Determination of groundwater and geological factors using geoelectrical methods to design a suitable drainage system in Gol-e-Gohar iron ore mine, Iran

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Abstract

Various problems caused by the presence of underground water in Gol-e-Gohar iron ore mine have made mining experts seek proper solutions. One of the best solutions is to make a suitable drainage system for leading the mine waters to an area outside of the mine limits. However, the groundwater situation and geological structures such as active faults present in the mining area should be, first, recognized and then considered carefully for designing an optimal drainage system.

Since the presence of groundwater has almost stopped the mining operations in the main area (area No. 1) of Gol-e-Gohar mine, area No. 3 of this mine, which contains the largest iron ore deposit in southern Iran, has been considered for mining. Due to the expected negative influence of subsurface water on the mining activities in this area, a suitable drainage system should be installed before mining operations are commenced. Geoelectrical surveys using resistivity methods have been carried out in the area to determine subsurface geological features such as faults, depth to bedrock, and lithologic specifications of geological layers, and the groundwater situation (e.g. porosity or permeability, depth and thickness of water-bearing formation). Alluvial overburden and moderate topographic conditions in area No. 3 of Gol-e-Gohar mine have made it practically easy to apply the resistivity methods in the area. The above-mentioned groundwa-

ter and geological factors can be determined accurately as a result of correct interpretation of the measured resistivity data.

A square grid of 500 m by 500 m was considered to cover the study area thoroughly for resistivity sounding surveys carried out using the Schlumberger electrode configuration with maximum electrode spacing of 1400 m. One-dimensional (1-D) interpretation of the sounding data showed the depth to water table to be 40-60 m with an average thickness of 20-30 m for the water-bearing formation in the area. The resistivity of the water-bearing formation was estimated to be 15-23 Ω-m, indicating high electrical conductivity (EC) of groundwater (due to high salinity and concentration of total dissolved solids (TDS) in groundwater) and clay content in the formation. These results were confirmed by 2-D section interpretation. Low correlation between the results of sounding in different places in the study area can be attributed to complex geology, especially various faulting systems in the area.

To investigate lateral resistivity changes and faulting systems, it is recommended to carry out resistivity profiling in the area. Using other geoelectrical methods, such as induced polarisation (IP) and self-potential (SP) methods, the ambiguities arising from the interpretation of resistivity data can be removed or reduced.

1   Introduction

The presence of underground water in mining activities is one of the main problems which reduces the production efficiency. In addition to its economical and environmental impacts on the mining area, design of drilling and blasting patterns would be more complicated in such conditions.

Surface water flowing to a mine site can also cause serious problems in mining operations. The most important problems due to the presence of surface water in a mine are outlined in the following:

1. The water has to be pumped out to an area outside the mining operational site. This will obviously increase the mining costs.

2. The mine walls, roads, and drainage canals will gradually be eroded.

3. The eroded material will be accumulated in the mining site.

4. The water may be frozen in the winter season. This will also cause the mine roads to be swollen and slippery.

4. The surface of the mine roads will be loosened.

5. Slope stability of the mine walls will be reduced due to the water penetration into the existing joints and fractures in the walls.

Greater problems occur due to the presence of groundwater in a mining site. These problems can be divided into technical and operational problems. The most important technical problems are listed in the following:

1.   Reduction of the shear strength of the soils and rocks.

2.   Enlargement of various destructive forces and pressures in the mine walls due to filling the pores, joints and fractures by groundwater.

3. Reduction of slope stability of the mine walls. This may necessitate lower slope angles for the mine walls in the case of open-pit mines.

These technical problems lead eventually to operational problems such as drilling, explosion, exploitation and transportation problems as well as environmental problems, which will result in increasing the mining costs. For example, expensive special explosives will be needed such as slurry explosives, which are several times more expensive than ordinary explosives. Other important operational problems caused by the presence of groundwater in a mining site may be:

1. Reduction of ore recovery to avoid slope stability problems in the mine walls with consequent reduction of mining profit.

