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Three-dimensional modeling of the permeability of the rock masses of Khersan 2 dam using geostatistical methods.

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Abstract: *Permeability is one the geotechnical parameters of the rock mass of dam sites, which threatens the stability of the dam site and wasting water stored behind the dam. In this study, using data from 28 exploratory boreholes in the Khersan 2 dam and using the inverse-square method (anisotropic method), the changes of permeability were evaluated. Lugeon test results and rockmass quality designation were used to study the permeability of the rock masses of the dam site. Furthermore, two and three-dimensional models were prepared using statistical and geostatistical analysis of the data. According to the studies and proposed models, the domain under study is suitable for dam construction in terms of permeability. However, according to the proposed model, operations of improvement are essential especially in some parts of the coast and the left abutment. Finally, some suggestions are presented to reduce the level of estimation error for future drilling in the region.*
Keywords: *geostatistics; Khersan 2 dam; Rockmass Quality Designation; Lugeon test; modeling*

1. INTRODUCTION

Geostatistics was first proposed by Matheron in French Centre for menology Mathematics in 1963 (Matheron, 1963). With the advancement of the science, geostatistical methods are increasingly used in engineering studies, especially geotechnical studies, including Payameni et al., 2013; Morshedi and Memarian, 2010; Karim Poli et al., 2010; Abdollahi Sharif et al., 2014; Ajal Loyeian et al., 2013; Rahimi Shahid, 2015; Owladeghaffari et al, 2008, Bushara et al, 2002, Wei-hong et al, 2009, Gothall & Stille, 2009; Nikbakht, et al, 2010 (Payameni et al., 2013; Morshedi and Memarian, 2010; Karim Poli et al., 2010; Abdollahi Sharif et al., 2014; Ajal Loyeian et al., 2013; Rahimi Shahid, 2015; Owladeghaffari et al, 2008, Bushara et al, 2002, Wei-hong et al, 2009, Gothall & Stille, 2009; Nikbakht, et al, 2010). Nowadays, geostatistics combined with a lot of different ways is used to solve most of the problems in Earth Sciences. One of the problems that always Geologists and Engineers of civil projects such as dams seek to solve it is to estimate the spatial distribution of geotechnical parameters in the domain under study. The new geostatistical methods have been proposed to solve the problems, such as three-dimensional modeling by geostatistics in the form of software packages such as RockWork software. Three-dimensional modeling provides the possibility to study the trend of increase, decrease or tracking possible scenarios of the parameters. Moreover, values for the entire domain under study can be estimated and the location of additional drilling can be determined using modeling (Morshedi and Memarian, 2010). In recent years, much attention has been paid to the geomechanical properties of the rock mass of dam sites and its role in water storage in the reservoir. Some researchers have confirmed Using Rock-quality designation (RQD) as a rough measure of the degree of jointing or fracture in a rock mass and Lugeon test results. In the present study, statistical and geostatistical analyses were performed on exploratory boreholes in the Khersan 2 dam and using the inverse-square methods. Furthermore, two and three-dimensional models were prepared to consider structural realities of rock masses and determine the location of additional drilling.

2. Site under study

Khersan 2 dam is located in higher part of Khersan River in Charmahal va Bakhtiari Province in south-west of Iran with eastern longitude of 50° and 36 °and northern latitude of 31° and 25° with approximate distance of 60 km from Lordegan City. The geographical location of the region and ways to access it are presented in Figure 1.

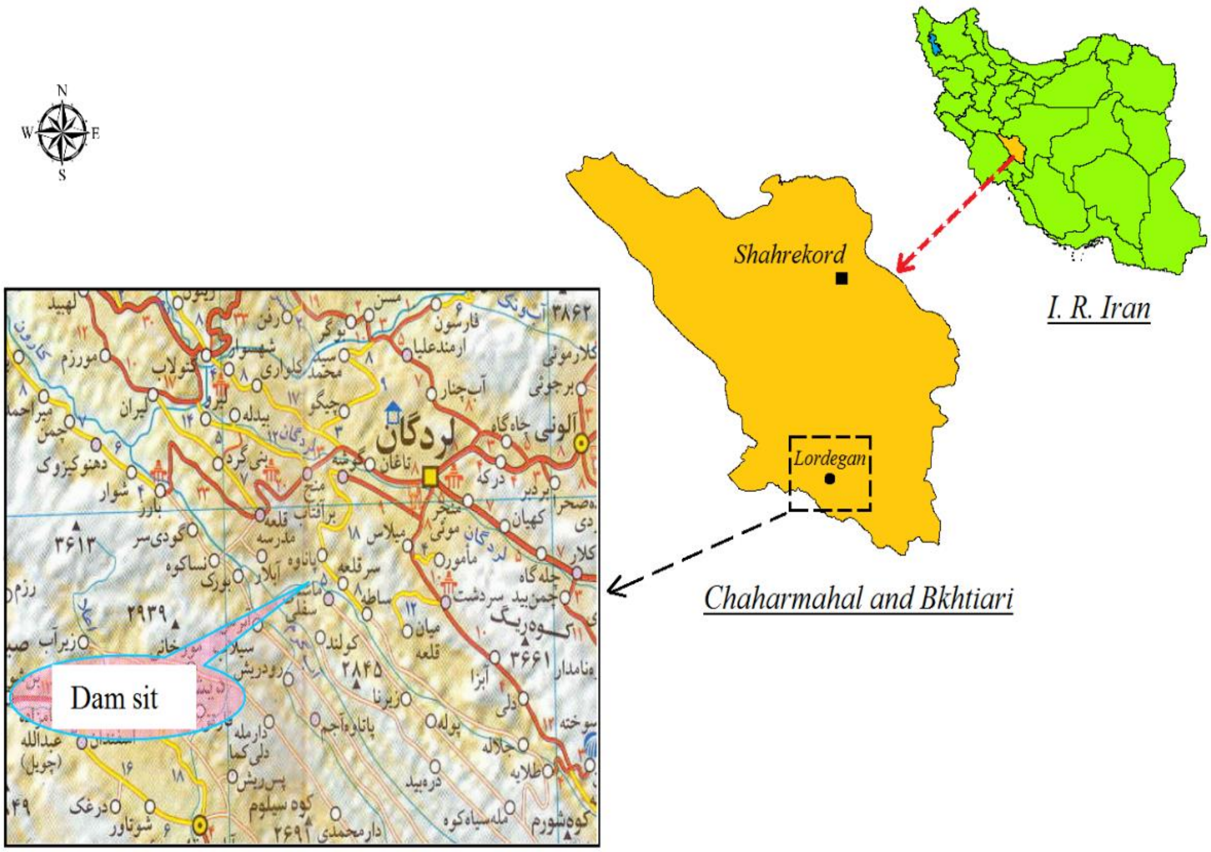

Figure 1– geographical location of the region and ways to access it

This site is located in south-west of Iran and north-east slopes of Zagros Mountains. As shown in Figure (2-a), there are geological formations of Cretaceous to Recent on the upstream dam. stratigraphic units in the domain under study include units of Asmari, Gachsaran, Aghajari, Bakhtyary and alluvial deposits (Mahab Qods, 2010) (Fig. 2 B). lineaments and faults in the domain under study include Bakhtiari lineament, bending edge fault , Duplan fault , Dena fault, Ardal fault (Iran Water and Power Resources Management Company , 2009).

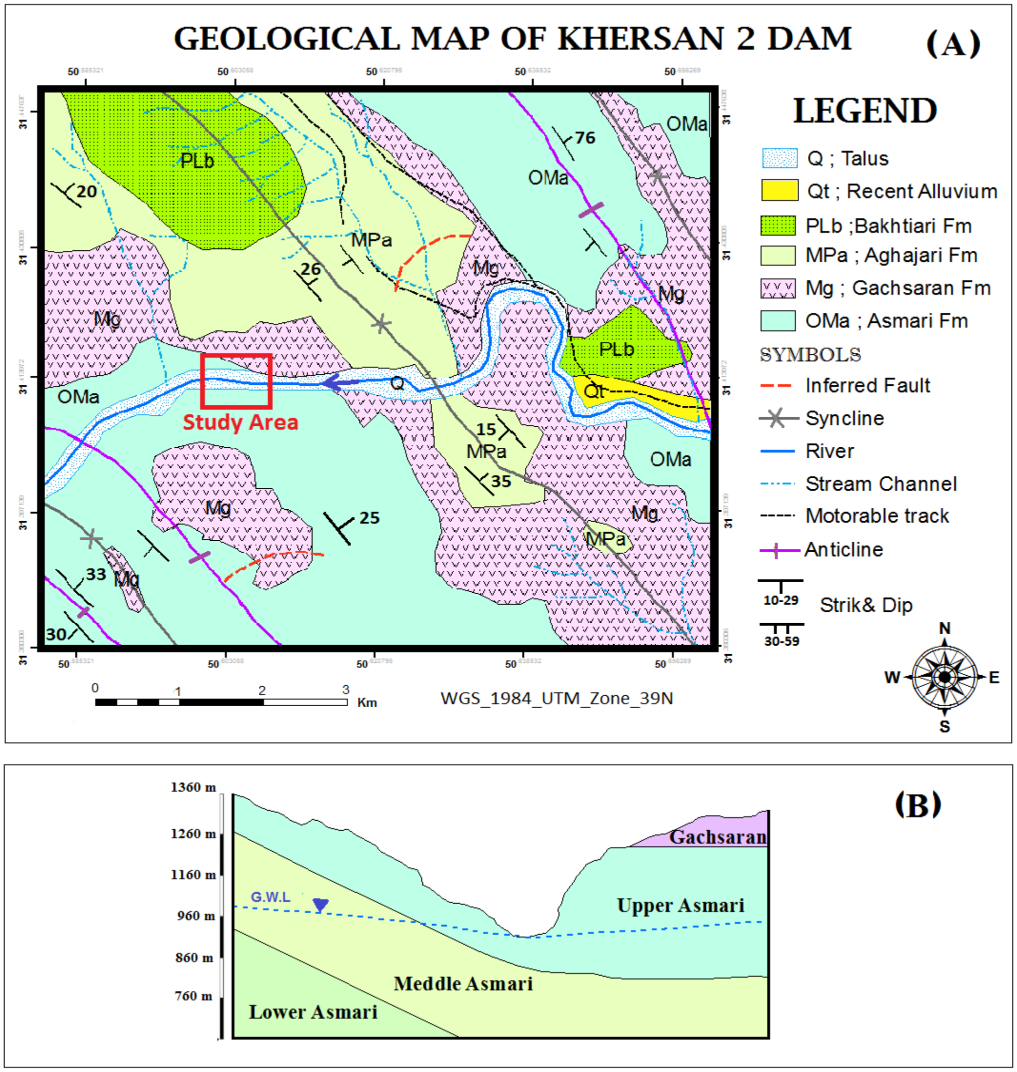

Figure 2– (A) Geological map, (B) geological cross-section of Khersan 2 dam site (Mahab Qods, 2010)

