Evaluation of geological properties of rockmass of Loktak downstream damsite with emphasis on its groutability

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Abstract

Successful application of grouting requires thorough knowledge of geological conditions, a great deal of experience and an awareness of equipment capabilities and limitations. In order to ascertain groutability of the overburden and bedrock in relation to its permeability, groutability test is a standard practice in the Dam area of Hydropower projects during investigation stages. It is an important tool for determining the sensitivity of the bedrock to grouting required for design of grout curtain during construction stages. The study area selected is Loktak Downstream project on river Leimatak in Manipur due to its unique topographic and lithological features. The topography of the area depicts an asymmetrical profile with wide valleys on left bank and linear ridges on the right bank along dam axis indicating structural control. The area is under the influence of regional axial fault trending along Leimatak river which is evidenced from the encounter of angular caughtup pieces below bedrock in two boreholes on the right bank. The lithology of the dam area comprises of fine grained sandstone intermingled with shale belonging to Disang group of Tertiary age. The rock is highly fractured meaning permeability of the bedrock is governed by high frequency of joints. The main aim of this study is to determine the significance of geological properties of rockmass such as rock type, mineralogical composition, RQD, frequency and aperture of the rock joints in controlling the permeability which in turn governs groutability of the bedrock. Correlation between depth of bedrock and permeability, interpretation of flow conditions, depthwise comparison of grout consumption and lugeon values have been attempted. Efficacy of grouting is analyzed from the results of pre and post grouting permeability.

Keywords: *Groutability test, Permeability, Loktak Downstream, Geological properties*

1. Introduction:

For many engineers grouting is considered an art rather than a science. Its successful application requires a great deal of experience, thorough knowledge of geological conditions and an awareness of equipment capabilities and limitations.The process of grouting was primarily developed as a technique for making vertical seepage barriers beneath dams and hydraulic structures and is an essential tool to prevent leakage of water through fractured rocks or porous materials of a dam foundation and avoid negative seepage pressure in borrow materials.

For effective utilization of grouting technique, thorough knowledge of the geological conditions of rock masses (lithology, strength of the rock, distribution of primary and secondary discontinuities, quality and strength of the joint-filling material) and their permeability conditions (Sadeghiyeh et al. 2012) are required.

The dam body and foundation seepage are one of the most important points in design parameters. The decision to install a grout curtain depends largely on the results of water pressure tests (WPTs), as introduced by Lugeon (Ewert 1997c).The focus of this study is to evaluate a correlation between engineering geological properties and groutability of the rockmass based on case study of Loktak Downstream Hydroelectric project in Manipur as depicted through a flow chart (Fig.1).The geological and permeability conditions of rockmass were evaluated based on surface and subsurface investigations through geological mapping, drill hole logging and water pressure tests in the drilled holes.Groutability testswerecarried out in the left abutment of dam site of the project to assess the response of in-situ rock mass to the process of grouting. The permeability conditions were then assessed basedon hydrogeologicalbehaviour and P–Q diagrams werederived from WPTs infour groutabilityholes.Finally, groutability was evaluated based on permeability [Lugeon value (LU)], geological conditions [rockquality designation (RQD)] and cement intake (CT).

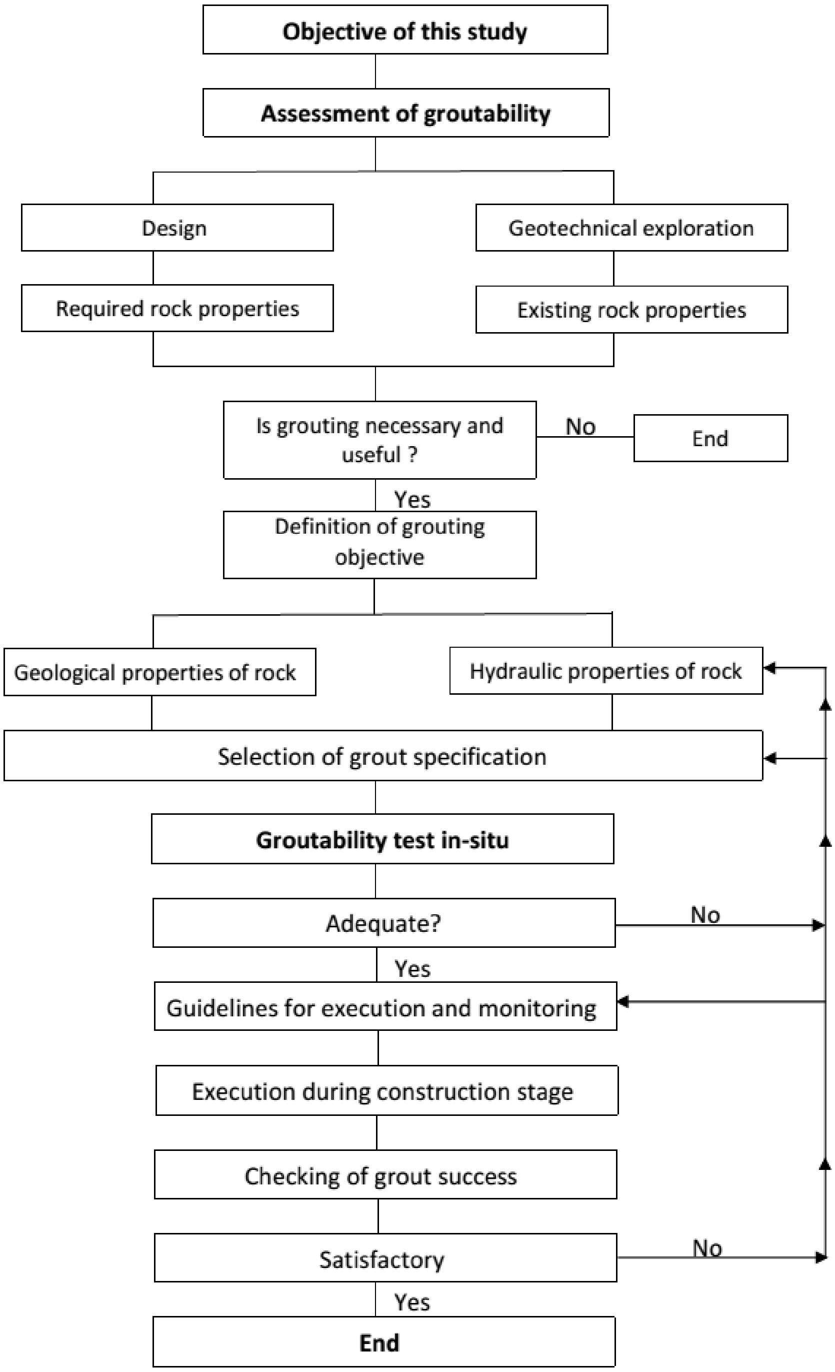


Figure 1 Flow chart for design and execution of grouting (modified after Widmann, 1996)

