Research Article

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Comparison between electrical resistivity tomography and tunnel seismic prediction 303 methods for detecting the water zone ahead of the tunnel face: A case study

<https://doi.org/10.1515/geo-2020-0193>

received August 06, 2019; accepted September 17, 2020

Abstract: In deep tunnels with hydro-geological conditions, it is paramount to investigate the geological structure of the region before excavating a tunnel; otherwise, unanticipated accidents may cause serious damage and delay the project. The purpose of this study is to investigate the geological properties ahead of a tunnel face using electrical resistivity tomography (ERT) and tunnel seismic prediction (TSP) methods. During construction of the Nosoud Tunnel located in western Iran, ERT and TSP 303 methods were employed to predict geological conditions ahead of the tunnel face. In this article, the results of applying these methods are discussed. In this case, we have compared the results of the ERT method with those of the TSP 303 method. This work utilizes seismic methods and electrical tomography as two geophysical techniques are able to detect rock properties ahead of a tunnel face. This study shows that although the results of these two methods are in good agreement with each other, the results of TSP 303 are more accurate and higher quality. Also, we believe that using another geophysical method, in addition to TSP 303, could be helpful in making decisions in support of excavation, especially in complicated geological conditions.

Keywords: geophysics, tunnels, rock mechanics, groundwater hydrology, site investigations

1 Introduction

During excavation, prediction of geological features ahead of a tunnel face, such as a fault or fracture zone as well as potential water sources, is very important. Both destructive methods and nondestructive methods can be used for this purpose [1]. Destructive methods such as percussion drilling and core drilling methods, because of the direct access to rock samples, can be used to calculate geotechnical properties of rock with high accuracy; however, these methods can be expensive and time consuming [2]. On the other hand, there are nondestructive methods with good speed-up prediction that are more economical. Because they do not access the rock wall directly, the accuracy is generally lower than that for destructive methods. To achieve a good prediction, the first step is to drill a few boreholes in advance of the tunnel and then apply a nondestructive method to increase the accuracy of exploration points [3]. In addition, nowadays, the quality of logging evaluation data can be improved by deep learning [4,5] and machine learning [6] methods.

Electrical resistivity tomography (ERT) is a nondestructive method commonly used to evaluate rock properties, with applications in many different geological conditions such as groundwater resources [7,8], fault imaging [9], and geotechnical applications [10]. Given the number of parameters influencing electrical resistivity, such as saturation, rock or soil type, porosity, and fluid electrical conductivity, the ERT method has a wide range of applications. ERT surveys are timesaving and relatively cost-effective due to the simplicity of operation, requiring only 1–2 h of staff time and using multichannel and automated switching systems to decrease acquisition time [11]. Using ERT between boreholes provides valuable information about the various geological structures and rock types surrounding the tunnel.

The TSP 303 method is another nondestructive evaluation method, which is relatively a new technology for tunnel exploration [12]. TSP 303 is based on propagation and reflection of seismic waves through rock layers ahead of an excavation face along the tunnel's route.

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Amberg Technologies® developed one seismic prediction method for use in tunnel construction called the TSP 303 method. This method is similar to the seismic reflection method, but uses an advanced migration imaging technique in the data processing, one that makes full use of both kinetic and dynamic characteristics of seismic waves, that is, both travel time and amplitude. Also, in the processing, the signal-to-noise ratio can be increased by new methods that cause to improve the quality of data [13]. The TSP 303 method has been widely applied in Europe and Asia [14,15]. Simple operational high-speed data acquisition shot points and good accuracy in detecting geological structures ahead of the tunnel face are some of the advantages of the TSP303 method. In the process of separating P and S waves, the Poisson's ratio and Young's modulus of the wall rock can be determined.

The parameters involved in seismic and electrical methods are sensitive to different types of rock properties and anomalies that exist at the tunnel location, for instance, the ERT method is sensitive to clay content and pore fluid, while the seismic methods such as TSP 303 are sensitive to cementation, bulk properties, and so on.

