JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.87, January 2016, pp.97-104

# Prediction of the Collapsing Risk of Mining Slopes Based on Geostatistical Interpretation of Geotechnical Parameters

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**Abstract:** Almost all collapses of rock slopes especially in open pit mines are related to discontinuities such as bedding planes, faults and major joints.Geostatistical assessments can be used for understanding the distribution of regionalized variables in any spatial study. In this paper3D spatial dispersion of the fault planes in the Gole Gohar open pit iron mine, located in Kerman province, south east of Iran, is modeled. Then, regionalized variable theory is used to analyze and interpret spatial distribution of the following geotechnical parameters: Geological strength index (*GSI*), Rock quality designation (*RQD*), Cohesion (*C*) and angle of internal friction ($\phi$). In order to define regionalized variable distribution, variogram functions were determined for identifying the regional behavior. Structural analysis of variograms showed that the mentioned parameters have spatial structures that make it possible to set up a geostatistical model to predict their values for each non-sampled block on the pit wall. Results showed that there is a relation between the low values of geotechnical parameters and the existence of discontinuities around the pit area. The role of discontinuities in the occurrence of collapses in the area was clearly demonstrated by comparing the estimated parameters models and the model of discontinuities dispersion.

**Keywords:** Discontinuity, Geotechnical parameters, Geostatistics, Slope stability, Gole Gohar iron mine, Iran.

## INTRODUCTION

In surface mining operations, unanticipated movement of the ground can pose hazardous conditions which may lead to endangerment of lives, destruction of equipment, and the loss of property. In the last decades, the study of discontinuous rock mechanics has developed tremendously (Girard and McHugh, 2000). It has been recognized that discontinuities have a major role on the mechanical properties of a rock mass. This perception has major consequences for the assessment of the engineering behavior of a rock mass (Hack, 1997). In most classification systems, the persistence of discontinuities, which is important in slope stability, is only taken into account as a qualitative rather than a quantitative factor (Hack and Price, 1993).

Discontinuities such as beddings, faults and major joints are regarded as weak planes within rock that reduce rock strength. Barton et al. (1985) pointed out that discontinuities within rock masses have very low tensile strength. This means that every single point on discontinuities has reducing effects on the stability of rock masses, hence the potential of rock failures becomes prominent. Priest (1985, 1993) found that the stability of rock slopes depends kinematically on the orientation of discontinuities. The stability of rock slopes is therefore dependent on the intersection between the orientation of discontinuities and the direction of slopes: whether the dip direction of discontinuities is nearly parallel to the direction of slopes, or perpendicular to the direction of slopes (Priest, 1985). Another parameter that influences the stability of jointed rock masses is the shear strength of discontinuities which depends on the roughness of discontinuities (Priest, 1993). Weathering will then negatively influence this roughness, weathered jointed rock masses will have lower shear strength compared to that of unweathered jointed rock masses (Agustawijaya, 1996).

Geotechnical engineering is constantly evolving and its practitioners are always looking for tools which can handle the large variations inherent in soil and rock properties. In recent years, several authors have attempted to apply geostatistics to the problems of geotechnical engineering.

Geostatistics, as a methodology for estimating recoverable reserves in mining deposits, was mathematically formalized by French professor Georges Matheron in 1963, inspired by the pioneering work of South African mining engineer D.G. Krig in the 1950's. Today it is extensively used in the mining and petroleum industries, and in recent years it has been successfully integrated into remote sensing

