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ORIGINAL PAPER

Prediction of grout take using rock mass properties

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Abstract Seepage through foundation and abutments of a dam can potentially result in waste of the water stored in the dam reservoir, erosion of foundation materials, and development of uplift pressure in the dam foundation which, consequently, threatens the long-term stability of dam. A grouting process, which is carried out based on the results of the Lugeon test, is among the techniques applied for seepage control. In this paper, factors affecting the grouting process were assessed in the Bazoft dam site. Bazoft dam is a hydroelectric supply and double-curvature arch dam with a height of 211 m located in Chaharmahal and Bakhtiari Province of Iran. The bedrock of the dam site consists of Asemari formation (limy marl and marly limestone), in the middle and upper parts of left abutment, and Jahrom formation (limestone and dolomite) in the right abutment, river bed, and lower part of left abutment. As test grouting, two trial grouting programs were applied in the right and left abutment of this dam site. At a first step, using the existing relations and engineering geology reports, Q system, SPI, grouting pressure, joint aperture and grout take were determined for 5 m segments of the trial grouting boreholes. Then, using SPSS software (version 21) the grout take was estimated based on the parameters noted. According to the results, grout take showed good correlation with Q system, grouting pressure and joint aperture. There was no correlation between SPI and grout take. Examination of the necessary assumptions of the model, such as normality, multicollinearity (eigenvalues, condition index, tolerance and VIF), and independence of errors revealed the moderate accuracy of the model obtained.

Keywords Trial grouting boreholes · SPI · Q system · Grouting pressure · Joint aperture

Introduction

Cement grouting is a method by which grout material is injected into the joints and cracks or voids of rock and soil formations, improving the engineering properties of these materials by decreasing the permeability of the layers, enhancing the strength of soil layers, and reducing the deformability of rock mass. Ground properties are the most important factors in the grouting process. The overall properties of joints that affect grout take and grout penetration include aperture, roughness and irregularity of joint surface, spacing, and consistency (Houlsby 1990).

Currently, a considerable share of the budget allocated to dam construction processes is spent in cement grouting processes. Cement grouting is carried out in dams to improve the strength of the dam foundation and the related structures and sealing. If there is a high degree of uncertainty about the efficiency of the grout process, a trial grouting will be designed before dam and grout curtain construction. The main aim of the trial is to compare the ratio of permeability before and after grouting, but this will also provide excellent information about grout take for each stage. Finally, the maximum spacing between grout boreholes and injection pressure will be estimated from this investigation. In this way, it is

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possible to measure the ratio of permeability before grouting to average permeability after grouting, average take of grout mix in each step, and the maximum spacing between the last grouting borehole and the pressure needed.

Usually there is no direct relationship between water and grout take in rock masses because the properties of both fluids, water and cement slurry, are very different. The main differences are: (1) water is a Newtonian liquid, grout slurry is a Bingham body; and (2) slurries are particulate, and cement grain size limits penetration into fissures and pores. In this regard, Ewert (1997) believes that this difference can be explained by the fact that grout cannot migrate within joints into which water can easily flow, so that the hydraulic jacking induced by the grouting pressure results in washout of particles inside the joint. Considering the considerable size of excavation and grouting processes, determination of grouting pressure needed in the grouting process is a critical requirement for project planning. Because of the decisive differences between water and slurry, and because of the various rock mass parameters intervening in the grouting process, a direct, simple and universal relation between the Lugeon test and grout absorption cannot exist (Kutzner 1996). Some investigations on grout take and joint properties are listed here:

> The cement take based on some methods such as the mean method, the linear regression method and back-propagation neural network (BPN) method was estimated (Yang 2004).
> A relationship between water-loss and grout take was investigated and a linear formula with a moderate explanatory power was established by statistical analysis (Karagüzel and Kilic 2000).
> Kirlay (1969) suggested a methodology to derive the hydraulic conductivity of the fractured rocks using mathematical formulas in which the terms in these formulas can be derived by a detailed mapping survey of the fractures.
> Sohrabi-Bidar et al. (2016) presented an equation for calculating the joints aperture based on the permeability and joint spacing.

In this paper, the influence of grouting pressure, Q system, joint aperture and secondary permeability index (SPI) on the grout take in trial grouting boreholes at the dam site were investigated. Then, using SPSS software, a multiple linear regression was fitted to the mentioned parameters. In this regard, first, using the geotechnical reports and related equations and tables, grouting pressure, joint aperture, parameters of Q system, and SPI were determined for 5 m borehole segments.

Dam location and geological characteristics of dam site

Bazoft dam is designed for optimum use of the river with the same name, and for generation of hydroelectric power. The dam is a double-curvature arch dam with a height of 211 m, and is located 200 km SW of Share Kord (Chaharmahal and Bakhtiari Province of Iran) (Fig. 1).

The bedrock consists of two geological units dating from Eocene, Oligocene and Miocene. The Asmari Formation (As in Fig. 2), which defines the bedrock of the upper part of left abutment, consists of limy-marl, marly-limestone and thin layers of limestone. The right abutment and the lower part of the left abutment are built over the Jahrom Formation (Ja in Fig. 2), which consists of crystalline limestone and dolostone with interbeds of marly limestone. Figure 2 shows a geological map of the dam site.

There are karstic features in the rock mass at the right abutment of the dam site that may affect permeability and grout take (Fig. 3).

