

Preliminary analysis of spatial development of karst using a geostatistical simulation approach

Morteza Akhondi · Zargham Mohammadi

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Abstract Earth science phenomena are primarily spatially dependent with variations occurring on varying scales. Geostatistics is a well-known approach for the assessment of spatial models of regionalized variables, such as porosity. In this study, we used the results of 953 Lugeon tests (402 tests in exploratory wells and 550 tests in grouting wells) to assess effective porosity and karst development at the Tangab Dam site, Iran. Lugeon values were first normalized, following which the variogram method (i.e., range, sill, and nugget effect) was used to identify the spatial variability of Lugeon values. A high correlation range of 200 m was obtained along the grout curtain galleries, while the range was about 40 m in the vertical direction. The simple kriging method with Gaussian variograms was determined to be the best method for estimating the Lugeon values in the study area using cross validation-criteria (e.g., RMSE = 0.835 and $\rho = 0.914$). Spatial variation of Lugeon values was mapped using a simulated annealing approach. The analysis revealed: (1) a higher potential for karst development on the left abutment of the Tangab Dam site, (2) the average of simulated Lugeon values decreased from values of about 180 close to the ground surface at 1,440 m a.s.l. to lower values of about 50 at 1,260 m a.s.l., and (3) high Lugeon values in the abutments of the dam site approximately followed the 15° bedrock dip, which confirms the potential development of karst features in the Asmari limestone. A schematic model for development of karst at the Tangab Dam site is proposed based on hydrogeological data and results of simulated Lugeon values around the dam site.

Keywords Karst development · Lugeon test · Geostatistics · Tangab Dam · Iran

Introduction

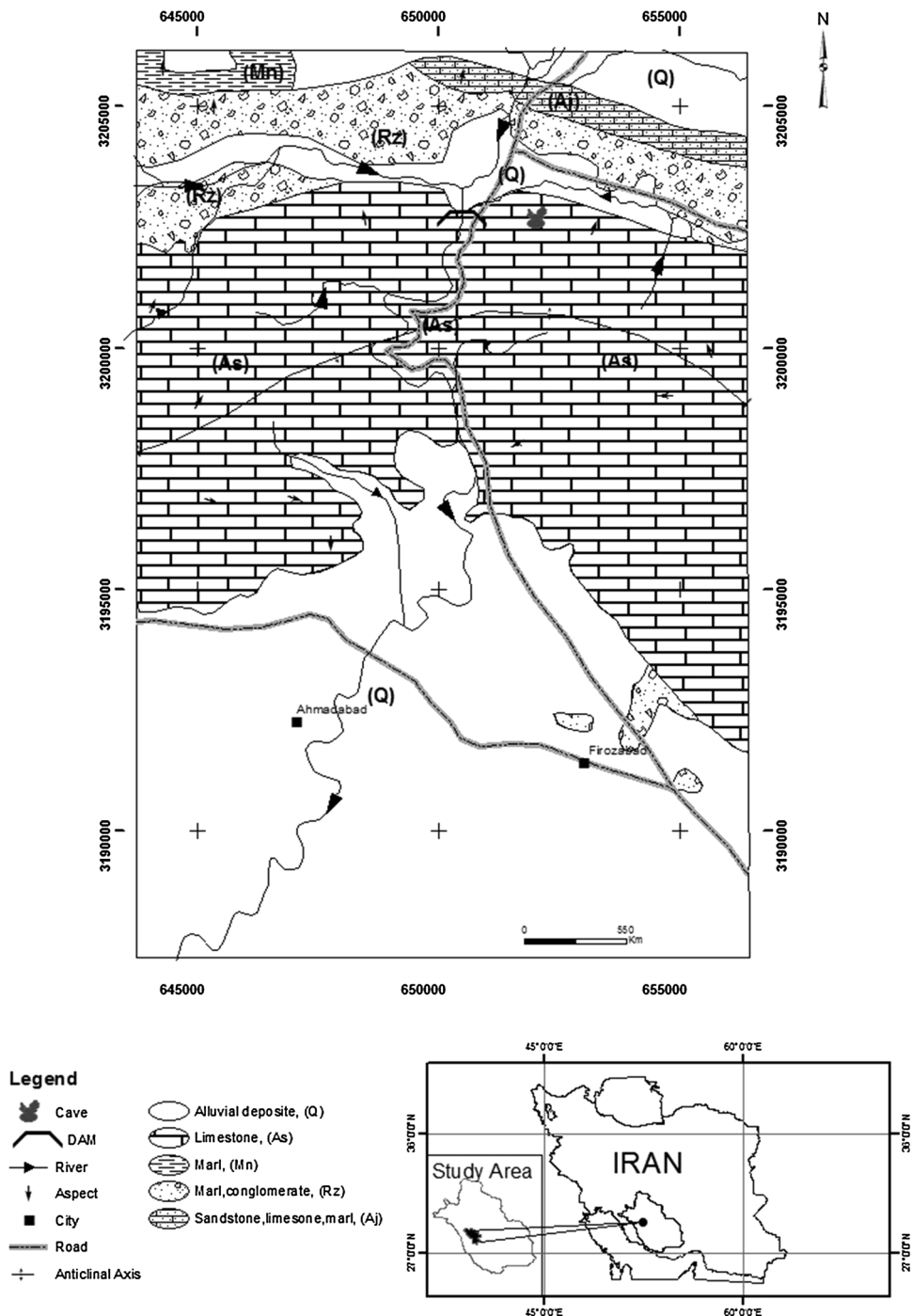
Karstic aquifers represent one of the most important freshwater resources in the world, with approximately 20–25 % of the world's population dependent on water from karstic areas (Ford and Williams 2007). Dams are often constructed across large rivers in karstic areas because the karstic landscape is often characterized by the development of narrow valleys and gorges. Accordingly, knowledge of the development of karst topography and of its hydrogeological characteristics, such as porosity, direction of groundwater flow, and the probable variation in hydraulic condition of groundwater circulation following dam construction, is considered to be of primary importance (Milanovic 2004). Development of karst features, such as sinkholes, solution conduits, among others, result from the intensive interaction of several hydrogeological and hydrochemical dissolution processes.