3. Methodology

Because of the complexity of natural systems, a full understanding of them is very difficult. Modeling is an attempt to streamline this complexity. In recent years, the use of modeling for geotechnical studies has become one of the main elements. In this study, using data from 28 exploratory boreholes in the Khersan 2 dam and using the inverse-square method (anisotropic method), the changes of permeability were evaluated. The inverse-square method is one of the stochastic simulation methods that use statistics to predict and simulate the geostatistical laws. The following steps should be taken to use this method:

1. Initial assessment of the data
2. Geostatistical investigation of data
3. Draw diagram of Lugeon - rock mass quality index and the relationship between these two parameters
4. Determine the domain under study regarding the position of exploratory boreholes
5. The three-dimensional modeling of parameters using Inverse Square of distance (anisotropic method)

6- Validate the block model (concordance between the results of modeling with real data)
7. Preparation of the sections and models of fence diagrams using three-dimensional models
8. Check the status of the permeability of the rock masses of the site according to the proposed model
9. Discover the optimal locations for additional drilling

3.1 Statistical and geostatistical analysis of geotechnical data obtained from drilling boreholes

The most important tests in the Project area include tests to determine rock mass quality index (RQD) and Lugeon test. Rock mass quality index as a percentage of the drilling core with the length of 100 mm and more is defined according to equation (1) (Goodman, 1989):

$$\%RQD = \frac{\sum_{i=1}^{n} X_i}{h} \times 100 \qquad X_i \geq 100\ \mathrm{mm} \qquad (1)$$

In equation (1), RQD represents the rock mass quality index which is typically expressed in percentage. Xi is core fragment length and h is the overall length of exploratory boreholes (Goodman, 1989). The Lugeon test is used to measure the amount of water injected into a segment of the bored hole under a steady pressure; the value (Lugeon value) is defined as the loss of water in litres per minute and per metre borehole at an over-pressure of 1 MPa (Lugeon, 1933). To carry out geotechnical studies, 28 boreholes have been drilled in project scope whose positions are presented in Figure 3 and Table 1.

Table 1: Location of exploratory boreholes Khersan 2 Dam (Iran Water and Power Resources Development Co., 2010)

Raw	Location of borehole	borehole name
1	Abutments	BH1, BH2, BH3, BH4, BH5, BH6
2	Dam foundation	BH23 و BH24
3	upstream cofferdam foundation	BH26
4	Right beach	BH22, BH21, BH20, BH13, BH11, BH10, BH9
5	Left beach	BH18, BH17, BH16, BH15, BH14, BH12, BH8, BH7, BH25, BH19
6	Upstream cofferdam channel	BH27
7	Subsurface plant output	BH28

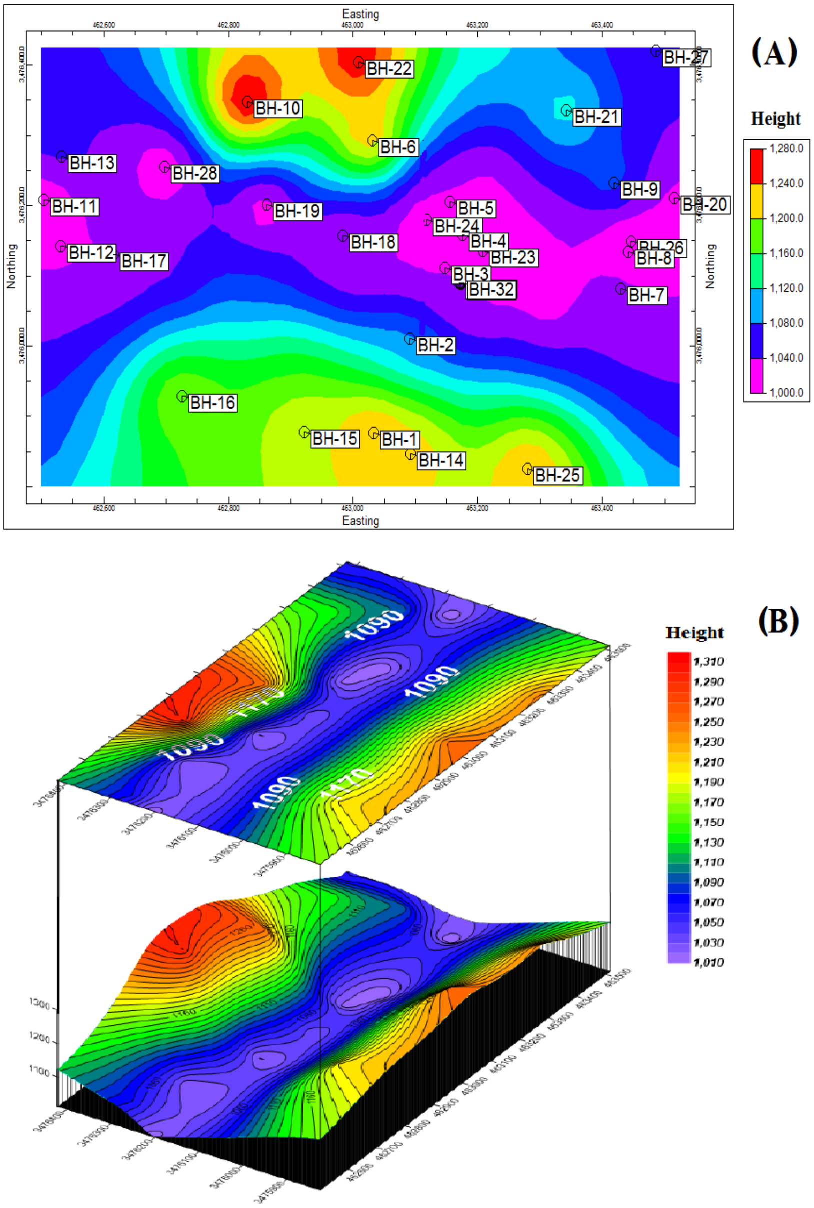

Figure 3– A zoning plan prepared by drilling boreholes and (b) the topographical maps for the domain under study (Rahimi Shahid, 2015)

3.2 Frequency distribution of data from Lugeon test

Lugeon data were estimated in all 28 exploratory boreholes at different depths. Figure 4 shows frequency distribution of Lugeon values in the geotechnical sample. To determine the statistical distribution of the data, Lugeon values with distribution functions of Weibull, logistics, normal and log-normal are compared in Figure

(5). As can be seen in this figure, Lugeon values are highly adapted to the log-normal distribution function (correlation coefficient: 98.4%).