Discontinuities

Generally, the dominant sets of joints have a large effect on, and play an important role in, the groutability and permeability of dam foundations. The rock mass at the left abutment area is intersected by three main discontinuities including bedding planes and two major joint systems: J1 and J2 (Fig. 4).

Six discontinuities including bedding planes and five major joint systems: J1, J2, J3, J4 and J5 were identified in the right abutment (Fig. 5).

Pattern of trial grouting boreholes

The pattern proposed for grout panel boreholes in both abutments was a 3 m length equilateral triangle (Fig. 6). The boreholes were drilled above the water table and vertically, and the maximum depth of the boreholes was 75 m and 70 m for the left and right abutments, respectively. The core recovered permitted to check that the bedrock consists of limestones, from surface to 59 m depth, and marly limestone to the bottom.

Throughout the drilling process, sampling using a thin-walled core sampler in all boreholes, water pressure tests (WPT) in some segments with 5 m intervals for measuring rock mass permeability, and top-down grouting processes were carried out. Once grouting was finished, a control borehole was drilled in the center of the triangular pattern in order to check the efficiency of the injection. These boreholes were also 75 m depth, and a new 5 m test section

Fig. 1 Location map of Bazoft dam site

length WPT was carried out in order to assess the permeability decrease (Qods Niru 2011).

The trial grouting described above was designed in order to study the relationship between permeability and grout take before dam construction. This procedure permitted us to define parameters such as: effective radius of the grout penetration (by drilling at greater radii from center), the most suitable spacing between grout boreholes for grout curtain, and the optimum composition of the slurry necessary for the consolidation grouting and grout curtain.

The information obtained from the grouting trial was evaluated determining the Q classification, joint aperture, defining the SPI and the grouting pressure. The procedure applied in this process was as follows:

Q classification system

The Q classification system, which is currently used in various applications, was initially presented by Barton et al. (1974) for selecting a suitable pattern of rock bolts (and anchors) and thickness of shotcrete for ground support in rock mass. Q is calculated using the following equation:

$$Q = \frac{\text{RQD}}{J_{\text{n}}} \times \frac{J_{\text{r}}}{J_{\text{a}}} \times \frac{J_{\text{w}}}{\text{SRF}}, \tag{1}$$

where RQD is the ratio of sound cores with length >10 cm in each core run (Deere 1989), J_{n} is joint set number, J_{r} is joint roughness number, J_{a} is alteration or filling number of joints, J_{w} is score of water flow and water pressure effects that might result in washout of infill in discontinuities. J_{w}
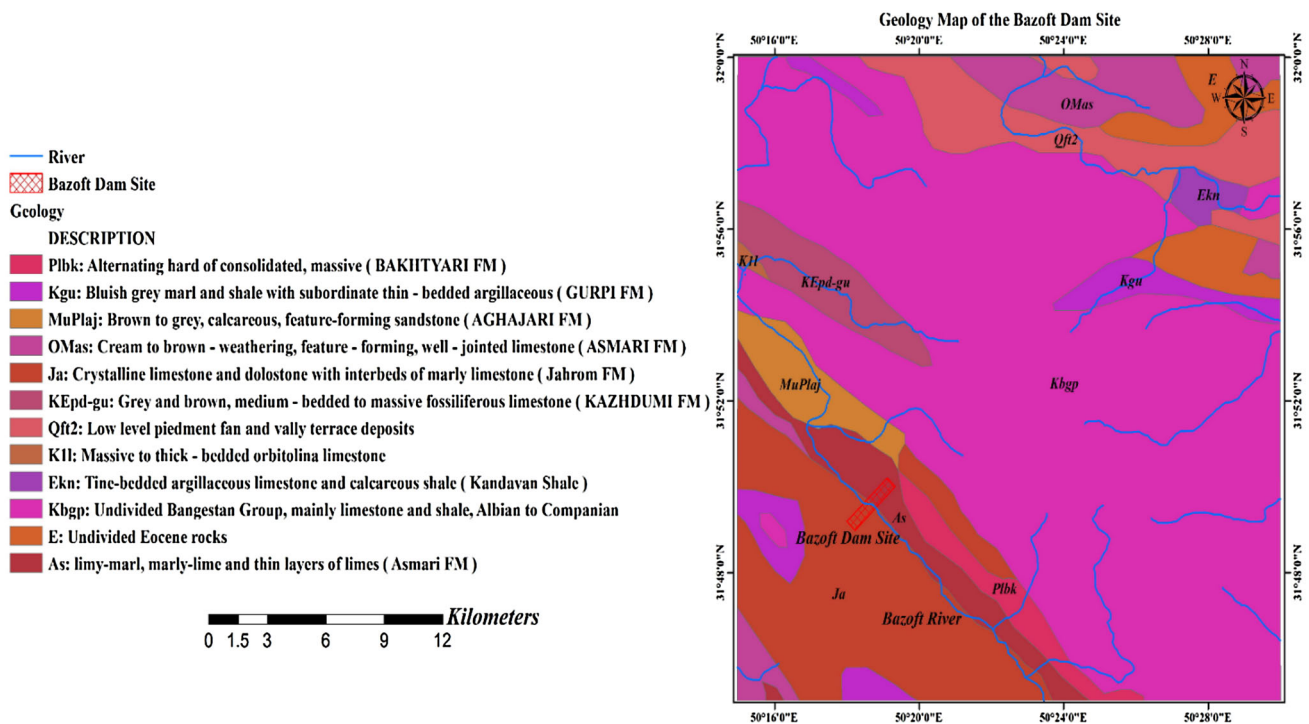
Fig. 2 Geological map of Bazoft dam site (Qods Niru 2011)

Fig. 3 Photographs of karstic features in the right abutment of Bazoft dam site

uses a somewhat arbitrary rating for the combination of seepage and water pressure at the periphery of an underground opening. It should represent the influence of groundwater on the effective stress in the rock mass. For the rock of the grouting test, the J_w score is constant and equals 1 because of the dry condition of grouting boreholes.

