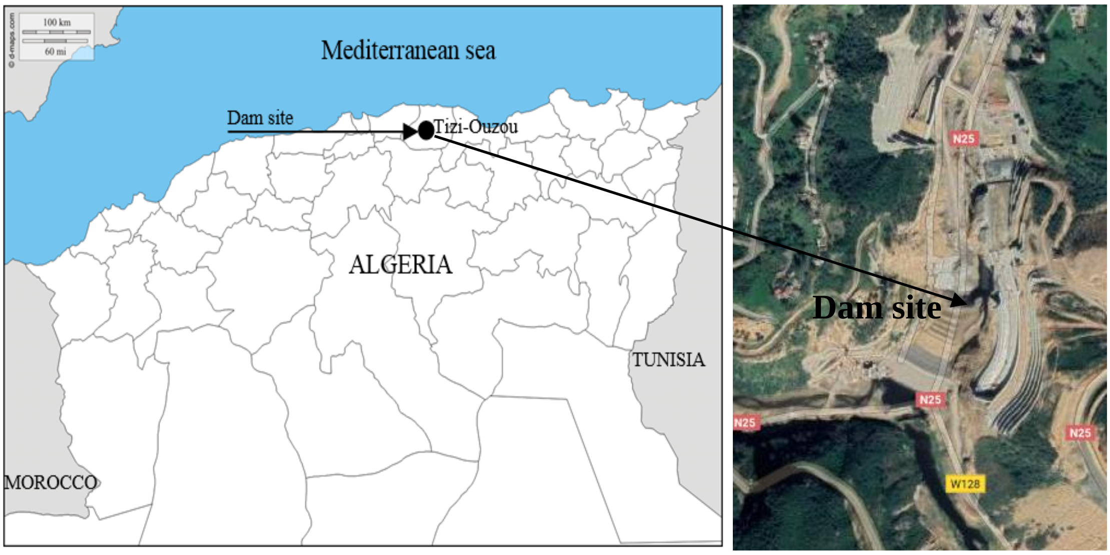
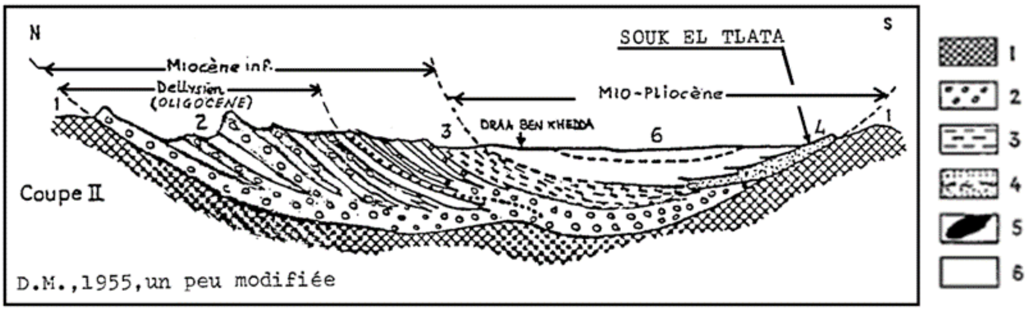


Fig. 1 – Location of Souk Tleta earth Dam

An understanding of the regional geological aspect of where the dam is located is essential to the grouting design of the dam foundation. In the study area, two main geological units can be distinguished: quaternary deposits and sedimentary rocks of the Mio-Pliocene formation. The geological map of the study and the surrounding area is shown in Fig. 2.

The quaternary formations are deposits of the riverbed; it covers a large portion of the area. It is composed of riverbed alluvial deposit, colluvium and talus materials. The thickness of the alluvial deposits in the dam area is changing and has reached a thickness of about 21 m, as indicated by drillings.

The Miocene unit is mainly characterized by Burdigalian sandstone and forms the foundation of the dam (Fig.2 and Fig. 3). It is composed of sandstone with interlayers of conglomerate, siltstone and shale. The conglomerate formation is exposed in a large part of the left abutment. The conglomerate formation is overlain by thickly bedded, relatively homogeneous Burdigalian sandstone stratified in layers. The sandstones are exposed on both the right and left abutments of the dam site with a thickness of about 40 m and 70 m, respectively. The layers dip toward the north according to the flow direction of the river, with a dip of 15° to 20°. The conglomerate is covered with quaternary deposit in the riverbed.



1.Pre-Miocene . 2. Lower Miocene. With "dellysien"facies

3.Lower Miocene with marl highly calcareous. 4.Mio-Pliocene.

5. Eruptive 6. Plio-Quaternary.

Fig. 2 – Dam site geological map (Dame. and Magné) [29]

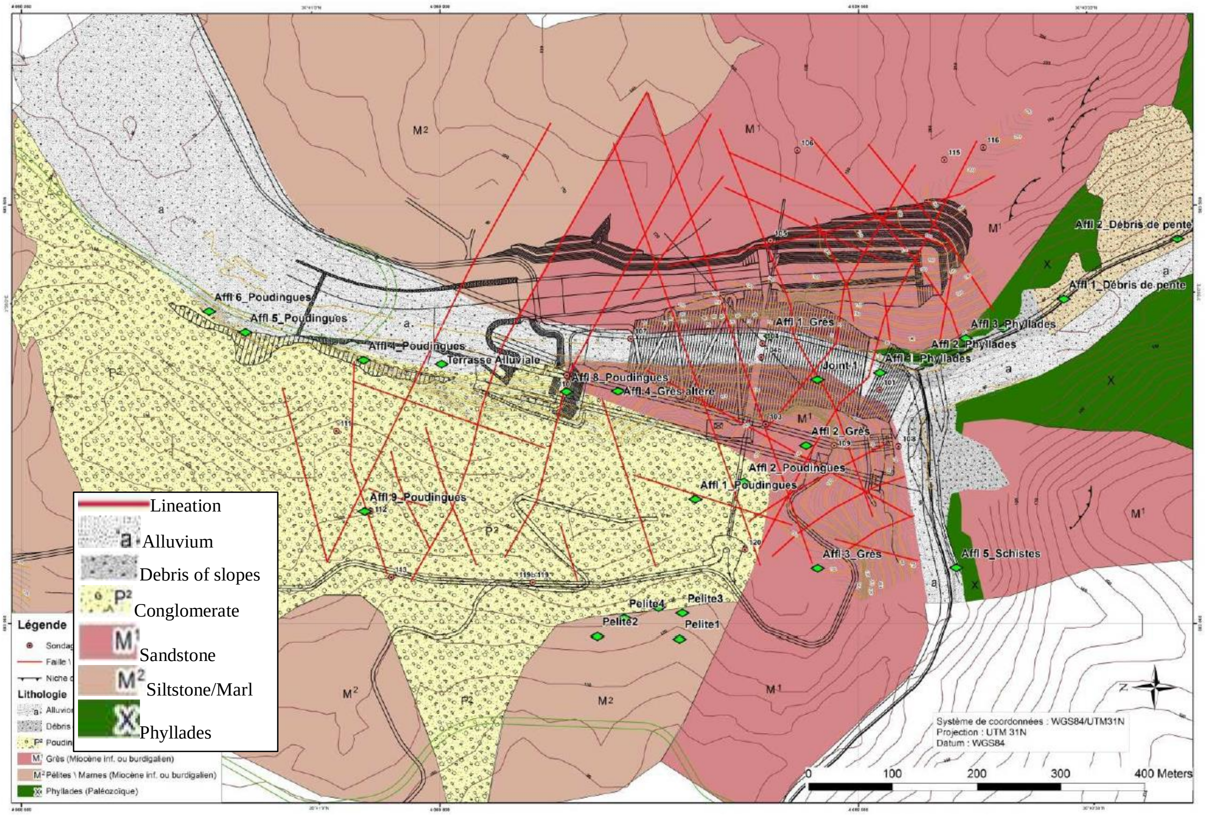


Fig. 3 – Lithofacies outcrops extension in the dam site ANB [30]

3 Rock Quality Designation (RQD)

Geotechnical investigations were entrusted to Geotechnica Brazil and Geomag laboratories. During the drilling process, sampling and water pressure tests (WPTs) were conducted, and RQD values were measured ASTM D6032 / D6032M-17 [31] from 23 boreholes drilled in different parts of the dam site (Fig.4). However, only 15 drill holes have been selected for study in detail (Table 1).