2. Salient Features of the Project Area:

The proposed Loktak Downstream Hydroelectric Project (LDHEP) is a run of river schemelocated on the river Leimatakin district Tamenglong in the western part of the state of Manipur (24º44'00"N Latitude and 93º35'25"E Longitude)about 22km downstream of the powerhouse of existing Loktak hydroelectric project.The project envisages construction of 20m high dam(river bed El. ±289.0M) across Leimatak riverand river discharge will be diverted through a 5.85km long head race tunnel (HRT) into Irang river through tail race channel (river bed El. ±159.713M). Asurface powerhouse is proposed to generate 66MW comprising two units of 33 MW each, driven by vertical axis Francis turbines with an overall efficiency of generation 90%. The yearly energy generation during the 90% dependable year with 95% machine availability is 330.24MU. The project is scheduled to be completed within 78 months. The location map of the project and detailed layout planis shown in Fig. 2.

3. Regional Geology of the Project Area:

Topographically, Manipur valley is a flat elongated basin extending over an area of about 50km by 50km with an average elevation of 750M. Rugged hill ranges trending North to South surround the valley on all sides. The area lies within the Naga-Lushai-Patkai orogenic belt of Tertiary age. The area constitutes a part of NNE-SSW trending western hill ranges of Manipur, representing the young fold mountains. Prominent perennial tributaries like LonggeLok nala and SupangThok nala contributing its discharge into Irangriver and Leimatak river respectively, control the drainage network of the area. Extensive meandering of the Leimatak river alongwith reversal of dip ofrockmass onitseitherbankreveals thatthe region is structurally controlled (ref. Fig.3a&b).The project area is located within Disangand Barail Group ofLesserHimalayas.The contact between Disang and Barailis gradational and its traces cut across HRT in its middle part. Disang formation comprises of shale and sandstone. The dam and part of HRT are located in this formation. The downstream part of HRT and powerhouse complex is located within Barail Formation. This formation comprises of sandstone with bands of shale and siltstone (ref. Table 1).

4. Climate and Rainfall Pattern:

The state of Manipur where Loktak HE Project is situated has a humid subtropical temperate climate which receives occasional rainfall throughout the year. Heavy rainfall is generally confined to the period of south-west monsoon from end of May to September.

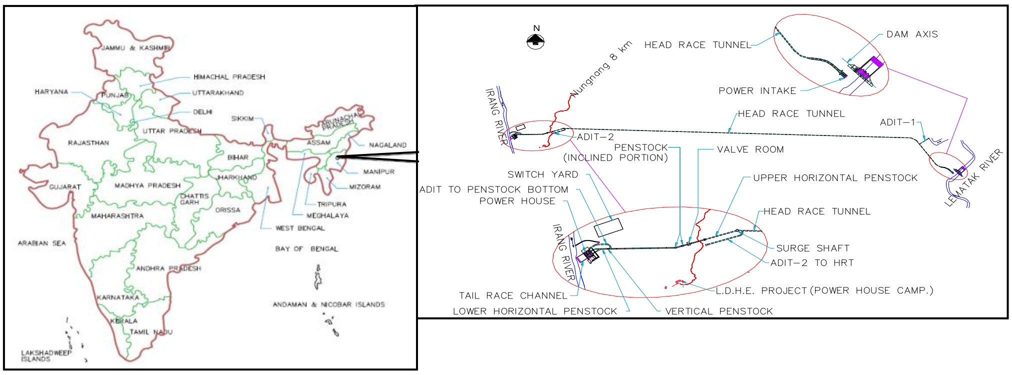


Figure 2 Salient feature of Loktak DS project (NHPC DPR, 2016)

Table 1
Geological Succession of Loktak HE Project, Manipur

Age	Formation	Lithology
Recent	Alluvium	Sand, silt, mud and clay.
Oligocene	Barails	Flaggy sandstone, coarse bedded with sandy shale.
Eocene	Disangs	Dark to grey splintery shale intercalated with fine grained sand stone, occasionally carbonaceous shale.

5. Geological Setting of the Dam Area:

Earlier 64.5m high earth dam was proposed at a distance of 2.80km downstream of present Dam axis. In order to make the project more viable, a barrage was envisaged in place of earthen dam. After detailed site investigations, a concrete gravity dam of 20m height in place of barrage has been proposed.

Dam area exhibits anunique geomorphic feature.Topographic layout depicts an asymmetrical profile with wide valleys on either side of linear ridges. The left bank of the Leimatak river along dam axis, depicts a wide valley with elevation as low as the level of the river while its opposite bank represents steep ridges upto a height of more than100m from river level. These unique features are also expressions of some structural control and geologically these low lying valleys alternated with ridges may represent weak zones that have undergone more erosion and denudation than the adjoining ridges.

Detailed field investigations in the form of topographic surveys, surface geological mapping as well as subsurface geological investigations by drilling & geophysical studies were carried out by adopting standard methodologies. Apart from these, other investigations including remote sensing studies, regional geologicalstudies, petrographic studies, seismotectonic studies, laboratory & in-situ rock mechanics tests and construction material survey were carried out in dam and appertunant structures.
In the dam area, rocks are generally weak to medium strong with exposures of sandstone with shale on both the abutments. The rock is slightly weathered to fresh and moderately to closely jointed. On the left bank river bed portion along dam axis, the bed rock is about 9m deep as deciphered by exploratory drilling. On the right bank, continuous rock outcrop is exposed upto a height of 5 to 6m from river edge. The rock units show reversal of dip on either bankalong Dam axis indicating a non-plunging antiformal fold with opposite dipping limbs on left and right banks and fold axis running along the river alignment.

The existence of fault is also manifested in the regional structural and lineament map of Manipur where Pen fault running along the Leimatak river alignment in the present dam area is shown. The surface topography of extensive meandering of the river alongwith unpaired river terraces also signifies the presence of structurally controlled features. The geotechnical mapping carried out from limited outcrop revealed presence of three prominent and few random joint sets (Table2).

6. Assessment of Rockmass Groutability:

6.1 Deterministic approach:

The rock mass may be considered as an amalgamation of discontinuities with geological, mechanical and hydraulic properties.For determining the adequacy of rock for grouting, extensive in-situgeotechnical and hydrogeological investigations are required. The designer also provides preliminary guidelinesfor the grouting operations: the required and permissiblegrouting pressure, borehole spacing and then finally derive a specification for grouting (Widmann,1996). The specifications thus derived are then monitored during implementation and modified as per actual site conditions. This procedure is depicted in a flow chart (Fig. 6).

