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A Proposal for Geological Groutability Index (*GGI*) of Cement Grouting in Rock Foundations

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Abstract

The groutability of fissured rock masses is strongly dependent on fracture characteristics: degree of joint spacing, joint aperture, continuity, and presence of weathering in fill. Survey of the drill core boxes permits for estimating the degree of jointing spacing and joint aperture. Nonetheless, weathering in-fill and continuity cannot be detected. In this concept, the rock fracture groutability quality is defined by the Geological Groutability Index (*GGI*). A Geological Groutability Index (*GGI*), denoted as F_{GGI}, may thus be defined as a numerical function of the components: joint spacing (*BS*) and joint hydraulic (*JH*), i.e., $F_{GGI} = f(BS, JH)$. The rock mass foundation with this index can be zoned according to different quality classes and each particularly improved zone. The proposed technique requires the interpretation of the results, from which the Lugeon (Lu) value effect in the section is certified, and the rock fracture classification criteria are applied. The *GGI* is an effective reference to foundation improvement design.

Keywords: Cement Grouting, Geological Groutability Index (*GGI*), Rock Mass Classification, Water Pressure Test

1. Introduction

Grouting is very common method of sealing rock and repairing concrete structures[1–5], and there are many examples of its use to the engineering of dam-foundation improvement[6–8]. In practice, to achieve the intended purpose, boreholes are drilled into the rock mass, and grout is injected under pressure until the fractures around the borehole are filled. The complete filling of these fractures is possible if they are connected to each other in such a way that the remaining water and air can be displaced outside the designed grouting zone[9]. Here, the term ‘grouting’ means the process by which fluid material flows into cracks in the rock or concrete structures. A general summary of various methods was prepared by Houlsby[3].

A number of studies were carried out for the rock injection work. Most of these studies were related to the procedure to be followed during the injection[2–3, 6–7]. However, the main question for injection work is where and how the injection is to be carried out[10]. Many parameters must be evaluated for injection. The science of grouting is interdisciplinary and requires understanding of geology, hydrology, rheology chemistry, and rock mechanics. Grouting is complex, and in spite of great effort many questions have still to be solved[11]. For example, the number of boreholes, designed for the treatment of the rock foundation of the Seyahoo dam, country Iran, was 350 boreholes with 15000 m. However, the number of boreholes in the building documents of Seyahoo dam read 792 grout holes with 29943 m[12]. This disagreement resulted in a doubling of the quantity of gross number of boreholes from what was required in the primary design. This example shows the difficulty in number of grout holes approximation. Issues associated with sealing of dam by grouting are divided into three main areas: geology and the characterization of the rock mass; grouting materials; and grouting technology. These topics and related equations are treated below. Then, GGI is presented.

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2. Methods and Data Collections

The presented data collections include scan-lines, drill cores, water pressure tests and grout curtain boreholes in Seyahoo dam. The general characteristics of the dams are described as follows:

The Seyahoo dam is a segment earth fill with a clay core dam with a height of 32 m and a length 352 m. The dam located in the east Iran in South Khorasan province, and is managed by the South Khorasan Water Agency. It provides a barrier for water from the Seyahoo River. The catchment area is approximately 3028 Km^2, and the reservoir is 15×10^6 m^3. The dam is torrent control and capable to supplying the needed water for the area of downstream lands and 650 hectares of Doroh lands[13].

Grouting, i.e. pumping of cement grout through drill holes, was performed according to preset pressure thresholds. In Iran, the field of dam engineering geology considers that the Pumping pressure is defined, based on the maxim of additional pressure, increasing about 0.3 MPa per meter depth. The injection pressure accepted for the grout curtain building of the Seyahoo dam foundation was 3 to 12 bar from top to the bottom of the borehole[14].

Table 1 lists the data analyzed for 792 grout holes and 5860 grout sections. The analysis Lugeon includes 148 water pressure tests in 18 Exploration boreholes and 438 water pressure tests in 63 Control boreholes. The borehole diameter is 76–86 mm. The tests were performed with a simple packer system at descending sequence. The test section length varies from 3.00 to 5.00 m, this range being the most common.