RQD is perhaps the most commonly used parameter for evaluating the degree of fracture in a rock mass. RQD was proposed by Deere [32] as a measure of quality of borehole core. RQD is defined as the percentage of the sum of the length of the core pieces longer than 10 cm to the total core run length [33] as Equation (1). The relationship between RQD and engineering quality of rock mass, as proposed by Deere et al [34], is very poor ($0 < RQD \leq 25$), poor ($25 < RQD \leq 50$), medium (50 < RQD ≤ 75), good (75 < RQD ≤ 90) and very good (90 < RQD ≤ 100). Low RQD will be improved by grouting when the grout is injected, it penetrates into rock mass discontinuities; therefore the cracks are sealed and RQD is increased.

$$RQD = \frac{Length\ (L) of\ core\ pieces > 10cm\ length}{Total\ length\ of\ core\ run} * 100 \quad (1)$$

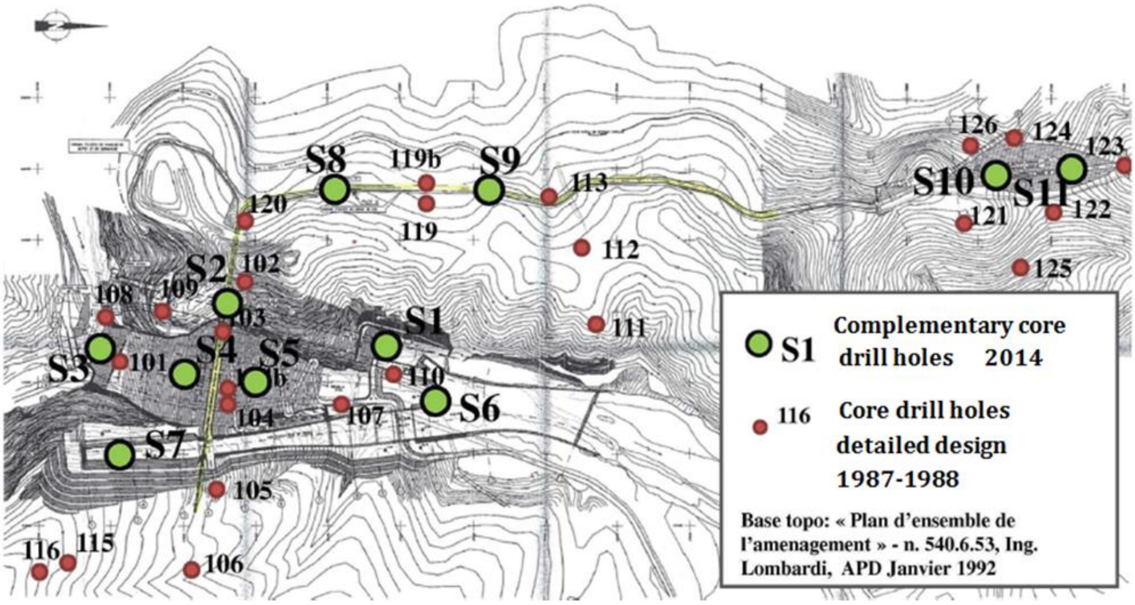


Fig. 4 – Plan view of the boreholes position in the Souk Tleta dam site ANB [35]

Fig. 5 illustrates the distribution of mean RQD records in different parts of the Souk Tleta dam site. The rock quality assessment of the dam site shows that the rock quality of the right abutment is remarkably higher in comparison with the quality of the dam foundation and the left abutment rock formations. As presented in Fig.5, most of the RQD values in left abutment and dam foundation are 25 < RQD ≤50 and RQD<25% which indicate poor and very poor quality. In contrary, this condition is different in right abutment because most RQD values are 50 < RQD≤75, 75 < RQD ≤ 90 and RQD > 90 which indicate medium, good and very good quality, respectively.

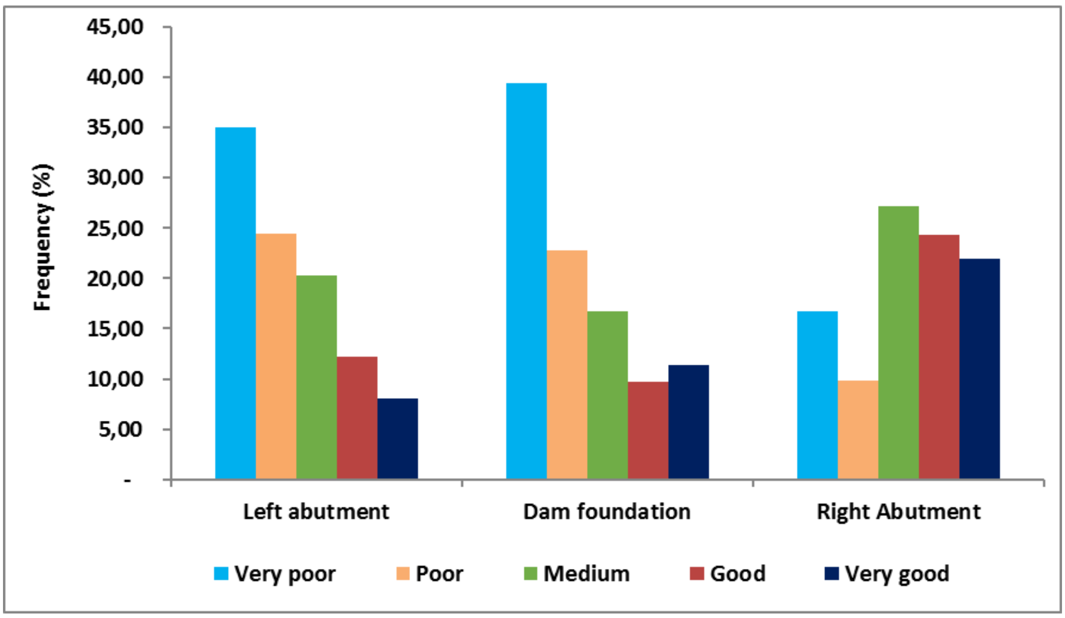


Fig. 5 – Variation in average RQD records with rock quality and position of borehole study

4 Water Pressure Tests (WPT)

The permeability dam rock foundation is usually investigated by means of water pressure tests or Lugeon tests [36]. The main purpose of these water pressure tests is to determine the "Lugeon coefficient" [37]; the water absorption is measured in liters per meter of test per minute at a pressure of 10kg/cm², equation (2). Existing standards on the Lugeon test ASTM D4630-96 2008 [38] and ISO 22282-3 2012 [39] describe terms, definitions, symbols and units used in the test, as well as the test preparation and procedures.

$$Lu = \frac{10\,Q}{Pe\,L} \qquad \mathrm{L/m/min} \tag{2}$$

Where Q is the flow rate (L/min), L is the length of the test section and Pe is the effective pressure in the test segment (bar). The maximum pressure applied in the dam foundation packer tests is 10 bars. Lugeon values on the Souk Tleta dam rock foundation can be categorized in accordance with Houlsby [40] classification in four scales ($Lu < 3$ as very low permeability; $3 < Lu<10$ as low permeability; $10 < Lu<30$ as medium permeability and $Lu > 30$ as high permeability).