There are several known methods for determining the characteristics of flow and transport in karst aquifers, including dye tracing, drilling of exploration and observation wells, study of the spatial and temporal variation in the hydraulic and hydrochemical parameters in the wells and springs, water-balance calculations, analysis of spring hydrographs, and modeling approaches (White 1988; Bakalowicz 2005; Ford and Williams 2007; Goldscheider and Drew 2007; Mohammadi et al. 2007; Parise and Gunn 2007; North et al. 2009).

Despite the shortcomings of boreholes (Merritt 1996; Milanovic 2000), one of the most common methods used to study dam sites in karst terranes is the drilling of boreholes,

M. Akhondi · Z. Mohammadi (✉)
Department of Earth Sciences, Shiraz University,
71454 Shiraz, Iran
e-mail: zmohammadi@shirazu.ac.ir

Fig. 1 Geological map of the study area



installing piezometers, and conducting Lugeon tests on the boreholes. The Lugeon test is widely used to estimate the average hydraulic conductivity of rock masses (Houlsby 1976; Brassington and Walthall 1985; Milanovic 2000). The Lugeon test (Lugeon 1933), also known as the Packer test, refers to the measurement of rock permeability on isolated sections of boreholes, obtained by applying a series of increasing pressure steps and measuring the water intake at each pressure step. The Lugeon unit, i.e., the measure of rock permeability, is defined as the volume of

water intake per unit length of borehole during 1 min at a pressure of 1 m of water (Milanovic 2004; Krešić 2007). The Lugeon test is generally performed in a limited number of wells in an area of karstic dam sites due to economic and/or topographic constraints. Accordingly, information obtained from these tests are not representative of the whole karst region because solution features are inherently very heterogeneous and unpredictable.

The aim of our study was to attempt to answer the following questions:

1. Is it possible to predict karst development using a limited number of Lugeon tests in a dam site in karst areas?
2. Is it possible to improve hydrogeological schematic models for karst development using a geostatistical simulation of Lugeon test data?

We chose the Tangab Dam site, Zagros region, Southwest Iran, as the study site (Fig. 1). Extensive hydrogeological and karst studies were conducted at this site to evaluate the results of geostatistical simulations in this area.

The study area

The Tangab Dam was constructed on the northern flank of the Podenow karstic anticline, at the entrance of a gorge on the Firozabad River, about 80 km southeast of Shiraz, Zagros region, South Iran (Fig. 1). The dam is designed as a rock-fill embankment with a clay core. The main geological formations consist of Asmari (Oligocene–Miocene), Razak (Lower Miocene), Mishan (Upper Miocene), Aghajari (Pliocene), and alluvial deposits (Quaternary) (see Fig. 1). Asmari limestone forms the walls of the gorge at the dam site. The core of the Podonow Anticline is composed of Asmari Formation limestone, which is overlain by the Razak Formation, comprising silty marl to silty limestone with interbedded layers of gypsum (Karimi et al. 2005). At the Tangab Dam site, the Asmari Formation is about 400 m thick, and it gradually transforms into the 100-m thick Razak Formation. The thickness of the transition zone between the Asmari Formation and the Razak Formation varies from 0 to 300 m, and it is composed of alternating layers of marl, marly limestone, and limestone (Karimi et al. 2005). The Asmari Formation constitutes the bedrock at the selected site. The beds dip very gently upstream of the river. Fractures and joints are widely spaced (more than 5 m) and moderately opened (about 0.3–10 cm). A minor fault system passes close to the left abutment of the dam site.

Various types of surface karst features, such as dry valleys, grikes, and caves, have developed in the Asmari Formation in the study area. Two caves that have developed along the master joints were explored by Karimi et al. (2005) at distances of 500 and 100 m, respectively, from the inlet of Tangab Gorge on the northern flank of Podenow Anticline. The larger one, Sirezjan Cave, is located at 1,450 m a.s.l. and very close to the future normal water level of the dam reservoir. The cave entrance is a narrow vertical shaft about 3.5 m in depth (Karimi et al. 2000). The length of the cave is about 180 m with a relief of 35 m (Karimi et al. 2000). The cave is single passage type (Palmer 2000) and has developed perpendicular to the anticline axis along a master joint. The second cave,

reaching at least 50 m depth, is located 300 m distant from Sirezjan Cave. This cave was not explored, but Karimi et al. (2000) suggested a joint control mechanism for its development. This cave contains a 30-m deep shaft with a diameter of 3 m which was discovered during tunnel excavation at the dam site.