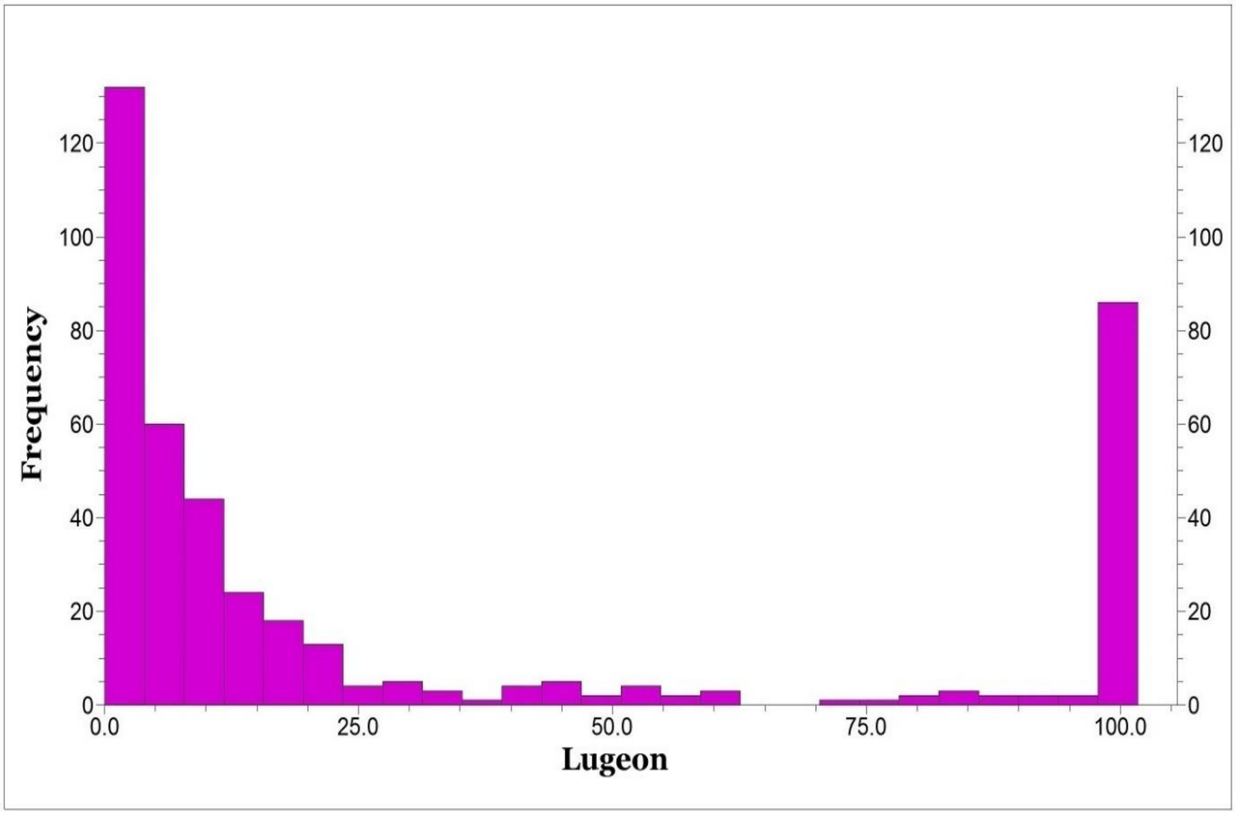

Figure 4– Frequency distribution of Lugeon values in the geotechnical samples

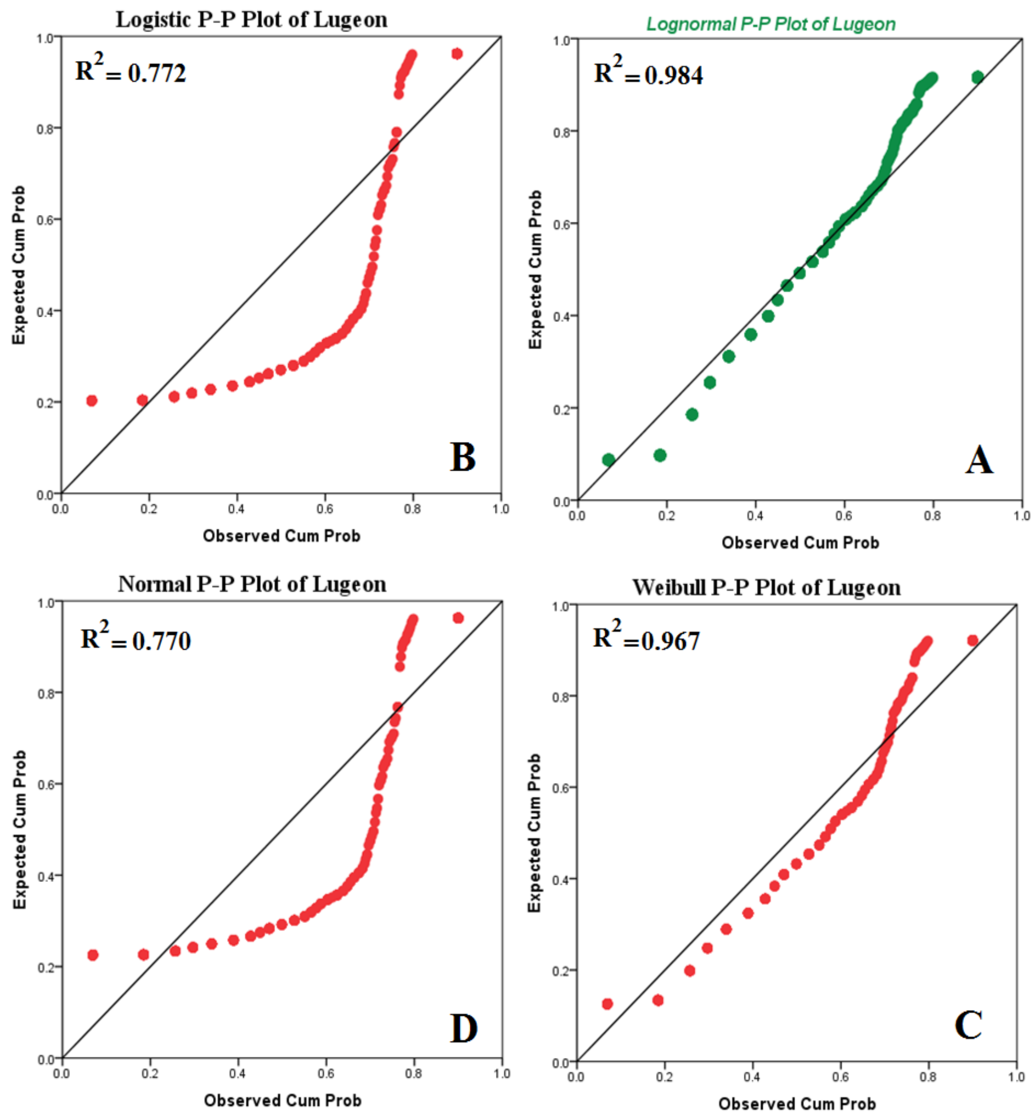

Figure 5– Comparison of the probability distribution for Lugeon data; (A) log-normal, (B) logistics, (C) Weibull, (D) normal. Lugeon values are highly adapted to the log-normal distribution function.

3.3 Frequency Distribution of RQD

RQD values were estimated in all 28 exploratory boreholes at different depths. Frequency distribution of the values shows to a large extent the normal nature of data (Figure 6). For more studies of features and statistical distribution of the data, RQD values were compared with the normal distribution function (Figure 7). As shown in Figure 7, correlation coefficient for RQD is 93.6% reflecting the normal distribution. RQD changes in the column of boreholes indicate that with increasing depth, the RQD values in most boreholes are improved and continually increase. Due to the increased levels of RQD, it can be said that changes of this parameter is the normal for Khersan 2 Dam.

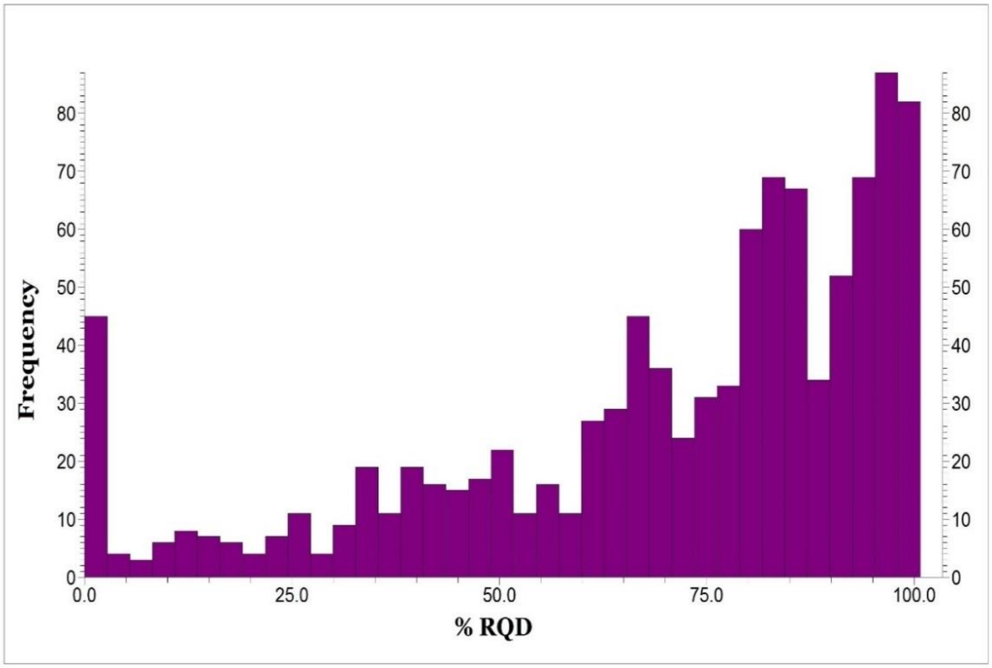

Figure 6– Frequency distribution of RQD values in geotechnical samples

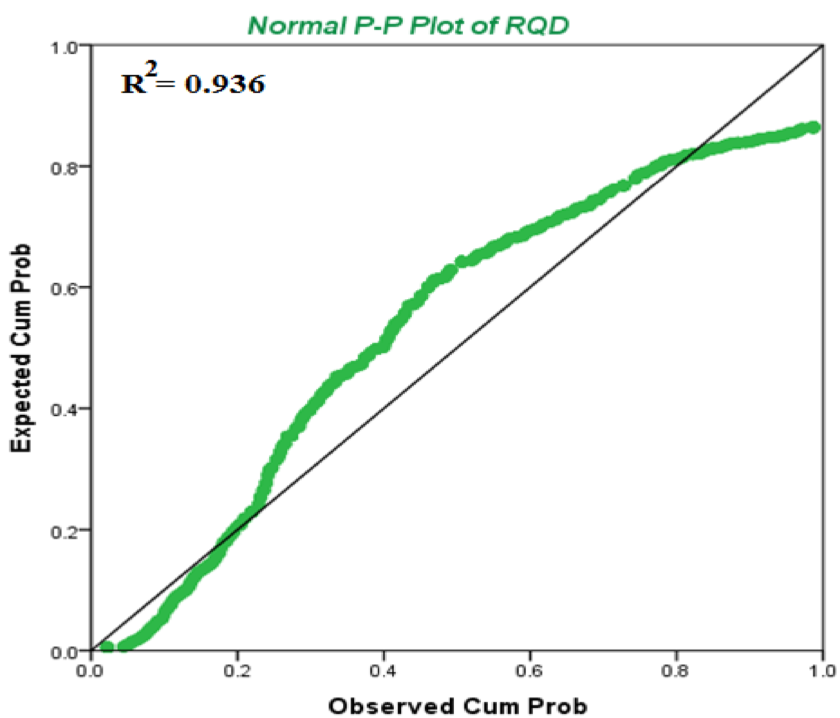

Figure 7– Comparison of the probability distribution of RQD data with normal distribution

According to Lugeon test results and RQD, there is a weak correlation between them. As shown in Figure 8, the correlation coefficient is 11.5 %.