SRF is the stress reduction factor, which indicates the ratio of stress to strength in hard massive rock, and also ratings for swelling and squeezing rock (Barton et al. 1974). Barton (2006) believes that the grouting pressures

do not affect the SRF parameter; hence, in this paper, the parameter of SRF is assumed constant.

To study scores of RQD, J_a, J_r, SRF, J_n, and J_w parameters in cores, Q tables were used (Barton 2002). The inclination angle of the joint surface is a critical parameter when measuring J_n score. Joint set number in cores of a box is determined by measuring the surface inclination angle with respect to drilling axis, as joints with equal inclination angle make one joint set (Clarck and Budavari 1981). Furthermore, to ensure accuracy of the joint set rating, once the inclination angle between the joint surface
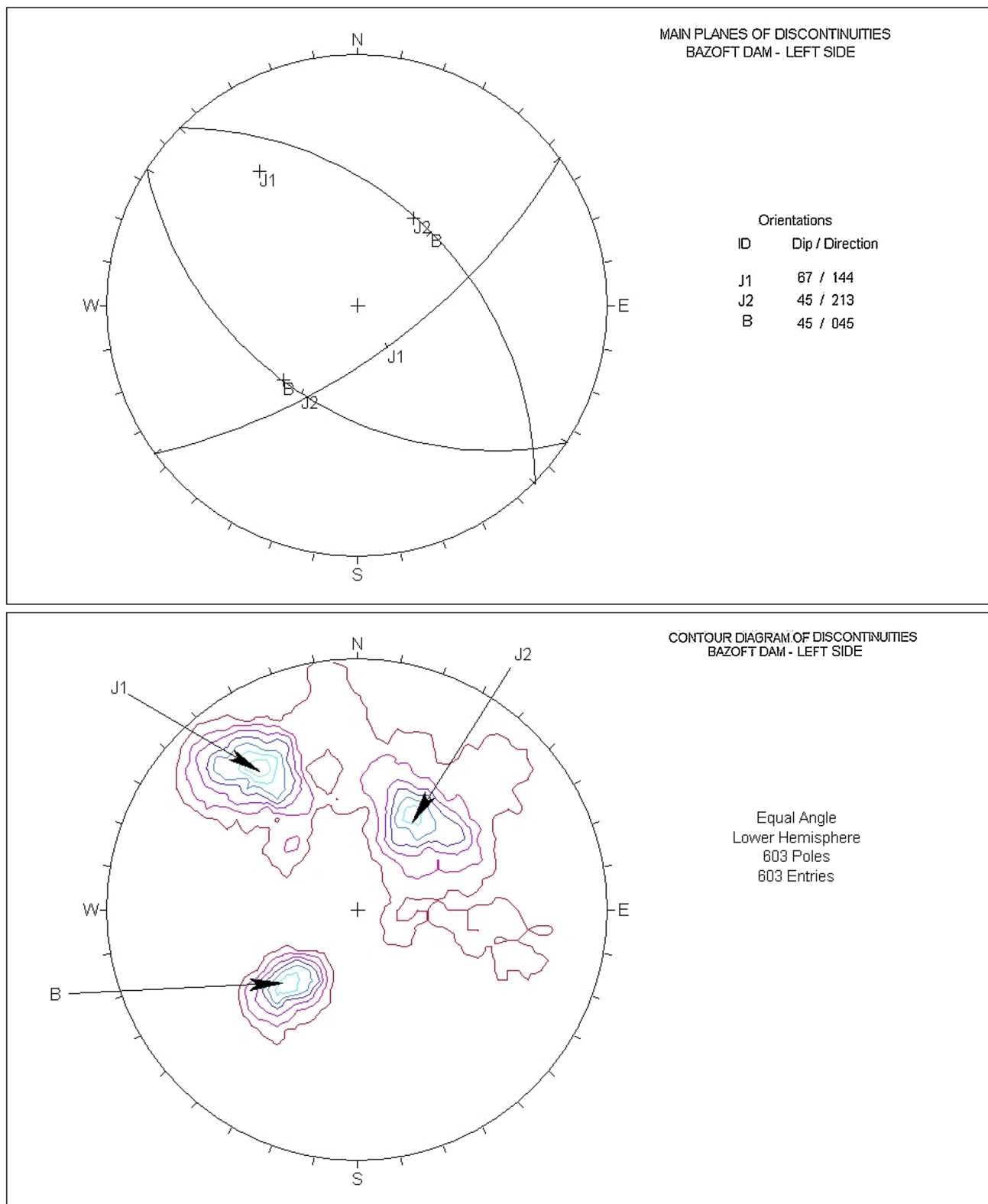
Fig. 4 Stereographic pictures of left abutment joint sets

