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Geoelectrical Imaging Surveys used for Pre-Investigation and Subsurface Layers Modeling at a Water Transfer Tunnel (Case Study)

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Abstract: The resistivity method is one of the oldest geophysical survey techniques. The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. By evaluating the result shows that virtually every change in geoelectrical image coincides with a change in rock conditions and topsoil. The general trend was that high resistivity corresponded with good quality granit whereas low resistivity corresponds to poor quality rock, e.g., high weathering, low RQD, low Lugeon and/or low SPT and low lef for soil. The intermediate resistivity is often dolomite or rock with water bearing fractures. The study involved measuring VES at 144 locations in SW-NE direction and 124 in SE-NW direction using the Schlumberger array.

Key words: Geoelectrical surveys, Kani Sib tunnel, resistivity, VES, Schlumberger, SE-NW

INTRODUCTION

Construction in rock is associated with risks as the knowledge of the geology and ground conditions usually is limited. Unforeseen rock conditions involve a large risk to the project and can in the end entail delays and extra costs. To minimize the risks a profound and optimized pre-investigation has to be conducted where the necessary information is gathered in order to make the best decisions throughout the construction project.

Different geophysical methods are important in these investigations. Geoelectrical imaging is one of the geophysical methods that have proved to be important at a large scale, especially for pre-investigations at the feasibility stage (Cavinato *et al*., 2006; Dahlin *et al*., 1999; Ganerod *et al*., 2006). The method can also be relevant in small scale and used for cross hole tomography studies (Auken and Christiansen, 2004; Barker, 1981; Farquharson and Oldenburg, 1998; Inman, 1975; Rucker and Noonan, 2013) and as logging tool (Barker, 1989; ISRM, 1981).

In this study, the main focus is on the applicability of the geoelectrical method as a tool for predicting geological and rock mass conditions. By applying the geoelectrical method at different scales and together with other geophysical methods it has proven to give useful information at different stages of rock tunnel construction.

For this geoelectrical data measured at the Kani Sib tunnel in Northwestern Iran are evaluated regarding its ability to resolve different properties of the rock mass (Fig. 1). This tunnel can transfer approximately 650 million cubic/meter water from Kani Sib dam to lake Urmia gravitationally. The tunnel has 100-500 m overburden and a high water pressure, 5.5 m diameter with the free flow slope of 0.085, 35.7 km length which is divided into 2 parts of 21 and 14 km in its output and input span, respectively (Fig. 2).

MATERIALS AND METHODS

Basic resistivity theory: The resistivity method is one of the oldest geophysical survey techniques (Loke, 2015). The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock (Farquharson and Oldenburg, 2004). Electrical resistivity surveys have been used for many decades in hydrogeological, mining, geotechnical, environmental and even hydrocarbon exploration (Rucker and Noonan, 2013; Szalai and Szarka, 2008).

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Fig. 1: Location of the Kani Sib tunnel in North Western Iran

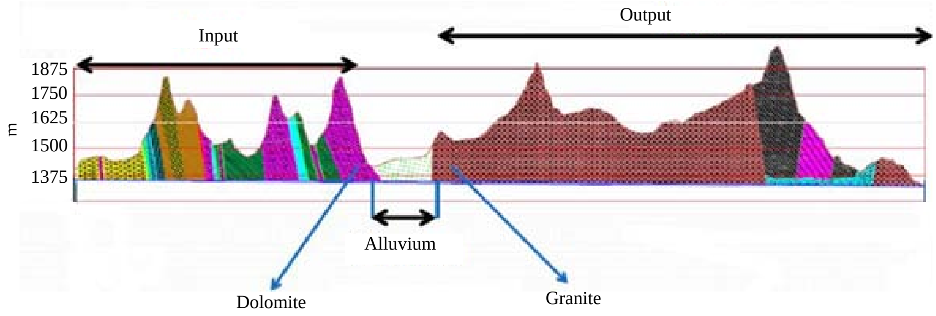

Fig. 2: Overview of the water conveyance tunnel project

Actual field surveys are invariably conducted over an inhomogenous medium where the subsurface resistivity has a 3D distribution. The resistivity measurements are still made by injecting current into the ground through the two current electrodes (C1 and C2 in Fig. 3) and measuring the resulting voltage difference at 2 potential electrodes (P1 and P2). From the current (I) and potential (Δϕ) values an apparent resistivity (ρa) value is calculated by Eq. 1-3:

$$\rho_a = k\frac{\Delta\phi}{1} \qquad (1)$$

Where:

$$k = \frac{2\pi}{\left(\frac{1}{r_{c1p1}} - \frac{1}{r_{c2p1}} - \frac{1}{r_{c1p2}} + \frac{1}{r_{c2p2}}\right)} \qquad (2)$$

k is a geometric factor that depends on the arrangement of the four electrodes. Resistivity measuring instruments normally give a resistance value, R = Δϕ/I, so in practice the apparent resistivity value is calculated by:

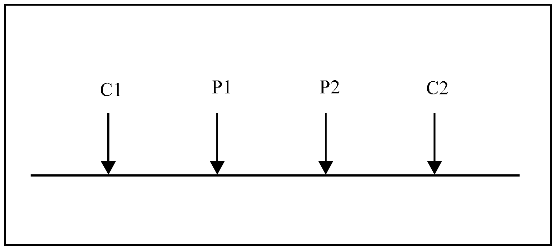

Fig. 3: A conventional array with four electrodes to measure the subsurface resistivity

$$\rho_a = kR \qquad (3)$$

Figure 4 shows the common arrays used in resistivity surveys together with their geometric factors. In a later study, we will examine the advantages and disadvantages of some of these arrays. Note that the dipole-dipole, pole-dipole and Wenner-Schlumberger arrays have 2 parameters, the dipole length "a" and the dipole separation factor “n”. While the “n” factor is commonly an integer value, non-integer values can also be used. Geoelectrical imaging is used for measuring the spatial variation of resistivity of the subsurface. The resistivity of the different geological materials differs greatly from about 10^{-6} Ωm in minerals such as graphite to more than 10^{12} Ωm for dry quartzitic rocks (Fig. 5). Most rock forming minerals are insulators, so, the resistivity of crystalline rock depends basically on the amount of water present and the degree of weathering of the rock. Therefore, rock without water bearing fractures or weathering has a high resistivity whereas clayweathered rock or rock with water bearing fractures has a considerably lower resistivity (Parasnis, 1997; Binley and Kemna, 2005).

Geoelectrical imaging surveys at the Kani Sib tunnel: To study subsurface structures along Kani Sib water conveyance tunel, 144 vertical electrical soundings along SW-NE in 12 profiles and 124 soundings along NW-SE in 12 profiles by Schlumberger method are collected (Fig. 6). Generally the depth of investigation of the method increases with increasing electrode distance. The current will seek to obtain the lowest possible total resistance on the path between the 2 current electrodes. For example, a very low resistive layer near the surface would prevent the current from penetrating deeper into the ground. In this case, the resolution of the deeper layer will be limited. By contrast a very high resistive layer close to the surface would force the current down to a less resistive lower layer. The depth of investigation therefore depends on the resistivity of the different layers as well as the largest electrode separation.

Collected soundings data are interpreted by 2 layers curves fitting method and using geological information. After recognizing layers and related resistivities along each sounding, pseudo 2D resistivity sections are plotted