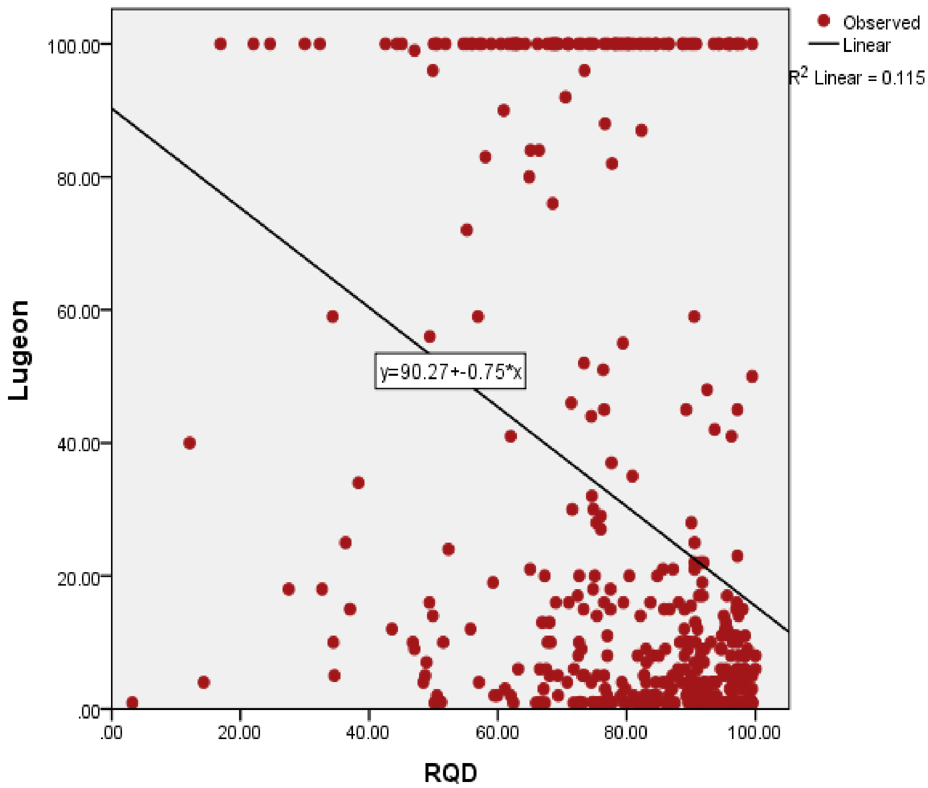

Figure 8– The diagram of correlation between Lugeon test results and RQD

3.4 Isotropic and anisotropic analysis of geotechnical data

When variable values change the same in all directions, the environment is isotropic. When variable values change in certain directions, the environment is anisotropic. Variogram must be drawn in different directions to determine the anisotropic environment. The structural characteristics are shown as a function of the direction. Directions and different slopes were examined to determine the isotropic and anisotropic environment using the variogram map. In Figure 9, an example of a spherical variogram of Lugeon is presented in different directions. As shown in Figure 9, anisotropy of variables is clear. Figure 10 shows an example of a spherical variogram of RQD in different directions. According to Figure 10, RQD values show a weaker anisotropy.

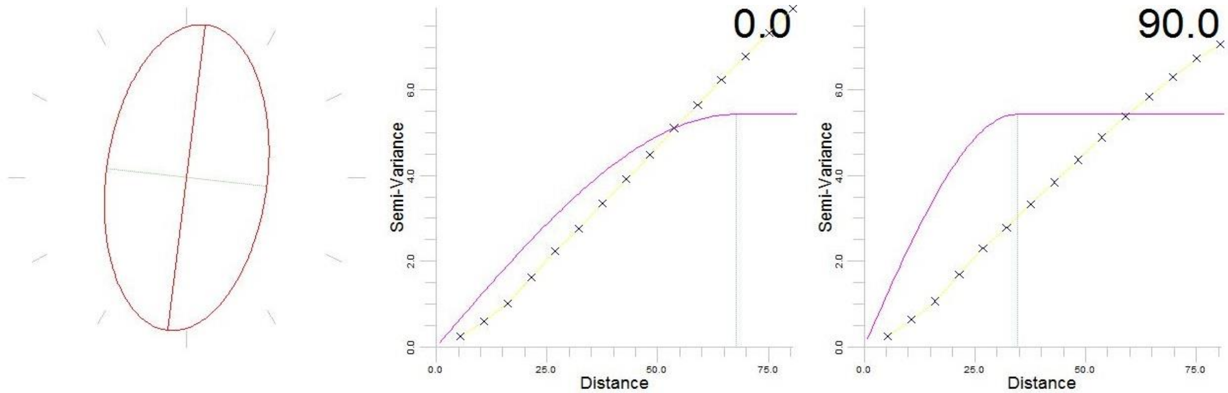

Figure 9– spherical variogram of Lugeon is almost the same in different directions and different range.

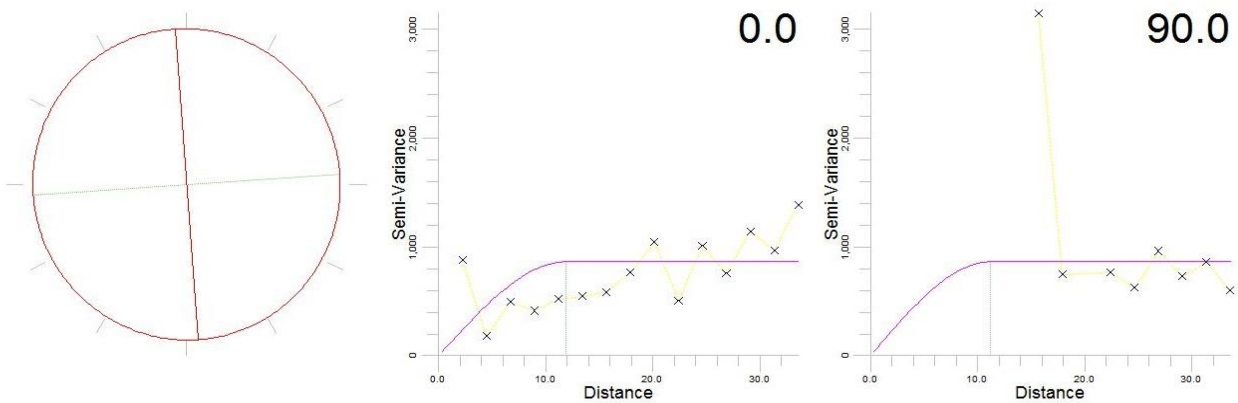

Figure 10– RQD spherical variogram is almost the same in different directions and different range

4. Modeling

4.1 Determine the range of estimates

A space of the region under study where the unknowns are estimated by the data is called estimation space. This space in any software is determined in a way. In Rock Work software, this range is defined as minimum and maximum coordinates (Mahbobi Niyeh, 2007). Table 2 shows the estimation range of Khersan 2 Dam.

Table 2: the estimated domain of the Khersan 2 dam

	Minimum	Maximum	Spacing	Nodes	Range
X	462 500	463 525	25	42	1025
Y	3475800	3476425	25	26	625
Z	740	1320	20	30	580

Block dimensions were determined in line with the domain under study and the sample. Distribution of samples should also be evaluated according to the domain. In the domain under study, there are numerous shortcomings for collecting and reporting the data. The block model of the domain under study is displayed in Figure 11.

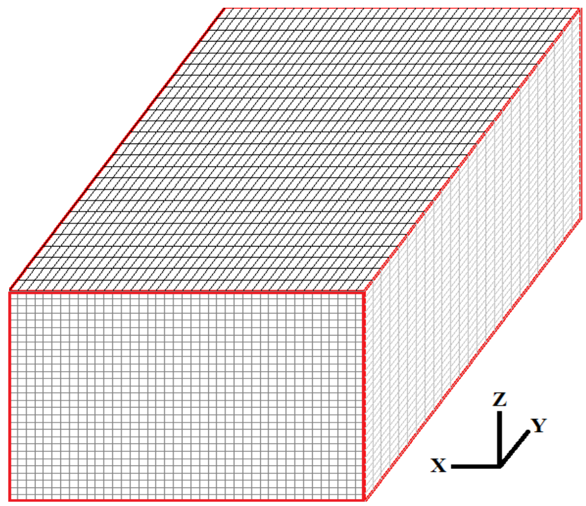

Figure 11– Block model of the domain under study

4.2 inverse-square method of distance (anisotropic method)

Inverse-square method of distance is one of the common statistical methods in networking. In this way, the numerical value of each node of data is weightier. This method usually provides a smooth and continuous network (Mahbobi Niyeh, 2007). After variography of data, determining the anisotropy of parameters and estimation by inverse-square method of distance (anisotropic method) and the block method were separately performed for each variable. Using data from 28 exploratory boreholes, three-dimensional model of Lugeon values is displayed in Figure 12 and RQD is shown in Figure 13.