Table 2
Joint details and rock characteristics of Dam area

Joint set	Av. Orientation		Persistance	Roughness	Spacing	Aperture/ Filling	Remarks
	L. Bank	R. Bank					
S1	270-300/40-80º	110-130/60-87º	VeryHigh	Slightly Rough	Moderately toclosely spaced	Tighttoopen atplaces	Overallrock is moderately toclosely jointed
S2	110-130/50-70º		High	Slightly Rough	Closely Spaced	Tighttoopen atplaces	
S3	025/55-85º		Medium	Rough	Moderately	Tighttoopen atplaces	
Random	330/65-80º		Low	Rough	Moderately toclosely spaced	Tight	

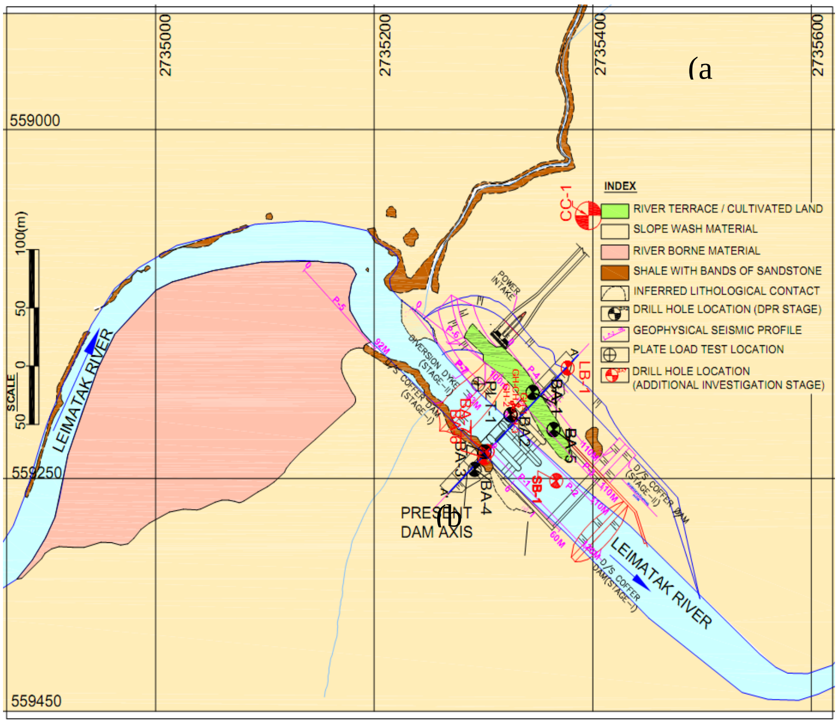


Figure 3a Geological Plan of Loktak DS Dam area(NHPC DPR, 2016)

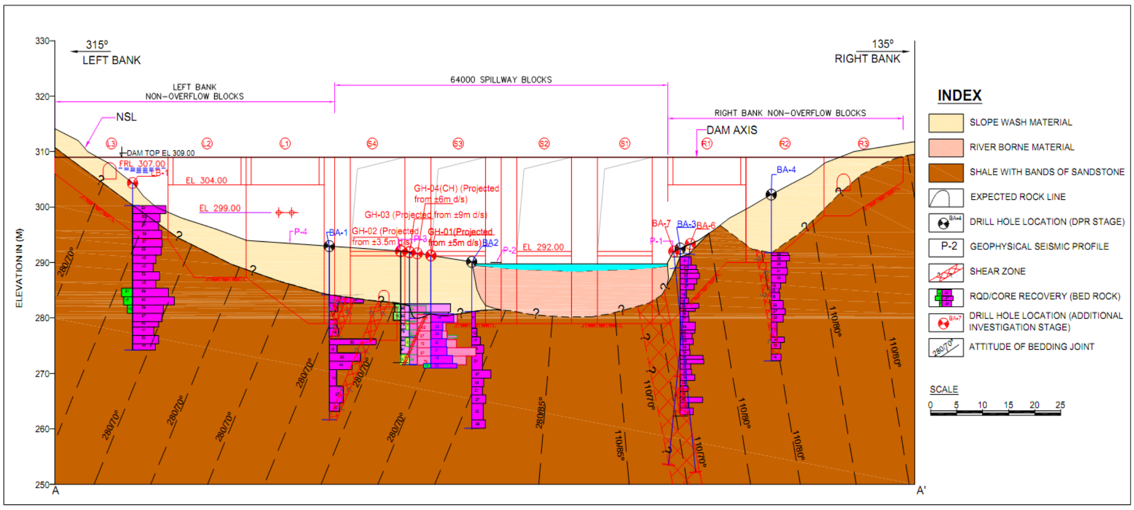
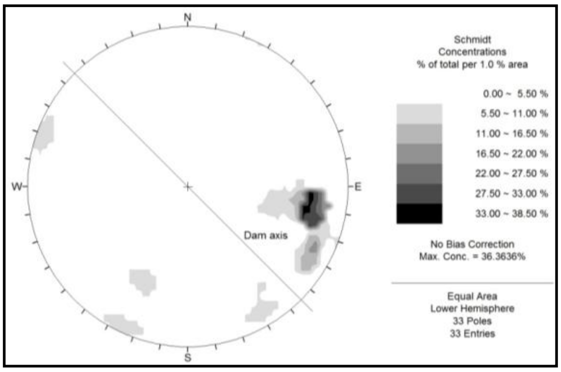


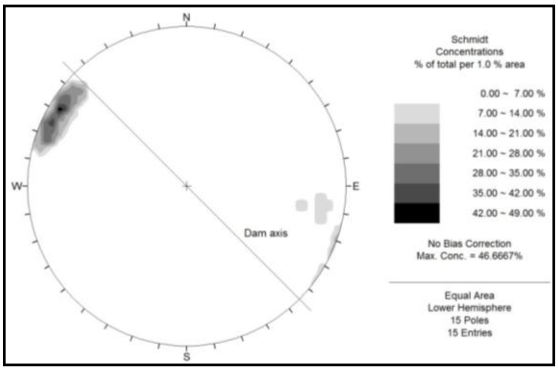
Figure 3b Geological cross-section of dam axis showing RQD and Core recovery in percentage in each drill holes (NHPC DPR, 2016)

6.1.1 Determination of geotechnical parameters:

The structure of therock not only determines its mechanical behaviour,but perhaps even more its permeability and groutability.The orientation of joints (ref. fig. 4 & 5-Stereographic projection of major joint sets in left and right abutment along dam axis), RQD/core recovery in the rock mass influencesthe permeability, hence the groutability. Deterministic description of the structure and discontinuities has been found helpful in assessing in-situconditions.Quantitative approach has been used in determining geological characteristics of rockmass in terms of RQD and following discontinuityparameters-Orientation,Spacing/frequency, Outcrop length/joint dimension, Roughness, Opening widths and Fracture intensity to derive a relationship between fracture frequency and efficacy of grout.