In this study, the basic principle of ERT and TSP 303 methods are introduced and applied. Based on the engineering background of the Nosoud Tunnel, the characteristics of the seismic wave reflections in the tunnel were interpreted. All important information for guiding tunnel construction was collected, and the application effect of prediction techniques is discussed. The feasibility and the accuracy of the TSP 303 technology are proved through comparison between ERT and TSP 303.

2 Site location and geology

The study area is located in the Zagros Mountains in Kermanshah Province, Western Iran. The tunnel is located at a distance of approximately 50 km from Javanrud city and designed to transfer water from Sirvan River to the Zahab plain. This area, in terms of geology, consists of simple structures with reverse faults and symmetrical anticlines and synclines [16]. As shown in Figure 1, the geology at the location between the seismic receiver reference location at km 19 + 835 and its face location at km 19 + 908 is defined as a massive to cliff-forming dark gray limestone. The average overburden at the site is about 315 m. The cross-section of the tunnel is characterized by layers of subsurface that they have a high slope and their orientation is also along the route of the tunnel (Figure 1). Because of

the sloping layers is $\leq 82^\circ$, the slope values must be considered in the design, due to reflecting the rays of the steep layers are received by the recipients.

3 Methodology

3.1 Electrical resistivity tomography

The electrical resistivity method is based on sending the constant direct current into the ground between two electrodes and measuring the resulting voltage at two potential electrodes. This method is based on the multi-electrode and multicable system. The geometry of the electrode array is very important; it specifies the position of current and potential electrodes during the measurement. Pole-dipole, dipole-dipole, Wenner, and Schlumberger are four different arrays commonly used [18].

This methodology is based on the following principle: a current is introduced into the material through a pair of electrodes AB (input dipole), and the resulting potential difference is measured through another pair of electrodes MN (receiving dipole). A voltmeter measures the potential difference.

The apparent resistivity ρ_s (Ωm) can be defined as follows:

$$\rho_s = K \frac{\Delta V_{MN}}{I_{AB}}, \quad (1)$$

where I_{AB} is the intensity of the throughput current between A and B, which is inserted on the surface by a pair of current electrodes; ΔV_{MN} is the difference potential measured between M and N (by a second set of electrodes); and K is the dimensionless geometric factor that depends on the arrangement of current and potential electrodes by the following equation:

$$K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{AN} - \left(\frac{1}{BM} - \frac{1}{BN} \right)}, \quad (2)$$

where AM, AN, BM, and BN stand for the distances between two electrodes.

In ERT, current electrodes are placed as sources in one borehole and potential electrodes are placed as receivers in other boreholes or vice versa [19]. The ERT method can be performed in more than two boreholes, and it can be performed when the tunnel boring machine (TBM) is working.

Figure 1: Longitudinal extract of geological forecast between km 16 + 200 and 20 + 300 with face location at TSP campaign No. 2 at km 19 + 908 [17].

ERT, due to its sensitivity to water and clay content, is known as an efficient tool for revealing fractures and karstified zones characterized by low electrical resistivity values.

Some important advantages of ERT are as follows: various working models, use a variety of electrode arrangements, abundant information, and more detailed structural information; function of data preprocessing, profile shapes to visual display, and abstract data for visualization; and a survey completed the 2D data acquisition at low cost realizes the high-efficiency work and obtains the result of rich information, which will greatly enhance the capacity for exploration.

Practical applications of ERT, suitable for deep buried especially for tunnel surveys, using the apparent resistivity difference, relative thickness of the overburden layer and weathered layer, and hierarchical classification of the surrounding rock are carried out to realize qualitative distinctions and utilize low apparent-resistivity anomalies to identify faults, fracture zones, karst soil cave development, and deep water conditions [20].

3.2 Tunnel seismic prediction 303

The TSP 303 method developed by Amberg Technologies detects changes in rock mass such as irregular bodies, discontinuities, faults, and fracture zones ahead of the tunnel face by evaluating and comparing longitudinal and shear wave velocities in the surrounding rock. This method is commonly employed as a predictive method during excavation of both drill-and-blast and TBM headings; access to the face of tunnel is not required to perform the measurements, which are taken during tunneling production breaks. When blasting occurs, the seismic waves travel through the geological structures ahead of the tunnel (such as fault, fracture zones, and underground water anomalies). Structural features encountered in the rock are recorded by the receivers and later revealed through computer processing of the seismic data.