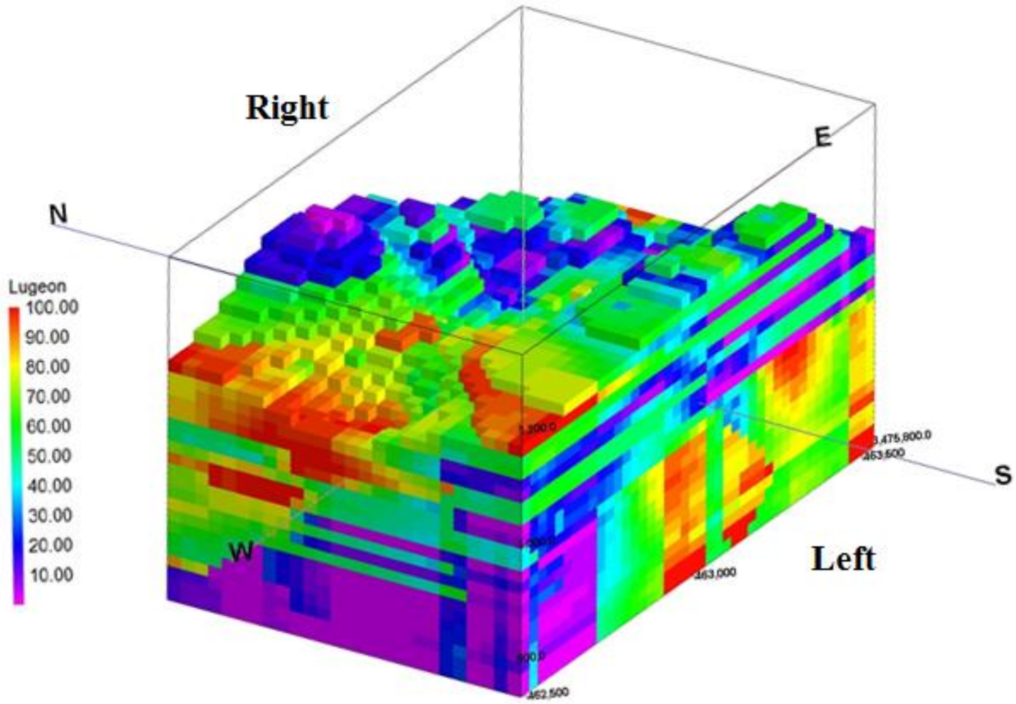

Figure 12– Three-dimensional model of the Lugeon status for the site under study

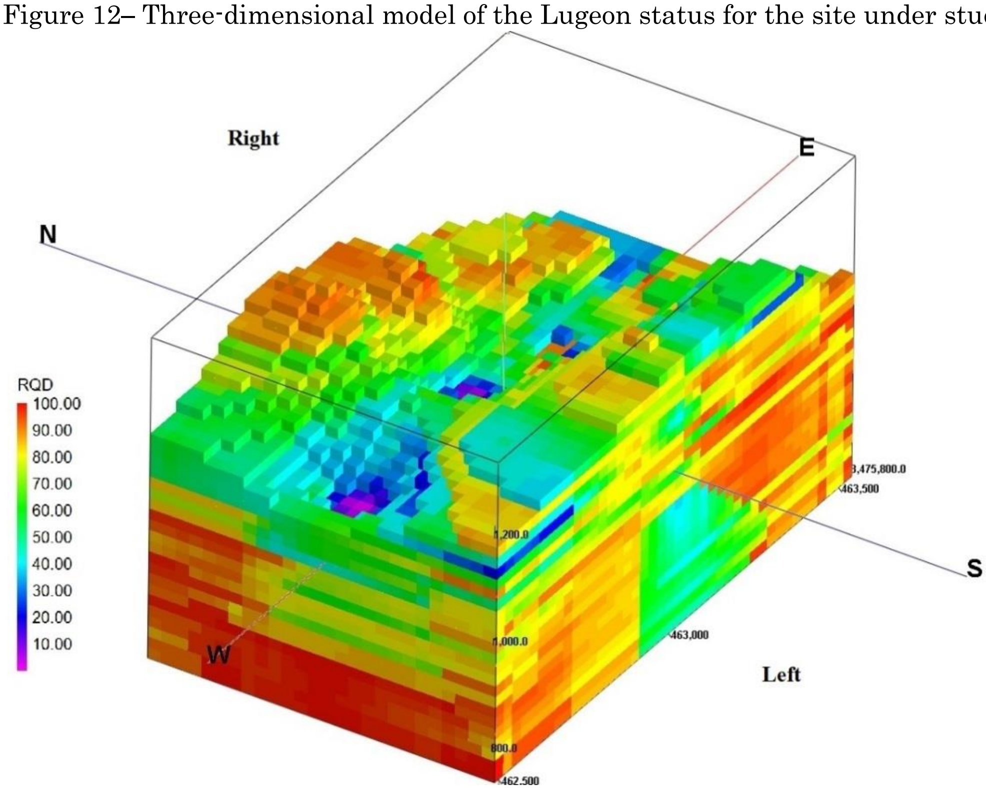

Figure 13– Three-dimensional model of the RQD status for the site under study

4.3 Block model validation

Estimation of validation is done in different ways, including comparing the estimated values for a spot or block with the actual data values or comparing estimation statistics with statistics of raw data. In this study, the values of the input data to the Rockwork software were compared with values estimated by this software in Figures 14 and 15 for validation of the proposed model.