2. Reduction of the efficiency of mining equipment and increase in maintenance costs.

Such problems caused by the entry of groundwater to the main mining site (area No. 1) of Gol-e-Gohar iron ore mine have almost stopped the mining operations in the site. Therefore, the mine managers have looked for a proper method to solve or alleviate the problems. Since the presence of groundwater leading to the above problems has not been taken seriously into account when designing and performing the mining operations, any solution will only decrease the intensity of the above-mentioned problems. To avoid the occurrence of such problems in area No. 3 of Gol-e-Gohar mine, the greatest iron ore deposit in southern Iran, a careful mine design has to be considered for this area in which the mining operations have not been started yet. A proper solution chosen for the case is to make a suitable drainage system for leading the mine waters to an area outside the mine limits. To design an optimal drainage system, which can solve the problems in the best manner, the groundwater situation and geological structures such as active faults present in this area need to be known thoroughly. For this, geophysical electrical surveys have been carried out in the area to determine subsurface geological features, such as faults, depth to bedrock, and lithologic specifications of geological layers, and also, the groundwater situation (e.g. porosity or permeability, depth and thickness of water-bearing formation). The interpretation results of the geoelectrical surveys to determine the above groundwater and subsurface geological

factors for designing an optimum drainage system in the area are discussed in this paper.

2   Geology and hydrogeology of the survey area

The survey area, namely area No. 3 of Gol-e-Gohar mine, is located 53 km northeast of the city of Sirjan in the south of Iran. The average elevation of the area is 1750 m above sea level. The area annually receives 144 mm of precipitation, mainly in the form of rain, and thus, having a very dry climate, relies on groundwater for all water needs including domestic and agricultural purposes. The geology of the area comprises metamorphic rocks of the Paleozoic era including gneiss, schist and amphibolite at the bottom, followed by limestone and dolomite sedimentary rocks of the Mesozoic and Cenozoic eras, overlain by late Quaternary alluvium and alluvial sediments. The iron ore deposit of the area is embedded in the metamorphic rocks.

Preliminary studies, based on the groundwater bores drilled in the area, show that the groundwater table in the study area occurs at a depth of about 40 m below surface, indicating the alluvial overburden, from this depth downward, is saturated from water. Thus, mining operations must inevitably be carried out below the water table. Geological investigations of the area also suggest the existence of probable faults as suitable paths facilitating groundwater movement.

3   Geoelectrical surveys

In order to investigate groundwater and the subsurface geological situation, geoelectrical surveys using resistivity techniques were designed, and then carried out in the study area. These techniques are mainly popular for such applications because of their low cost, simple interpretation, high speed and non-invasive technology, and also relative success in practice. The aim of this research work was mainly to estimate the depth to water table and thickness of water-bearing formation. An additional aim was to evaluate the thicknesses of geological layers, depth to bedrock and, if possible, the positions of faults.

From a practical point of view, moderate topography and alluvial overburden allowed the resistivity surveys to be performed easily and quickly in the study area. The surveys were carried out using the resistivity sound-

ing method, which is also called vertical electrical sounding or the VES method.

3.1   Resistivity data acquisition

The resistivity equipment which was used in the field consisted of a ter-rameter SAS (signal averaging system) 4000, produced by the Swedish company of ABEM. In addition, four steel spike electrodes were used in connection with the terrameter. The injection of a direct electric current into the ground using a 12-volt battery was made through one pair of steel electrodes (e.g. current electrodes A and B in Fig. 1) and electric potential difference was measured with the second pair of steel electrodes (e.g. potential electrodes M and N in Fig. 1). In general, the resistivity methods commonly use such a four-electrode system as shown in Fig. 1. The potential difference V, created between the potential electrodes M and N, is measured and then converted into apparent resistivity ρ_a by a simple transformation given by the expression

$$\rho_a = K \frac{V}{I} , \tag{1}$$

where K is a geometric factor and I is the amount of electric current injected into ground through the current electrodes. For a four-electrode configuration AMNB, K is defined as

$$K = \frac{2\pi}{\dfrac{1}{AM} - \dfrac{1}{BM} - \dfrac{1}{AN} + \dfrac{1}{BN}} \tag{2}$$
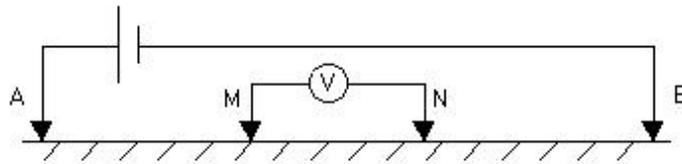
Fig. 1. Common collinear four-electrode arrays used in resistivity surveying. A and B are current electrodes and M and N are potential electrodes. If there is the condition of MN<0.2AB, the configuration is called the Schlumberger array.