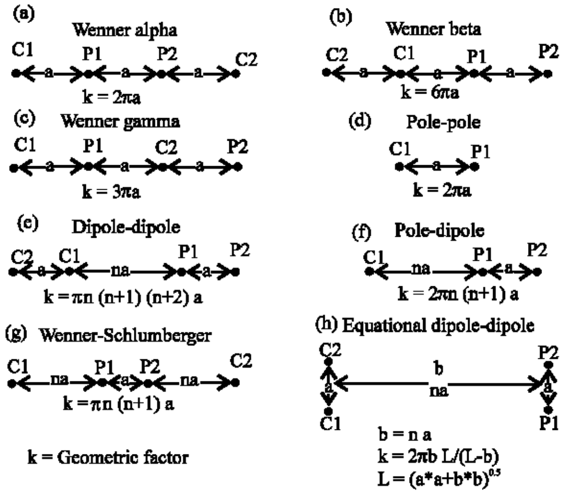

Fig. 4: Common arrays used in resistivity surveys and their geometric factors

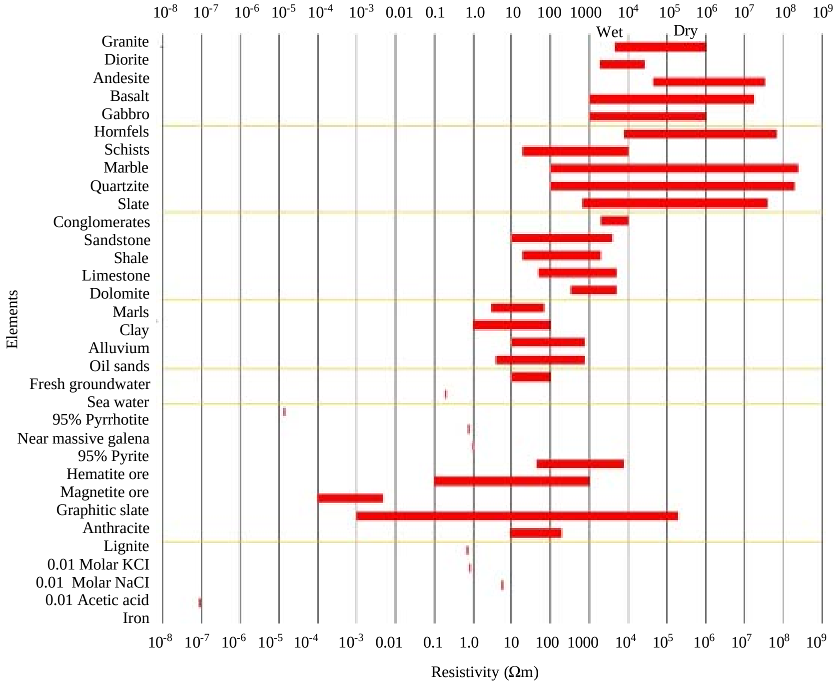

Fig. 5: The resistivity of rocks, soils and minerals

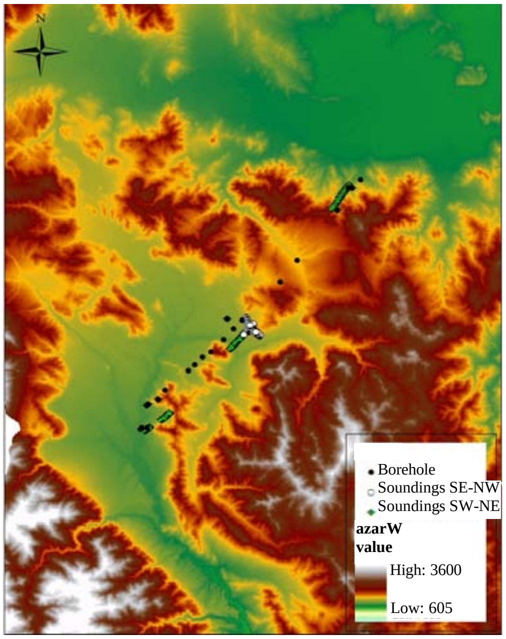

Fig. 6: Location of borehole and electrical soundings in study area

and then using geological information and drilling logs subsurface structures are delineated. Then to optimize the results, 2D inversion are used to invert measured apparent resistivities to real resistivities. By interpreting 2D geoelectric sections from the inversion, study of geological structures, estimating thickness of alluvial, hydrology, delineating fractures and faults, position and material of rock and separating overburden along axis tunel are made.

The resistivity data were measured as 2D profiles while the subsurface is 3D. To assume a 2D earth might in some cases be problematic. This would create 3D effects in the resistivity data, especially in this particular case where the geology changes relatively fast. In order to obtain the best 2D situation the profiles should always be perpendicular to the geological structures.

RESULTS AND DISCUSSION

To plot the data from a 2D imaging survey, the pseudo-section contouring method is normally used. In this case, the horizontal location of the point is placed at the mid-point of the set of electrodes used to make that measurement. The vertical location of the plotting point is placed at a distance that is proportional to the separation between the electrodes. The pseudosection gives a very approximate picture of the true subsurface resistivity distribution (Roy and Apparao, 1971).