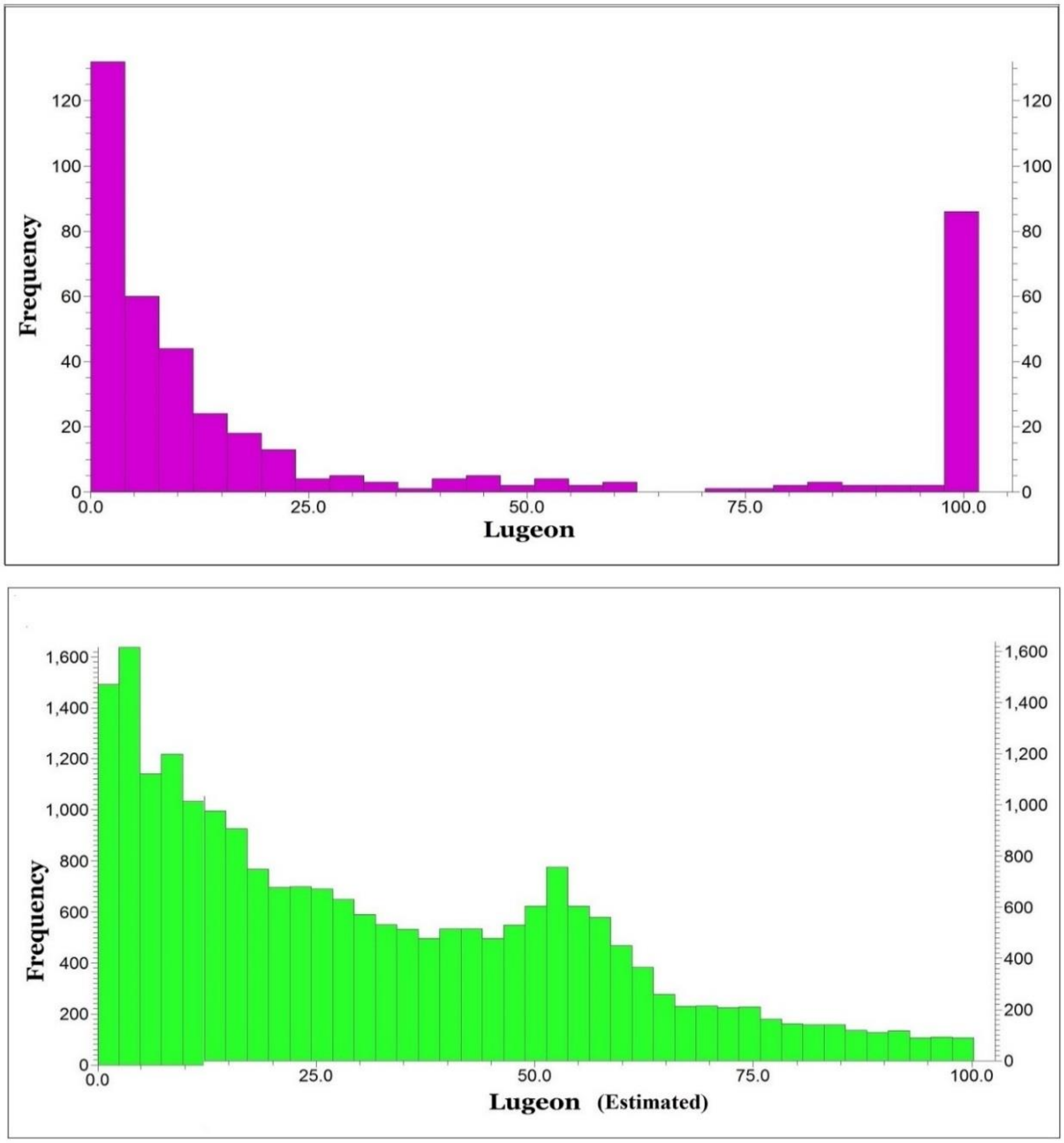

Figure 14– frequency comparison of Lugeon actual and predicted values

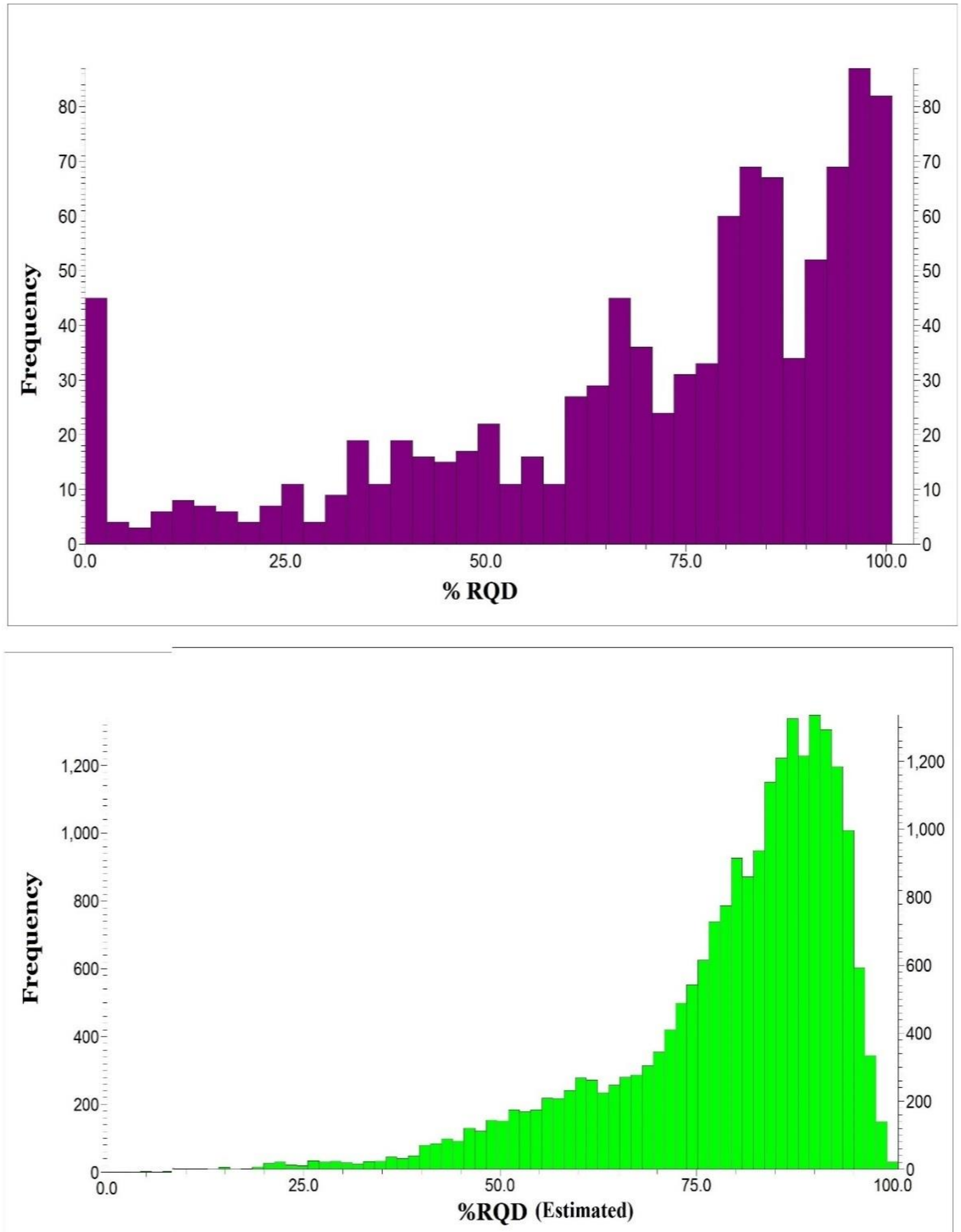

Figure 15– frequency comparison of RQD actual and predicted values

As shown in Figure (14) and (15), the estimated values are consistent with the overall distribution of data. In other words, Lugeon actual and predicted values are consistent with log-normal distribution and RQD actual and predicted values are consistent with normal distribution.

4.4 The status of the permeability of the rock masses of the site under study

According to Figure (16), the status of the permeability of the rock masses of the site under study and also potential areas for leaks were considered using cross sections and models of fence diagrams from the Lugeon block model and RQD.

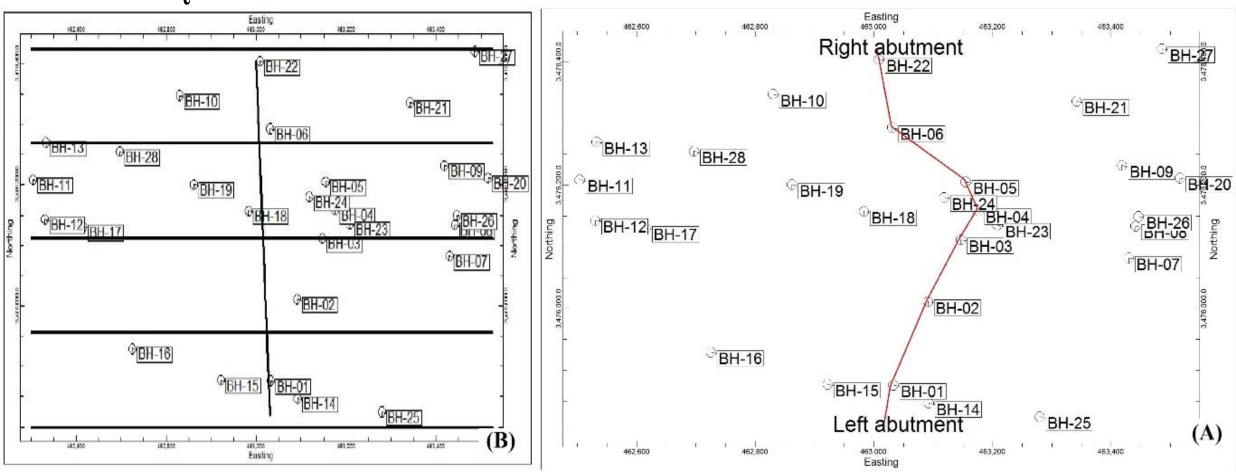

Figure 16– cross-section direction of the dam axis and (b) Direction of the selected fence diagram

As shown in Figure (17), right abutment has lower values of Lugeon and higher values of RQD in comparison with the left abutment. According to models of fence diagram in Figure (18), the parameters have no sudden changes and acceptable values in all five chosen path almost perpendicular to the axis of the dam. Furthermore, high levels of Lugeon and low levels of RQD are mainly related to the downstream site. As shown in Figure (18), the permeability of the right range is lower than other parts of the range.

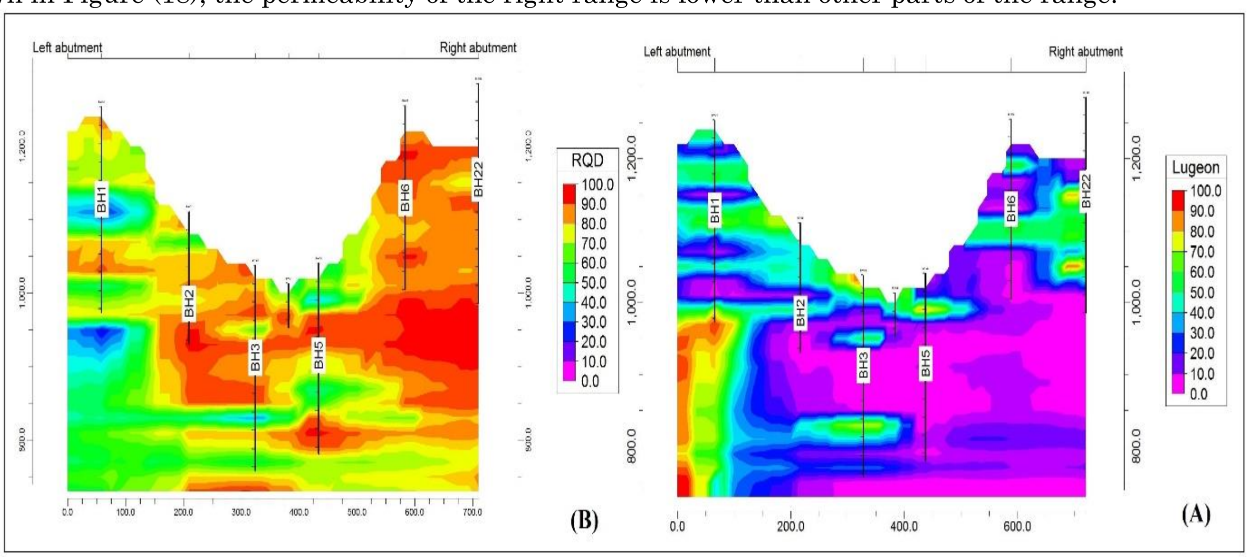

Figure 17– A cross-section of data (a) Lugeon and (b) RQD

Forasmuch as the upstream permeability of the dam is very important, actual values of Lugeon and RQD are separately presented in Figure (19) for upstream and downstream values. This figure shows the mean values of Lugeon are focused on low values and the mean values of RQD are focused on high values and most of the rock masses of the domain under study have high quality.