The water pressure tests are the only practical method of investigating the permeability of a rock mass, and they generally help ascertain whether grouting works are necessary. Houlsby [40] suggests that when the LU values are below three, no grouting is necessary; when they are between three and ten; a single row of grouting holes is required, while with values over 10, a grout curtain should include three rows of grouting holes.

In this study, 109 WPTs from 148 WPTs have been are considered to investigate the permeability of rock masses in the Souk Tleta dam site. The results of WPTs are presented in table 1 and Fig. 6. Results indicate that 47% of the measured permeability is less than 3 Lu and 25% is concentrated in the range 3-10 Lu, however 15% are more than 30 Lu and 13% is concentrated in the range 10-30 Lu which correspond to high permeability.

Table 1 – Excavated Boreholes details and summary of Lugeon and RQD results on different rock units at Souk Tleta dam site

Borehole			Depth (m)			Permeability (Lugeon)				RQD (%)			
Borehole N°	**Orientation**	**Position**	**Total**	**Quaternary deposit**	**Rock mass**	**Number of tests**	**Min**	**Max**	**Average**	**Number of tests**	**Min**	**Max**	**Average**
BH102	Vertical	Left bank	145.0	2.50	142.50	12	0.73	45.21	16.73	89	0	100	32.08
BH103	Vertical	Left bank	116.0	3.30	112.70	16	0.79	34.78	5.92	66	0	100	46.58
BH108	Horizontal	Left bank	40.0	0.00	40.00	4	1.00	90.13	21.43	31	0	100	31.26
BH109	Vertical	Left bank	100.0	0.00	100.00	10	0.58	66.15	12.58	83	0	100	47.75
BH110	Vertical	Left bank	25.0	1.70	23.30	3	0	104.40	45.35	20	0	100	51.30
BH113	Vertical	Left bank	25.0	10.18	14.82	2	0.16	2.00	1.15	1	18	18	18.00
BH120	Vertical	Left bank	35.0	4.07	30.93	4	0	42.77	15.39	29	0	95	63.62
BHSC1	Vertical	Left bank	30.3	6.50	23.80	2	0	16.04	6.84	10	67	100	89.80
BHSC2	Vertical	Left bank	80.0	0.00	80.00	10	0.23	98.75	11.74	32	17	100	74.47
BH101	Vertical	River Bed	50.0	17.10	32.90	4	1.06	22.96	11.67	16	0	34	7.56
BH104	Vertical	River Bed	60.0	18.00	42.00	5	1.00	5.00	1.88	28	0	50	19.68
BH107	Vertical	River Bed	78.0	21.10	56.90	11	0.95	17.82	5.57	44	12	100	71.39
BH105	Vertical	Right bank	105.0	1.00	104.00	13	1.61	101.53	25.95	72	0	100	55.57
BH106	Vertical	Right bank	100.0	3.00	97.00	9	0.20	7.18	2.54	50	0	100	61.92
BHSC7	Vertical	Right bank	54.5	0.00	54.50	4	0.17	4.00	1.64	28	1	100	65.57

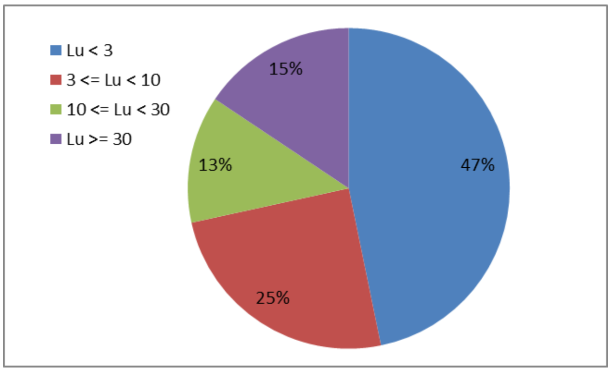


Fig. 6 – Variation of measured Lugeon values on Souk Tleta dam

5 Alteration and Permeability

5.1 Right Abutment

On the right abutment, a total of 26 WPTs were carried out in three boreholes to determine the permeability in the rock mass of this part, including sandstone and conglomerate formations.

In this side, approximately 22% of the sections have an RQD more than 90 and 17% have an RQD less than 25, which places them respectively, in the “Very Good” and “Very Poor” classes (Fig.5). In addition, 54% of the sections are present in a rock with “Very Low” permeability, which indicates that there is no need for ground treatment (Fig. 7). Moreover, 23% of the sections are present in areas with “Low” permeability and approximately 23% show “Medium” to“High” permeability, especially, in BH105. In general, in this abutment, except for BH105, permeability decreased with increasing depth. The test sections with high permeability (such as in section 46–50 m in BH105) showed a sub-vertical fracture and altered sandstone was present. In depth (14–17 m and 27–30 m), a high permeability should be noted, as they indicated the presence of numerous joints in sandstone formation.

5.2 Dam foundation

Along the dam axis, 20 WPTs were carried out in three boreholes to determine the permeability of the dam foundation. In this zone, about 39% and 23% of the sections, respectively, showed an RQD less than 25 and 25<RQD<50, which corresponds to “Very Poor” and “Poor” classes, whereas approximately 10% and 11% of the tested sections were classified under “Good” and “Very Good” classes, respectively (Fig. 5). After taking the RQD variation as a function of depth into consideration, the overall results are found to suggest that increase in depth does not lead to better quality. Poor quality and low permeability of rock formation are observed, especially, in BH101 and BH107 owing to the presence of an important layer of laminated shale formation (a layer thickness of 25 m in BH101).

Figure 7 shows that 60% of the Lugeon results are very low and 25% are low i.e. 85% of permeability results are from very low to low. In the other hand figure 5 shows that 39% of very poor quality and 23% of poor quality, i.e. 62% of RQD results are from very poor to poor quality. This can be attributed to plains of sandstone formation in riverbed that are parallel to flow direction of the river. With time and under high water pressure, preferential infiltration pathways can be created in sandstone formation and weaken its stability. Fifteen percent of tested sections show medium permeability (Fig. 7). These high Lugeon values are caused by alteration of sandstone formation in the riverbed.

5.3 Left abutment

On the left abutment of the Souk Tleta dam, 63 WPTs were performed in nine boreholes to determine the permeability of the rock mass formation. The alteration of the formations crossed during drilling reaches a significant depth (70m) in the left abutment, while in dam foundation 40m and in right abutment 10m. On the left bank we find the outcrop of sandstone, conglomerates; and in depth, an alternation of several formations hence the need to carry out several WPT tests to measure the permeability along the stratigraphic contacts between the different formations.

In this abutment, 35% and slightly more than 24% of the sections have RQD values of less than 25 and 25 RQD<50 respectively, which fall under the "Very poor" and "Poor" classes. Further, more than 20% and 12% of the sections fall under the "Medium" and "Good" classes, respectively; and only 8% fall under the "Very good" class (Fig. 5). Based on the RQD values, the left abutment of the dam is categorized as "Poor". In altered sandstone, 80% of the tests indicated that RQD values were less than 50, which represents the "Poor" and "Very poor" classes. In the unaltered sandstone formation, 61% of the sections present high RQD values and are classified as "Good" and "Very good", whereas 27% are categorized as "Medium" to "Good", owing to the intercalation of siltstone. These layers considerably reduce the quality of the formation.

In a majority of the tests conducted using a WPT in this abutment, there is an accurate correlation between the rock mass quality defined in the RQD results and permeability (Fig. 5 and Fig. 7). Moreover, when the Lu values were gauged, almost 40% of the borehole sections in the left abutment indicated Lu values less than 3. The higher values, 14% and 21% respectively, indicate the characteristics medium permeable ($10 \leq Lu < 30$) and high permeable ($Lu > 30$), which may be related to the rate of weathering of the sandstone unit and its lithology, as well as the weak cementation of the conglomerate rock unit.