Core recovery (CR) and RQD (Rock QualtiyDesignation) of the rockmass have been determined from subsurface exploration carried out through drilling of nine no. holes in the dam area including Groutability holes. Holewisedetails of RQD, core recovery and permeability are given in Table 3.





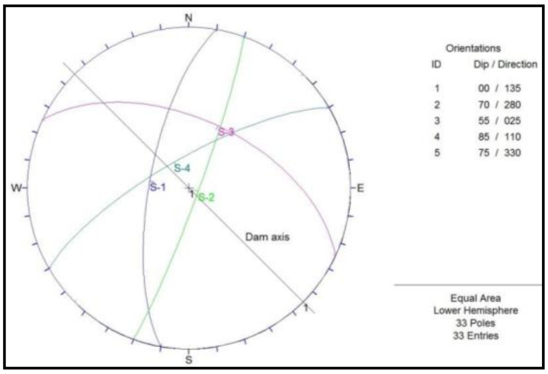


Figure 4 Stereographic projection of left abutment of joint sets

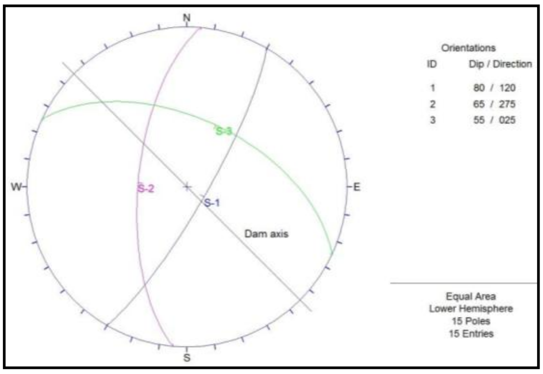


Figure 5. Stereographic projection of right abutment of joint sets

6.1.2 Determination of hydraulic properties:

The groutability of the rock mass dependson its hydraulic properties which in turn isgoverned by the system ofcavities and joints.For many structures in or on rock, it is important to know the wayin which water flows through crevices such as bedding joints,joints or the pores of coarse-grained rocks suchas sandstone. An initial estimation of the permeability ofthe rock mass can facilitate the selection of the mosteffective test method.In dam area of Loktak DS, permeability tests in bedrock were performed in ten drill holes (including Groutability holes) by water pressure test (WPT) method and in two drill holes by constant head method. The methodology adopted for computing permeability test in bedrock was in accordance with IS:5529 Part-II.

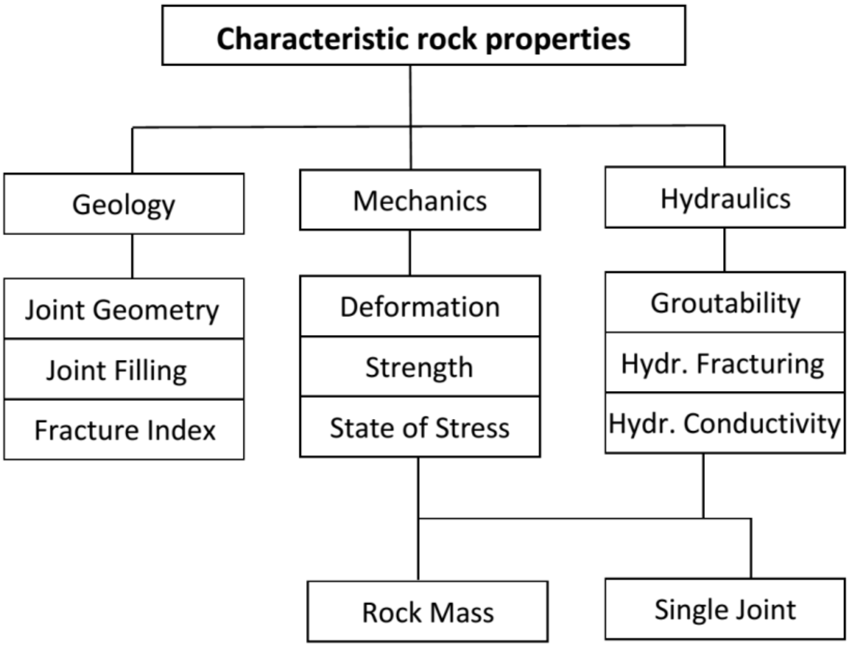


Figure 6 Flow chart depicting rock properties necessary for assessing groutability (Widmann, 1996)

Table 3
Statement showing RQD, CR and Hydraulic Conductivity of bedrock in dam area, Loktak D/S (NHPC DPR, 2016)

Area	Bore hole No.	Location	RQD (%)	Avg. Core recovery (%)	Av. Permeability/ Hydraulic conductivity	Remarks
Left bank	BA-1	Dam Abutment	0-7	15-30	(7.45-26.74) x10^{-3}cm/sec	Permeability determined through constant head method
	BA-2	Dam axis	0-6	17-30	(6.07-32.37)x10^{-3}cm/sec	
	BA-5	D/s of Dam axis	0	3-30	24 Lugeon	Permeability determined through WPT method. Permeability of GH-4 determined after grouting of GH-1,2 &3
	LB-1	Dam axis, Left abutment	10-21	40-80	----	
	GH-1	U/s of Dam axis, Left bank	14 in one section only	22-50	1.21-15.36 Lugeon	
	GH-2		11-14 in two sections only	73-96	7.94-32.96Lugeon	
	GH-3		7-19	32-92	1.06-1.49 Lugeon	
	GH-4		0	55-97	0.06-2.23 Lugeon	
Right bank	BA-3	River edge, Dam axis	19 in one section only	16-45	1 Lugeon	
	BA-4	Dam Abutment	8-11 in two sections only	11-35	11-42 Lugeon	
	BA-6	Angular Hole	8-32	73-98	17-29 Lugeon	
	BA-7		7-26	92-99	18-21 Lugeon	
River Center	SB-1	Stilling basin	7-44	65-99	1-18 Lugeon	