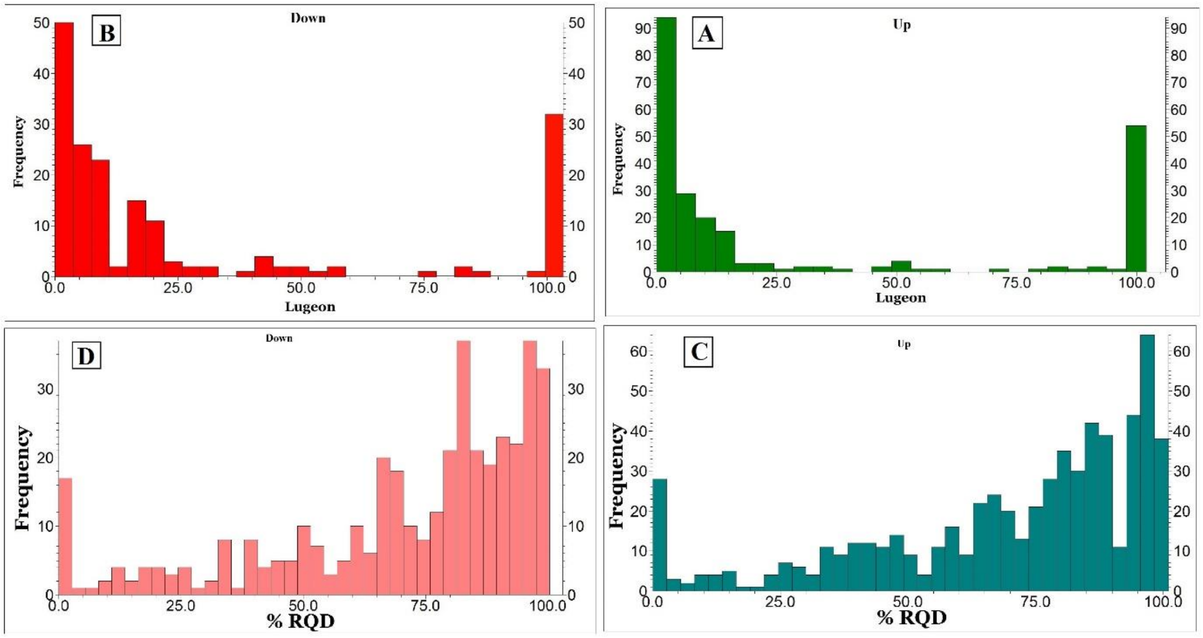

Figure 19: Frequency of Lugeon values in (A) upstream and (b) downstream and frequency of RQD values in (C) the upstream and (d) downstream of the dam

4.5 The discovery of optimal locations for additional drilling

Forasmuch as it is not possible to change the arrangement of the drilled boreholes, it is needed to drill additional boreholes in places that have the most errors and the point is selected at which the reduction of the overall error is more. It is expected that the appropriate location for drilling can be easily detected by calculating the relative standard deviation for each borehole drilling from the equation (2). Showing error as contour lines is the applicable solution that engineers can quickly identify areas for additional drilling.

In most sources, the relative standard deviation is provided as follows:

$$\mathrm{RSD} = \frac{2\mathrm{S}}{\mathrm{M}\times\sqrt{\mathrm{N}}}\times 100 \qquad (2)$$

Where N is the number of samples, M is the variable mean and S is standard deviation (Hohn, 1999 and Randal, 1991).

Figures (20) and (21) show the relative standard deviation for the actual values of Lugeon and RQD. According to the map of relative standard deviation of Lugeon (Figure 20) the highest values are observed for the upstream of the dam.

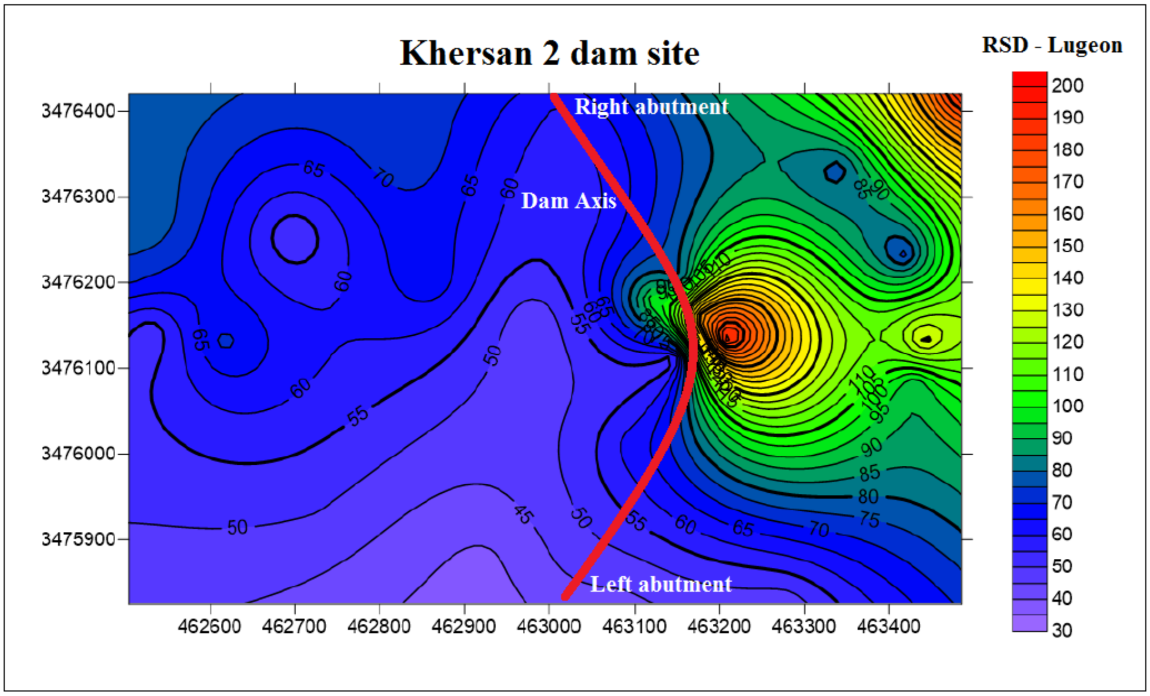

Figure 20– the map of relative standard deviation of Lugeon

The map of RQD Standard deviation (Figure 21) presents lower values and the high values in this map are also related to the upstream dam.

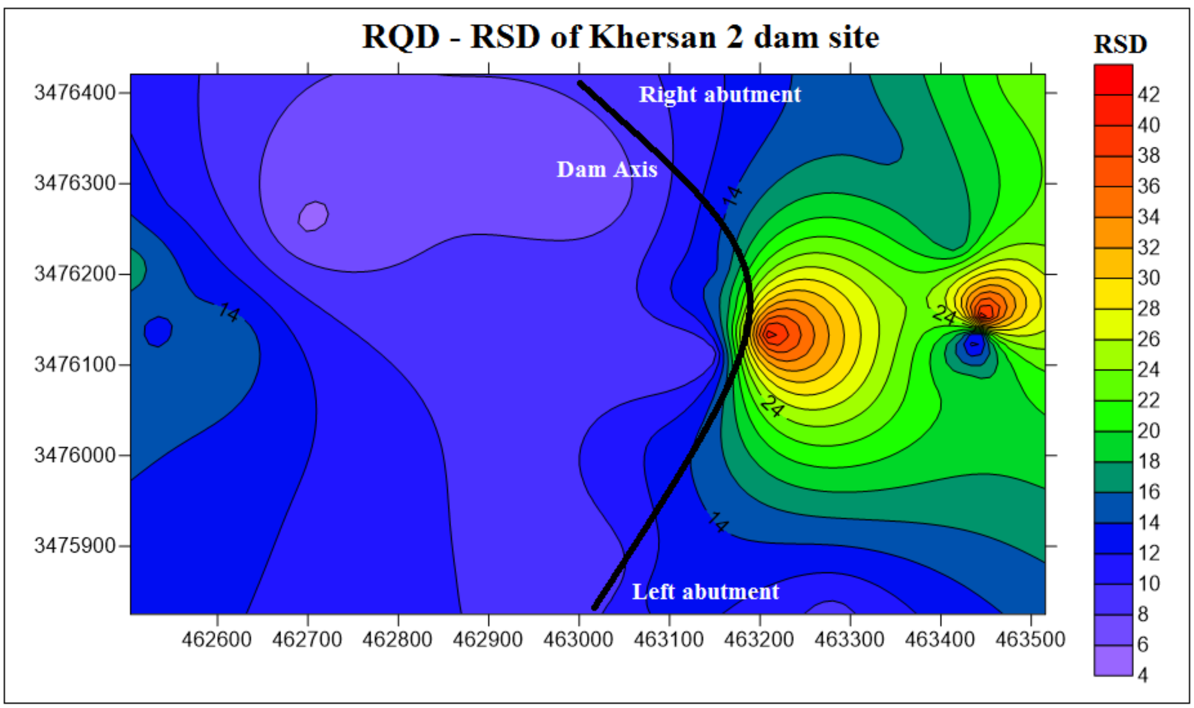

Figure 21–The relative standard deviation of the RQD

In points where there are a few samples, it is expected RSD has higher values but figures (20) and (21) show to the contrary. According to equation 2, the RSD is calculated from the standard deviation, s, and is commonly expressed as parts per thousand (ppt) or percentage (%). Forasmuch as Lugeon distribution is log-normal and centralization of data is on low values, wherever the number of samples is low and the variable value is close to 100, RSD is drastically reduced. Instead, where the variable value is close to 1, RSD unexpectedly increases, so here RSD is not a good measure. So in this study, instead of RSD, the following measure is used to find optimal locations for additional drilling (equation 3).

$$D = \pm 2S \qquad (3)$$

In this case, data centralization on the distribution of variables has no effect on mean error. Figures (22) and (23) show D changes for Lugeon and RQD values.

