Application of geophysical methods as an integral part of geotechnical site characterization

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ABSTRACT: Authors has been involved in carrying out hundreds of geotechnical subsurface characterization projects in which geophysical methods (electrical resistivity tomography, ground penetrating radar and seismic refraction method) were integral part. The projects were performed in diversity of environments (including coast, mountain and desert) while the projects' targets were widely ranged including lithological and geo-technical characterizations, karsts discovery, landfill studying, soil sliding observation, pavement evaluations and so on. Such a variety of environmental condition as well as the diversity of projects' goals enables one to accumulate a wide experience in the field of cost-effective integration of geophysical and geotechnical methods and develop common methods of their application. The purpose of this article is to consider a general approach to post-processing of geophysical engineering methods the output of which is understandable to engineers / project managers. This general approach is discussed in the article with two examples. The results of application of geophysical methods were the basis for decision making for application geotechnical methodology and vise versa the results of application of geotechnical methods were used for crosschecking the geophysical data received.
Keywords: Applied geophysical methods, electrical resistivity tomography; data statistical assessment

1. Introduction

The engineering geophysical methods being modern and fashionable for the subsurface study are mainly nondestructive, less risky and time-consuming, cover larger areas than control wells point-wise methods. However, their application requires significant experience for collected data interpreting and avoiding uncertainties. Of the many geophysical methods, three are most often used: electrical resistivity tomography (ERT), ground penetration radar (GPR) and seismic refraction method (SR). The ERT method is widely used to determine the characteristics of subsoil, since the value of electrical resistivity is sensitive to soil physical properties. The use of 2D and 3D measurement and post-processing schemes significantly improved the quality of the ERT data obtained. In a GPR survey, transmitting and receiving antennae are placed on the ground surface and electromagnetic (EM) waves are injected into the ground from the transmitter antenna. Reflected EM waves from subsurface geological boundaries or objects are then received by the receiving antenna. The SR method is based on the phenomenon of refraction of elastic waves from the boundaries of underground layers with different elastic properties. The SR method is applicable if the speed of an elastic wave increases with the depth that is the usual situation in the near surface in a rock/soil site.

The geophysical methods suffer from many limitations and sometimes give non-unique results, the use of which for building planning can be unfair. Two main approaches have been developed to improve the quality of underground data obtained by geophysical methods. The first method consists of applying several geophysical methods [1-9]. However this way of application is highly time-consuming and expensive. An alternative method involves using 3D or quasi-3D methods of data acquisition and processing [10-13]. Despite the undoubted advantages of three-dimensional methodology, its engineering application is still limited, due to the high cost and significant time for data acquisition and processing [12,14]. It is seen, the time-consumption and cost of application are the disadvantages in both cases that restricts the wide utilization of engineering geophysical methods. Another problem in their application is the misunderstanding in communication with the site engineers/project managers who being faced with the dilemma of risk/safety assessment, drilling planning and assessing the bearing capacity of the earth's surface are hardly understand the concept of geophysical anomaly. On the contrary, the concept of the probability of anomalies is more understandable for them, and then its assessment is often requested. Our analysis shows that, despite this requirement, an estimate of the probability of anomalies is still rarely used to process engineering geophysics data [15-17]. Here we present a method for assessing the probability of geophysical anomalies (both positive and negative). It should be noted that the methodology considered here does not exclude or replace any mandatory stage of geophysical data processing, e.g. synthetic modeling, filtering, processing, inversion, etc., rather, it can be used at the stage of data evaluation, subsurface modeling and interpretation.

2. Assessing the probability of geophysical anomaly

The methodology has been developed in geostatistics based on the definition of normalized statistical quantity (NQ) [15,18,19]:

$$NQ = \frac{X-\bar{X}}{\sigma_X} \quad (1)$$

where X is the measured parameter, $\bar{X}$ and σ_X^2 are the mean and variance estimates, typically interpreted as background quantity and its stability, respectively. We then denote X, $\bar{X}$ and σ_X^2 to be processed value of geophysical parameter, its mean and its variance, respectively.

The probability function is then calculated as follows [18]:

$$NQ = \begin{cases} 0.5(1+\sqrt{1-e^{\frac{-2NQ^2}{\pi}}}), NQ \geq 0 \\ 1-0.5(1+\sqrt{1-e^{\frac{-2NQ^2}{\pi}}}), NQ < 0 \end{cases} \quad (2a)$$

for positive anomalies, e.g. air-filled underground karst characterized by high electrical resistivity;
or

$$NQ = \begin{cases} 0.5\left(1+\sqrt{1-e^{\frac{-2NQ^2}{\pi}}}\right), NQ < 0 \\ 1-0.5(1+\sqrt{1-e^{\frac{-2NQ^2}{\pi}}}), NQ \geq 0 \end{cases} \quad (2a)$$

for negative anomalies, e.g. water/clay-filled underground karst characterized by low electrical resistivity.