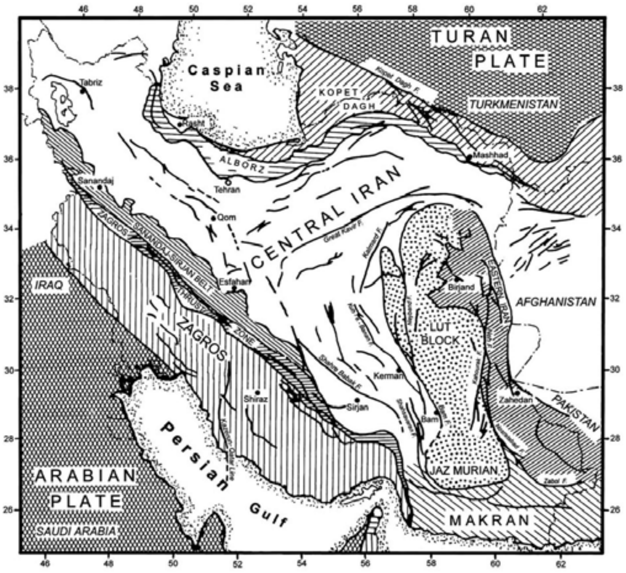


**Fig.1.** The location of the Gole Gohar iron mine in Iran.

(Atkinson and Lewis, 2000; QingminMeng et al., 2009; Pardo-Iguzquiza et al., 2011), Geographic information systems (GIS) (Cshoi and Park, 2006), soil science (Choi and Park, 2006; Emery, 2006; Tavares et al., 2008), hydrology (Hossain et al., 2007; Chowdhury, 2010) and statistics. In this paper, regionalized variable theory is used for analyze and interpret the spatial distribution of Geological strength index (GSI), Rock quality designation (RQD), Cohesion (C) and angle of internal friction ($\phi$) at Gole Gohar iron mine which makes it possible to predict these parameters for every other block on the pit wall, these parameters can be used simultaneously with discontinuities to predict the risk of collapses.

## GEOLOGICAL SETTING

The Gole Gohar iron mine is located NW of Sanandaj-Sirjan zone in Iran. The mining area is 53 kilometers southwest of the Sirjanat latitudes 55°15' to 55°24' E and longitudes of 29°3' to 29°7' N (Fig.1).

Through geophysical exploration, 6 enormous iron anomalies were detected in the area which covers an area of 40 km$^2$. In the present study, the slope stability of anomaly 1 is considered. There are three zones within anomaly 1: upper magnetite, oxidized hematite and lower magnetite. The mine has been exploited by open pit method with the slope of 45° for rocky units and 33° in alluvium. The current mining depth is 130 m and the final depth will be about 300 m and the reserve of the mine is estimated at 1135 million ton with the mean grade of 54.7% Fe.

The anomalies are located within Paleozoic metamorphic complexes covered by alluvium. In some cases the footwall of ore body consists of the gneisses, mica schist, amphibolite and hanging wall include quartz schist and greenschists.

Given the tectonic setting, the remote sensing survey of the area around the mine, the geological survey of the mine and the area around it, the following results about structural geology of the mine were obtained.

There is a variety of discontinuities such as reverse, strike-slip and normal faults, and tensile major joints with considerable aperture. Figure 2 shows distribution of faults around the pit No.1 of Gole Gohar mine.

A buried right lateral strike slip fault with the NW-SE strike is responsible for the occurrence of above mentioned faults which has leaned to left. This situation has led to the formation of a compressional lens-shaped structure such

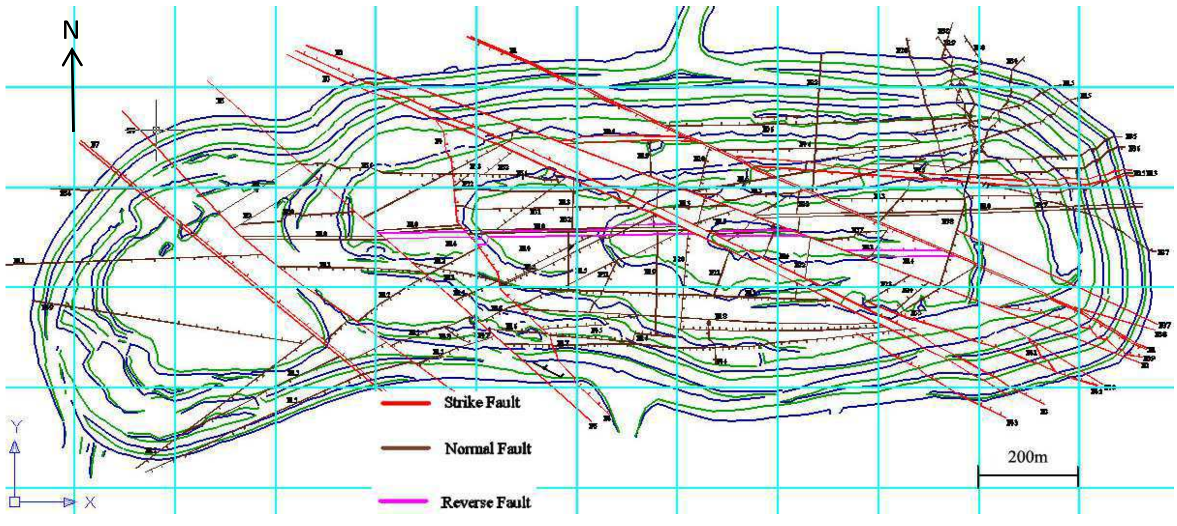


**Fig.2.** Distribution of faults around pit No.1 of Gole Gohar iron mine (Hasanpoor, 2010).


**Fig.3.** Flower faults structure in southwest wall of the Gole Gohar mine.

that its northeast and southwest boundaries are thrust faults with dips towards the southwest and northeast, respectively.