6.2 Groutability Test:

As mentioned in sec. 5 above, damsite of Loktak D/S project predominantly consists of highly fractured sedimentary rocks such as sandstone and shale. Sandstone is known known for its porosity and the shale although generally impermeable but may develop permeability due to its fractured nature.Since the exploratory drillholes in damsite reveal such fractured nature of rocks extending upto the dam foundation, they need to be strengthened by grouting during construction of dam. In order to assess the acceptability of the rock mass for grout, groutability tests were carried out at dam site.
Three 20m deep drill holes were drilled to assess the permeability of the bedrock at three apices of an equilateral triangle of side 6m. During the entire drilled depth of all the three drill holes, bedrock encountered consists of fine to medium grained sandstone with laminae of shale.Permeability tests were performed by water pressure test (WPT) method with single packer in bedrock progressively with drilling to obtain pre and post groutingpermeability values. After completion of drillingand permeability test, grouting with cement and water componentwas carried out as per IS code 6066-1994.After completion of grouting, a check hole was drilled at the centre of the triangular network of grouting holes as shown in Fig.10to ascertain efficacy of grouting process.

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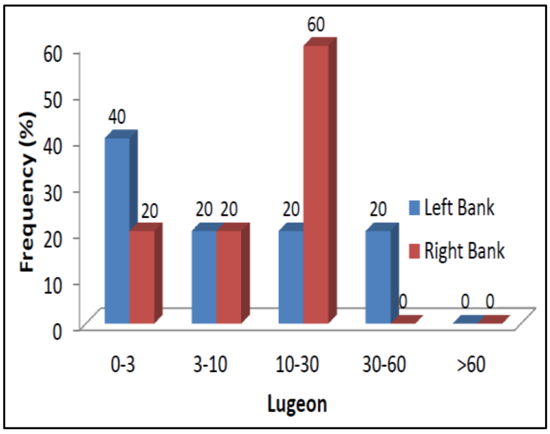

Figure 7. Frequency distribution vs. Lugeon fordrill holes in left and right bank

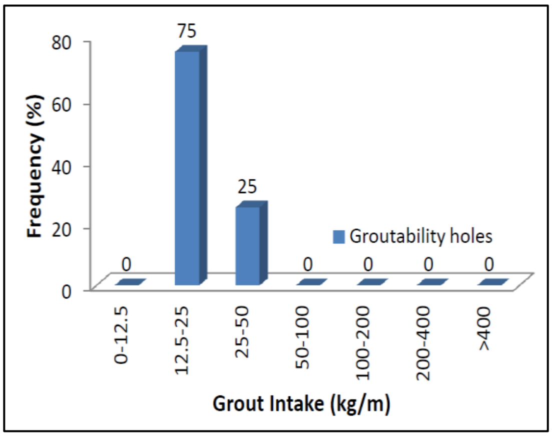

Figure 8. Frequency distribution vs. grout intake for groutability holes

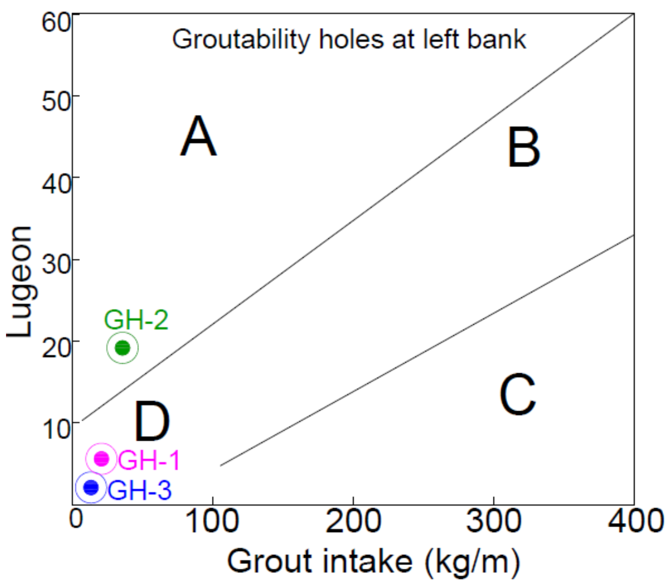

Figure 9 Plot of Lugeon vs. grout intake on Ewert (1985) graph; **A**-large WPT rates, little takes-fine fissures, **B**-approx. proportionality between WPT rates and grout takes, **C**-small WPT rates, large takes-hydraulic fracturing, **D**-too little takes not worthy to be grouted.

6.1.3 Procedure of Groutability Test:

Grouting was carried out in ascending order with length of each stage of grouting test section restricted to 1.50m in bedrock.The maximumpressure is kept below the overburden pressure so as to avoid any chances ofhydrofracturing / forced opening of weak joint surface. The grouting was started withcement/water ratio of 1:5, i.e. 50 kg of cement in 250 litres of water and depending upon thegrout intakeis abnormally high at relatively low pressure,cement/water ratio was increased to 1:4 and finally to 1:2 or lowermaking the grout more viscous. The maximum limit of the rate of intake was kept at 20 l/min for a period of 10 minutes. The limiting pressure was varied from 3.0 kg/cm^2 to 4.0 kg/cm^2 depending on the grout intake and categorization of the strata so as to achieve grout refusal till the maximum allowable pressure.

6.1.4 Drilling and Grouting sequence:

Initially, groutability hole GH-1 was drilled followed by GH-2 and GH-3 in same order. In-situ water permeability of bedrock was ascertained progressively with drilling by single packer method / double packer method. The drill hole GH-2 was the first hole to be grouted. After completion of grouting in GH-2, water permeability of the rock mass was determined in GH-1 & GH-3 respectively. This was followed by grouting of GH-3. Again bedrock permeability was determined in GH-1 by double packer method and finally GH-1 was grouted in the ascending order. After completion of grouting of all the three holes, one test hole GH-4 was drilled at the centre to check the effect of grouting on in-situ permeability of the bedrock by carrying out water permeability test by single packer method in descending order progressively with drilling. Post-grouting lugeon values were compared with the lugeon values obtained during pre-grouting stage vis-à-vis cement consumption. A comparison of pre-grouting i.e. primary permeability of the bedrock and post grout permeability vs. depth for each holeis presented in Fig. 12.

Figure 10 Location of groutability holes at left bank, Loktak D/S dam site

6.2 Interpretation of Groutability test results:

From the comparison of the lugeon values of all the holes including the test hole(GH-4) as shown in table 3, it is evident that pre-grouting water permeability ofbedrock is more in GH-2 than in GH-1 and GH-3. However, theprimary permeability values in the beginning and towards end of the hole has beenrather erratic and higher (ref. fig. 13). Average bedrock permeability values vary from 1-15 Lugeon in GH-1, 8-33 Lugeon in GH-2 and1-1.5 Lugeon in GH-3 except at few test sections in all the four holes where high permeability values were obtained due to highly fractured nature of bedrock.