The main data set on fractures is from drill core boxes, which implies that the rock foundation quality and their subordinate parts are classified from this data collection. Note that the jointing in drill core boxes is regarded as higher than in situ jointing due to the applied stress during drilling. Measuring true aperture or Orientation of fractures in the drill cores was not viable due to mobility of the cores during drilling and within the storage boxes and the drill cores are not oriented. Locally, the coverage of drill cores is variable. Especially along stretches of un-fractured host rock, drill cores have not been collected and/or stored. Also, where the rock mass has very poor quality, as in fault cores, core lack is usual. To quantify the rock zones, and for plotting purposes, class values of fracture frequencies were pre-set for occurrence of (non-

Table 1. Number of grout holes and grout section at each zone of grout curtain of the Seyahoo dam

Zone	Number of Grout holes	Number of grout sections	Total length of grout holes		Number of Permeability tests
			with Core (m)	Non Core (m)	
(Ex_1-Ex_2)	33-58	402	65	2005	49
(Ex_2-Ex_3)	30-32	248	40	1200	40
(Ex_3-Ex_4)	11-13	96	52	465	23
(Ex_4-Ex_5)	16-22	158	62	730	28
(Ex_5-Ex_6)	16-20	149	60	720	26
(Ex_6-Ex_7)	25-125	670	170	3320	78
(Ex_7-Ex_8)	24-93	625	135	2957	52
(Ex_8-Ex_9)	20-23	176	58	852	24
(Ex_9-Ex_{10})	14-18	136	45	671	12
(Ex_{10}-Ex_{11})	21-25	184	65	855	18
(Ex_{11}-Ex_{12})	77	625	74	3102	38
(Ex_{12}-Ex_{13})	65	530	68	2642	32
(Ex_{13}-Ex_{14})	65	520	65	2580	31
(Ex_{14}-Ex_{15})	65	520	65	2565	38
(Ex_{15}-Ex_{16})	33	327	65	1620	34
(Ex_{16}-Ex_{17})	29	248	65	1222	32
(Ex_{17}-Ex_{18})	29	246	65	1218	31
Sum	**792**	**5860**	**1219**	**28724**	**586**

cohesive) fault rocks, representing breccia (50 f/m) or gouge (70 f/m). All frequencies below these thresholds are measured fracture frequency and values below this level represent actual fracture frequency.

An important challenge in in-situ analysis of rock foundation is the different resolutions of accessible data collection. That is, drill cores expose results on mm to meter scale; while dam data generally covers intervals on meter, in our case with intervals of 5 m. The engineering data, such as the grouted cement is linked with excavation campaigns, generally of 5 m length, setting off a new swarm of drill-holes. The permeability foundations along these holes are unknown but supposed to be more permeable near the tip, in the formerly un-injected 5 m section at the base of the hole. Thus, standard engineering results on grouting can at best be considered viable on 5 m, and can only be regarded exact on 20 m. This lends help to the discussion above, in that jointing zoning of rocks below a minimum 5 m, the threshold may not be revealed in rock foundation data, as indicated for some Features. We stress that these are guiding numbers, rather than exact facts, since the calculations are hampered with significant uncertainty.

Porosity calculations and permeability assessments are, in general, challenged by the heterogenic nature of fracture aquifers, which will flavor interpretations of injection data in a swarm of drill holes. For example, a single long and highly permeable fracture may conduit cement, and thereby trigger injection in a large volume of porous, fractured rocks. Without this fracture, the volume of available porous rock would be significantly smaller[15, 16]. However, even with these uncertainties, it is likely that large-scale in- situ injection data is better representing rock porosity and permeability fields than the up-scaled result of laboratory measurements of selected structures within major rock zones[17], where the flow characteristics of rocks are established through numerical models.