The section perpendicular to the strike of the zone is like a flower (Fig.3).

In bedrock including ore bodies, faults often have east-west trend with dip 45 to 80 degree toward the south. As shown in Fig.4, these faults lie almost exactly at the boundary between ore bodies and host rocks. Since these faults have small angle with the northern benches of mine and since their slope is consistent with trenches slope, instability is inevitable (Hasanpoor, 2010).

The basic mode of failure which may occur are planar, wedge, circular and toppling (Girard and McHugh, 2000; Osanloo, 2005). The types of failures which have occurred in pit No.1 of Gole Gohar mine according to the field survey is shown in Fig.5. As is shown, rock mass in Gole Gohar mine have the potential for different kinds of failures (Hasanpoor, 2010).

## THE ROLE OF DISCONTINUITIES IN OCCURRED COLLAPSES

The slope stability in open pit mines is controlled by persistence and characteristics of discontinuities such as beddings, faults and major joints. The spatial distribution of collapses in open pit mines positively correlates with the distribution of discontinuities, hence structural instability is significantly influenced by discontinuities (Shademan et al., 2013). Therefore, the persistence has to be considered as an explicit factor for the slope stability.

Since strike and dip measurements are made for each faults within the surveyed open pit mine, the distribution of fault orientations is formulated by using the following equation:

$$a(x-x_0) + b(y-y_0) + c(z-z_0) = 0 \quad (1)$$

where $x_0$, $y_0$ and $z_0$ are the coordinates of the point on fault plane. $a$, $b$ and $c$ are the components of the normal vector.

A 3D model of the available fault planes in Gole Gohar open pit iron mine is demonstrated in Fig.6.

## GEOSTATISTICAL MODELING AND DISTRIBUTION OF GEOTECHNICAL PARAMETERS

In this research geostatistical variables are *GSI*, *RQD*, and *C* which are obtained from data measured within bore holes. The location of these bore holes is shown in Fig.7 and the statistical parameters of the variables are given in Table 2. Investigation of the distribution of the regionalized variables of interest in the given pit wall is carried out by determining the variogram functions which is defined as half the average quadratic difference for N pairs of measurements of the variable z separated by a distance h (Armstrong, 1998; Isaaks and Srivastava, 1989; Journel, 1989; Journel and Uijbregts, 1978):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x+h) - z(x)]^2 \quad (2)$$

After calculating the experimental variogram, it is

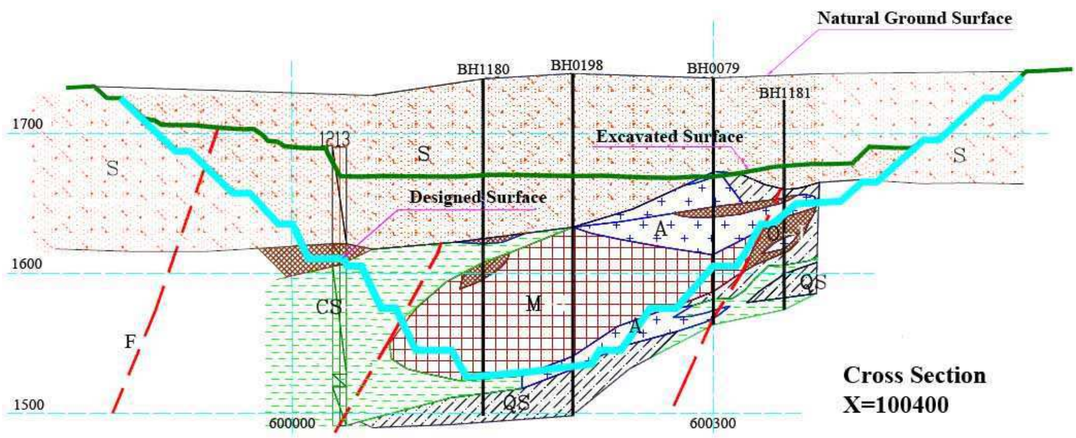


**Fig.4.** The geological section of pit No.1 at X=100400m. (Sandy clayed gravel with cobble (S), Quartz Schist (QS), Chlorite schist (CS), Amphibolite (A), Oxide (Hematite) (O), Magnetite (M), Fault (F), Borehole (BH).) (Hasanpoor, 2010).