Following preliminary studies, a square grid of 500 m by 500 m was considered to cover the study area thoroughly for the resistivity sounding surveys carried out using the Schlumberger configuration (Fig.1) with maximum electrode spacing of 1400 m. Thus, as shown in Fig. 2, 30 points or locations were primarily selected in the area for the sounding surveys although some locations were out of the limits of the area No. 3 of Gol-e-Gohar mine. Since many irremovable cultural features were found around point P4 and locations of points P26, P27, P29 and P30 (shown by red circles in Fig. 2) were on the steep of hard limestone formation, the sounding surveys were not performed at these points, which were out of the area No. 3. Eventually the Schlumberger sounding surveys were only carried out at 25 locations, shown by black small circles in Fig. 2.
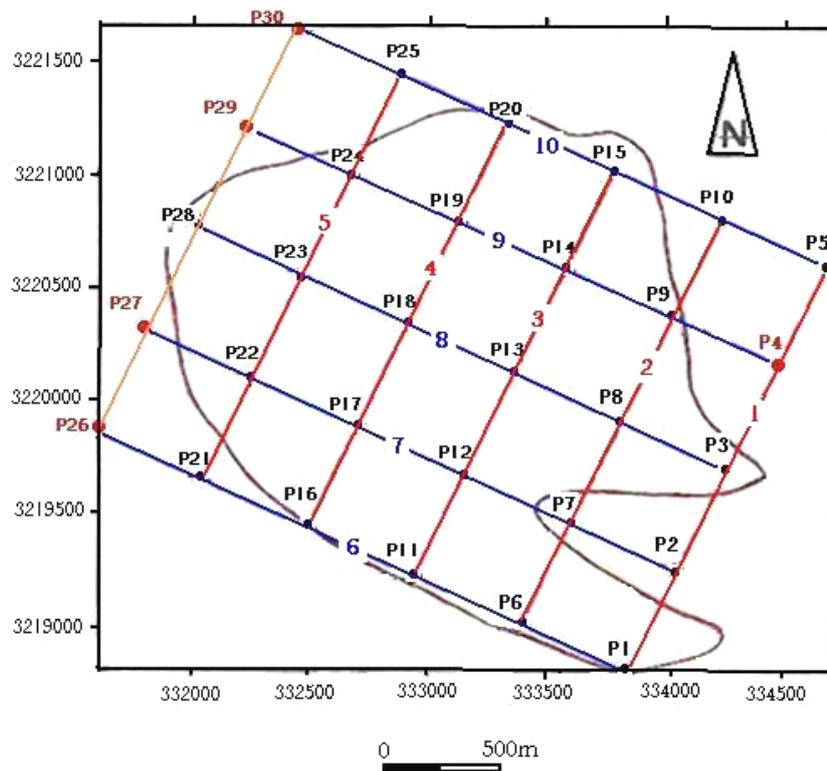
Fig. 2. The square grid of 500 m by 500 m and selection of 30 points or locations for the resistivity sounding surveys. The closed curve, surrounding most of the points, shows the limits of the area No. 3 of Gol-e-Gohar mine. Points P4, P26, P27, P29 and P30, shown by red circles, were not used in the survey.
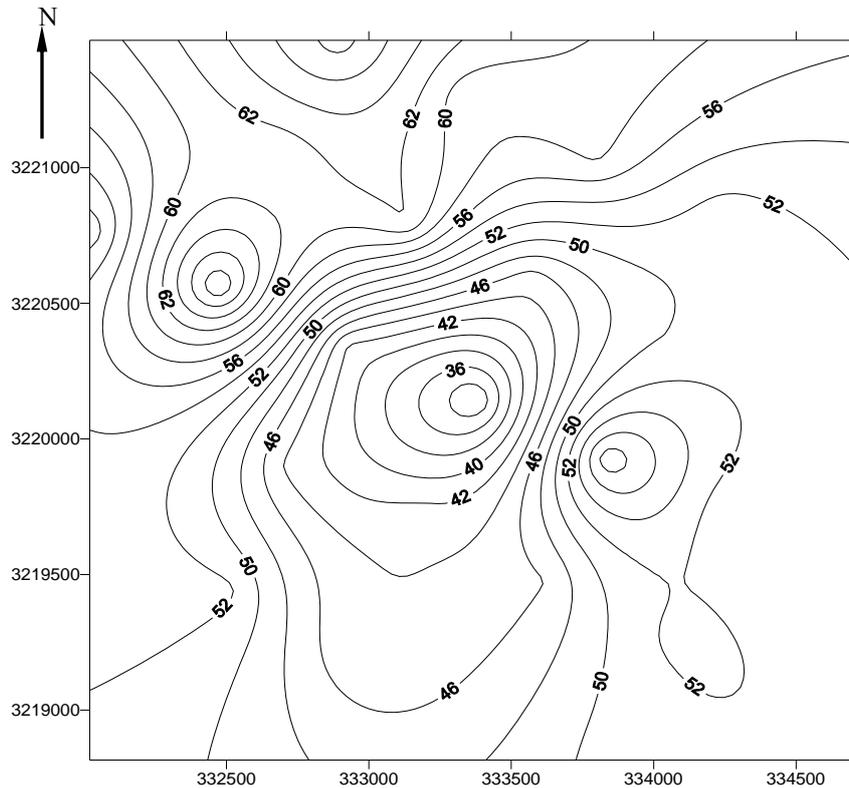
3.2 Resistivity data interpretation