It is noticed that the permeability rises in low-quality rock masses. The high Lugeon values in BH110 and BH102 were recorded. This is due to the high-jointed rock masses and the presence of discontinuities. As most RQD values ranged from "Very poor" to "Poor", high Lu values were observed. In general, this abutment shows a correlation between permeability and depth, and indicates a reduction in permeability with increasing depth.

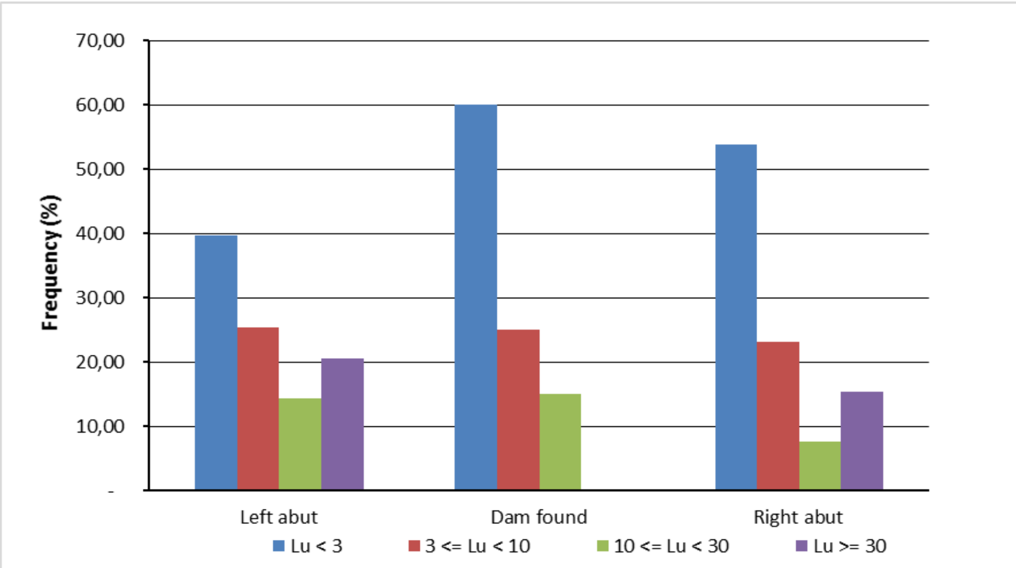


Fig. 7 – Permeability of rock masses (Lugeon values)

The investigation of water pressure tests' results in all boreholes revealed that the permeability of rock mass increases from the right abutment toward the left abutment of the dam. This could be caused by the degree of weathering and fracturing experienced by rock masses and the weak cemented sandstone. The assessment of RQD [29] values in the right and left abutments and in the dam foundation further showed that the RQD values were mostly poor and medium.

As presented in Fig. 5, most of the RQD values along the dam axis were <50, indicating the poor quality of rock masses. The rock quality of right abutment was found to be slightly higher in comparison to the quality of the river bed foundation and left abutment.

6 Secondary Permeability Index (SPI)

To better identify the permeability, and provide a good evaluation of the permeable left bank rock mass and understand its groutability, secondary permeability index (SPI) was calculated.

Foyo [18] proposed the secondary permeability index as a modified form of Lugeon relation (ASTM D4630-96 2008 and ISO 22282-3 2012) which combined a modified form of Lugeon relationship with the radial permeability of a rock mass, as well as the geometry of the borehole (radius); to propose a new equation giving a value closer to the permeability coefficient than that of the Lugeon relation. It describes and estimates the permeability of the jointed rocks. Therefore, the SPI is defined as follows Equation (3):

$$SPI = C \times \frac{\ln(\frac{2Le}{r}+1)}{2\pi Le} \times \frac{Q}{H\,.\,t} \quad (3)$$

Where: SPI is the Secondary Permeability Index, (l/s per m2);

C is a constant coefficient which is $1{,}49.10^{-10}$ that depends on the fluid viscosity in a rock at 10 °C [41],

Le is the length of the tested borehole segment (m),

r is borehole radius (m),

q is water take in tested section (L),

H is total applied pressure expressed as water column (m),

t is the time of each pressure step (s).

The SPI was calculated at 5 m intervals; rocks are classified into four groups, an excerpt of SPI results is shown in Table 2.

Table 2 – Excerpt of SPI results of the left abutment

Borehole no	Depth		SPI class	SPI (l / s*m²)	Classification
	From	To			
BH102	50	55	C	1.4641E-12	Poor
	55	60	D	1.9880E-12	Very poor
	54	60	B	1.4398E-13	Good-fair
	60	65	B	3.7110E-14	Good-fair
	70	75	C	9.0205E-13	Poor
	75	80	C	2.1032E-13	Poor
	80	85	C	2.2518E-13	Poor
	85	90	C	6.2822E-13	Poor
	95	100	B	1.4946E-13	Good-fair
	100	105	C	5.8706E-13	Poor
	105	110	C	6.6355E-13	Poor
	110	115	C	7.0155E-13	Poor
	120	125	C	2.0697E-13	Poor
	135	141	B	3.9497E-14	Good-fair
BH109	10	15	C	1.4607E-12	Poor
	15	20	B	5.5708E-14	Good-fair
	30	35	C	8.0814E-13	Poor
	40	45	C	2.2559E-13	Poor
	45	50	B	5.4501E-14	Good-fair
	65	70	C	6.4844E-13	Poor
	75	80	A	1.2909E-14	Excellent
	80	85	A	1.9558E-14	Excellent
	85	90	A	1.6820E-14	Excellent
	90	95	A	1.2517E-14	Excellent
	95	100	A	1.4082E-14	Excellent
BH 120	10	15	C	1.4581E-12	Poor
	15	120	C	8.8181E-13	Poor
	20	25	C	8.3647E-13	Poor
	25	30	C	9.0319E-13	Poor
	30	35	A	1.9454E-14	Excellent

Using the classification given by Foyo [18] (Table 3), analysis of the SPI values was carried out by class in left bank. The results are given in percentage in Table 3. Based on calculated SPI values (table 2 and table 3) for each tested section and Foyo classification [18], we have realized a detailed mapping of rock quality and the treatment to be proposed for the left abutment (Fig. 8).

Table 3 – Rock mass classification based on the SPI and ground treatment considerations and left abutment SPI results of Souk Tleta dam.

Secondary Permeability Index (l/s m²)	SPI ≤ 2.16× 10^{-14}	2.16×10^{-14} < SPI ≤ 1.72 × 10^{-13}	1.72×10^{-13} < SPI ≤ 1.72×10^{-12}	SPI > 1.72× 10^{-12}
SPI class	Class A	Class B	Class C	Class D
Classification	Excellent	Good-fair	Poor	Very poor
Ground treatment	Needless	Local	Required	Extensive
Equivalent lugeon value	≤1	1 - 8	>8	>80
Left abutment SPI results (%)	**10%**	**30%**	**50%**	**10%**