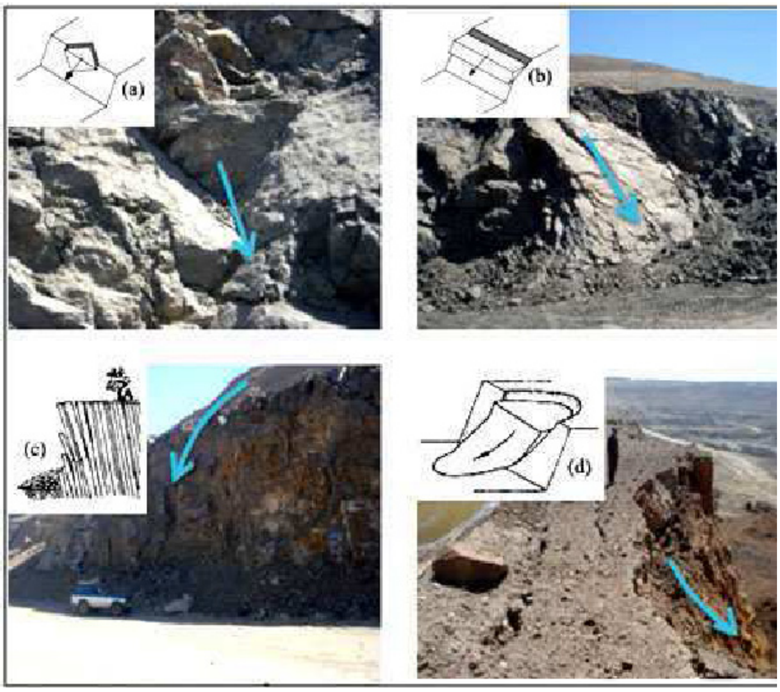


**Fig.5.** Types of failures which have occurred on the pit wall of Gole Gohar iron mine. (a) wedge failure, (b) planar failure, (c) toppling failure and (d) circular failure.

necessary to adjust the mathematical model to represent the variable as realistically as possible. It is important that the mathematical model represents the trend of the variogram with relation to distance h.

Of the experimental variograms calculated for all parameters in several directions, those which showed the best fit were chosen. It should be mentioned that 582 composite data were utilized to perform calculations.

Spherical models, presented in Fig.8, were fitted to the variograms. The optimum sill and range were chosen for each variogram by a cross validation method. The results of this method are illustrated in Fig.9, which shows the scatter of the actual values against estimated values. They should be exactly the same in the ideal conditions, but it is obvious that in the natural conditions, this hypothesis is clearly out of question. The best we can expect is that our estimation is conditionally unbiased which means

$$E\left[Z(x_0)|\hat{Z}(x_0)\right] = \hat{Z}(x_0) \qquad (3)$$

From this it follows that the regression should be 1, therefore the covariance between the true values and the estimated must be equal to the variance of the estimates (Webster and Oliver, 2001). The parameters of the variogram functions are given in Table 1.

Among the spatial interpolation (geostatistical estimation) techniques, a process called kriging is the best linear unbiased estimator of unknown characteristics (Isaaks and Srivastava, 1989;Journel, 1989), which make it possible to understand the regional behavior of the natural phenomena for every point in the study area (Krige, 1962).

If magnitudes of data are available at specific locations, it is possible to estimate the values of it at other locations through kriging. The goal of kriging is to predict the average value at specific point of the study area. If $Z(x_1)$, $Z(x_2)$, $Z(x_3)$.... $Z(x_n)$ are known values of parameter, then the estimated value of a parameter at point $x_0$ is given by:

$$Z(x_0) = \sum_{i=1}^{n} w_i Z(x_i) \qquad (4)$$

where $w_i$ are weights applied to the respective values $Z(x_i)$, such that:

$$\sum_{i=1}^{n} w_i = 1 \qquad (5)$$

**Table.1.** The parameters of the variogram function

| Parameter | Variogram Model | Azimuth | Dip | Range (m) | Sill | Nugget |
|---|---|---|---|---|---|---|
| *GSI* | Spherical | 90 | 0 | 972 | 87.38 | 6 |
| | Spherical | - | 90 | 40 | 83.33 | 5.62 |
| *RQD* | Spherical | 90 | 0 | 631 | 549.33 | 92.3 |
| | Spherical | - | 90 | 30 | 531.93 | 87.98 |
| *C* | Spherical | 90 | 0 | 946 | 0.046 | 0.005 |
| | Spherical | - | 90 | 30 | 0.041 | 0.002 |
| ϕ | Spherical | 90 | 0 | 809 | 82.4 | 6.67 |
| | Spherical | - | 90 | 37 | 75.15 | 4.53 |