In few test sections, permeability values could not be determined due to leakage of water as well as packer could not be fixed to the bedrock due to its highly fractured nature.The permeability value of check hole GH-4 ranges from 0.06-2.23 Lugeon. Thus, post-grout lugeon values when compared with the pre-grout lugeon values, shows a significant decrease in the permeability indicating positive impact of grouting. The grouting was able to bring down the in-situ bedrock permeability considerably. This is further supported by the comparison of plot of averagepermeability prior to grouting and post-grouting permeability as obtained in the check hole GH-4 and shown in Fig. 12(a)-(d). Fig.12(d) also shows the corresponding average cement consumption, which has resulted in permeability reduction.

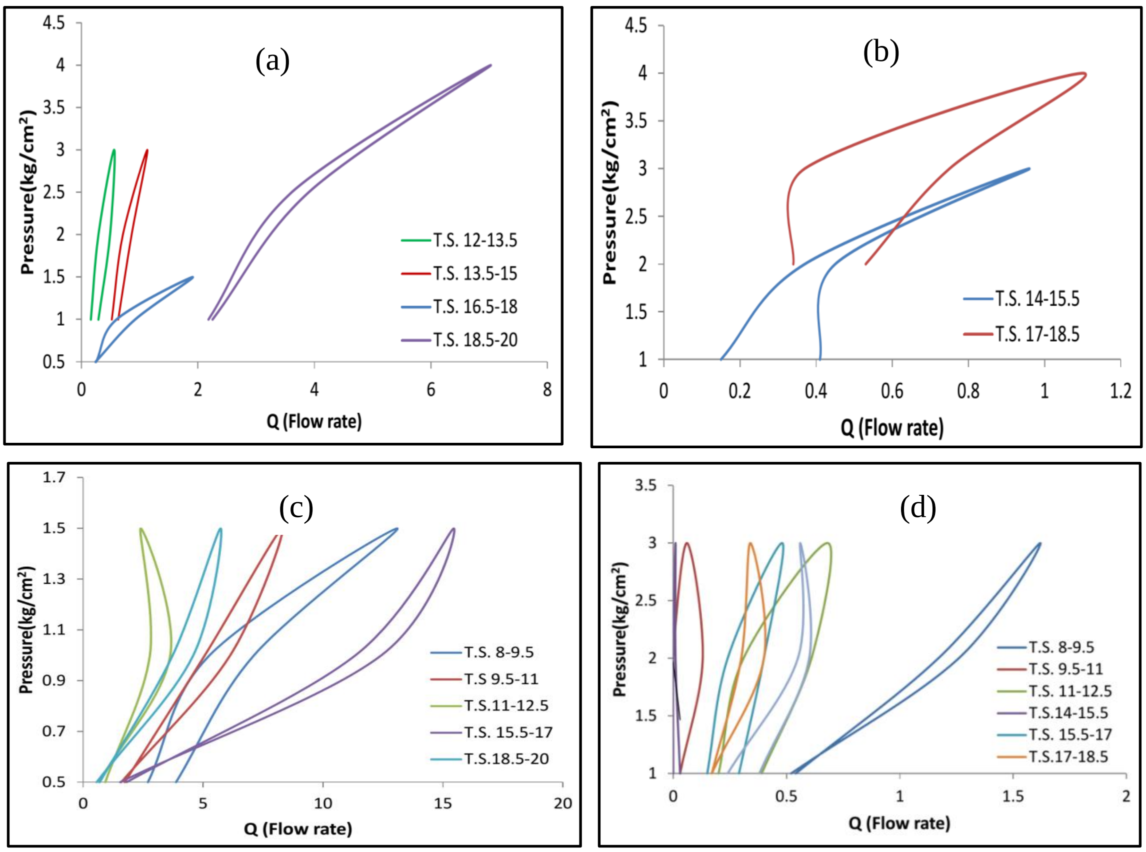

Figure 11. Relation between pressure (P) and flow velocity (Q) of water pressure test of (a)GH-1, (b)GH-2, (c) GH-3 and (d) GH-4

7. Conclusions:

Water leakage through the foundation and abutments of a dam which is built on fractured formations,is one of the most important challenges of the dam construction and operation.Based on available drill hole data of Loktak DS damsite, joined strata with intermittent fractures is likely to be encountered in dam foundation. As mentioned above, the right bank river edge holes have encountered 4-5m thick shear zone. Based on surface data, antiformal fold has been established, having both banks dipping in opposite direction with axial plane following the course of river (Fig. 3b). Under such geological scenario, thorough investigation is required at the time of foundation excavation and suitable treatment measures in the form of grout curtain is a mandatory for stability of the dam.For effective grout curtain design,groutability test is a prerequisite.Forevaluating groutability of a rock mass in a more objective manner, in addition to its relation with permeability, geological andlithological characteristics, cementintake, etc. have also an impotant role to play (Goodman et al.,1964, Barton et al., 1985).

In the present paper, a deterministic approach has been attempted to assessgroutability of rock strata in dam area of Loktak DS project in terms of its relationship with geological and hydraulic characteristics of the rockmass.Following conclusions are drawn from the study:

(i) Ewert's (1985) qualitative method has been used to interpret the relationship between groutability and permeability in the dam foundations. Permeability in terms of Lugeon values are plotted in Fig. 9 over the groutability values in terms of cement intake, for all groutability holes.Following the qualitative separation of different Ewert'sclasses, the lines dividing the four Ewert groups are also graphed in Fig. 9.It has been found that groutability holes GH-1 and GH-3 are falling in Class D whereas GH-2 is falling in Class A.Thus higher Lugeon value and low grout intake in GH-2 indicates that water can pass through thenumerous fine fissures in the rock, but the corresponding grout is not permitted whereas in case of GH-1 & GH-3 low lugeon and grout intake valuessignify thatinspite of high fracture frequency, water and grout couldn't pass through the rockmass.