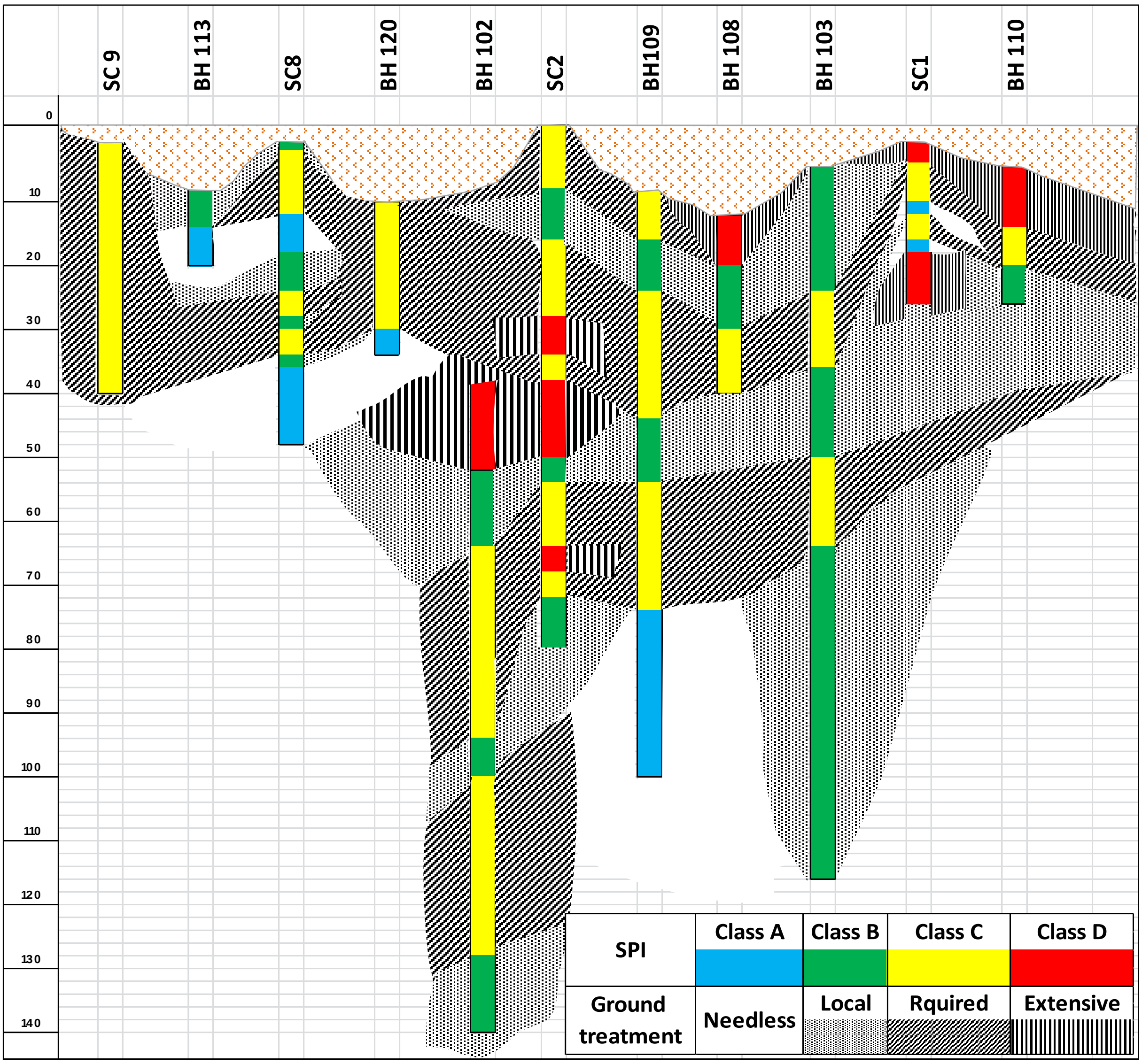


Fig. 8 – SPI Profile along the left abutment of Souk Tleta Dam

Based on the Foyo classification [18], SPI results are classified into four groups. SPI informs about rock quality [42, 18] and allows zoning respecting different quality classes and determining the required ground treatment.

Class A, SPI ≤ 2.16× 10-14 means that the rock section quality is excellent and considered as impervious (where) the water take is equal or less than 1Lu and a ground treatment is not needed.

Class B, 2.16×10-14 < SPI ≤ 1.72 × 10-13 signifies that the rock mass quality is classified as good-fair and greater water takes are recorded, greater then 1Lu and less than 8Lu; in this class, local ground treatment must be local.

Class C, 1.72×10-13 < SPI ≤ 1.72×10-12 poor rock quality, water takes greater than 8Lu and less than 80Lu are denoted, where the necessity of ground treatment.

Class D, permeability is SPI >1.72×10-12, the rock mass quality is very poor and its permeability is equivalent to over 80Lu. In this case, ground treatment must be extensive.

The rock mass permeability is largely affected by discontinuities; it is, therefore, evident that the rock quality indicator (RQD) has a direct relationship with SPI.

Among the four classes (Table 3), and based on observation of the foundation mapping (Fig. 8 and Fig. 9), it is noticed that left abutment rock mass is dominated by large portion (50%) of poor rock quality (class C) where ground treatment would be required. Ten percent (10%) of results are situated in zone of extensive ground treatment as they categorize as very poor quality (class D).

Indeed, in borehole BH102 and SC2, at depth 42-52m, the highest permeability (SPI) values are recorded, at the contact between conglomerate and sandstones formations. It is justified by an alteration at the contact of the two formation, observed during the drill core examination; hence the creation of preferential zones of infiltration.

At borehole BH103, the altered zone is fairly homogeneous and reaches a depth of 75 m. With 30% of the rock mass zoned as Class B (fair quality), local ground treatment is needed. Furthermore, only 10% of the left abutment is classified as Class A, requiring no ground treatment.

Fig. 9 – SPI classification at left bank of Souk Tleta dam foundation

A comparison of the SPI, Lu and RQD results is conducted (performed) in the left abutment. The SPI results and their corresponding Lu and RQD values are presented for two representative drillings in Table 4.

After examination of the Table 4, a comparison between SPI and the rock quality of eleven boreholes in the left abutment leads to an expected result; SPI and RQD are generally in correlation. However, there are rock sections with low RQD and low permeability and, conversely, sections with relatively high RQD and high permeability. For instance, in borehole BH103, the SPI in section (20-25m) is placed under Class C and high Lugeon values but shows a high RQD. This may be explained by the presence of a single large permeable feature such a deep minor fault zone; therefore, treatment is necessary. The section 70-75m of the same borehole is classified as very poor RQD, low SPI (class B) a low Lu value. This situation can be the attributed to the broken and irregular fractures caused by drilling.

Table 4 – Comparison of rock mass quality based on RQD, Lugeon and SPI

Borehole N°	Depth		RQD (%)			Lugeon value	SPI (l/s m²)	SPI class
	From	To	Min	Max	Mean			
BH102	50	55	0	71	22.38	258.89	1.464E-12	C
	54	60	37	79	50.5	4.08	1.440E-13	B
	60	65	0	89	40.6	1.11	3.711E-14	B
	70	75	17	56	30.66	45.21	9.021E-13	C
	75	80	34	75	57.33	5.62	2.103E-13	C
	80	85	0	54	24.75	6.87	2.252E-13	C
	85	90	0	51	20.75	32.26	6.282E-13	C
	95	100	44	80	60.75	4.77	1.495E-13	B
	100	105	0	36	23.8	31.21	5.871E-13	C
	105	110	0	54	30.5	31.04	6.635E-13	C
	110	115	9	54	33.75	35.37	7.016E-13	C
	120	125	0	47	35.16	17.20	2.070E-13	C
	135	141	0	61	30.11	0.73	3.950E-14	B
BH103	5	10	0	95	68.33	3.37	7.794E-14	B
	10	15	69	75	73	2.91	8.926E-14	B
	15	20	61	83	68.33	2.42	9.483E-14	B
	20	25	0	100	60	34.78	6.079E-13	C
	25	30	33	72	50	10.48	2.709E-13	C
	30	35	52	64	57.25	10.66	3.154E-13	C
	35	40	18	95	58.33	2.09	7.100E-14	B
	40	50	33	87	64.75	2.72	1.093E-13	B
	50	55	22	44	33	11.88	2.785E-13	C
	70	75	0	71	22.18	3.35	1.218E-13	B
	75	80	7	70	47	1.78	6.884E-14	B
	80	85	61	64	62.5	1.38	5.062E-14	B
	85	90	75	81	78	2.85	1.141E-13	B
	100	105	39	53	46	0.85	3.328E-14	B
	105	110	34	80	59.6	2.94	1.038E-13	B
	110	116	55	92	67	0.79	2.758E-14	B

The comparison of the calculated SPI and Lu values is carried out based on the classification proposed by Foyo [18]. We notice that although the results are far from perfect, they generally show a good agreement between the two parameters; the SPI classes to which the Lu values correspond confirm those mentioned by Foyo [18]. Minor variances, such as deviation and gaps, are observed and justified by the uncertainties arising during the measurements, especially in boreholes. Even though the boreholes are drilled deep enough (except some, because of the instability of these boreholes against collapsing) during the geological investigation, satisfactory founding quality conditions have not been encountered. At the bottom of deep boreholes, we expected to reach a very good quality of rock mass which does not require treatment class A (BH102 reaches 140m and SC02 reaches 80m), but class C is the most dominant class (Fig. 8) and deemed to require ground treatment.