**Table 2.** Statistical parameters of the geotechnical variables

| Parameter | No. | Mean | Median | Variance | Min | Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| *GSI* | 1240 | 34.11 | 35 | 72.96 | 0 | 60 | -1.51 | 4.98 |
| *RQD* | 1240 | 24.86 | 16 | 766.78 | 0 | 100 | 0.94 | -0.20 |
| *C* | 1240 | 0.265 | 0.256 | 0.0483 | 0.023 | 3.069 | 7.04 | 72.03 |
| ϕ | 1240 | 29.12 | 28.4 | 82.598 | 9 | 116.5 | 3.29 | 21.73 |

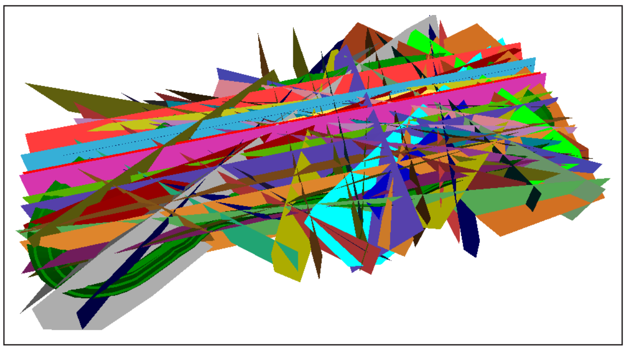

**Fig.6.** 3D model of the fault planes in surveyed open pit iron mine

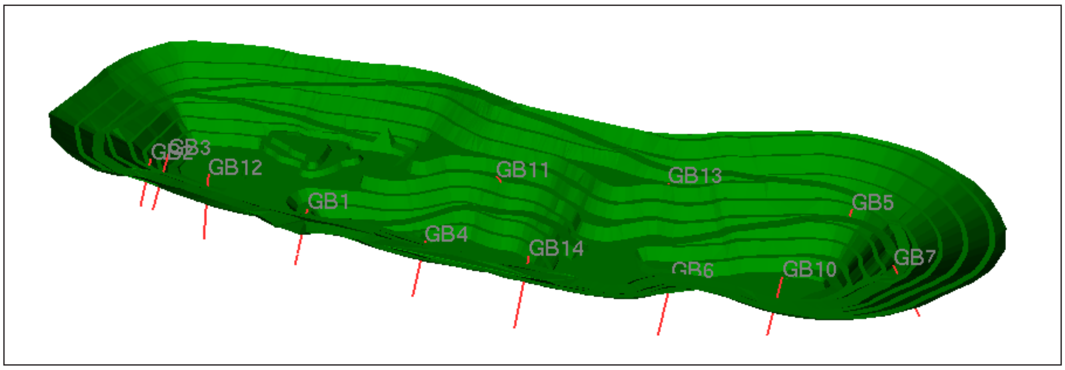


**Fig.7.**The location of geotechnical bore holes on the pit wall

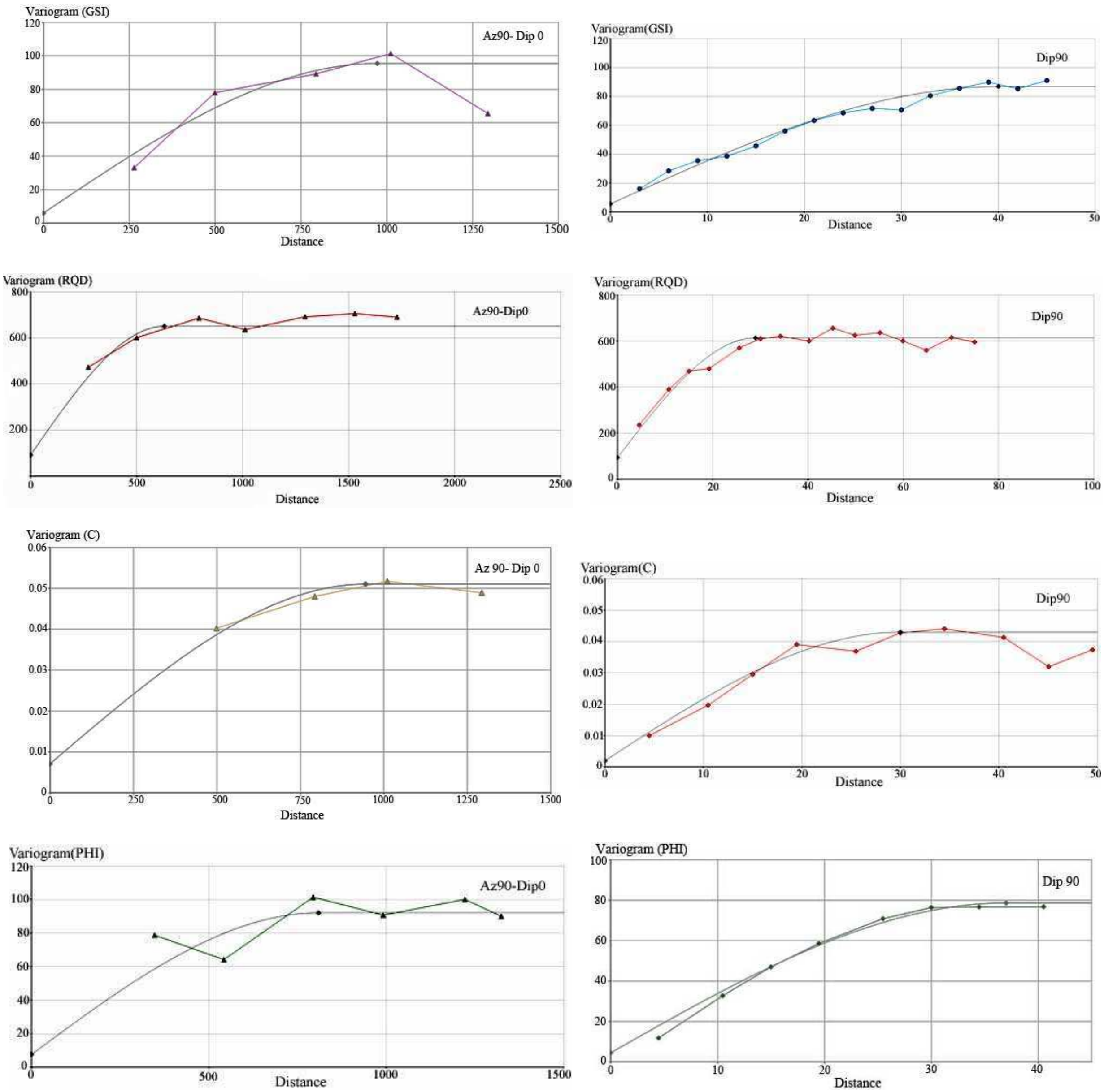


**Fig.8.**Spherical model used to fit experimental variograms calculated for parameters values

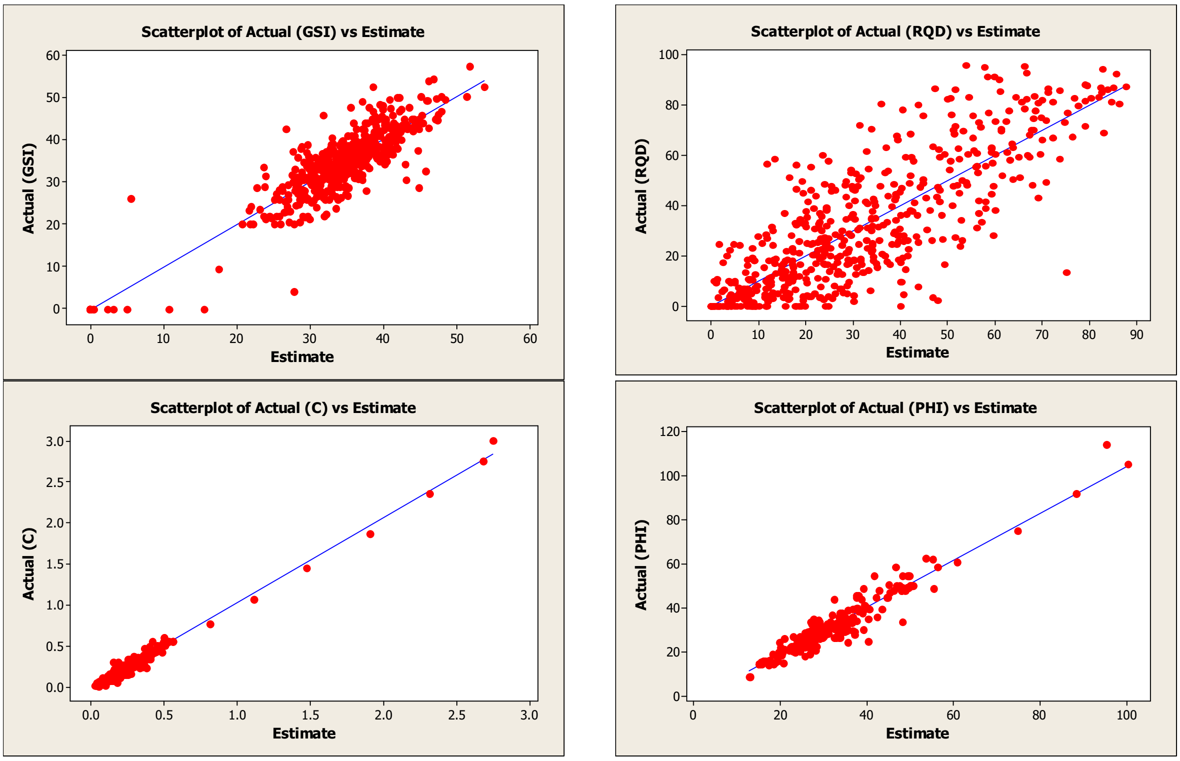


**Fig.9.** Scatter diagrams of the actual geotechnical parameters values against the estimated parameters values

The weights $w_i$ are determined through kriging matrix (Isaaks and Srivastava, 1989, Subyani, 1997).