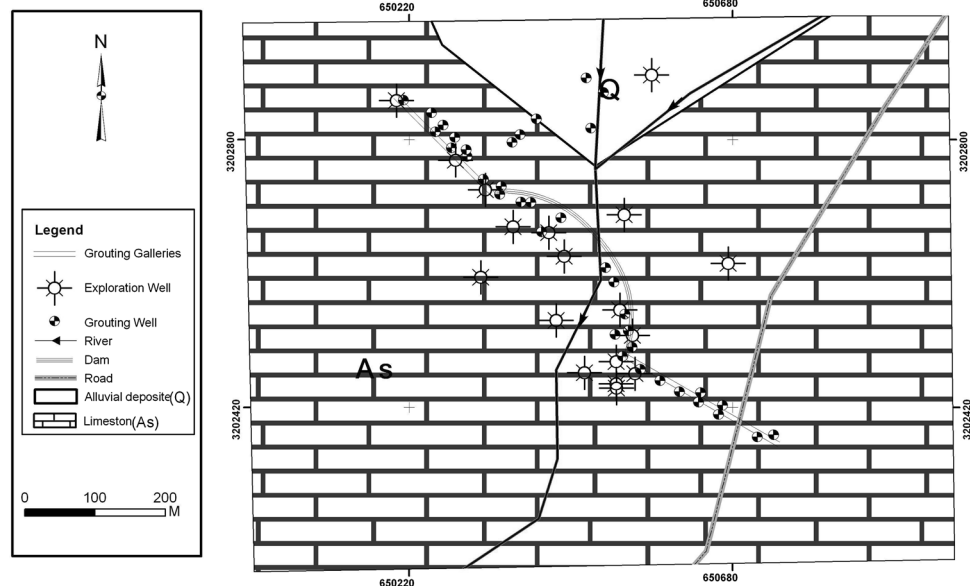
Groundwater level in the karst aquifer close to the dam is lower than that of the river under present conditions. However, in the past the limestone was recharged by the river along joints. The joints are perpendicular to the anticline axis, and the caves developed along the intersection of bedding planes and joints. Karimi (1998) proved that the Asmari Limestone in the northern and southern flanks of the Podenow Anticline is hydraulically connected. There is also a considerable difference between the elevation of the caves on the northern flank and the springs which emerge from the southern flank. The caves developed on the northern flank of the anticline as a result of the potential for transferring water from this flank to discharging points in the opposite, southern flank. It would appear that the hydrogeological condition facilitates the development of caves with multiple vertical shafts (along joints) that are interconnected by passages and halls (developed along bedding planes).

A tracer test using uranine dye (Acid Yellow 73) on the right abutment proved that a hydrogeological connection between the dam site and the main springs of the Tangab region does exist (Asadi 1998), and the high groundwater flow velocities (21–200 m/s) suggest that a conduit-flow system underlays the east abutment. A second tracer test using rhodamine B (C.I. Basic Violet 10) was carried out by Talaei (1999) on the left abutment, revealing that the main passage of water flow is through the left abutment. According to the results of these two dye tracer studies and other investigations in the study area (Karimi 1998; Mohammadi and Raeisi 2007), there is no conduit flow from the right to the left abutment, but a conduit-flow system does exist beneath the left side of the dam.

Methods

Geostatistical techniques have been widely used to estimate important hydraulic parameters of aquifers (Neuman et al. 1980; Ahmed and De Marsily 1987). In cases with a complex geological setting, such as karst aquifers, kriging of various parameters should be done carefully to incorporate all of the available geological data (Ahmed 2007). Although geostatistical approaches have been rarely applied for the study of karst aquifers, several research articles on this topic have recently been published. Jaquet et al. (2004) suggested a geostatistical model for the simulation of the geometry of karstic networks at a regional

Fig. 2 Location map of the wells where Lugeon tests were performed



scale, and their model integrated the relevant physical processes governing the formation of karstic networks. Razack and Lasm (2006) modeled the distribution of the transmissivity in highly fractured hard rock aquifers using a geostatistical approach in the crystalline and metamorphic rocks of the Western Ivory Coast (West Africa). Yu (2010) used several geostatistical approaches to evaluate and select the more appropriate approach for interpolating a highly negatively skewed RQD dataset in a geotechnical model. The conditional and non-conditional stochastic simulation of karst conduit networks in the Shuanghe karst network in Southwest China was achieved by Pardo-Igúzquiza et al. (2012).

The permeability of karstic rock at dam sites is measured using Lugeon tests. The influence of karstic features during this test is a function of the degree of porosity interconnection. Lugeon values vary more or less continuously in the spatial domain and can be assumed to be a regionalized variable, where necessary, for geostatistical investigations. Basically, geostatistical investigations are performed in three steps: (1) exploratory data analysis, (2) variogram modeling, and (3) estimation and/or simulation.

The first step, exploratory data analysis or structural analysis, is the initial phase in the simulation of regionalized variables and includes a few preliminary studies (e.g., preparation of a location map, check for normality, data transformation, matching of data with geological and hydrogeological setting). The histogram is one of the most common methods for the presentation of the distribution of datasets. Most of the conventional geostatistical methods use histograms and/or variogram parameters for predicting data distributions in two and three dimensions. Many of these methods perform better if the distribution of the

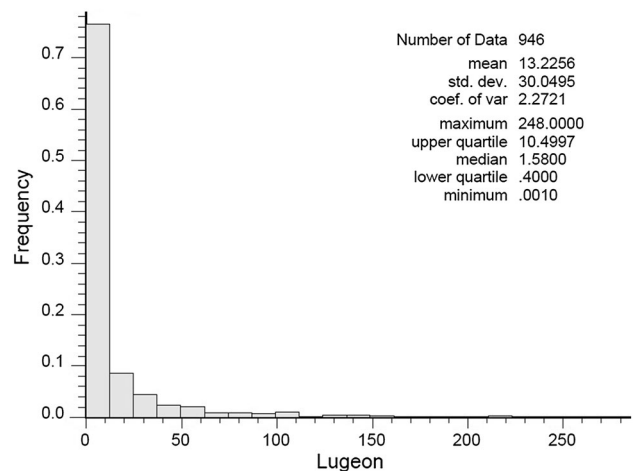


Fig. 3 Histogram and summary statistics of Lugeon values in the study area

datasets is close to a normal distribution (Isaaks and Srivastava 1989). However, many of the original data sets are not normally distributed. Therefore these data need to be converted to a normal distribution using the method of Deutsch and Journal (1998):

$$y_I = G^{-1} \left(\frac{C_I - C_{I-1}}{2} \right) \quad (1)$$

where C_I is the cumulative probability associated with the I th largest data value Z_I , y_I is the normal score transformation of Z_I , and $G^{-1}(C)$ is the numerical approximation of inverse standard normal cumulative distribution function for the C quantile (Deutsch and Journal 1998).