The velocity of a P wave V_P can be calculated using equation (3):

$$V_P = \frac{L_1}{T_1}, \quad (3)$$

where T_1 and L_1 are the first arrival time and the distance between the seismic source and the receiver, respectively.

T_2 is the transmission time of the reflected wave, obtained with equation (4):

$$T_2 = \frac{(L_2 + L_3)}{V_p} = \frac{(2L_2 + L_1)}{V_p}, \quad (4)$$

where L_2 and L_3 are the distances from the blasting hole and sensor to the reflector, respectively. During exploration, if V_p decreases, it means that cracks are developing or porosity is increasing.

The calculation of Poisson's ratio (equation (5)) and Young's modulus (equation (6)) for the prediction of unfavorable geology ahead of the tunnel is done as follows:

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}, \quad (5)$$

$$E = \rho V_s^2 \left(\frac{3V_p^2 - 2V_s^2}{2V_p^2 - V_s^2} \right), \quad (6)$$

where V_p and V_s are the longitudinal and shear wave velocities, respectively, and ρ is the rock density [21]. For fluid or soft rock, Poisson's ratio increases suddenly. Also, if the S-wave reflects more strongly than the P wave, a rock rich in water is indicated. Reflection amplitudes can predict whether the rock is hard in the case of a regular reflection amplitude or soft for a negative reflection amplitude [22].

The acoustic signals were produced by a series of 24 shots (usually 50–100 g of detonation cord) aligned along one wall. An additional shot line along the opposite side, in cases of more complex geology, can be very useful. Four highly sensitive triaxial receivers, which are protected by tubes whose tips are firmly cemented into boreholes, are of 45–50 mm in both sidewalls. The receivers pick up the seismic signals reflected from beyond the tunnel face. Highly sophisticated processing and evaluation software has been devised for ease of operation [23]. The capability of the system to record the full wave field of compressional and shear waves in conjunction with intelligent processing software enables the determination of rock mechanical properties such as Poisson's ratio and Young's modulus. Figure 2 shows the case recording unit, receiver units, multifunctional trigger box, cables, and TSP 303 receiver located at a depth of 2 m inside the tunnel wall.

Figure 2: TSP 303 recording unit and accessories; (left side of the picture) TSP 303 receiver already set 2 m deep into side wall.

4 Operation

4.1 ERT operation

Geoelectrical surveys involve the use of a number of wooden stakes connected to a multipolar shielded cable. Each stake was coupled to an electrode that contains the control electronics connected to the central unit. The central unit performed a sequence of measurements according to the walk-away technique. The Wenner array was used for the data collection. The Wenner array has one of the strongest signal strengths, maintaining a high signal-to-noise ratio, especially when working in areas of low resistivity. In our array, electrodes were equally spaced. The automation of the acquisition procedure using an intelligent switch controller improved the speed of operation.

The signal used depends on the type of measurements desired. Each signal has a defined number and duration of square wave cycles, the amplitude of the current entered (mV), and the stack number (which is a repetition of measures used to reduce background noise). The data used in this study were acquired by a Multi-Electrode System Abem Terrameter LS with passive electrodes. The survey also included the use of multipolar shielded cable connections between the acquisition unit and 21 electrode cables.

The evaluation of the geomechanics and hydrogeologic characteristics was based on the use of boreholes realized in the niche. It was performed at four boreholes as shown in Figure 3 and allowed definition of a regular net from which geoelectrical sections were acquired and

Figure 3: Geometry of four boreholes used for ERT method.

used to process the data according to the 3D model. The azimuth of the tunnel axis is 215° , and the azimuth of each borehole is shown in Figure 3. With this geometry, the vertical distance between the boreholes position was very low, and the space between boreholes was limited and similar to a slab. Another geometrical limit was given from the remarkable divergence between holes (Table 1).

Data processing was carried out using the following software: EarthImager 2D and 3D data analysis and tomographic inversion, Res2DInv 2D and 3D data analysis and tomographic inversion, Matlab routines, and Voxler 3: 3D geometric analysis.