2.1 Grouting Material and Grouting Technology

An important difference between water (used in hydraulic tests) and grout is the rheology. Here, water is referred to as a Newtonian fluid, having the viscosity, μ_w, whereas cement grout, being a particle suspension is commonly described as a Bingham fluid with the viscosity, μ_B, and yield strength, τ_0. It is difficult to give general advice as to how grout should be made up to create the conditions for successful grouting. This is mainly because of the complex interaction between, w/c and use of super plasticizers, etc. in the grout mix[18]. The requirement on grouting can basically be divided into two parts, related to short-term properties or long-term properties. Obviously, the short-term properties are related to that the grout should have good penetration capability. Penetration capability is a general term for the ability of the grout for spreading in cracks and through constriction in cracks. The penetration capability of fresh grout must therefore be divided into two parts, one based on rheology (flow properties), and the other on filtration tendency (plug formation). Both must be optimized to attain adequate penetration of the grout, according to several researchers[19, 20]. The long-term requirements mainly involve the long-term durability of the grout. To meet durability requirements, water separation during hardening and solubility of the grout in the surrounding environment should be observed. Adequate grouting means an age-resistant filling of the geometric space.

Except the grout properties, a number of other areas have also to be rigorous planning of the grouting operation before starting the operation. The main advances regarding grouting technology in the last 10 years are concerned with better registration and controlling of the injection process. New technology has enabled the flow and pressure of the grout-mix to be continuously registered. The basic equipment and technology, however, remains the same[3, 9].

In principal, grouting shows two methods of application, the old, and the new. The older method uses a thin, unstable mix, (considerable water separation) which after transport into the crack plane becomes increasingly se-watered and so creates a plug at some restriction along the crack plane. The newer application method uses a stable mix (limited water separation) from the outset. The method that depends on de-watering the grout to creak a sealing plug is not acceptable, because it is difficult to predict where plug formation takes place. If sealing consists only of the formation of individual plugs, and the remainder of the crack volume is empty or poorly filled, small movements in the rock or concrete structure will be enough to cause leakage through the sealing plug. This older method is something of a paradox because grouts with higher w/c are more difficult to de-water than the more stable ones[19, 21]. The effect of de-watering is to create a plug.

In this study, the cement-based grouts used here were: injection, a Portland cement grout that is sulphate resistant with blain 5000–8000 cm^2/g, and then mixed for 10 min with a mixer using a speed of 1400 rpm. BV super plasticizer was added to some of the cement–water mixtures, 0.3%–0.5% by weight of dry cement, in order to increase the grout fluidity. Following this process, the prepared grouts with w/c ratios 1and 1.25 were poured into the pressure tank and injected into the rock mass. The grout properties are given in Table 2.

2.2 Geological Groutability Index (GGI)

Rock mass classification systems try to consider the most important aspects, affecting the rock mass in order to rate its quality. The aspects, assumed to be independent from each other, become parameters to which ratings are assigned. The most common systems quantify the rock mass quality as a scalar value that is a function, linear or non-linear, of the above- mentioned independent parameters. However, contrary to the term rock mass, the parameters used are not related to the rock mass itself. Stress regime, water pressure, and direction of excavation are examples of parameters employed by various systems that do not characterize the rock mass quality but the construction of the project as a whole. A GGI, marked as F, may, thus, be distinguished as a numerical function of the components jointing spacing and joint hydraulic, i.e., $F = f(BS, JH)$. Equipotential contours may, thus, be drawn in the rock structure-joint hydraulic coordinate system, with the component joint hydraulic as the abscissa.

$$F = f(BS, JH) \tag{1}$$

2.2.1 Rock Structure Component

Block size may be chosen as the common entity, quantifying the rock structure in the various systems. It is related to the discontinuity spacing and the drill core quality. Discontinuities delineate the independent blocks, found in the rock mass. Many authors describe the block size qualitatively and quantitatively[22]. Was the first to classify rock mass into categories defined by the block size? Discontinuity spacing is standardized by ISRM[23], relating qualitative descriptions with numerical measurements, shown in Table 3[24]. Standardized qualitative rock mass structure descriptions with their numerical equivalents, are shown in Table 4.