In the variogram modeling step, the computation of variograms is followed by the best fitting of a permissible

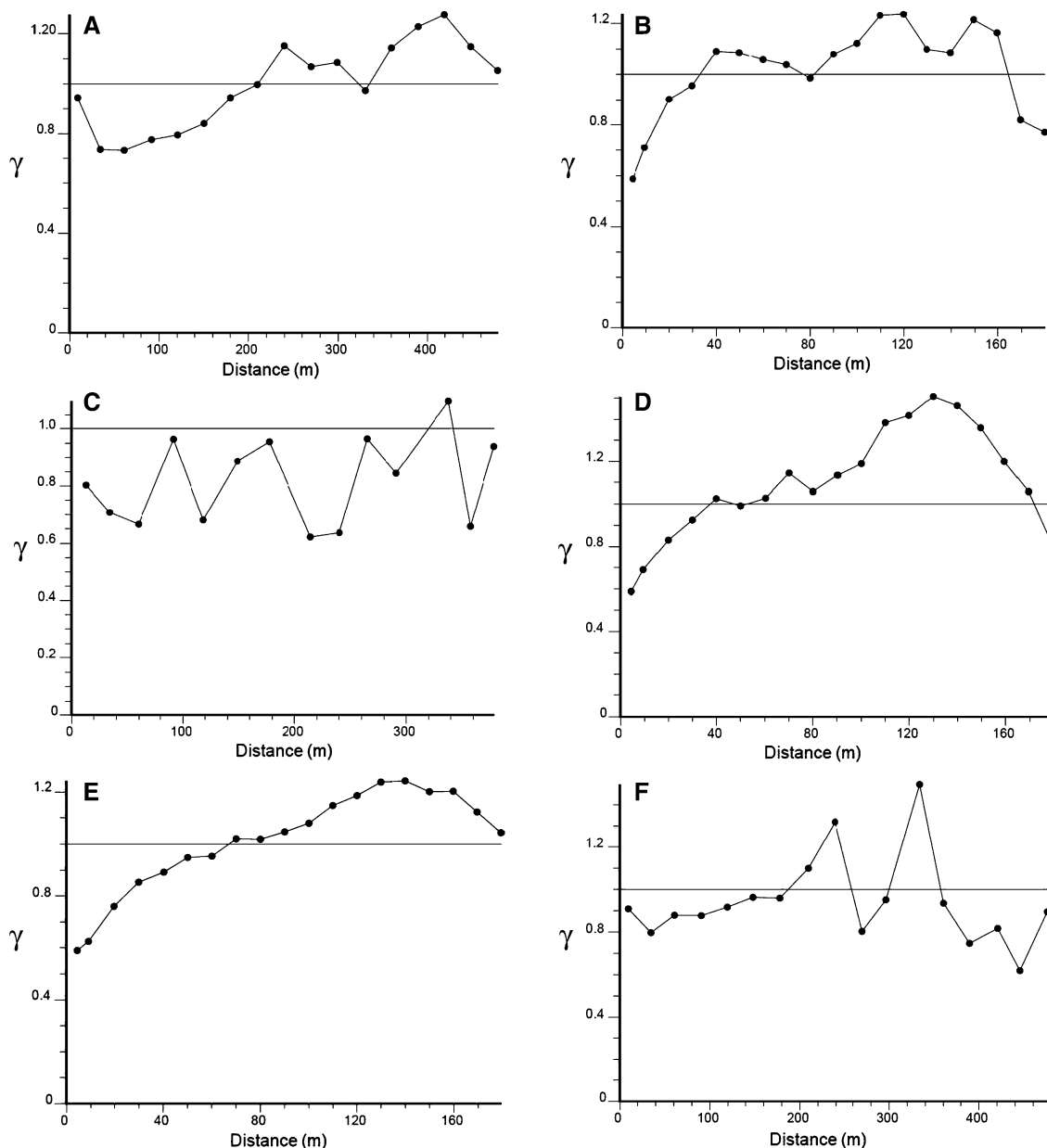


Fig. 4 Variogram of Lugeon values in different direction. For the definition of figure parts (a–f), see Table 1

theoretical variogram. We conducted variogram analysis of Lugeon data to identify the spatial variability in the study area. A variogram analysis of the spatial structure allows the determination of the variation of Lugeon values in space. Variogram models of Lugeon values are used to estimate and simulate the spatial variation. The variogram is half the average squared difference between the paired data values (Isaaks and Srivastava 1989):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} [Z(u_{\alpha}) - Z(u_{\alpha} + h)]^2 \quad (2)$$

where $\gamma(h)$ is the variogram and $N(h)$ is the number of pairs of samples used in the calculation of each interval h . The

number of pairs is a function h , and Z is variable in the position (u_{α}).

The final step in a geostatistical investigation, i.e., estimation and simulation, covers a wide range of approaches to determine the weight associated with each data point and to predict the optimum value for the attribute of unsampled points. The kriging principle has been presented in detail by Isaaks and Srivastava (1989) and Goovaerts (1997). The procedure for determining the weight associated to each observation is the main difference between all versions of kriging. In simple kriging (SK), the following generalized linear regression algorithm is used (Deutsch and Journel 1998):

Table 1 Characteristics of the variograms selected for the different directions

Direction	Range (m)	Sill effect	Nugget effect	Relative mean square error	R ²	Fitted model
Along galleries in horizontal surface (Fig. 4a)	250	1	0.75	0.16	0.69	Gaussian
Along galleries in vertical surface (Fig. 4b)	35	1	0.6	0.17	0.44	Exponential
Perpendicular to galleries in horizontal surface (Fig. 4c)	0	0.8	0.8	0.14	0.10	Nugget effect
Perpendicular to galleries in vertical surface (Fig. 4d)	40	1	0.5	0.25	0.10	Spherical
Omni directional in horizontal surface (Fig. 4e)	80	1	0.5	0.2	0.01	Spherical
Omni directional in vertical surface (Fig. 4f)	230	1	0.8	0.18	0.58	Gaussian
Omni directional	130	0.95	0.65	0.21	0.14	Exponential