and the borehole axis was measured, it was compared with the angles of joints measured at different outcrops. Trial grouting boreholes at the Bazoft dam site were placed above the water table, so that the J_w score is constant and equals 1. A sample of computations for borehole GSL1 is shown in Table 1.
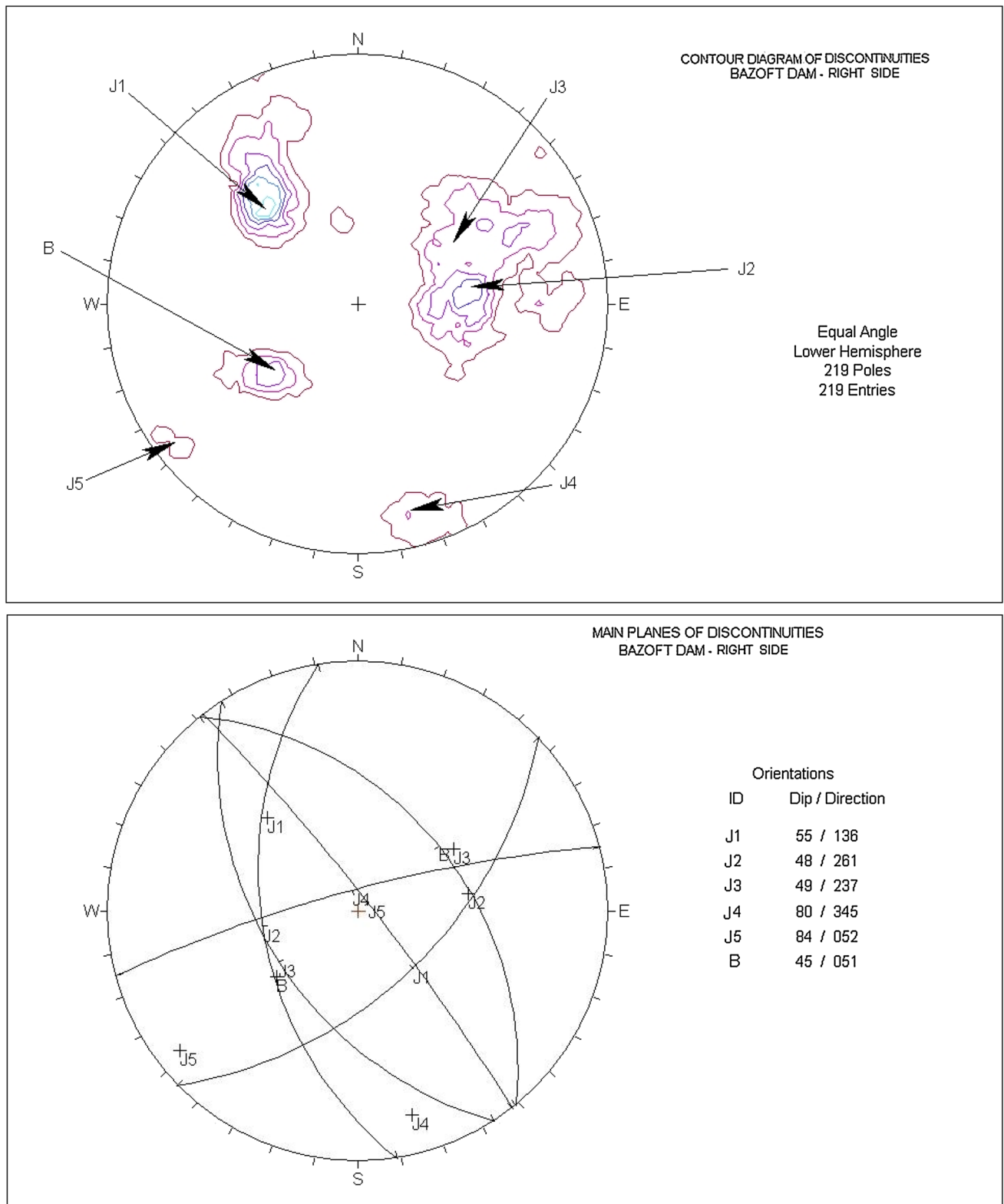
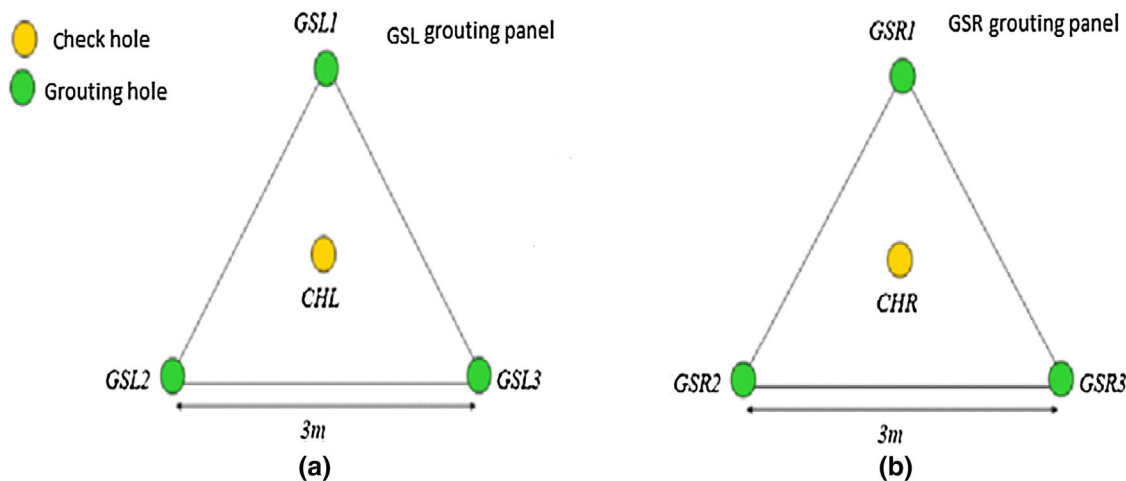**Fig. 5** Stereographic pictures of right abutment joint sets