4.2 TSP303 operation

Operation of the TSP 303 system, such as installation of the receivers and system setup, is simple and can be done in 30 min. Figure 4 shows the seismic geometry of the acoustic source and receiver positions. Twenty-four sources, all of them charges of 100 g dynamite, were close to the tunnel face – the first one about 73 m from the face. Four triaxial receivers were located after shot points in boreholes about 50 mm deep in both sidewalls. The use of high-frequency

waves is very helpful in processing because the resolution of seismic waves attenuates rapidly away from the source (near the tunnel face).

Quality data processing software is necessary to make accurate seismic predictions ahead of the tunnel. To achieve high-quality 3D results, it is important to maximize the number of data acquisition points. Using four receivers, two in each sidewall, and using a second source line along the opposite wall of the tunnel can provide meaningful information when the geological structure is complex in terms of alternating strike angles or irregular obstacles such as cavities or karst features.

The TSP 303 3D data processing software, along with 3D-VMR technology, exploits the information in the seismic wave field by separating compression (P) and shear (S) wave analysis. The 3D-VMR technology provides an adequate and detailed 3D image of the rock body, leading to a more reliable interpretation compared to conventional 2D approaches [24].

5 Result and discussion

5.1 ERT results

Determination of the geological structures in front of tunnel, particularly the fracture zones or faults, is so crucial for groundwater evaluation in the hard rock with highly heterogeneous areas. Studding the fracture density, orientation, and connectivity can detect the fracture or fault zones that contain the water buildup.

The EarthImager software was used to evaluate the root-mean-square values (RMS), data filtering, signal analysis and editing of the electrodes, and noisy reading points, to obtain a high quality dataset. At this point, the data were corrected on the basis of planimetric coordinates and elevation values associated with each station.

Table 1: Properties of boreholes using the ERT method

Borehole	Depth (m)	Position	Sidewall position	Azimuth	Vertical angle	Distance from workface	Seepage (l/s)
L1	18	h9 (a little bit below h9)	Left	41°	90°	14.5	20
L2	11	h10 (a little bit below h10)	Left	35°	90°	14.5	20
R1	40	h3 (a little bit below h3)	Right	29°	90°	14.5	2
R2	42	h2 (a little bit below h2)	Right	35°	90°	14.5	2

Figure 4: Actual TSP layout at campaign: receivers, red dots: shots

Figure 5: Geoelectrical survey result at (a) depth 616 m and (b) legend.

The graphical representation of the measured data as a 2D section allowed us to identify and delete outliers, so individual resistivity values, corresponding to a single measurement point strongly higher or lower than the surrounding materials, are linked to a system disturbance and not to a real abnormality in the subsurface. An iteration analysis was performed to obtain a reliable high-resolution geological model via tomographic inversion. The resistivity values calculated were represented by 2D contouring using Surfer software. Figures 5 and 6 illustrate the horizontal section at depths 616 and 619 m, respectively; four different units are seen in front of the tunnel.

These geoelectrical models show that the lower electrical resistivity portions are located on the left side of the tunnel, which corresponds to a high water presence indicative of the fractured rock. The most distal part from the tunnel face is characterized by a resistivity decrement. This situation seems to be confirmed by R_1 – R_2

boreholes that have experienced almost no water ingress during drilling, compared to L_1 – L_2 boreholes located on the left side.

In data processing, it was necessary to use a geoelectrical anisotropy damping factor; apparent resistivity data were lower for corresponding (homologous) electrodes and higher (40 times) when the measurements were between distant electrodes. This consideration may confirm the presence of lineaments. The water is positioned on the left side of the tunnel as indicated by an area of low electrical resistivity; these conductive data occurred at lower altitude.

Therefore, this method can be applied to illustrate the properties of the hydrogeologic zones in the areas elevated in front of the tunnel. To improve the perception of the ERT results and accuracy in finding the water zone, it can be combined with other geophysical or hydrogeological methods [25].

Figure 6: Geoelectrical survey result at (a) depth 619 m and (b) legend.