We conclude that RQD alone is not enough to identify the characteristics of a rock (sandstone).A combination with SPI and a comparison of the two parameters can be indicative element to decide on the permeability of sandstone joints as well as its groutability. In order to treat sections with high RQD and high SPI (such as 20-25m in BH103) and sections with low RQD, low SPI (such as 70-75m in BH103) special considerations should be taken by giving due consideration to discontinuity parameters that govern permeability in accordance to ISRM (1981) [43] in order to design the suitable grout mix.

In such conditions of low RQD, low SPI (such as section 70-75m in BH103) reveals densely clogged or tight fractures groutable only using a thin grout mix or high Blaine cement. It can also be attributed to the broken and irregular fractures caused by drilling; engineering geological investigations and rock mechanics studies including core drilling should be performed as per ASTM D5079-08 [44], ASTM D2113 – 14 [45] and ASTM D6032 / D6032M-17 [46].

7 Trial grouting

Due to the large quantity of data, complexity of rock mass quality as well as rock mass permeability, it was not possible to conduct the groutability evaluation through a geological investigation alone as well as WPTs and RQD. The instructions for performing trial grouting (ISRM 1996) [49] at the Souk Tleta dam was prepared so as to investigate the effect of grouting on permeability reduction and for sealing the permeable dam foundation.

According to the geological condition, the right abutment presents a good rock quality and a low permeability; the trial grouting tests were performed in two panels in the river bed (TGRB) and the left abutment (TGL) of the planned dam site (Fig. 10). In the trial grouting stage of the borehole panels, an equilateral shape was prepared and six boreholes (A, B, C, D, E and F) (Fig. 10) of each panel with a diameter of 140 mm were drilled into the bedrock up to the length of 70 m in TGRB. In TGL, the boreholes length varied between 64 and 90 m. The trial holes were extended to the depth that allowed the observation of a minimum permeability (less than three Lugeon) [47].

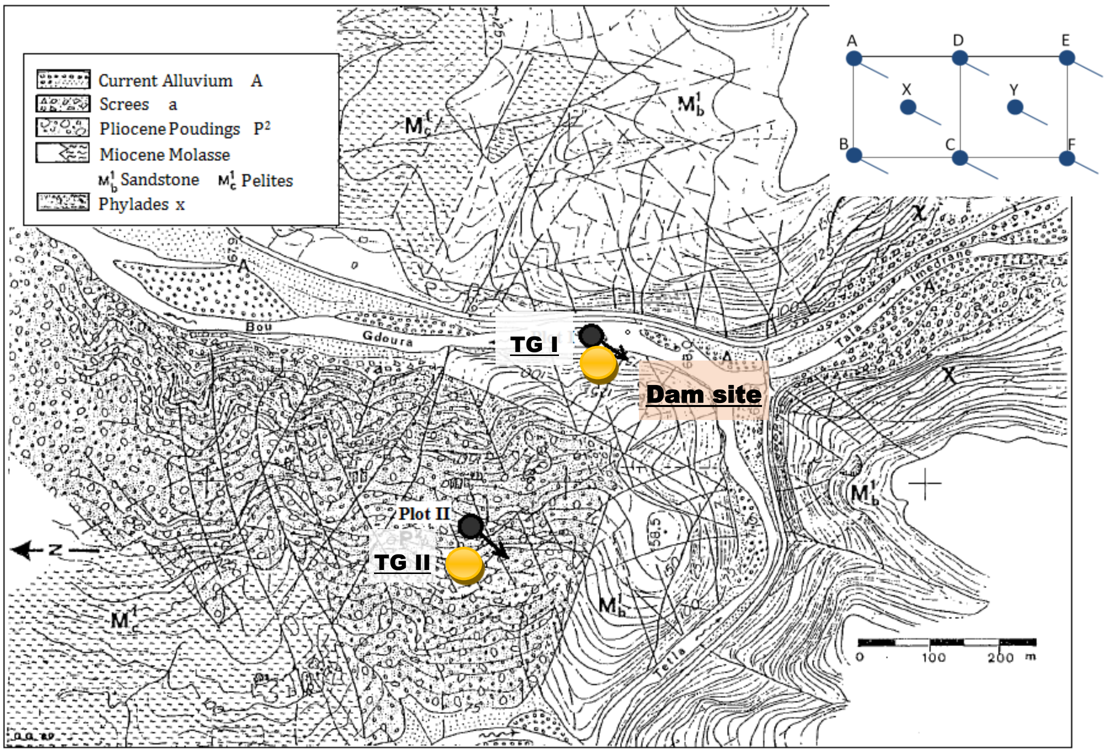


Fig. 10 – Trial grouting location ANB [35]

Furthermore, two check holes (X and Y) were drilled in each panel, and WPTs were performed along every 5 m intervals to measure the permeability of rock mass, examine the groutability and also assess the success of grouting before finally filling with cement. The check holes were not grouted and only drilled and cored. The spacing is chosen that the expected grout penetration zones will not overlap. In both panels TGRB and TGL, the holes were drilled with a well head distance of 5m and 4m, respectively.

Grouting was undertaken through inclined boreholes with an inclination of 35° to the vertical to encourage and achieve an optimum number of intersections with geologic defects that may constitute potential conducts for seepage under reservoir conditions; while the check holes were drilled vertically. During the grouting operation, it was noticed that the stability of the inclined boreholes against collapsing could not be assured.

Water pressure tests were conducted in stages on all the grout holes before grouting. The upstage grouting method was used for the rock formations when the entire holes were drilled down to the planned depth. The GIN model [48] was implemented in trial grouting. During grouting operation, applying high grouting pressure creates hydraulic jacking; in the other hand low grouting pressure can reduce grout penetration radius which disadvantageous for grouting curtain construction (ISRM 1996)[49]. The GIN method is a self-regulating approach, it focuses on controlling grout spreading to avoid a combination of high volumes, high pressure and achieve uniform grout spreading around the grouting boreholes.

In the grouting operation, the grout quality is important to achieve the best permeation grouting results. Trial grouting work in the Souk Tleta dam site was completed using stable cement-based grout in which the main ingredients are cement (Normal Portland type II with Blaine numbers larger than 3000cm²/g) and water. Bentonite additive was added to the cement-water mixture to prevent bleeding and segregation in the poorly cemented sandstone rock formation. The used grout was prepared with a mix of water to cement ratio (W:C) of 1:1. The advantages of using stable thick grout mix during grouting include less sedimentation, less bleeding, and great stability. After grouting works, thicker grout will lead to less shrinkage in the rock mass, besides providing higher mechanical strength, less porosity and lower permeability [48]. In sections with very high permeability (Lu > 60), especially in the conglomerate of TGL, a new, thicker W:C of 0.8:1 was selected to continue the grouting.