The profile a located in input portal of Kani Sib tunnel which is includ 7 electrical soundings. The central part of the profile figure exhibits low resistivity clay from the upper part to lower sides. The low resistivity anomalies may be due to the presence of alluvium, clay and weathered bed rock. The higher resistivity (80-200 Ωm) may be due to the presence of sand or massive. The minimum and maximum apparent resistivity is 5 and 200 Ωm (Fig. 7) and all the VES are multilayered geoelectrical sections. The central portion of the profile shows the least resistivity in the range of 0-40 Ωm, indicating highly conducting formations like clay, clayey sands or formations with high conductive water. Based on the geological, hydrogeological and geoelectrical investigations, the entire profile is a hard rock formations (consolidated) represented by minor lithological units of alluvium, clay, sand which are resulted by weathering and gneiss with good ground water potential.

The inversion model in shown in Fig. 8. The thickness of the lower resistivity weathered layer is generally about 10-20 m. There is a narrow vertical low resistivity zone between the soundings 2-3 and soundings 5-6 that is probably a fracture zone or fault in the bedrock. According to Fig. 7 and 8, the general trend was that high, resistivity corresponded with good quality granit whereas low resistivity corresponds to poor quality rock, e.g., high weathering, low RQD, low Lugeon and/or several lithological contacts and the result shows that the topsoil had included of low SPT (standard penetration test) and low lefranc (Lefranc permeability test).

Since, all geological structures are 3D in nature a fully 3D resistivity survey using a 3D interpretation model should in theory give the most accurate results. About 3D view of the model obtained from the inversion of the study area survey data set displayed with the rock program (Fig. 9). Note that the color contour intervals are arranged in a inverse distance manner with respect to the resistivity (Wittaker and Frith, 1990).

The ISO resistivity maps are the resistivity contour maps and ISO is a Greek word meaning ‘equal’ and contours are imaginary lines on map connecting equal value (Barton *et al*., 1974). The values may be of any parameter, like elevation, TDS, layer thickness and so on. Accordingly, the layer thickness contour maps of the study area have been generated incorporating all the 30 VES data for different formation with their co-ordinates, joining equal layer thickness of the depth of investigation. Figure 10 shows ISO-resistivity map to be obtained from geoelectrical survey along Kani Sib water conveyance

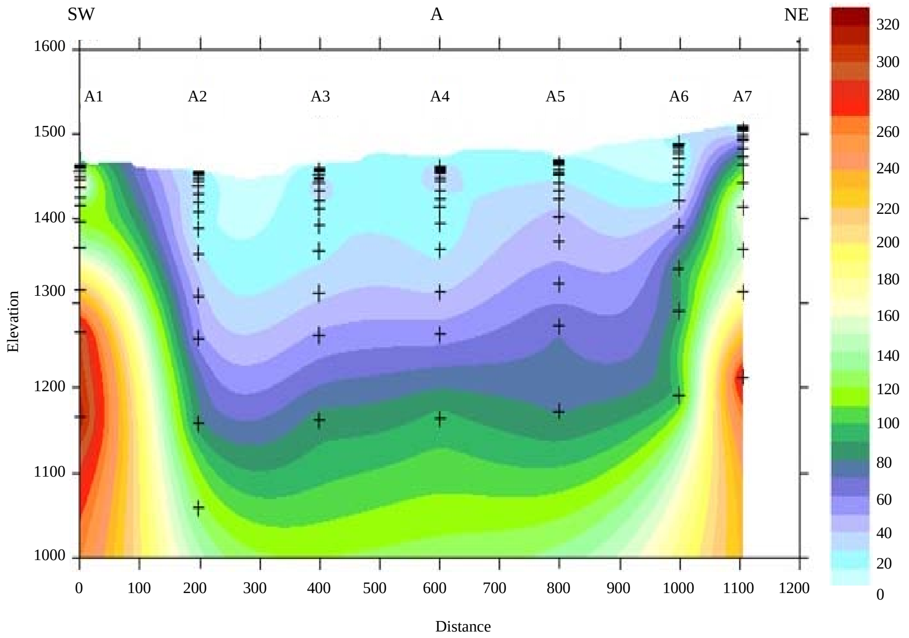

Fig. 7: Apparent resistivity pseudo-section for the survey to pre-investigation and subsurface layers modeling in the Kani Sib tunnel