Fig. 6 Trial grouting boreholes pattern. **a** Left abutment, **b** right abutment

Table 1 Rock mass classification based on secondary permeability index (SPI) and ground treatment consideration (Foyo et al. 2005)

Secondary permeability index (SPI($\frac{l}{s}$ per m²))	SPI $\leq 2.16 \times 10^{-14}$	2.16×10^{-14} < SPI $\geq 1.72 \times 10^{-13}$	1.72×10^{-13} < SPI $\geq 1.72 \times 10^{-12}$	SPI $\geq 1.72 \times 10^{-12}$
SPI classes	Class A	Class B	Class C	Class D
Rock mass description	Excellent	Good–fair	Poor	Very poor
Ground treatment	Needless	Local	Required	Extensive

Joint aperture

The joint aperture was calculated based on the permeability of rock and the joint spacing, as presented by Sohrabi-Bidar et al. (2016):

$$e = \frac{\sqrt[3]{0.133\,Kb}}{10}, \qquad (2)$$

where e is the equivalent joint aperture (cm); b is the average joint spacing (cm), and K is the hydraulic conductivity of the rock mass (cm/s). This equation corresponds to the so-called "cubic law", which applies to laminar flow of Newtonian liquid in a parallel-walled channel (Snow 1965).

Secondary permeability index

SPI was estimated using the following equation, as presented by Foyo et al. (2005):

$$\text{SPI} = C \times \frac{Ln\left(\frac{2l_e}{r} + 1\right)}{2\pi l_e} \times \frac{q}{Ht}, \qquad (3)$$

where SPI is secondary permeability index (L/s m²); C, which is 1.49×10^{-14}, is a constant coefficient controlled by fluid viscosity in a rock with temperature of 10 °C; r is borehole radius (m); q is water take (L), H is the total hydraulic head of the water column (m); t is the time taken

for each pressure step (s); and l_e is the length of studied segment (m). The ln-term is an approximation for inverse hyperbolic sine, which typically can be used for short test stages and the elliptical configuration of equipotential lines. The conversion between intrinsic permeability (cm²) and hydraulic conductivity (cm/s) is roughly: 10^{-5} - cm² = 1 cm/s.

The absorbed water (q) for the 5 m segments along each borehole was determined using the pressure-water take curves obtained from the Lugeon test. SPI is simply a standardized format for the Lugeon tests (normalizing for borehole diameter and stage length). If used in conjunction with the cubic law, only those Lugeon tests, or parts of tests, that correspond to the laminar flow regime should be used.

SPI, as a base for rock mass classification, indicates rock mass permeability and hydraulic conductivity. In this classification, hydraulic properties of rock mass are presented and rock mass grout take at project sites is described within various classes (Table 1) (Foyo et al. 2005).

Grouting pressure

Grout penetration radius in rock mass is affected by parameters such as joint conditions (aperture and roughness), flow properties, and effective pressure of grouting.

Applying high grouting pressures is allowed up to a certain level, as it results in grout penetration to farther distances, and, consequently, lower costs. The empirical European ($P_{max} = 1$ bar/m) and American ($P_{max} = 0.22$ bar/m) relationships are applied in many countries for selecting optimum grouting pressure. However, these empirical equations do not take into account geological conditions, and pressure rise is correlated linearly with depth. Applying high grouting pressures, on the other hand, results in hydraulic jacking, which is a disadvantage for cases such as construction of grout curtain (ISRM 1996). Nevertheless, low grouting pressure can result in reduced grout penetration radius.

Inducing any flow of liquid or slurry in rock joints will inevitably change effective stresses and produce some jacking of joints. It is, therefore, either unsafe or uneconomic, or both, to use only pressure for controlling the grouting process. The GIN concept uses two parameters, P and V, and the product $P \times V$, which describes the energy introduced and therefore is safer for judging the effect of hydrojacking.

In this paper, the effect of grouting pressure on grout take was investigated in the trial grouting boreholes in the Bazoft dam site using SPSS 21 software. The applied grouting pressures for 5 m segments are listed in Table 2 for borehole GSL1.

Results and discussion

Analysis of SPI in dam site

To study SPI and perform rock mass classification based on this criterion within the 5 m segments in each borehole, the

equation and table proposed by Foyo et al. (2005) were used. At the Bazoft dam site, first boreholes GSL1 and GSR1 were drilled in the left and right abutments, respectively, and the Lugeon test was carried out in the 5 m segments. Then, based on the results obtained, the SPI criterion was determined, SPI-based rock mass classification was made, and grouting was performed. In the next step, the other boreholes were drilled and the grouting procedure was performed. Boreholes GSL1 and GSR1 present the natural permeability of the site on the basis of SPI values. Table 3 lists the results obtained for these two boreholes, and the boreholes grouted in the next steps. As the table shows, permeability was reduced after grouting from borehole GSL1 to GSL2 in the left abutment, but there was no change in permeability values from boreholes GSL2 to GSL3. In comparison, in the right abutment, rock mass permeability increased during the grouting process from borehole GSR1 to GSR2 in the 5–10 m and 10–15 m segments, implying that grouting did not improve permeability condition in these boreholes. This observation can be attributed to the inconsistency or low consistency of joints in the right abutment. Furthermore, a permeability increase was observed from boreholes GSR2 to GSR3 in 45–50 m and 55–60 m segments, while permeability values decreased for the shallow segments.