The field measurements were converted to resistivity data using equation
(1). The resistivity sounding data were then interpreted. One-dimensional
(1-D) interpretation of the sounding data was made primarily using the
curve matching method, and then using computer programs (i.e. VES
software packages) to obtain better estimation of resistivities and thick-
nesses of the subsurface layers. The interpretation of the Schlumberger
sounding data at 25 different locations in the area resulted in an estimation
of the groundwater table at a depth of 40-60 m below the surface in the
study area. As a result of the sounding data interpretation, the thickness
and resistivity of water-bearing subsurface layer were also estimated to be
about 20-30 m and 15-23 Ω-m, respectively. Low resistivity of the water-
bearing formation was attributed to high electrical conductivity (EC) of
groundwater (due to high salinity and concentration of total dissolved sol-
ids (TDS) in groundwater) and considerable clay content in the formation.
Induced polarisation (IP) surveys need to be carried out in the area to de-
termine the clay content in the formation more accurately. In some places
located in the south and west of the area (e.g. locations P6, P21 and P22),
no water-bearing subsurface layer was found.

Based on the results of 1-D interpretation of the sounding data, an isopi-
estic contour map, indicating the water table or piezometric surface of the
groundwater aquifer in the area, was provided. The isopiestic contour
map, shown in Fig.3, indicated a shallower depth to water table in the cen-
tral parts of the study area while the depth to water table was found to in-
crease in the northwestern parts of the area.

The 1-D interpretation of the sounding data does not indicate lateral
changes or distributions of resistivity which reflect geological factors in
the subsurface. To obtain a more accurate resistivity image from the sub-
surface of the area, 2-D inverse modelling was carried out on the resistivity
data using subsurface electrical imaging computer software packages such
as Ipi2Win (Bobachow 2002) and Res2dinv (Loke 2000). As a result, 2-D
models of different lines, in which each line contained several sounding
locations, were obtained. These 2-D models (Figs. 4 and 5) showed the re-
sistivity and thickness changes of subsurface layers in two directions: the
line direction (x) and depth direction (z). According to the resistivity cross
section along line 1 passing through the sounding points P1, P2, P3 and
P5, shown in Fig.4, the water-bearing formation is at a depth of about 47-
56 m with an average thickness of 27 m. The resistivity cross section
along line 1, shown in Fig. 5, was obtained using the Res2dinv software
after 3 iterations. The result was not good due to high RMS (root mean

square) error (i.e. 45.5%). Low correlation between the results of sounding at different locations P1, P2, P3 and P5 along line 1 can be attributed to complex geology, especially various faulting systems in the area.


Fig. 3. The isopiestic contour map, indicating the water table or piezometric surface of the groundwater aquifer in the study area. The map was plotted from the results of 1-D interpretation of the resistivity sounding surveys in the area.