Grout pressure is one of the controllable factors in the grouting process; it was specified to increase with depth. The grouting pressure values chosen for the trial grouting were quite low in order to prevent damages caused by the injection operation – they ranged from 2 to 12 bars. The limitation of grout pressure to the minimum along the grouting holes should be avoided and needs to be evaluated according to the location of injection and the rock mass quality.

7.1 Grout take

It is necessary to estimate the grout take to determine the grouting properties and the cost of the operation and check the groutability of the dam foundation. The grout takes were recorded during the trial process. Six boreholes, A, B, C, D, E, and F, of each panel of TRRB and TGL were grouted in sequence. First, the boreholes A, F, B, E, D and C were drilled, following which the water pressure tests were conducted. First, the grouting works were conducted for the borehole (A) from the bottom to the top of the borehole. Then the second borehole (F) drilled in the opposite corner grouted afterwards. Thereafter, similar to previous boreholes, a third and fourth (B, E) boreholes were grouted. Finally, a fifth and sixth (D, C) boreholes drilled and grouted between the previous drilled and grouted holes.

Table 5 and Fig. 11 presents the grout take results by lithofacies units obtained for each borehole of the two trial panels. As illustrated by the figure, the grout takes were not reduced for all boreholes—A, F, B, and E to D and C—in the river bed and the left abutment. Grout takes in left abutment are higher than that of river bed. High grout take is generally observed in intervals that exhibit medium to high permeability. Grout take variation generally follows the Lugeon trend. The average grout takes were found to be higher in the conglomerate (TGL) formation than in the other rock types.

Table 5 – Lithofacies grout take (kg/m) values for each borehole of the two trial panels

Dam foundation	TGRB A	TGRB F	TGRB B	TGRB E	TGRB D	TGRB C
Altered sandstone	17	4	4	2	25	5
Sandstone	3	6	10	3	3	3
Altered shale	3	4	5	4	4	8
Left abutment	**TGL A**	**TGL F**	**TGL B**	**TGL E**	**TGL D**	**TGL C**
Conglomerate	-	11	25	6	25	28
Sandstone	3	32	14	5	8	30
Altered Siltsone	6	8	5	5	2	10

TGRB boreholes crossed a sequence of an alternating sequence of sandstone and a thin layer of shale. The samples showed partially open joints and altered sandstone in the upper 8 m, where 57 kg/m of cement take and closed joints on the 16 m sandstone bed were recorded. During the first stages of grouting, it was found that the shale was practically impervious; an average of 8 bars was applied, although the shale formation had observed a moderate grout take (28 kg/m).

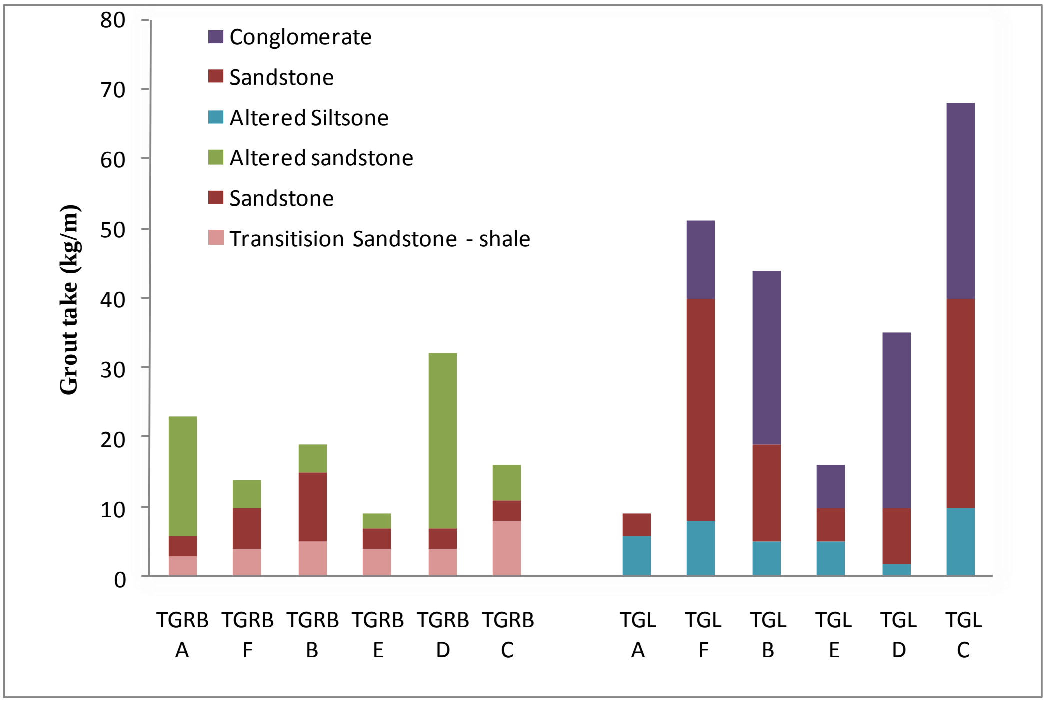
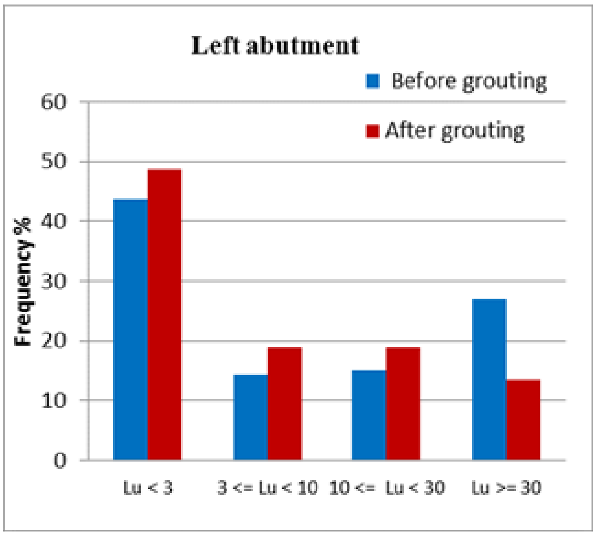


Fig. 11 – Average grout take by panel and lithofacies in riverbed and left abutment

In the TGL abutment, where the trial grouting panel was carried out, the boreholes crossed an alternating sequence of thick layers of conglomerate and sandstone and a thin layer (8 m) of siltstone. Grout takes were found to be considerably higher in conglomerate and sandstone (92 kg/m) than in siltstone formation. The cement takes were expected to drop from boreholes TGLA to TGLC, but the results showed that the cement takes increased from the borehole TGLA to TGLB and did not drop in TGLC. This is due the variability cementation of the important conglomerate formation and the alteration and dip direction of sandstone schistosities that are generally towards upstream. The siltstone rock mass has closed joints and narrow fissures, where small grout takes. Results of performed cement grouting in rectangle trial holes indicated that improvement of conglomerate and sandstone was not satisfactory.

Water pressure tests were conducted on the check holes to obtain more information on the permeability of the grouted formations in trial panels and inspect the groutability success, and the corresponding results are presented in Fig. 12.