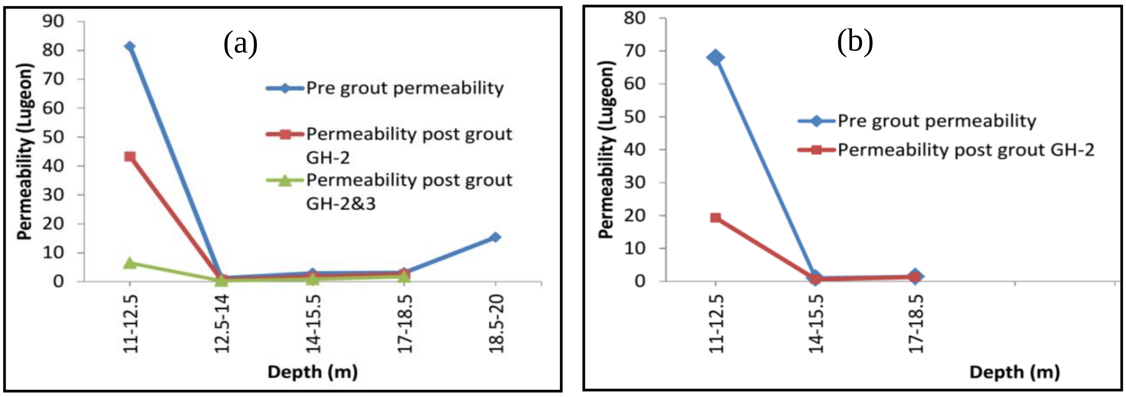

Figure 12 . Comparison of pre and post grout permeability of Groutability holes (a) GH-1, (b) GH-3

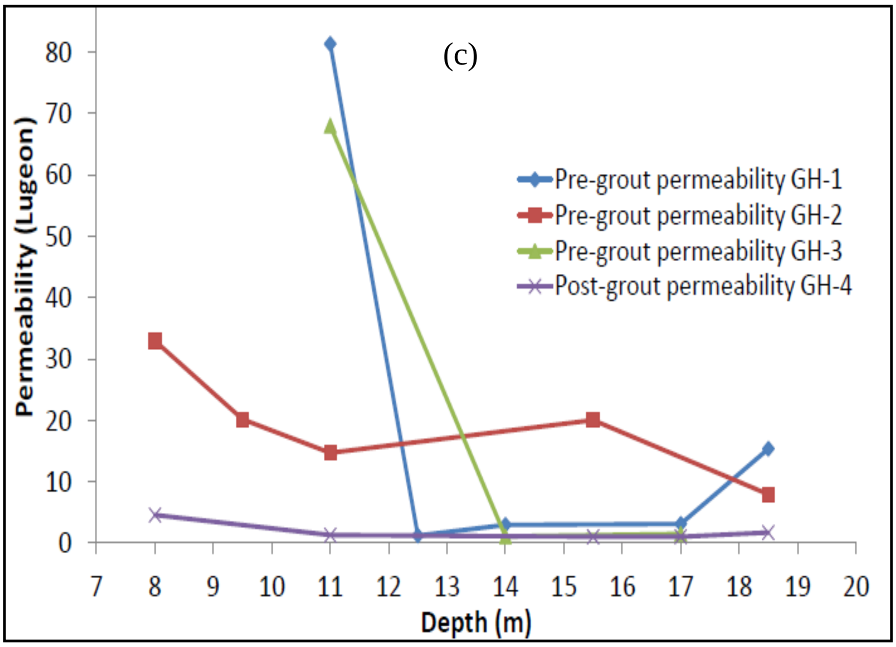

Figure 12(c) Comparison of pre & post grout permeability of Groutability hole GH-4

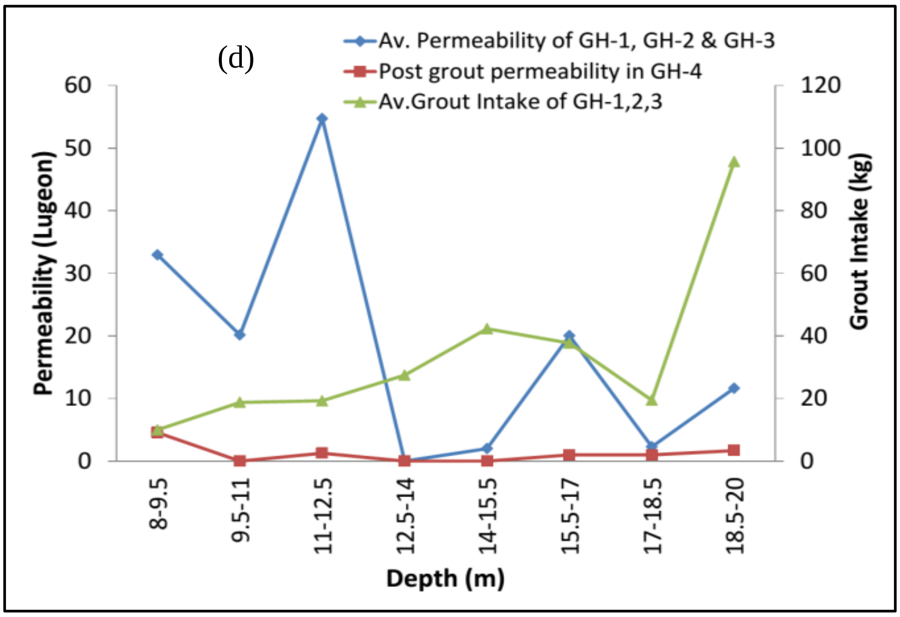

Figure 12(d) Comparison between av. permability and grout intake

(ii) The pressure-flow relationship (P-Q plot) (Fig.11a-d) provides useful guidance on the properties of therock mass (Widmann, 1996). From P-Q plot derived for each test section of four groutability holes (GH-1 to GH-4), it was found that rate of flow shows a non-linear relationship with pressure cycle. This shows erosion of joints in the rock with increase in pressure.In few test sections (e.g. T.S. 9.5-11, 11-12.5 and 18.5-20 of GH-3 and T.S. 8-9.5 of GH-4), erosion of joints have led to hydrofracturing.

(iii) The frequency distribution of Luegon (Lu) values from the water pressure test results grouped separately for the left and right abutment of the dam following the classification of Ghafoori et al. (2011). Fig. 7 shows correspondingbarplots of the frequency distribution of the Luegon values. Maximum limit of permeability is kept at 60 Lugeon. It has been found that 60% of holes in right bankare showing permeability values in the range of 10-30 lugeon whereas 40% of the holes in left bank areshowing permeability values in the range of 0-3 lugeon thus showing rockmassin right abutment is more permeable than that of left bank.

(iv) Since groutability test has been carried out in left bank only, frequency distribution of grout intake of the groutability holes was carried out following Deere (1982) classification keeping maximum limit of grout intake at 400 kg/m (ref. fig. 8) . It has been found that 75% of the holes show grout intake between 12.5-25 kg/m whereas rest 2% show grout intake between 25-50 kg/m.