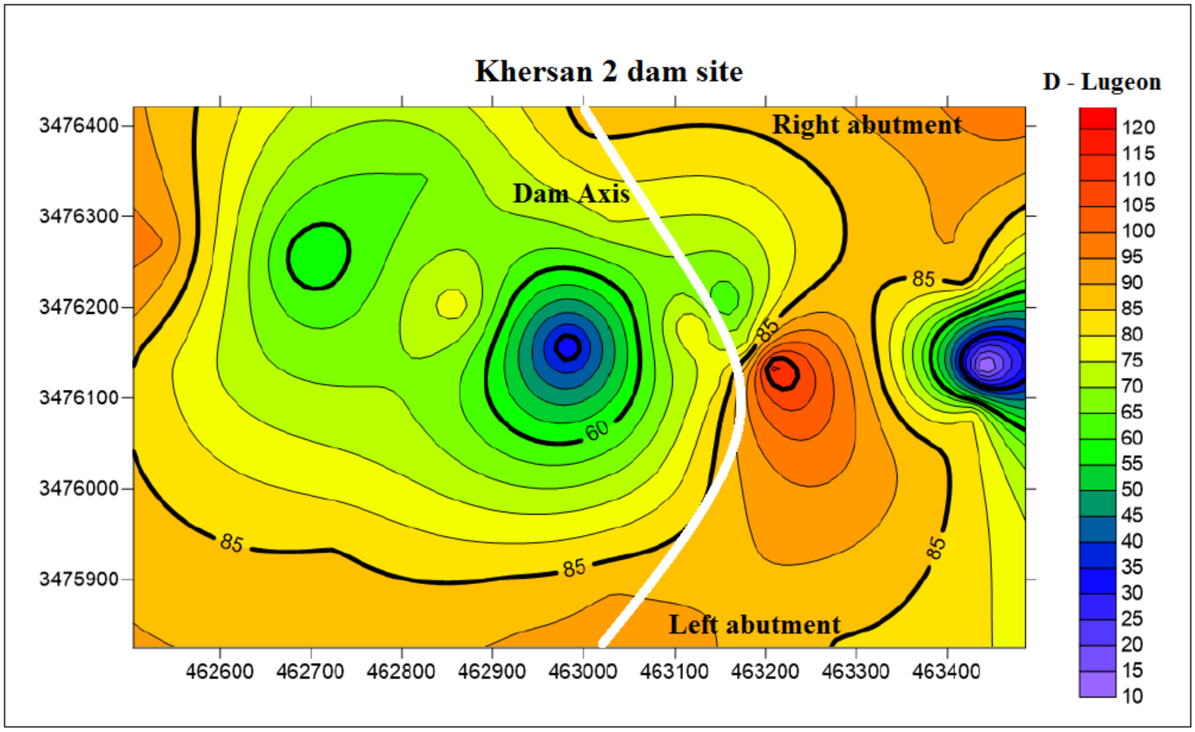

Figure 22–D Map (twice the standard deviation) for Lugeon

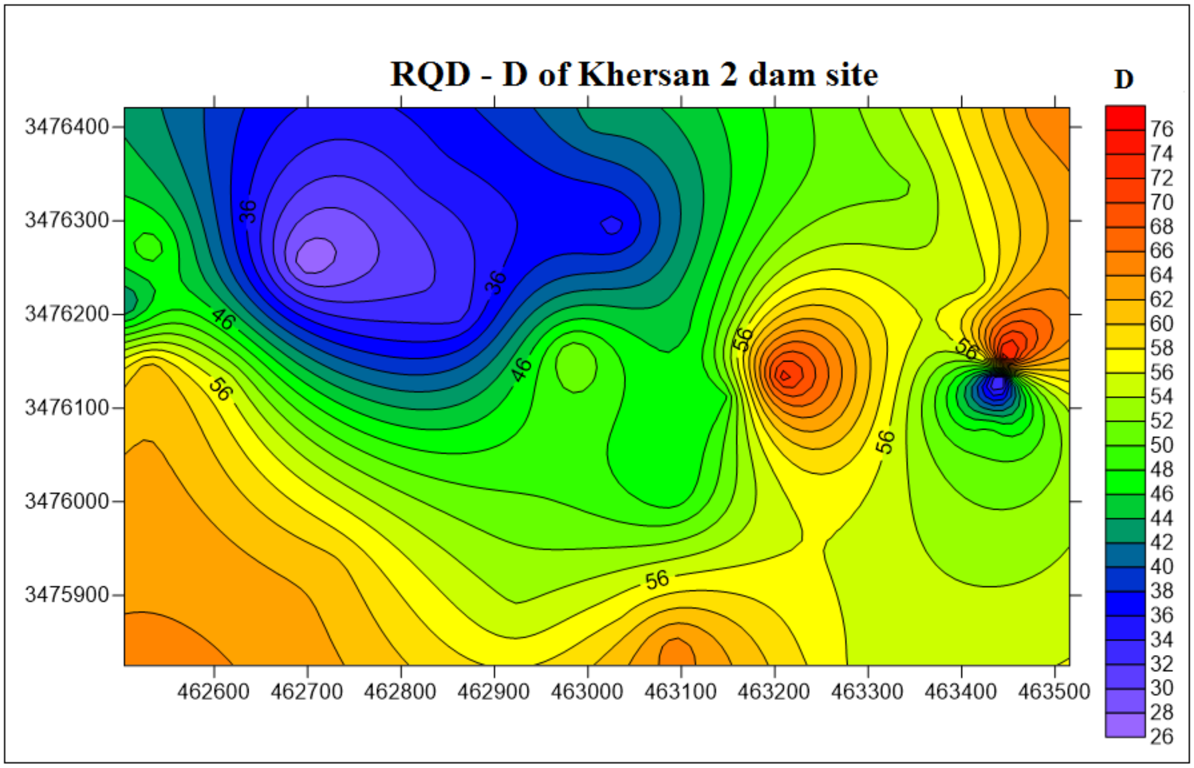

Figure 23–D Map (twice the standard deviation) of the RQD

In Table 3, additional drilling locations have been proposed based on sampling error of Lugeon and RQD in the region. Determining the definitive additional drilling locations is based on the other information contained in the region, including local access and financial constraints.

Table 3: the proposed areas for additional drilling in order of drilling priority

Drilling area → Drilling priority↓	X		Y	
1	463150	463300	3476000	3476200
2	463000	463200	3475820	3475900
3	463300	463520	3476300	3476420

Figure (24) shows the location of the proposed areas for additional drilling in order of priority. In area 1 due to several boreholes, increasing borehole depth is recommended but in areas 2 and 3 drilling the additional boreholes is recommended. As mentioned, determining the definitive location of additional drilling in the area is possible by taking into account other information.

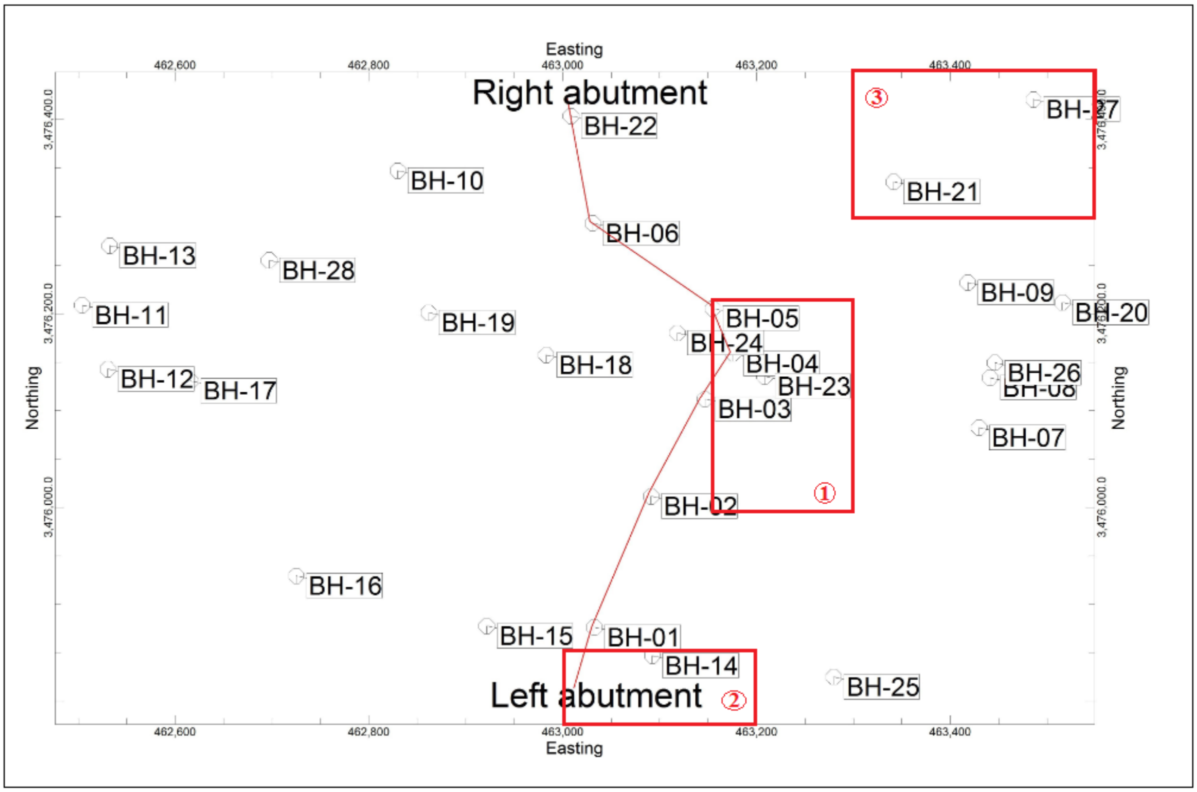

Figure 24–Location of the proposed areas for additional drilling

5. Discussion and conclusion

According to studies and models prepared from block models, the area has favorable conditions for construction of the dam in terms of area and permeability of the rock mass quality index for the following reasons:

A) The mean value for Lugeon samples and the estimated values are focused on low values.

B) The mean value for RQD samples and the estimated values are focused on high values and most of rock masses have good quality.

C) Changes in variables in stretches perpendicular to the axis of the dam is low and represent appropriate values.

However, improvement operations in some areas are necessary, especially the beach and left abutment based on the provided model. In this study, geostatistical modeling was used and the following items were provided by it: displaying the estimated values on the blocks, mapping the desired levels, preparing sections in different ways and comparing them with actual data. However, the impact of joint systems on the Lugeon distribution and rock mass quality index in the area was not considered in this study. It is suggested that geostatistical modeling for joints and its relation to Lugeon and rock mass quality index are investigated in future studies.

6. Acknowledgement

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