According to Cai et al.[25], block size in the GGI chart is quantified by the mean discontinuity spacing S or by the mean block volume V_b. For cases, where more than three regular joint sets occur, block volume V_b can be found from the joint spacing as

$$V_b = \frac{S_1 S_2 S_3}{\sin\gamma_1 \sin\gamma_2 \sin\gamma_3}, \tag{2}$$

where S_1, S_2, S_3 are the spacing between the individual joints in each set, and γ_1, γ_2, γ_3 are the angles between the joint sets. For a rhombohedral block, the block volume is usually larger than that of cubic blocks with the same joint spacing. However, Cai et al.[25] states that compared to the variation in discontinuity spacing, the effect of the intersection angle between joint sets is relatively small, and the block volume V_b can be approximated for practical purpose as

$$V_b = S_1 S_2 S_3 \tag{3}$$

Table 2. Grout type, mixing ratio and determined rheology parameters for the grouts used the grouting of the Seyahoo dam

Type cement	Colloid cement (C)	Fine cement (MC)
Specific gravity	2.96	2.93
Specific surface area (cm^2/gr)	5000	8000
Particles with 20 μm or over weight (%)	24	5
Particle size (μm)	G_{50} =9.1 G_{85}= 22	G_{50}= 4.2 G_{85}= 6
Mixing ratio (w/c)	1:1	1.25:1
Additive (%)	BV 0.3	BV 0.5
Density (gr/cm^3)	1.32	1.27
Bleeding (%)	5>	5>
Yield value τ_0	0.5	0.5
Viscosity μ (Pa.s)	0.05	0.05
Compressive strength (Mpa) (28 days)	41–46	44–48

Table 3. Discontinuity spacing descriptions[23]

Discontinuity spacing	Description
<20 mm	Extremely close
20–60 mm	Very close
60–200 mm	Close
20–60 cm	Moderate
60 cm–2 m	Wide
2–6 m	Very wide
>6 m	Extremely wide

Table 4. Classification of block volume[24]

Block volume V_b	Volumetric joint count J_v	Joint spacing S (Block diameter) $S = \sqrt[3]{V_b}$	Degree of jointing or (density of joints)
Extremely large size>1000 m^3	Extremely low<0.3	>10 m	Massive/no joints
Very large size 30–1000 m^3	Very low 0.3-1	3–10 m	Massive/very weakly jointed
Large size 1–30 m^3	Low 1-3	1–3 m	Weakly jointed
Moderate size 0.03–1 m^3	Moderately high 3-10	30 cm–1 m	Moderately jointed
Small size 1–30 dm^3	High 10-30	10–30 cm	Strongly jointed
Very small size 0.03–1 dm^3	Very high 30-100	3–10 cm	Very strongly jointed
Extremely small size <30 cm^3	Extremely high>100	<3 cm	Crushed

2.2.2 Joint Hydraulic Component

Water pressure test or Lugeon permeability test is the maximum general and suitable method in order to determine rock foundation permeability due to the presence of weak planes, such as faults, bedding planes, joints, fissure, and etc[26, 27]. Eq. (4) is the description of the Lugeon value (Lu).

$$Lugeon \quad value = Lu \frac{VP_s}{TP_i L}(1/m/\min) \tag{4}$$

where V is the water take (L), P_s is the standard pumping pressure (9.81 MPa), Pi is the pumping pressure used (MPa), T is the pumping time (min) and L is the length of grout section (m).

The results of the water pressure test are forcefully dependent on the weathering rating, and geometric characteristics of the conductive paths[10, 28]. The core of drilling allows the assessment of the joint aperture through which water flows, but it does not permits for the definition of the joint persistence.

On the other hand, the degree of jointing in the core of boreholes defined by Fracture frequency constitutes the main reference to predict the test section behavior under water pressure test. This classification is often engaged to decide if the test must be done. The degree of joint spacing and the Lu value quantity should be in a direct relation. However, it is Fracture frequency that rock mass areas, having a low degree of jointing, show high Lu values, and even the opposed situation is possible. In this sense, hydraulic quality is defined by the joint hydraulic (JH).

$$JH = \frac{Lu}{F_k}, \tag{5}$$

On the other hand, hydraulic of the water paths[29] has a special importance.

$$F_h = \frac{F}{3}, \tag{6}$$

2.3 Application

For the validation of the proposed GGI chart, project was examined. Rock structure-discontinuity hydraulic conditions ratings and boreholes number are zones that were extracted, following the project: Seyahoo Dam Site, Iran.