Here we present two examples of the application of a methodology on the basis of the analysis of electrical resistivity tomography data, while our experience shows that it is successfully used to process the GPR and SR data as well.

3. The example of positive anomaly processing

A positive anomaly means that the anomalous value is above the average, e.g. high resistivity caused by the presence of karst filled with air, high values of the propagation velocity of elastic or electromagnetic waves, measured during seismic or GPR surveys, and so on.

The presented study was carried out at the Southern Israel. The presence of numerous underground artificial caves with a diameter of about 3-4 m each complicated the construction process on the site, even making it to be dangerous. The exposed rocks consist of several kinds of chalk occasionally inter-bedded with flint and marl, and covered by the relatively thick caliche calcareous crust. The typical chalk properties are as follows:
uniaxial compressive strength is 12±3MPa, Young Modulus - 30±6GPa, Poisson ratio - 0.33±0.03.

The ERT method was used to search for cavities. More than 100 2D ERT lines were carried out. The length of lines ranges 72–204 m while the distance between nearby electrodes was 3 m. All measurements were carried out using Direct and Reverse Dipole-Dipole arrays merged as a unified file to improve the data repeatability. The collected ERT data has been inverted using commercial package EarthImager 2D (AGI, Inc) while the topographic effect was systematically taken into account. We utilized smoothness-constrained least squares technique for the anomaly finding together with finite element method for the forward resistivity calculations. The procedure also included subsurface division by the number of layers consisting of rectangles, and minimizing the difference between the calculated and the apparent resistivity. The unit size of each model cell was half the distance between the electrodes [12]. To avoid the appearance of artifacts, the inversion procedure was interrupted when the RMS error was less than the expected noise level (determined during the repeatability test) or the normalized L2 norm was reduced to unity. The procedure for processing the inverted resistivity data consisted of several stages:

(a) Distinguishing a boundary between two layers and extracting the data set corresponding to the chalk layer from the entire data set. Figure 1a shows the example of the full section of inverted electrical resistivity. The first step is to extract accurately the "goal layer" (the chalk layer including the underground caves). Figure 1b portrays inverted electrical resistivity cross-section of chalk layer extracted from the entire inverted resistivity data set (Fig. 1a). The procedure can be done by several ways: 1. manually - the boundary between the upper layer and the "goal layer" can be defined at the point of the maximum density of the curves of equal resistivity at the region of a supposed boundary, 2. calculating the point of maximum gradient of electrical resistivity at the region of a supposed boundary, 3. using the statistical procedure [20] based on the analysis of changes of standard deviation (confidence interval at the 95% level).

(b) Statistical analysis of the extracted data set, the aim of which was accurate defining the background value of electrical resistivity $\bar{X}$ and its standard deviation σ_X.

(c) Normalization the electrical resistivity of the extracted data set (Eqs. 1).

(d) Calculation the probability function (Eqs. 2) and building corresponding cross-sections for the rock stratum including underground anomaly (Fig. 1c). It can be seen that such a cross-section demonstrates an anomaly with a selected level of probability and can be clearly understood by the project manager.

More than 30 underground cavities were located based on a probability level of anomalies of at least 90%, and then confirmed by drilling/excavation campaign.

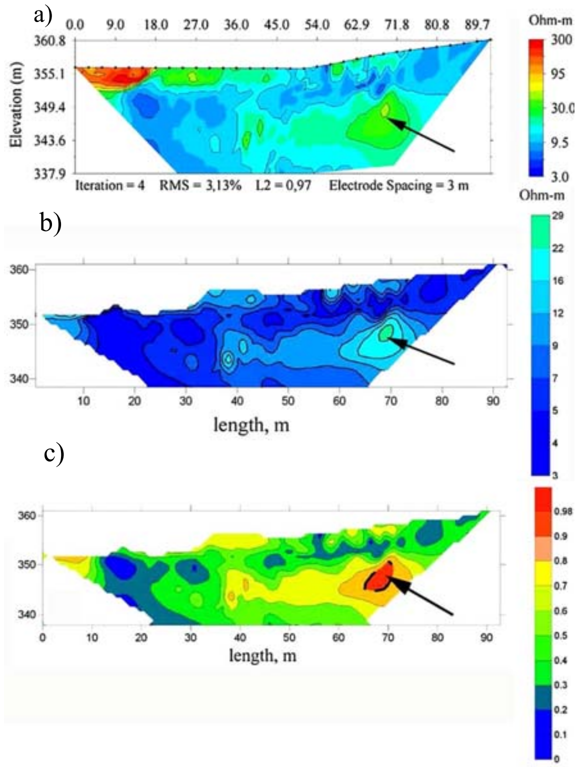

Figure 1. The example of the positive anomaly processing: inverted electrical resistivity section consisting of the entire data set (a), the partial section including only inverted electrical resistivity data associated with the chalk layer - the "goal layer" (b), which was "extracted" from the entire inverted resistivity data set, the probability cross-sections for the chalk layer including underground anomaly (c).