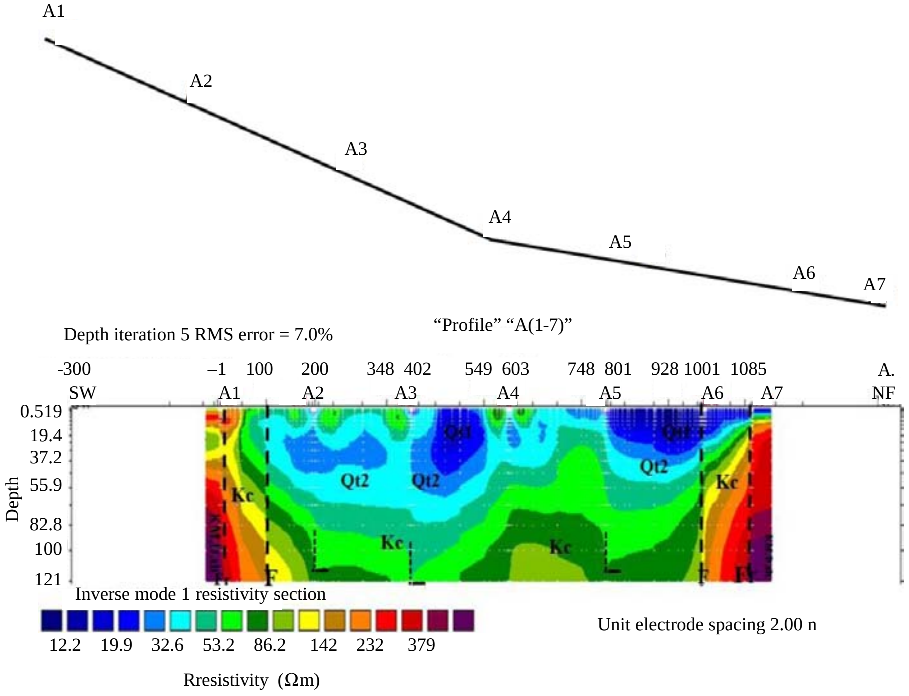

Fig. 8: Inversion model for the profile A

tunel. The difference between 2 consecutive contour lines is termed the contour interval. The contour maps can be generated using surfer 8 software packages. The ISO resistivity maps can be used for qualitative interpretation of the groundwater and by quantity by demarcating the low and high layer thickness anomalous zones (Takahashi *et al*., 2006). This also further helps to delineate the granular and clayey zones in weathered,

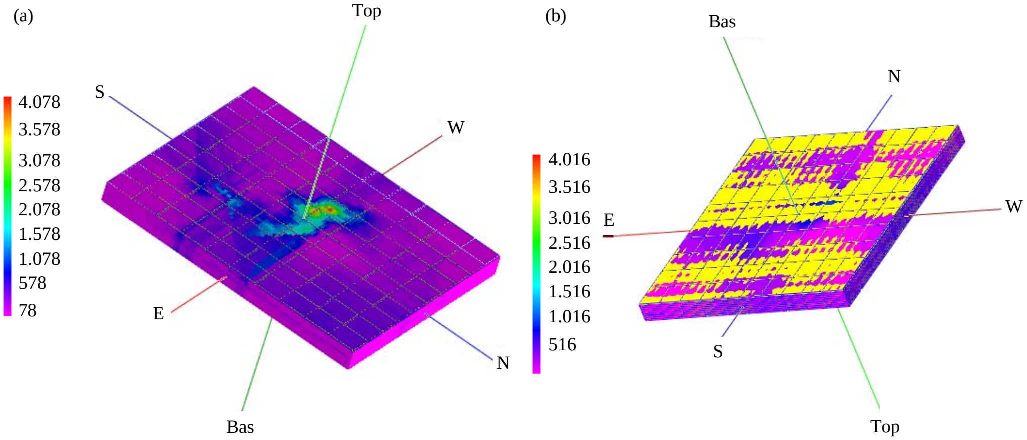

Fig. 9: 3D surveys in the study area by modeling methods: a) Isotropic and b) Anisotropic