The rock mass in the foundation consists of strongly tectonized Miocene-Oligocene andesite, agglomerate, massive or vesicular basalt and fractured pyroclastic breccias. This dam was foundation mainly in weak rocks that were classified as blocky/ disturbed, disintegrated and foliated/ laminated/ sheared rock using the GSI system only (Figure 1). On the basis of GSI classification, rock foundation quality is 20% very blocky, 25% blocky disturbed, 30% disintegrated, and 25% foliated/ laminated/ sheared. Figure 2 depicts Visualization of Joint Hydraulic (JH) for the profile-section in axis Seyahoo dam. This figure compared the degree of jointing (FF) and the water-absorbed quantity (LU) with JH.

Dam Grout Curtain started in spring 2008, and was completed during the winter of 2013. "For published work on the Seyahoo dam, refer[14, 30]. In the Seyahoo dam's grout-curtain building, the boreholes were of the split spacing method. Split spacing means that the boreholes were ordered in the sequence of primary, secondary, tertiary and quaternary holes. Complementary boreholes may be added to enhance the locations with more fractures in the rock foundation or near the boreholes that required more grout take. Basically, the embellishment of boreholes was based on the quality of rock foundation. In the Seyahoo dam, the grout holes were arranged at intervals of 0.16 to 1.25 m. When the injection process of a specific hole lasts for 10 min, the amount of grout take does not reach 10 L; the injection for this section should be stopped. Finally, the drill inspection holes used for performing the water pressure test to check the permeability of the rock foundation were improved. The process of injection in each section was ordered in the following arrangement: drilling, washing, hydraulic testing, and cement grouting. During hydraulic testing, the water pressure tests need to be performed to obtain the Lugeon value, which gives the permeability of that specific grout section. Each section had data collection, such as zone, sequence and borehole depth, length of grout section, rock fractures, Lugeon value, grouting pressure, grout take, and number of boreholes. Dataset were accumulated from the inspection chart of the grout curtain building for the Seyahoo dam in 2013[14]. Afterward, all the data collections were entered into Excel application software for computations before the analysis began.

Figure 3 shows Visualization (interpretational 3-D isometric map) of the GGI indices system by the data analyzed at Seyahoo dam. The analytical spread of this study covers only blocky/ disturbed, disintegrated and foliated/ laminated/ sheared rock with a joint hydraulic lower 4. For the facilities of analysis, this research has accepted the symbol GGI to display the GGI of a grout section. This apart, because the numbers of the boreholes analyzed were not the same (between 11 and 125 number), the boreholes of a grout section was divided by its distance to obtain the GGI per unit length GGI (n/m).

3. Results and Discussion

3.1 Interpretation of the Results Geological Groutability Classification Criteria

At present, it is widely agreed that the Lugeon test can induce modifications in the degree of jointing[9,31,32]. In rock layers deeper into the underground, the fractures are

Figure 1. Core barrel samples in Exploration borehole (Ex_{14}).

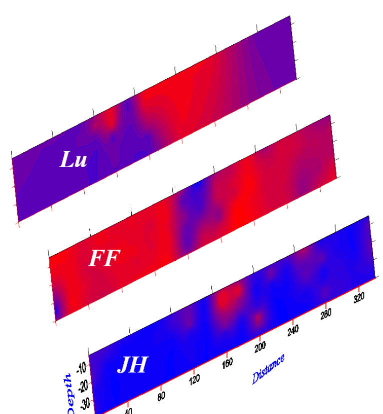

Figure 2. Visualization of Joint Hydraulic (JH) for the profile-section in axis Seyahoo dam.

tight and comparatively do not take in cement because of the greater tectonic stresses in lower elevation. When the geological stress is derived into consideration, the Joint Hydraulic (JH) of the grout section is considered as one of the factors that affect GGI. Thus, groutability designation, like rock fracture quality definition, requires that these modifications must be properly identified. The BS-JH parameter permits this stage to be carried out. These changes modify the GGI.

The test section can be considered inscrutable when the water pressure test is equal or less than one Lugeon Unit[3,6,9]. But a greater water take (i.e., 8 LU) is necessary different considerations about ground treatment. If the test section shows a low degree of jointing, the presence of the least one joint of very high conductivity is deduced. If the test section is highly fissured, the presence of least one joint of very low conductivity is deduced. Under this conditions and following the considerations about ground treatment, a different ground treatment is recommended. The rock mass groutability quality of the dam foundation has been defined from GGI, which allow for the determination of different zones that require a separate treatment. The final objective is that accurate sealing of the water paths be guaranteed.