The natural permeability of site (before grouting) in boreholes GSL1 and GSR1 indicates that the need for extensive grouting (class D) and no need for grouting (class A) states are not observed for these boreholes. Besides, the need for local grouting (class B) had maximum frequency for these boreholes (Fig. 7).

Figure 8 illustrates the overall frequency of SPI classes in the right and left abutments of the dam site. As shown in the figure, there is no class A for the left abutment, while it
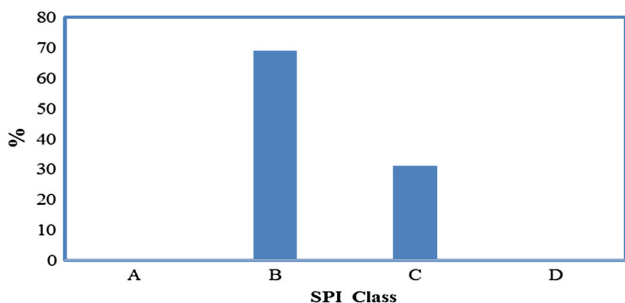
Table 2 Sample dataset for borehole GSL1

Depth (m)	RQD	J_n	J_r	J_a	J_w	SRF	Q	Grout take (Li)	Lugeon value	Spacing (cm)	K (cm/s)	Aperture (cm)	SPI (L/s $\times$ m^2) $\times 10^{14}$	Grouting pressure (bar)
10–15	100	4	2.20	3.00	1	1	18.33	378	26	56.10	0.0003	0.0063	36.14	6.00
15–20	96	6	2.40	2.00	1	1	19.20	161	8	38.76	0.0001	0.0038	23.20	6.00
20–25	100	6	2.20	2.50	1	1	14.67	500	28	56.10	0.0004	0.0065	32.88	5.50
25–30	100	2	2.25	0.87	1	1	129.31	210	19	56.10	0.0002	0.0057	22.32	11.00
30–35	100	6	2.50	1.00	1	1	41.67	63	1	56.10	0.0000	0.0021	12.80	13.00
35–40	91	9	2.70	3.00	1	1	9.10	1486	4	28.40	0.0001	0.0027	29.80	12.50
40–45	97	4	2.00	3.00	1	1	16.17	600	46	42.00	0.0006	0.0069	38.31	14.00
45–50	98	2	2.00	1.00	1	1	98.00	382	2	45.85	0.0000	0.0025	16.15	15.00
50–55	99	4	1.50	5.00	1	1	7.43	1003	28	50.48	0.0004	0.0063	39.62	17.00
55–60	96	4	1.50	5.00	1	1	7.20	2000	2	38.76	0.0000	0.0024	11.20	18.00
60–65	99	2	1.00	5.00	1	1	9.90	402	40	50.48	0.0005	0.0070	28.62	21.00
65–70	100	9	2.10	2.80	1	1	8.33	263	4	56.10	0.0001	0.0034	17.36	23.00
70–75	99	6	2.40	2.00	1	1	19.84	2313	1	51.52	0.0000	0.0021	8.03	25.00

Table 3 SPI classes assigned for the trial grouting boreholes (BH) in Bazoft dam site at 5 m intervals

Depth (m)	First BH GSL1	Second BH GSL2	Third BH GSL3	First BH GSR1	Second BH GSR2	Third BH GSR3
0–5	C	B	B	C	C	B
5–10	C	B	B	B	C	B
10–15	C	B	B	B	C	B
15–20	C	B	B	B	B	B
20–25	C	B	B	B	B	B
25–30	C	B	B	B	B	B
30–35	C	B	B	B	B	B
35–40	C	B	B	B	B	B
40–45	B	B	B	B	B	B
45–50	B	B	B	B	A	B
50–55	B	B	B	B	B	B
55–60	B	B	B	B	A	B
60–65	B	B	B	B	B	B
65–70	B	B	B	B	B	B
70–75	B	B	B			

Fig. 7 SPI class for boreholes GSL1 and GSR1 at the Bazoft dam site

Fig. 8 Frequency percentage of SPI classes for right and left abutments in Bazoft dam site

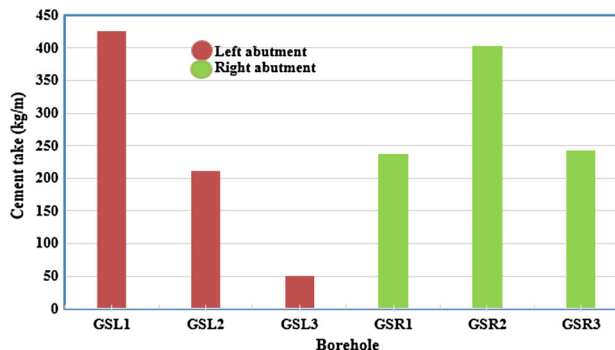**Fig. 9** The average of cement take in left and right abutments

is 4.8 % for the right abutment. Moreover, class B has higher frequency in the right abutment compared to the left abutment, while class C was more frequent in the left abutment than the right abutment. Finally, class D was zero for both abutments.