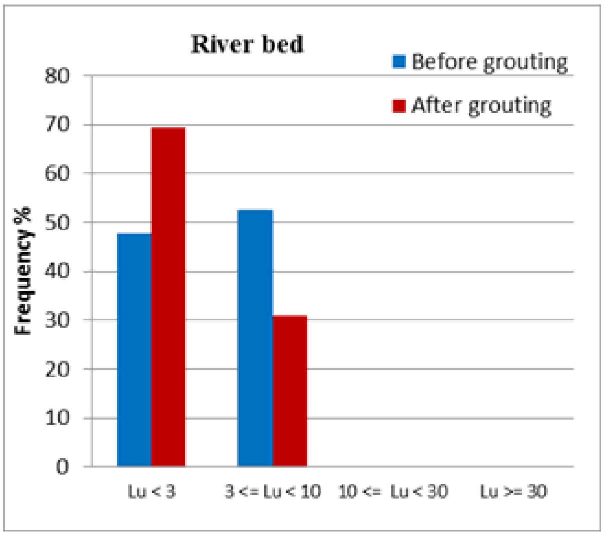


Fig. 12 – Lugeon frequency distribution before and after grouting in riverbed and left abutment

The overlapping curtain can be controlled from the vertical orientation of the check holes. It was observed after comparing the permeability results before and after grouting (Fig. 12) that the permeability of TGRB was reduced (69% frequency was less than 3 Lu rather than 47% before grouting, and a reduction of 21% frequency for permeability values between 3 and 10 Lu was observed).

At left abutment, the original permeability was not reduced to the desired degree; it was found that there was almost no reduction in TGL permeability after grouting despite a sizeable volume of grout. Permeability higher than 10 Lu presents an after-grouting frequency of 32% instead of 42% of the same before grouting. A close spacing of the grout holes is required to find all the voids and assure an overlapping for the aim of constructing an impervious dam foundation.

The RQD and Lugeon test provide useful information on the quality of rock mass and its permeability, respectively. Barzegari [17] evaluated in situ permeability of Peygham-chay dam rock mass foundation (andesite, basalt and diabase highly fractured in right bank) on the basis of water pressure tests (Lugeon) results and secondary permeability index (SPI). Test results indicated that permeability in 73% of test sections were less than 3 Lugeon and only 1% of tests were more than 30 Lugeon. By comparing rock jointing degree (RQD) and SPI values, the overall groutability of rock mass was evaluated and the results that permeability of rock mass in more than 66% of the tests were very low and did not require treatment. In the rest of sections, construction of preferred sealing system was necessary. Comparing to the Souk Tleta dam, overall Lugeon test results indicate that the permeability in only 47% of the test sections is less than (03) Lugeon and 15% greater than (30) Lugeon. We can clearly note that the permeability of rock masses in Souk Tleta dam site is high compared to that of Peygham-chay dam site; this can be justified by the nature of dam foundation; namely altered sandstone having bedding plains parallel to flow direction; hence the need to carry out grouting tests.

Trial grouting procedure permit comparing permeability ratio before and after grouting and providing excellent information about grout take for each stage. This will also define effective radius, suitable spacing between grout holes for grout curtain and optimal composition of the slurry. As trial grouting, Rastegarnia et al. [26] examined two trial grouting programs applied in right and left abutment of Bazoft dam composed by limy marl and marly limestone. The grout take was reduced in the left abutment from the first grouted borehole (415 kg/m) to last grouted borehole (50kg/m), implying success of the grouting process. On the other hand, during grouting tests carried out at Souk Tleta dam site, on the left bank, results showed that grout takes increases in the two grouting panels as grouting work progresses instead of decreasing. Small quantities and inhomogeneous takes in grouted boreholes of left abutment are recorded indicating a large distance between trial boreholes compared to trial holes distance adopted by Rastegarnia et al. [26], in addition to the significant depth of joints and their narrow aperture. Among the rocks encountered during grouting tests, conglomerates and sandstones are the two rock types that consumed the most of grout. Hu and Ma [15] confirm this result on the Pipasi dam foundation, which suffered from serious seepage problems for over 50 years caused by the presence of pervious rock layers. Despite early treatments, a complete water proofing system was not ensured. The foundation is composed of sandstone overlaid by pervious conglomerate, which is covered by quaternary deposits. The groutability of conglomerate varied widely; therefore, the effectiveness was doubtful and needed precise understanding.

It should be noted however that cement-based grouts do not have infinite durability. Their deterioration is attributed to physical or chemical mechanisms. Many of deterioration types depend on water and environmental exposures and can affect the structural integrity or chemical stability of rock mass. For that reason, it is important to consider the cement grout mixture. The long-term safety risks and grouting durability risks are important aspects to consider.

8 Conclusion

Determining the groutability of a dam foundation and choosing the seepage control measures depend on a number of conditions where large and detailed geological investigations should be achieved to appreciate the foundation character. Completed by core drilling survey, the geological study has provided useful information on the lithology of the rock mass. The geology of Souk Tleta dam foundation consists mainly of Burdigalian sandstone with interlayers of conglomerates, overlain by a thick deposit of alluvium with a thickness of about 20 m in the river bed. Lithological variation of the rock foundation has caused different behavior in its quality and its permeability.

To improve the dam foundation by decreasing permeability and increasing the rock mass strength, a good knowledge about geological properties including rock permeability, RQD and their variation in depth is required. The rock quality and permeability of the rock mass has been evaluated based on RQD and Lugeon values. Results show that the rock mass quality varies from 0 to 100%. The comparison of RQD values showed that the sandstones quality in right abutment is of higher quality when compared to those in river bed and left abutment. The permeability study from WPTs results indicates that the left abutment is more permeable than the right abutment and dam foundation.

The SPI allows estimating the rock quality, the permeability and helps to determine the groutability of the sedimentary rock foundation. Although the SPI parameter relies on WPT, the foundation mapping provides an illustration of the rock quality classification and the required treatment. According to the results in the left abutment, except in certain cases, the results show a good correlation between SPI, Lu and RQD. The SPI, Lu and RQD are three key parameters to predict the groutability of the sedimentary Souk Tleta dam foundation.

Through trial grouting, information about the grout mix, the pressure to adapt, the time of the operation, the grout take and the rock absorption variation with depth are obtained. The check holes allow the knowledge of the filling fractures by grout and the penetration length by checking how permeability is reduced with depth and they provide an accurate assessment of grouting influence radius. The left abutment of Souk Tleta dam site generally shows more groutability than the river bed. This general condition could be anticipated based on Lugeon values of trial grouting boreholes. Regarding the obtained results from trial grouting works, and in order to ensure the stability of the drillings; a grout curtain will be installed in vertical; in other words, direction of the grouting holes are to be vertical. Apart from the boreholes meshing that is proposed to be reduced and since the dam foundation trial grouting panel gave us good sealing results, the same parameters will be adapted for the right abutment. In addition to alteration of the sandstones, the presence of some fractures and weak cementation of the conglomerates and the bedding plains of the sandstone formation, which are parallel to the flow direction, results show that the greatest amount of water seepage occurs in the left abutment in terms of permeability and groutability. The borehole meshing is proposed to be reduced and the grouting pressure to be adjusted and controlled as the grouting works progress.

Cement grouting, involves the use of grout that is a mixture of water and cement to fill voids fractures within the rock masses. Water to cement (W/C) ratio is one of the main characteristics used to evaluate cement-based materials. The long-term requirements mainly involve the long-term durability of the grout. To meet durability requirements in grouted fractured rocks, special consideration is needed in design of cement blaine and grout mix (water separation during hardening and solubility of the grout in the surrounding environment should be observed). Correlation between W/C and other properties can be applied (including admixtures) and show a general trend for influence of W/C ratio on durability. For a joint to be groutable, the mix must satisfy the conditions of penetrability that depends on the size of cement grains. The cement-based grout used is a mix of Portland cement with Blaine larger than 3000 cm^2/g. Super plasticizer is added to thick cement–water mixture to increase the grout fluidity (to reduce viscosity and cohesion).

However, because of the complexity of geological conditions of the sandstone formations and the grouting operation, the sedimentary formation behaviour towards the grouting process and the chosen grouting parameters, a deep study of the permeable left abutment is being undertaken to understand its groutability by using chemical grouts. Resin grouts are chemical grouts, which are a good alternative to cement grout. They are limited to rock masses with narrow joints, where the cement suspensions cannot be injected or their penetration is very limited.

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