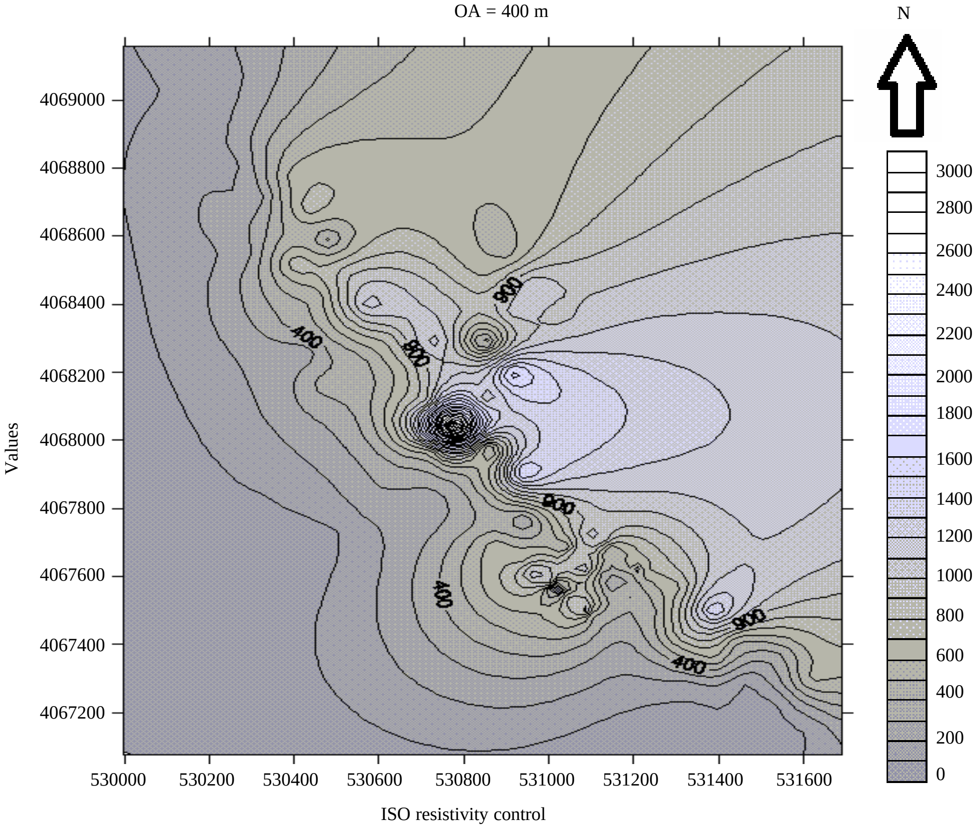

Fig. 10: ISO-resistivity contour map (OA = 400 m)

fractured and massive rock zones in crystalline terrains. The method of qualitative and quantitative interpretations helps us identify good ground water potential zones. There are different curve types inferred during the geophysical interpretations. The cost of the drilling greatly depends on the nature of sub-bottom sediments and Bedrock. A detailed aquatic survey was thus, conducted to determine the nature of the sediments and Bedrock (Fig. 11). Depth and thickness of subsurface layers were identified and type of Bedrock were indicated (Table 1). Bedrock of area is generally dolomite, granite and in small part is appeared as Alluvium.