Average cement take in trial grouting boreholes

Cement take is defined as the ratio between grout injected in the grouted segments and the segment length, and is expressed in kg/m. The average cement take in the left and right abutments of the dam site for each borehole is presented in Fig. 9. As shown in the figure, grout take is reduced in the left abutment from borehole GSL1 to borehole GSL3, implying the success of the grouting process. On the other hand, the right abutment indicates an irregular pattern, which is in agreement with Lugeon results. In general, cement take in the right abutment is higher than that of left abutment. Right abutment is drilled into the thick crystalline limestones in the middle of Asemari formation (AS2), so that the cement take values are

expected to be dropped from borehole GSR1 to GSR3. On the contrary, the result of trial grout test (Fig. 9) show that cement take increases from boreholes GSR1 to GSR2 and is not dropped in borehole GSR3.

Inhomogeneous take of grout in boreholes drilled in right abutment indicates the presence of karstic areas,

particularly for borehole GSR2. The frequent drop of drilling rod proves the presence of karst in the drilling path of borehole GSR2. This phenomenon was also observed during geotechnical investigations of the dam site.

Multiple regression analysis using SPSS software

Equation 4 was obtained between parameters including grout take (Gt), joint aperture (A), Q system and grout pressure (Gp) at the dam site using multiple linear regression analysis performed in SPSS 21.

Considering the significance level statistic (sig), SPI cannot be used in multiple linear relationship as its significance is above 5 % (Table 4).

$$Log(Gt) = 82.71 \times A - 0.004 \times Q + 0.066 \times Gp + 1.31.$$
(4)

In Eq. (4), Gt is grout take (Li), A is joint aperture (cm) and Gp is grout pressure (bar). Consider the model above, this regression suggests that, as joint aperture and grout pressure increase, grout take increases, but as Q rating increases, grout take decreases. Validation of this model is discussed in the following.

Regression diagnostics (assumptions of linear regression)

Many graphical methods and numerical tests have been developed over the years for checking regression diagnostics, and SPSS makes many of these methods easy to access and use. In this article, these methods have been tested and show how to verify regression assumptions and detect potential problems.

Normality of dependent variable

The dependent variable should be normalized. In this paper the grout take (dependent variable) values are not normal data, hence the log of this variable was used to normalize these data. Results of normality tests show that the grout take log is normal (Table 5).

Tests on normality of residuals

One of the assumptions of linear regression analysis is that the residuals are normally distributed. As presented in the Fig. 10, the mean of residuals is nearly equal to zero and the standard deviation nearly equal to one (Fig. 10). This means that the assumption of normality of residuals is satisfied.

Assumption of independence of errors

The multiple correlation ($R = 0.68$) between grout take and the four predictors is strong (Table 6).

Multiple regression assumes that the errors are independent and there is no serial correlation. Errors are the residuals or differences between the actual score for a case, and the score estimated using the regression equation. No serial correlation implies that the size of the residual for one case has no impact on the size of the residual for the next case.

The Durbin–Watson statistic was used to test for the presence of serial correlation among the residuals. The value of the Durbin–Watson statistic ranges from 0 to 4. As a general rule of thumb, the residuals are not correlated if the Durbin–Watson statistic is approximately 2, and an acceptable range is 1.50–2.50. The Durbin–Watson statistic for this multiple regression is 1.30, which is outside the acceptable range. Hence, this analysis does not satisfy the assumption of independence of errors (Table 6). ANOVA table (Table 7) shows that there is a statistically significant relationship between the set of independent variables (SPI, aperture, Q, grout pressure) and the dependent variable [Log (grout take)].

Beta expresses the relative importance of each independent variable in standardized terms. As presented in Table 4, firstly the joint aperture, grout pressure and Q-system are significant predictors; secondly, the joint aperture has a higher influence than grout pressure.

For the independent variable, SPI, the P value is 0.322, which is greater than the level of significance of 0.05. Hence, the SPI variable should be excluded from the

Table 4 Beta, coefficients, tolerance and variance inflation factor (VIF) of the model

Model 1	Unstandardized coefficients		Standardized coefficients	t	Sig.	Collinearity statistics	
	B	Std. error	Beta			Tolerance	VIF
(Constant)	1.288	0.296		4.356	0.000		
Q	−0.004	0.002	−0.253	−2.891	0.005	0.901	1.110
Grout pressure	0.059	0.013	0.422	4.522	0.000	0.792	1.262
Aperture	82.714	13.717	0.533	6.030	0.000	0.883	1.132
SPI	0.0072	0.007	0.093	0.997	0.322	0.794	1.260