3.2 Discussion

The chart (Figure 4) follows the GGI concept of a rock structure ordinate and a discontinuity hydraulic condition abscissa. Moving from left to right in the chart, discontinuity hydraulic quality is increasing. Moving from up to down, interlocking of rock pieces is also decreased. Overall, GGI quality is decreasing from very good quality in the upper left of the chart to very poor quality in the bottom right. A number of equipotential contours are also drawn to help the reader visualize better the relations among them. Nevertheless, in all circumstances the user must initially calculate the ordinate and abscissa components to arrive at an estimate of the GGI.

For the estimation of the F_{GGI} index the user may directly evaluate the index from the GGI chart. The index may also be evaluated more objectively by establishing the appropriate rating pairs. The pairs may be either SR (or J_v) as ordinate and JH as abscissa, or V_b as ordinate and JH as abscissa. Some contours of F_{GGI} are drawn in the chart.

4. Conclusions

Generally, the injection of the rock foundation requires the rock fracture, separated in area with different ground improvement. The GGI based on water flow through fractures, permits zoning the rock foundation regarding various quality categories. This index determines the rock fracture quality based on the characteristics of the fractures, present in the test section. In the interim, it is

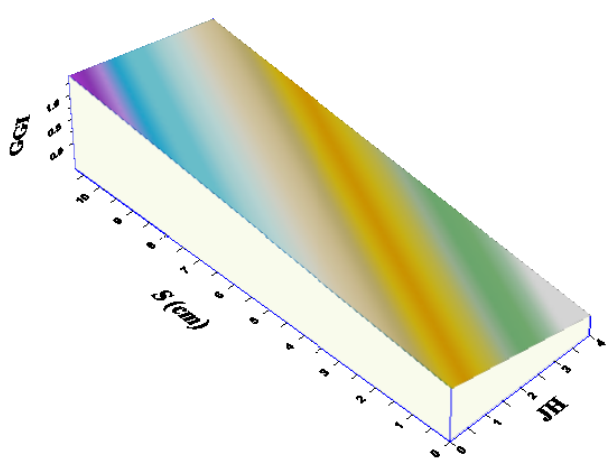

Figure 3. Visualization of the GGI indices system by analyzed Seyahoo dam.

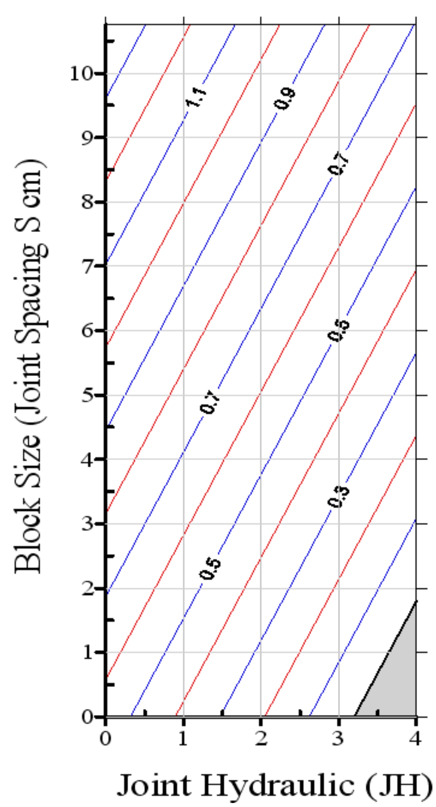

Figure 4. Quantification of GGI chart.

possible to design a ground improvement conformable to the particularities of each zone. As a result, a maximum benefit can be obtained from injection operation.

Parameters in these systems are those concerning rock structure, and joint hydraulic condition. The rock structure chart was used as the ordinate together with the joint hydraulic one as the abscissa of a coordinate system. Equipotential contours indices are drawn in this system. The paper offers determination of the GGI indices by employing the most handy ratings or descriptions available by the user.

The selection charts that were the main objective of this research are applicable in the design and homogeneity of measured data in projects. This index represents the geological groutability quality.

Therefore, the proposed charts provide a means for consistent groutability characterization, improve the utility of the geological groutability systems, and may be suggested for use.

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