(v) A pictorial comparison between RQD, lugeon value and grout intake have been made depthwise as shown in Fig.13. RQD values could be deciphered in very few test sections which depict that rock mass is intensely fractured. This can be clearly identified from the corresponding pictorialrepresentation of cores recovered from each groutability holes. Lugeon values more or less show a decreasing trend with depth although correlation between lugeon values and grout intake was found to be erratic and thus couldn’t be established.

(vi) From analysis of pre and post grout permeability values, it has been found that post-grout permeability values show a significant decrease indicating positive impact of grouting (ref. Fig.12).

(vii) From overall analysis, the rock strata is found to be suitable for grouting. Since the pre-grout permeability value in many test sections exceeds 3 lugeon, provision of a 20m deep curtain grout in dam foundation has been proposed in Dam design.

8. Limitations of Groutability test:

From the overall experience of Groutability test practised in different hydropower projects around the world, it has beenfoundthat the main obstacle in developing arigorous theory of grouting is the heterogeneity of theground. Although grout specifications have been selected based on detailed geological and hydraulic properties of the rock, experience confirms that itis not always possible to compare the results of RQD, fracture frequency and water pressuretests to the behaviour of the grout in the same borehole. Often, there is no proportionality between thetransmissivity and the grouting rate or the grout intake (Widmann,1996). One has little option, but to accept the validity ofindividual grout tests, thereby assuming again auniformity of the ground. It has to be accepted thatregrouting may be needed in some areas.It may be possible to reduce the bedrock permeability further upto the desired level by performing second stage grouting.

Grout intake not only simply depends on fracture frequency or RQD but also on interconnection between joints and fractures. Therefore a way out could be taking into consideration groutability tests and applying experience based judgement.

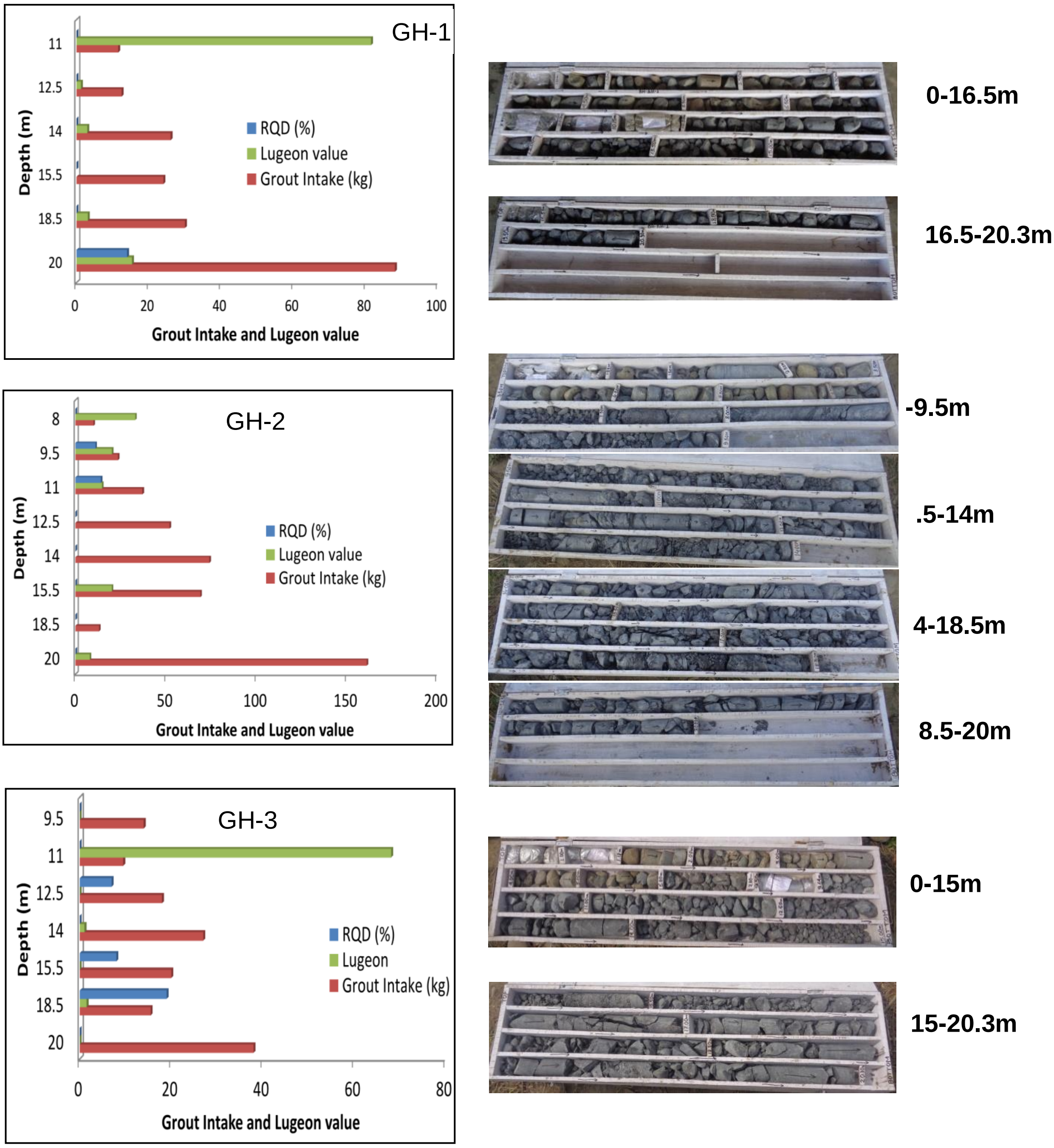

Figure13 Comparison of depthwise variation in RQD, pre-grout permeability (lugeon) value and grout intake in groutability holes GH-1, GH-2 and GH-3 vis-à-vis core photographs showing highly fractured bedrock with poor RQD in groutability holes at damsite

9. Scope for future study:

The scope of present study is limited to physical (joint survey, structural geological features) and hydraulic (permeability/hydrauic conductivity) characteristics of rockmass for evaluation of groutability. However mechanical behaviour (failure strength of the rock and shear strength of rock joints) of the rockmass vis-à-vis its relationship with tectonic stresses of the locality is also important in assessment of efficacy of grouting of the strata. Since the dam area of the project dominantly composed of sandstone with shale, apart from fracture frequency analysis of the rock, study of pore size distribution of the rock composed dominantly of argillaceous material like shale should also be kept under consideration while deciding grouting specification. Basic rheological properties of the grout material should also be studied to determine stability, setting time, permanence and toxicityalongwithgroutability.There is an impending need to document case histories with special reference to groutability tests and actual grout intakes in completed projects. The geological evaluation could be added to this recipe to get a valuable interpretation and use in further work.

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