Differences between estimated (or simulated) and measured values of Lugeon data were evaluated using cross-validation criteria, such as the relative mean square error and the correlation coefficient (R²)

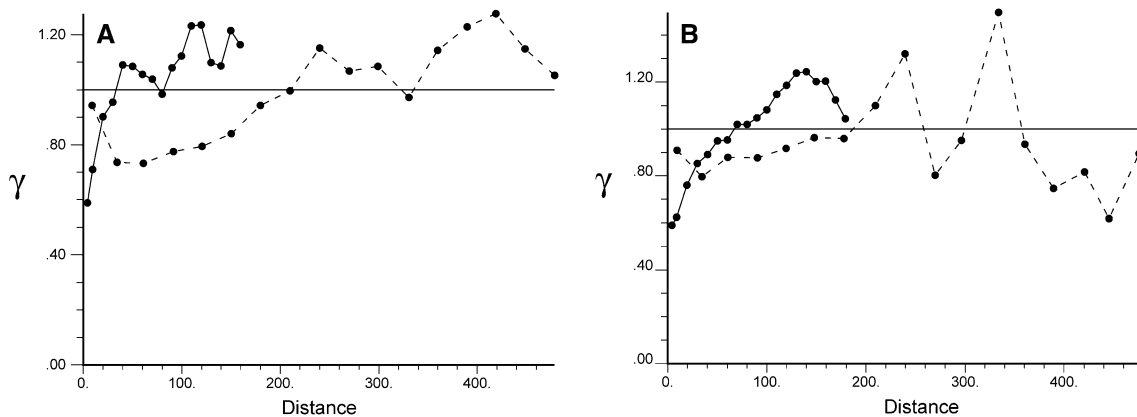


Fig. 5 Comparison of the variograms in the vertical direction (solid line) with those in the horizontal direction (dashed line). **a, b** Directions parallel (a) and perpendicular (b) to the grouting galleries

$$[Z_{SK}^*(u) - m(u)] = \sum_{\alpha=1}^n \lambda_{\alpha}(u)[Z(u_{\alpha}) - m(u_{\alpha})] \tag{3}$$

where $Z(u)$ is the Lugeon value at location u , u_{α} represents the n data locations, $m(u) = E\{Z(u)\}$ is the location-dependent expected value of $Z(u)$, $\lambda_{\alpha}(u)$ is the SK weights at location u , and $Z_{SK}^*(u)$ is the SK estimator. In SK, the attribute mean [i.e., $m(u)$ of the Lugeon values] is assumed to be constant and known over the studied domain. However, the attribute mean is constant but unknown in ordinary kriging (OK), resulting in the following OK estimator:

$$Z_{OK}^*(u) = \sum_{\alpha=1}^n \lambda_{\alpha}(u)Z(u_{\alpha}) \tag{4}$$

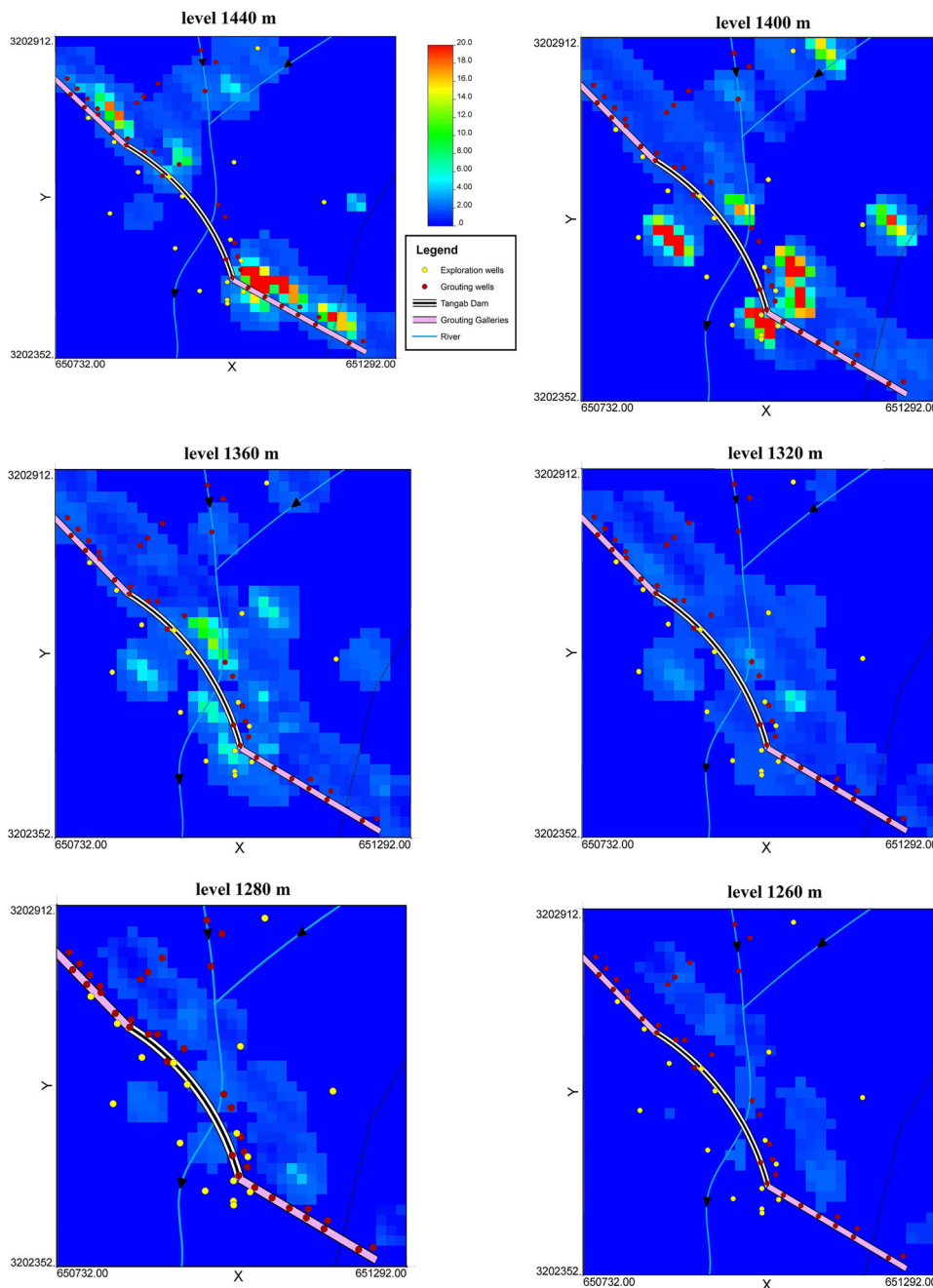
The applicability of the estimation and simulation approaches is validated based on the cross validation procedure (Isaaks and Srivastava 1989). Differences between estimated (or simulated) and measured values of Lugeon data were evaluated using cross-validation criteria, such as