After determining theoretical variograms and running the kriging technique, it is possible to estimate the parameters values for the each local block on the pit wall and prepare models to interpret the behavior of the regionalized variable.

Fig.10 to 13 shows the 3D block models of estimated parameters with the size of 25*25*10m for each block throughout the mine. The geostatistical processes have been determined by using Datamine software.

## DISCUSSION

According to Fig.6, fault planes, and Fig.10 to 13, there is a possibility of direct relation between low geotechnical parameters values and the existence of discontinuities (such as fault) in the neighborhood.

In other words, the distribution of low values of the surveyed parameters in pit No.1 of GoleGohar iron mine is related to the distribution of discontinuities. Therefore the covariance between the low values of these parameters and the density of discontinuities near them could be used to evaluate safety factor. As shown above, there is a possibility of instability in the northeastern, southeastern and western walls. As shown in Table 3 and Fig.14, the bivariate statistical relationship between geotechnical parameters can be easily obtained, but the most valuable achievement is to find a statistical relationship between a boolean parameter (existence of faults) and numerical parameters (*GSI, RQD, C* and $\phi$). This is strongly recommended by the authors. As illustrated in Table 3 and Fig.14, except for GSI and RQD, there is no visible correlation between any other two variables considered. Both GSI and RQD are dependent on discontinuities spacing, which is reflected in high correlation coefficient.

## CONCLUSION

Existence of discontinuities and their properties, as evaluated by geotechnical parameters consisting of *GSI*, *RQD*, *C* and $\phi$ are used to define risk of collapses in pit No.1 of Gole Gohar iron mine. Uncertainty and variation in mentioned parameters within the mining area can be processed through geostatistical methods and their values can be evaluated at various locations. Results showed that the distribution of low values of estimated parameters in

**Table 3.** Regression coefficient between geotechnical parameters

| | GSI | RQD | C | $\phi$ |
|---|---|---|---|---|
| GSI | 1 | 0.438 | 0.064 | 0.0117 |
| RQD | 0.438 | 1 | 0.004 | 0.002 |
| C | 0.064 | 0.004 | 1 | 0.153 |
| $\phi$ | 0.0117 | 0.002 | 0.153 | 1 |