Table 5 Tests of normality of the dependent variable

	Kolmogorov–Smirnov			Shapiro–Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Log (grout take)	0.085	82	0.200	0.962	82	0.086
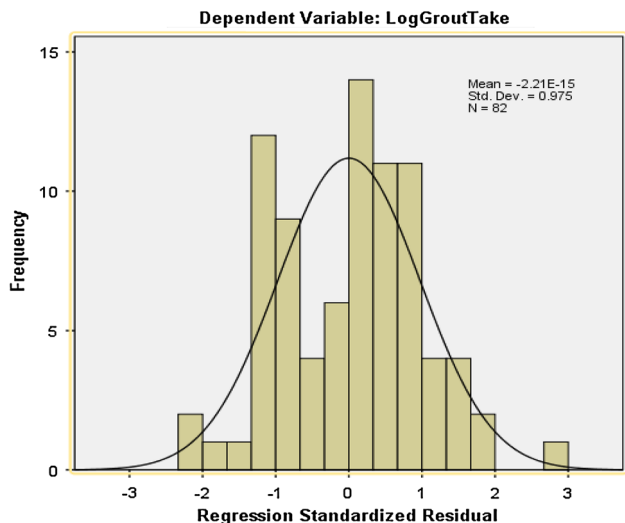
Fig. 10 Histogram of the normality of residuals

Table 6 Adjusted R-square and the Durbin–Watson statistic of the model. Predictors: (constant), SPI, aperture, Q, grout pressure. Dependent variable: log (grout take)

Model	R	R^2	Adjusted R^2	Std. error of the estimate	Durbin–Watson
1	0.695	0.48	0.44	0.52	1.304

Table 7 ANOVA: Dependent variable: log(grout take). Predictors: (constant), SPI, aperture, Q, grout pressure

Model 1	Sum of squares	df	Mean square	F	Sig.
Regression	19.002	4	4.751	17.000	0.000
Residual	21.517	77	0.279		
Total	40.519	81			

model, and it is concluded that there is no statistically significant relationship between SPI and grout take. The sign of the regression weights shows that the correlation between the Q-system and grout take is negative.

Assumption of multicollinearity

When there is a perfect linear relationship among predictors, estimates for a regression model cannot be uniquely computed. The term collinearity implies that two variables are near perfect linear combinations of one another. When more than two variables are involved, it is often called multicollinearity, although the two terms are often used interchangeably.

The primary concern is that, as the degree of multicollinearity increases, the regression model estimates of the coefficients become unstable, and the standard errors for the coefficients can become wildly inflated. In all multiple regression models, there is some degree of collinearity between the explanatory variables; however, not enough to cause a serious problem.

The "tolerance" is an indication of the percent of variance in the predictor that cannot be accounted for by the other predictors; hence, very small values indicate that a predictor is redundant, and values that are less than 0.10 may merit further investigation. In this regression, as shown in Table 4, the tolerance values for all of the independent variables are larger than 0.10, and multicollinearity is not a problem in this multiple regression.

The reciprocal of the tolerance is known as the variance inflation factor (VIF). The VIF shows how much the variance of the coefficient estimate is being inflated by multicollinearity. A VIF near to 1 suggests there is no multicollinearity, whereas a VIF near 10 might cause concern. VIF is (1/tolerance) and, as a rule of thumb, a variable whose VIF values is greater than 10 may merit further investigation. The VIF values for all of the independent variables are lower than 10, and multicollinearity is not a problem in this multiple linear regression (Table 4).

Eigenvalues and condition index

Eigenvalues indicate how many distinct dimensions there are among the regressors. When several eigenvalues are close to zero, there may be a high level of multicollinearity. Condition indices are the square roots of the ratio of the largest eigenvalue to each successive eigenvalue. A condition index above 15 suggests a possible problem, and values over 30 suggest a serious problem with multicollinearity. The variance proportions are the proportions of the variance of the estimate accounted for by each principal component associated with each of the eigenvalues. Multicollinearity is a problem when a component associated with a high condition index contributes substantially to the variance of two or more variables.

In the collinearity diagnostics table of the regression (Table 8), it can be seen that one of the eigenvalues is pretty small, but the condition indices are all below 15 so there is unlikely to be a problem with multicollinearity in this regression.

Table 8 Eigenvalues and condition index of the model

Model	Dimension	Eigenvalue	Condition index	Variance proportions				
				Constant	Q	Grout pressure	Aperture	SPI
1	1	3.880	1.000	0.00	0.02	0.01	0.01	0.01
	2	0.511	2.755	0.00	0.49	0.00	0.04	0.17
	3	0.351	3.323	0.00	0.10	0.02	0.26	0.40
	4	0.229	4.114	0.01	0.21	0.23	0.36	0.01
	5	0.028	11.774	0.99	0.18	0.74	0.33	0.41

Conclusions

In this work, impact of parameters including grout pressure, joint aperture, Q system, and SPI values on grout take in the trial grouting boreholes of Bazoft dam site were investigated and the following results were obtained.

Based on the SPI values, left abutment indicates higher grout take as compared to the right abutment. The grout take values during the trial grouting operation indicate higher groutability of the right abutment as compared to the left abutment. SPI index does not predict grout take; however, this index indicates, or helps to determine, the necessity of grouting. From the SPI index it is possible to estimate the rock mass quality from water flow through joints, and to identify the zones where grouting is necessary. Then, combining the index with joint features permits the best W/C ratio to be proposed.

Statistical analysis reveals that the maximum impact on the grout take is related to the joint aperture and grouting pressure, respectively. Generally, the analysis shows that there is a good correlation between grout take and the above-mentioned parameters except the SPI, which was excluded from the model, but the adjusted R-square is moderate.

Checking the assumptions of the multiple linear regression shows that all of the assumptions were acceptable except the Durbin–Watson statistic, which falls outwith the acceptable range. This means that the obtained model offers moderate accuracy for this multiple linear regression.

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