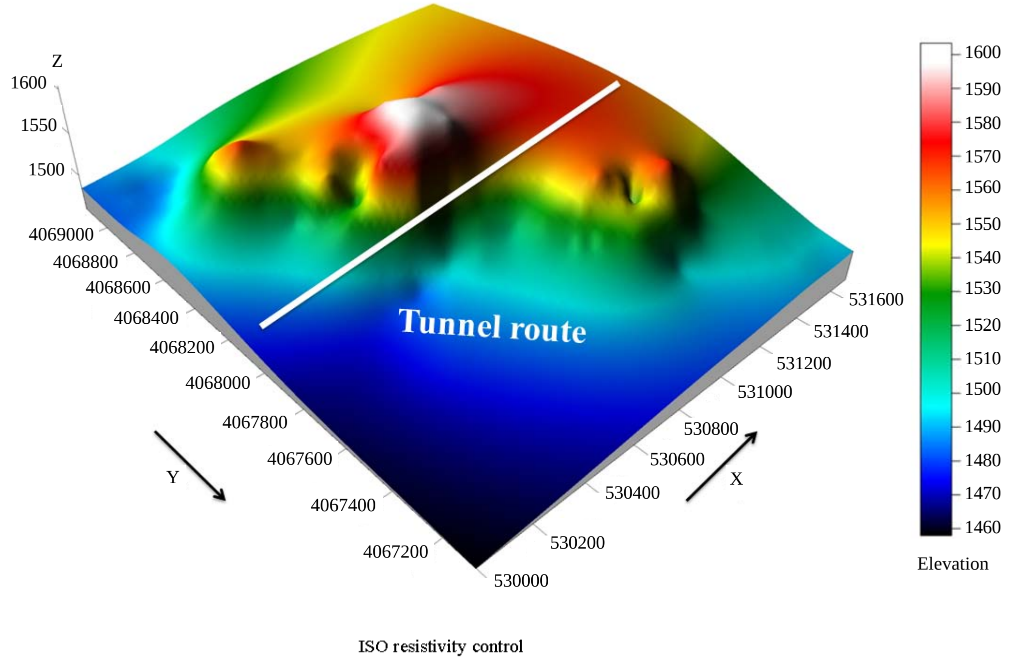

Fig. 11: Estimated Bedrock topography of the study area

Table 1: Summation of the thickness of the Alluvium in the intervals based on the resistivity data for the Kani Sib tunnel

Section	Profile	No. of soundings	Thickness (m)	VES-ID
0+0 to 0+560 km	G	4	7-35	1-3
	H	7	9-85	1-5
	I	4	15-90	1-3
1+920 to 2+960 km	A	7	40-66	1-6
	B	12	10-82	1-11
	C	7	42-66	1-6
12+200 to 15+420 km	D	16	60-160	1-13
	E	31	18-160	1-26
	F	16	7-170	1-14
30+600 to 33+600 km	J	16	Very limited	3-5, 7, 11, 15, 16
	K	16	Very limited	3-6, 11, 15, 16
	L	16	Very limited	2-5, 11, 15, 16

CONCLUSION

For the Kani Sib tunnel project in Northwestern Iran several kilometres of resistivity measurements have been made. The study involved measuring Vertical Electrical Sounding (VES) at 144 locations in SW-NE direction and 124 soundings in SE-NW direction using the Schlumberger array. resistivity was useful for the general distribution of fractures. In an early stage of the pre-investigations no information from drillings is usually available. But based on the general geologic information, resistivity measurements recommendations can be given on where to drill in order to improve the geological model. The comparison showed that a change in resistivity often corresponds to some kind of change in the topsoil or rock mass properties. The resistivity can be divided into three categories, i.e., high, low and intermediate resistivity. These three categories can generally be correlated to certain types of topsoil or rock mass conditions. In the rock mass, the high resistivity corresponds well with granite with a good quality. Intermediate resistivity is most likely dolomite with a relatively good rock quality. This is also supported by *in situ* measurements in the tunnel where the only rock with very high resistivity is granite. In some cases the intermediate resistivity can also be water bearing rock. The low resistivity is rock of a poor quality which is deeply weathered or has many contacts between different lithologies.

The existing faults contributed to seepage of runoff and infiltrated water to recharge the pleistocene layer. The Bedrock map indicated that there are 2 water flow directions. The first one is from east to west and the second one at the eastern side is from north to south. A more accurate mode of the subsurface is a 2-Dimensional (2D) Model where the resistivity changes in the vertical direction as well as in the horizontal direction along the survey line. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. In theory a 3D resistivity survey and interpretation model should be even more accurate. However, at the present time, 2D surveys are the most practical economic compromise between obtaining very accurate results and keeping the survey costs down. The experience from the Kani Sib water conveyance tunnel project can be used to improve the interpretation capability of the resistivity image.

As a tool for subsurface layers modeling and pre-investigations, resistivity imaging has the advantage that it is more time and cost efficient than other alternatives, e.g., seismic refraction. A priori information about the geological setting is crucial and the results have to be followed up by additional measurements, i.e. with other types of geophysical methods exploiting other physical parameters or by 3D resistivity measurements. The measurements can then be used as a base for deciding where to choosing the geotechnical drilling sites.

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