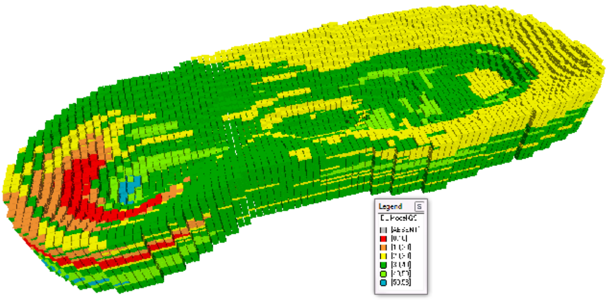


**Fig.10.** Block model of estimated GSI values

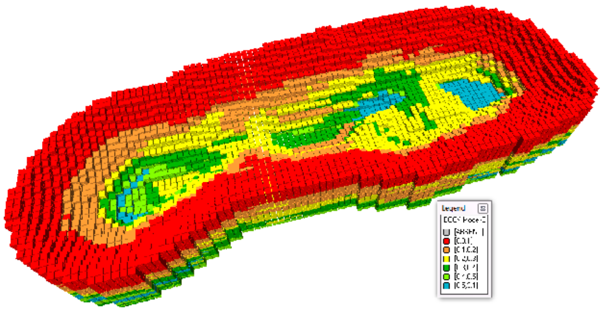


**Fig.11.** Block model of estimated RQD values

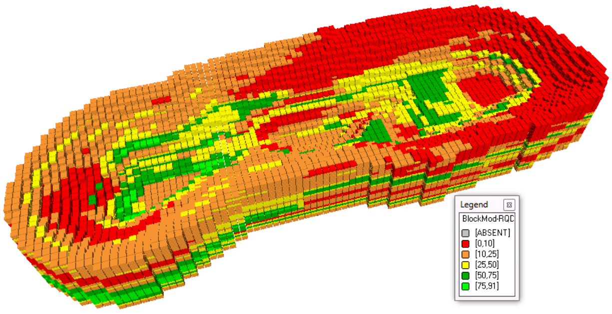


**Fig.12.** Block model of estimated C values

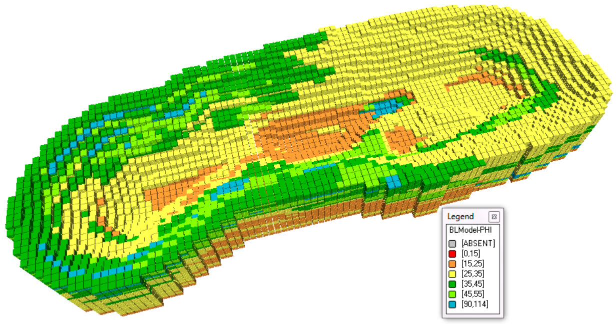


**Fig.13**. Block model of estimated ϕ values

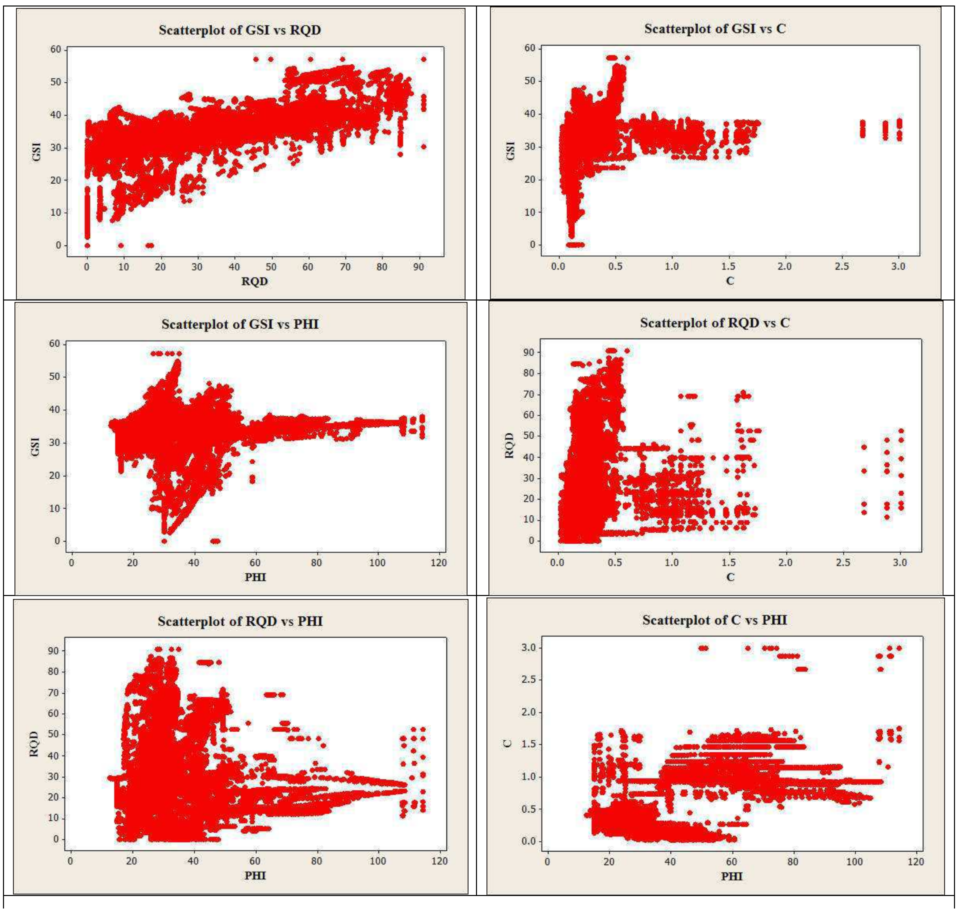


**Fig.14.** Bivariate statistical relationship between geotechnical parameters

the study area is related to the distribution of discontinuities, especially their intersections throughout the mine which clearly demonstrate the role of discontinuities in instable slopes. Hence, unloading and maintenance systems for the wall containing discontinuities should be considered to the better exploit pit walls.

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*(Received: 18 March 2014; Revised form accepted: 5 May 2014)*