4. The example of negative anomaly processing

A negative anomaly means that the anomalous value is lower the average, e.g. low resistivity caused by the presence of karst filled with water/clay or leachate presence in the subsurface, low values of the propagation velocity of elastic or electromagnetic waves, measured during seismic or GPR surveys, and so on.

The site under study was a V-shaped erosion valley, naturally formed in chalky rocks located at the central Israel. The survey was motivated by intensive surface disintegration and the need to understand the reason for the instability of the site surface. The working hypothesis was that the rupture of the surface was caused by the sliding of the subsurface layers due to increase in its moisture content. The combined ERT/induced polarization (IP) method was used to estimate moisture content: 8 ERT/IP lines of 130–240 m in length were performed with a 5-m electrode spacing. The data acquisition, preprocessing and inversion procedures were similar to those considered in Sect 3. Figure 2a shows the results of the resistivity inversion.

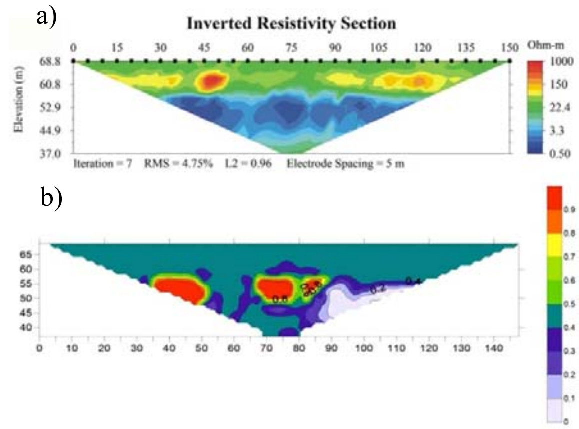

Figure 2. The example of the negative anomaly processing: inverted electrical resistivity section consisting of the entire data set (a), the subsurface probability cross-section including underground anomaly (b).

It is seen (Fig. 2a) that the site subsurface consists of three layers of different resistivity. Our experience shows that for an accurate assessment of moisture content in underground conditions, one parameter (value of electrical resistivity in this case) is not enough. In order to avoid inaccuracy in the assessment, the ratio of electrical resistivity to chargeability was used. This parameter was then used for statistical data post-processing. Figure 2b shows the same profile processed using the methodology discussed in Section 2. It is seen, the probability anomalies being more localized are quite different from the resistivity anomalies. The probability cross-sections were then used to construct an accurate model of the subsurface area (Fig. 3), where the zones with a high moisture content (marked in blue) are characterized by the probability value of more than 90%. The vertical section of the model was distinguished into three horizons (see blue horizontal lines in Fig. 3). The Upper horizon mainly consisted of rather dry soil with disconnected lenses of high moisture content. The soil condition of the Intermediate horizon is quite similar to the Upper horizon while the zones of high moisture content were mainly discovered at the site bottom.

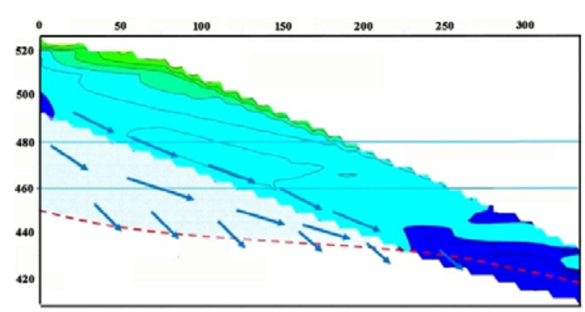

Figure 3. The example of the model of site subsurface built on the basis of probability cross-sections. The zones of the high moisture content (marked in blue) are characterized by the probability value of more than 90%. The arrows portray the water movement under surface that caused disintegration of the Earth surface.

Note that the probability anomalies were confirmed by the results of drilling campaign, DPSH tests and inclinometer measurements. Being statistically sound, this model was used for decision making by the project manager.

5. Conclusion

The method for assessing the probability of engineering geophysical anomalies (both positive and negative) is considered. It is shown that the underground anomalies can be located on the basis of specific level of probability (e.g. 90%) and then be confirmed by drilling/excavation campaign.

The serious advantage of the probability criterion considered here is its independence from any specific value of geophysical parameters and site subsurface condition that is why it admits to be utilized for anomalies comparison at different zones of even highly heterogeneous site. As we noted above, estimation of a likelihood of a geophysical anomaly is often a requirement of project principals due to necessity of risk/safety assessment. The presented methodology supplies obligatory and understandable information to project principals for decision making that is its additional advantage.

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