the relative mean square error (RMSE) and the correlation coefficient (R²) (Hevesi et al. 1992). RMSE and R² will be close to zero and one, respectively, if estimation processes are accurate.

Simulated annealing is an iterative trial and error approach to achieve statistical constrains. The simulated annealing process needs (1) the initial image of Lugeon data, (2) the perturbation mechanism, (3) the objective function, and (4) the convergence criterion (Isaaks and Srivastava 1989). The initial image is created based on the Lugeon data over the grid nodes. The Lugeon values in grid nodes is then modified many times, and the objective function is checked after each perturbation. The objective function can be defined for the histogram and/or variogram model (Deutsch and Journel 1998). The variogram of the simulated realization $[\gamma^*(h)]$ should match the pre-specified variogram model $[\gamma(h)]$. The objective function can be written as:

$$O = \sum_h \frac{[\gamma^*(h) - \gamma(h)]^2}{\gamma(h)^2} \tag{5}$$

Fig. 6 Two-dimensional maps of the estimated Lugeon values based on simple kriging (SK) at different levels



The Geostatistical Software Library (GSLIB; Deutsch and Journel 1998) was utilized to perform the above steps in the geostatistical simulation of the Lugeon data.

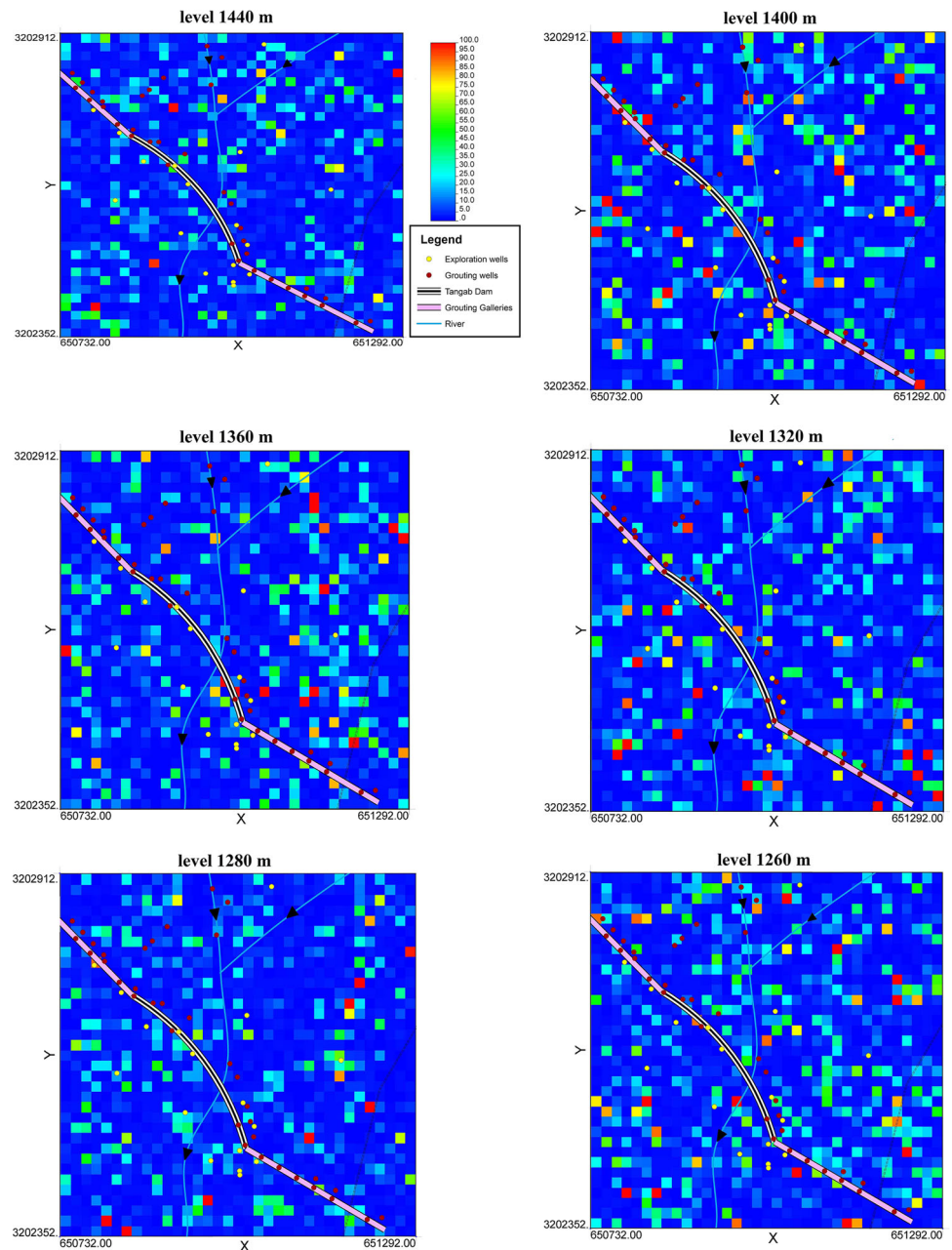
Results and discussion

The results of the studies at the Tangab Dam site are presented and discussed within the framework of the three steps of geostatistical investigations, as described in the “Methods” section.