Figure 7: P-Wave velocity distribution with two low velocity zones (LVZ) indicated.

Figure 8: P-Wave depth migration with low velocity zones (LVZ) indicated.

5.2 TSP303 results

After the selection of the proper seismic data, seismic data processing per receiver started running immediately according to a number of primary control steps. The most important of these steps are band-pass filter, first arrival pick, Q-estimation, P-S separation, velocity analysis, and depth migration. The time of reflected signal is

converted to the distance through the analysis of the reflected wave velocity.

The aim of the seismic data processing is to extract and enhance the reflected wave field. For this purpose, specifically designed processing steps are applied to the data. The result of each step is stored and enabled the processor to review during the processing.

Table 2: Seismic zones detected

Interval no.	Change (m)	
	From	To
1	19,919	19,922
2	19,925	19,928
3	19,938	19,942
4	19,954	19,957

The wave separation process of Amberg TSP Plus separates the recordings into wave types according to their polarization type by rotating the coordinate system as a function of recording time. At the end of the evaluation, all preprocessed data were processed using 3D-processing methods and a user-defined 3D-velocity model. In the following, extracted reflectors were interpreted geologically, and the calculated rock properties are presented.

Finally, based on P and S velocity and geotechnical parameters, the rock formation are divided and the results are interpreted. In this step, only the more eminent reflection signals in front of tunnel face are taken.

After entering the geometry of the Nosoud Tunnel profile into the Amberg TSP plus system, the recorded raw data were extracted for each receiver as the three components X, Y, and Z. The acquired data were high quality. First, arrival amplitudes dominated and resulted in high-resolution data. The maximum to 200 ms was processed. The errors of location are about 1 m, and for some other engineering investigation, this location error can be more than 5 m. The difficulty in determining the velocities of seismic waves is the reason for errors of the location.

Results from the test site showed some low-velocity anomalies (LVAs), which are interpreted as fault or fracture zones (Figures 7 and 8). Four low velocity seismic

Figure 9: Rock mechanical properties.

zones were detected that their locations are shown in Table 2. The thickness values of the anomalies are 3, 3, 4, and 3 m, respectively. LVAs are often attributed to excess temperature or water content.

Figure 9 illustrates a change in rock mechanical properties, the P-wave velocity and S-wave velocity ratio, and Poisson's ratio (the V_P/V_S variety range was between 1.80 and 2.41 and the Poisson's was between 0.28 and 0.40).

In compression with previous works, for instance, Qiyeshan tunnel in 2014 [18], Ma Jiazhai tunnel in 2012 [26], both located in the Karst area, and Shimenya tunnel of Yi-Ba highway in 2018 [27], the accuracy of our TSP303 operation results is very high even more than the results of the other works mentioned earlier, although our investigation is in the inappropriate condition due to existing water in the tunnel. This high accuracy is because of using high precision primary velocity in the data processing, which is due to the application of the ERT method and the presence of the boreholes in tunnel before the TSP303 operation.

6 Conclusions

The interpretation of recent geophysical and geoelectrical surveys has suggested better rock-mass conditions on the right side of the tunnel, especially in terms of fracturing and, as a consequence, expected water ingress when performing excavation and drilling operations.

The comparison between ERT and TSP 303 methods indicates that these two geophysical methods are suitable for tunnel exploration. The results are in agreement with each other, but the results of TSP 303 were more accurate with higher quality and greater compliance with rock properties in front of the tunnel. In summary, despite the low energy transmission in the given rock mass, the data lead to a geological forecast over a range of about 100 m from the face. However, some uncertainty about the location of the remote fracture zone needs to be verified later as excavation proceeds.

Based on the information obtained so far, the TSP 303 system can be successfully used in tunneling activities in the Nosoud region. Here, the prevailing rock types and expected geological structures offer the ideal scenario for using this technology. Data acquisition does not significantly delay or effect tunnel operations and can be performed on a continuous basis as needed. The use of seismic investigations together with complementary exploration tools helps reduce the risks associated with tunnel exploration considerably.

Therefore, proper investigations must be carried out using the advanced 3D TSP technology on a continuous basis.

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