Resistivity surveys using profiling method should be performed to investigate lateral resistivity changes and faulting systems in the area. Using other geoelectrical methods, such as induced polarisation (IP) and self-potential (SP) methods, the ambiguities arising from the interpretation of resistivity data can be removed or reduced.
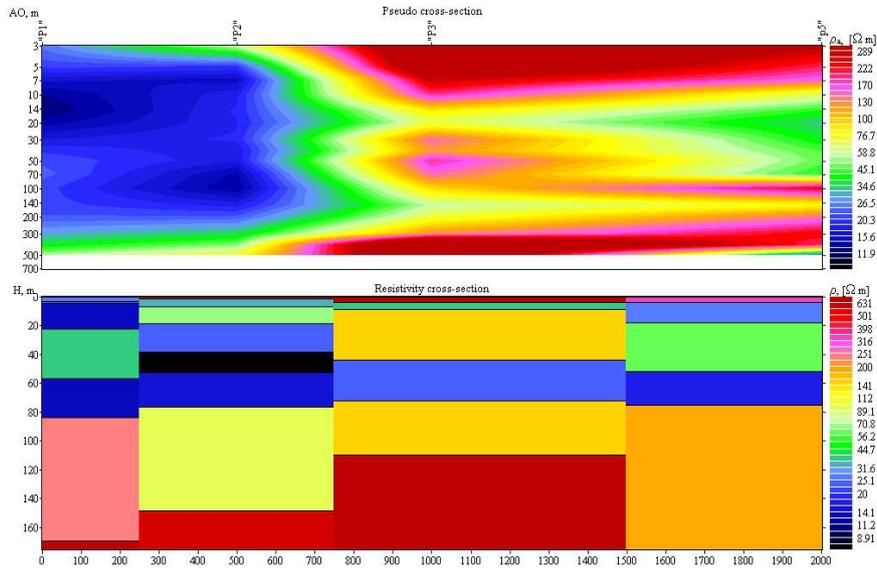
Fig. 4. Resistivity pseudo and cross section along line 1 passing through the sounding points P1, P2, P3 and P5 (obtained using Ipi2win software).
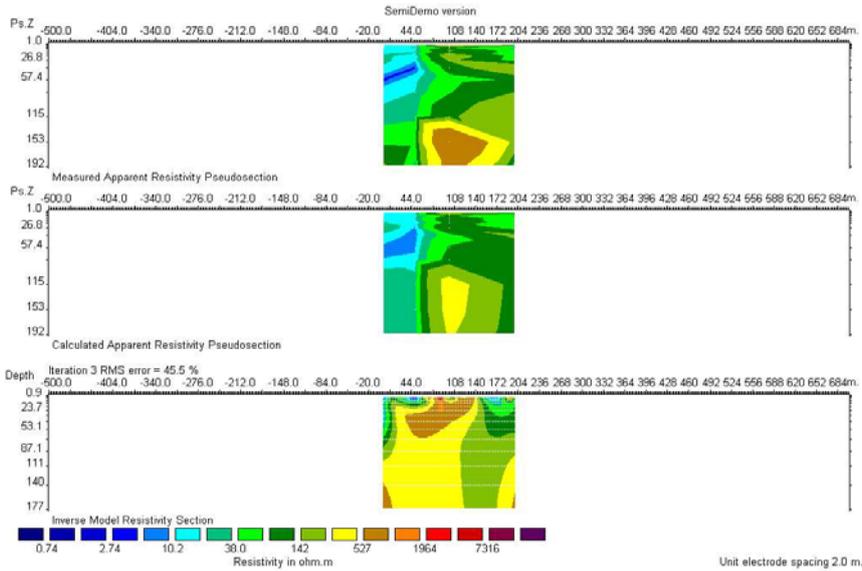
Fig. 5. Resistivity pseudo section and 2-D inverse model along line 1 passing through the points P1, P2, P3 and P5 (obtained using Res2dinv software).

4   Conclusions

Resistivity surveys were carried out in area 3 of Gol-e-Gohar mine to estimate the groundwater and geological features in order to design a suitable drainage system for removing mine water from the mining area. The results of 1-D resistivity data interpretation indicated a water bearing formation at a depth of 40-60 m with an average thickness of 20-30 m and resistivity of 15-23 Ω-m due to high EC or TDS of groundwater and clay content in the formation. These results were confirmed by 2-D section interpretation. Low correlation between the results can be attributed to complex geology, especially various faulting systems in the area. To delineate the faulting systems, resistivity profiling surveys need to be carried out in the area. IP and SP surveys in the area can also remove the ambiguities arising from the interpretation of resistivity data.

Acknowledgements

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