Exploratory data analysis

A location map of the data points is presented in Fig. 2. Lugeon tests were conducted in two types of wells: exploratory wells ($n = 17$) and grouting wells ($n = 58$) along the grouting galleries. A total of 953 standard Lugeon tests were conducted at 5-m intervals. A histogram was plotted to verify the normality of the Lugeon data distribution (Fig. 3), which also shows the summary statistics of the 953 Lugeon tests. The Lugeon values were <50 in 876 tests and >50 in 77 tests. Most of the

Fig. 7 Two-dimensional maps of the simulated Lugeon values based on simulated annealing at different levels



geostatistical approaches were developed based on the assumption of normality. The original Lugeon data were transformed to a normal distribution using Eq. (1).

The variogram function (Eq. 2) was used to determine the spatial relationship between the Lugeon values. Variograms can be calculated in different directions, thereby enabling the spatial relationships between Lugeon data and anisotropy in the data to be assessed by comparing the variogram functions in different directions. Therefore, we selected two directions in the horizontal surface, both along and perpendicular to the grouting galleries, and one vertical direction to calculate variogram functions (Fig. 4).

Variogram modeling

The nugget effect, based on the definition by Isaaks and Srivastava (1989), is relatively high and includes approximately 35 % of the total variance in the vertical dataset (Table 1). The models for the vertical variograms include a spatial structure with a range of 35 m, which accounts for 22 % of the total variance. Spatial variation of Lugeon data in the vertical dataset can be modeled using an exponential model with a range of 37 m.

The horizontal data set shows a longer range than the vertical direction one. This longer correlation length confirms the possibility of geometric anisotropy in the study area (Fig. 5).

The theoretical variogram function was fitted to sample variograms in different directions, and the characteristics of the selected variogram are presented in Table 1. The highest correlation range (about 250 m) was found between Lugeon values on the horizontal surface in the direction of the grouting galleries. The correlation range in the vertical direction was generally lower than in other directions.

Estimation and simulation

A grid node of $75 \times 35 \times 35$ cells covering $187.5 \times 560 \times 560$ m was selected to estimate and simulate the Lugeon values in the study area. SK and OK were used to interpolate these values at the untested nodes. The most appropriate model for variogram and kriging estimator was selected according to cross-validation criteria, such as RMSE and R^2 . Comparison of the cross-validation criteria showed that SK with a Gaussian model of omnidirectional variogram had the highest R^2 value and the lowest RMSE value. The final optimum spatial estimation of Lugeon values based on SK and simulation of the Lugeon value based on simulated annealing over the grid nodes is presented in Figs. 6 and 7, respectively.

Lugeon values in the left abutment of the dam, with an average value of 17, were generally higher than those in the right abutment, with an average of 12 (Figs. 6, 7), which agrees with values previously determined by the tracer tests results (Asadi 1998; Talaei 1999). Comparison of the estimated and simulated Lugeon values at different levels (Figs. 6, 7) revealed that the Lugeon values decreased from about 20 to 3 with increasing depth. This trend reveals decreasing of karst development with increasing depth in

the study area. The much greater karst development at higher levels (e.g., 1,400 m a.s.l.) may be due to water level fluctuations and a stronger aggressivity of recharge meteoric water near the surface.

Comparison of the estimated and simulated Lugeon values at different levels (Figs. 6, 7) also showed a systematic displacement from level 1,400 toward 1,320 m a.s.l. The grid nodes with high Lugeon values moved slightly from the right toward the left abutment with decreasing estimated values. This displacement follows the 15° bedrock dip. A geological cross-section along the dam axis is presented in Fig. 8. Variation of the lithology sequence in depth was mapped based on information obtained from the drilling of wells and galleries (Fars Regional Water Authority 2007). Taking the geological setting into account, we were able to develop a schematic model for development of karst (Fig. 9). As shown in Fig. 9, meteoric water recharge occurs from the surface of the karstic Asmari Formation through joint sets and vertical or subvertical infiltration due to the marl inter-bedded layer where it dips by 15° . Estimated and simulated Lugeon values (Figs. 6, 7) can be adjusted by the hydrogeological setting. According to the geological cross-section, the intersection of bedding planes and faults or master joints have a potential for karst development. Since water infiltrates from the surface to deeper levels along the surface openings, the potential for karst development generally decreases from the surface (1,440 m a.s.l.) to depth (1,260 m a.s.l.). Figure 10 shows the variation of the simulated Lugeon values from surface to depth at several arbitrary points. On average, Lugeon values decrease from 35 at 1,440 m a.s.l. to <1 at 1,260 m a.s.l. (Fig. 10).

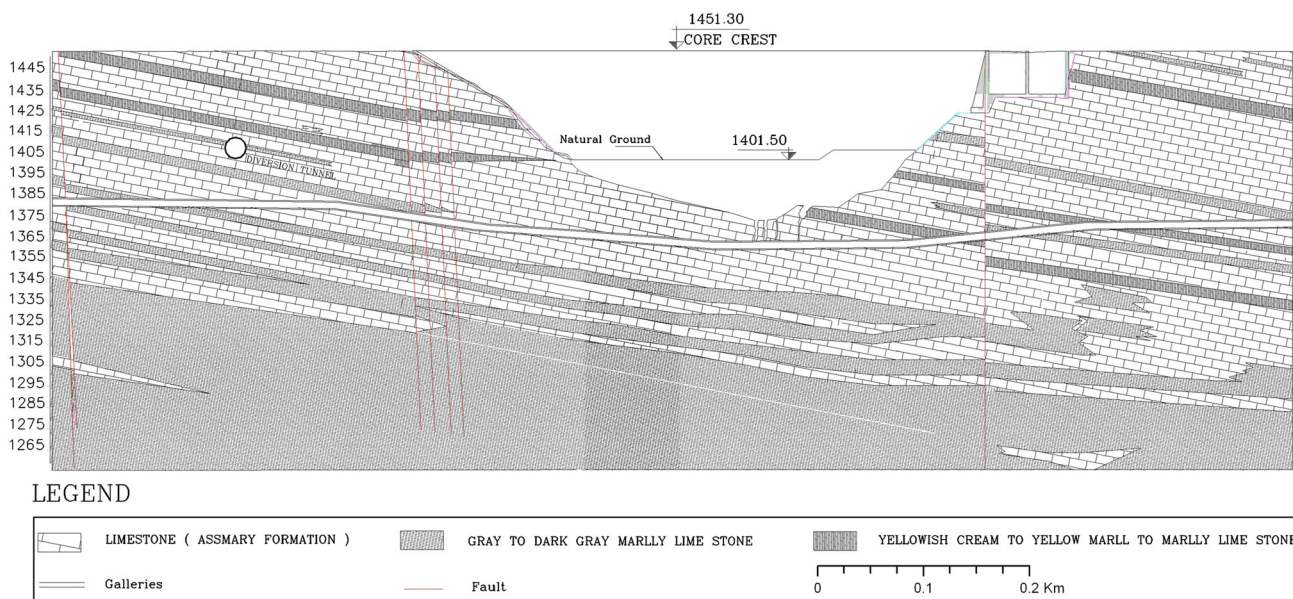


Fig. 8 Geological cross-section along the dam axis (Fars Regional Water Authority 2007)

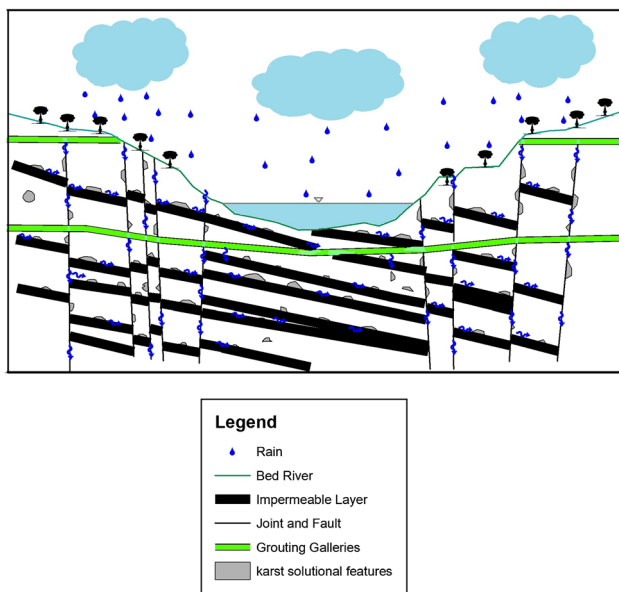


Fig. 9 Schematic hydrogeological model for development of karst at the dam site (not to scale)

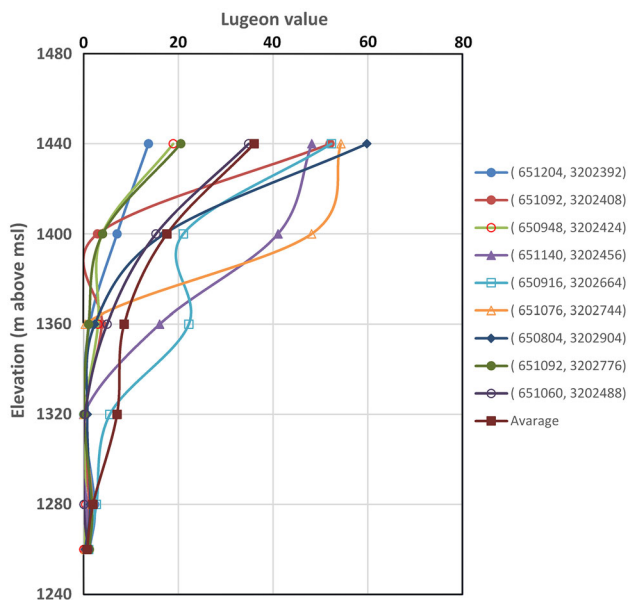


Fig. 10 Variations of simulated Lugeon values versus elevation at several points. The Universal Transverse Mercator coordinates of the points are given to the right of the figure

Conclusion

The purpose of this study was to survey the development of permeability in karst formations using geostatistical methods. To achieve this purpose, we used Lugeon data from exploration and grouting wells. Exploratory data analysis allows for the study of the spatial dependence of Lugeon values. We identified a geometric anisotropy by comparing variogram function in different directions. The

results of this study show agreement with previous investigations in the study area. A preliminary schematic model for karst development is proposed based on the simulation of Lugeon data and hydrogeological setting of the dam site. It would appear that karst and solutional conduits are more developed in the left abutment of the dam site than in the right abutment. A 15° dip is proposed as the more likely potential site of karst development, which could correspond to the marl inter-bedded layers. From a hydrogeological standpoint, the caves probably developed with multiple vertical shafts (along joints), interconnected by passages and halls (developed along bedding planes). Based on the inherent heterogeneity of the karst aquifer, each of the conventional hydrogeological approaches is uncertain when separately used. The uncertainties in characterization of the karst system may be reduced by considering all geological, hydrogeological, and statistical methods for studying it. As a result, geostatistical approaches could be applied to the study of karst development based on a limited Lugeon dataset when the hydrogeological framework of the study area is taken into account when the data are interpreted.

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