ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 624.131.32:551.1

APPLICATION OF GEOPHYSICAL INVESTIGATIONS IN UNDERGROUND ENGINEERING

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Subject review

Geophysical methods are non-destructive methods that have numerous advantages in relation to conventional geotechnical survey, primarily from the aspect of saving time and economic resources. They are used in underground engineering for determining geological-structural and physical-mechanical characteristics of subsoil. Determining the physical-mechanical characteristics most often involves determining the stiffness of subsoil and rock mass at small strains. An overview of geophysical methods significant in engineering practice is given including examples of successful implementation of geophysical methods in Croatia. Geophysical methods are used in combination with boreholes works, as preliminary phase of surveys for a more complete image of underground and better possibilities of interpretation of geological structures.

Keywords: *geological structure, geophysics, non-destructive surveying, small strain stiffness*

Primjena geofizičkih ispitivanja u podzemnom inženjerstvu

Pregledni članak

Geofizičke metode su nerazorne metode koje imaju brojne prednosti u odnosu na konvencionalna geotehnička ispitivanja, prvenstveno s aspekta uštede vremenskih i ekonomskih resursa. U podzemnom inženjerstvu koriste se za određivanje geološko-strukturnih i fizikalno-mehaničkih karakteristika podzemlja. Pod određivanjem fizikalno-mehaničkih karakteristika se najčešće podrazumijeva određivanje krutosti tla i stijenske mase pri malim deformacijama. Dan je pregled geofizičkih metoda značajnih za inženjersku praksu, kao i primjeri uspješnih primjena geofizičkih metoda u Hrvatskoj. Geofizičke metode koriste se u kombinaciji s bušotinskim radovima, kao preliminarna faza ispitivanja u cilju dobivanja potpunije slike podzemlja i većih mogućnosti za interpretaciju geoloških struktura.

Ključne riječi: *geofizika, geološka struktura, krutost pri malim deformacijama, nerazorna ispitivanja*

1 Introduction

Geophysical investigations in underground engineering imply a series of geophysical methods, used in a non-destructive manner, to determine geological-structural and physical-mechanical characteristics of the underground. From their original intention where geologists used them exclusively to search for natural resources, the last few decades has seen their intense development and they are increasingly being used in civil engineering, in the prevention of natural catastrophes and in environmental protection. Since they encompass a significantly large volume of soil or rock mass for which surveying is to be carried out, measurements can be carried out in a wide spectrum, from surveying providing global data on the Earth to localised measurements of the upper Earth's crust, which is necessary for engineering practice.

When talking of the advantages of geophysical investigations in underground engineering in comparison to conventional investigations in subsoil or rock mass, besides taking into account the need to obtain a much greater quantity of data due to the greater volume of earth or rock mass which assists in surveying, one should also take into account significant savings in time and economic resources. This arises from the fact that instruments are relatively cheap while investigation works are quicker and simpler. In order for a geophysical method to be rated as acceptable and successful, there must exist a change in the physical characteristics of the earth or rock mass for which a method is sensitive, and this change clearly determines the scope of its use [1]. Even though a majority of geophysical methods demand a complex methodology and relatively advanced mathematics for interpreting measurement results, much of the information can simply be evaluated at the investigated location. In the event that there should be a need for a detailed interpretation of collected data, knowledge and experience become necessary, because sometimes a data set gained from investigations does not necessarily have to indicate certain specific characteristics in the subsoil or rock mass. Consequently, it remains essential that along with geophysics, conventional engineering investigations are being applied, such as for instance borehole investigations. However, borehole investigations are expensive, and though providing unambiguous information on the subsoil and rock mass, informations are representative only in a discrete area (point informations). For the purpose of acquiring a better quality programme for investigation works, geophysical methods are recommended in the preliminary phase of investigations in order that they provide a general picture of the underground and on the basis of such data, an optimal number and position of investigation boreholes are then determined.

Besides their use in determining a geological structure of an investigation area, in underground engineering their use is very important in determining the physical-mechanical characteristics of earth or rock mass, i.e. in determining subsoil or rock mass stiffness at small strains [2]. This is especially important in urban surroundings where construction sites are very congested, and where tunnel excavations, construction of supporting walls, deep excavations, etc. cause subsoil or rock mass displacements that ultimately affect the nearby structures.

2 Geophysical methods in underground engineering

The range of geophysics that can be used in the domain of underground engineering is very broad:

- gravity method [3]
- magnetic method [4]

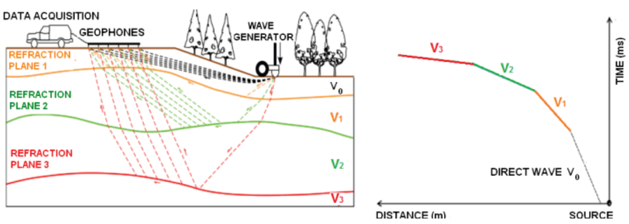
- seismic refraction method [5, 6, 7, 8]
- seismic reflection method [9, 10, 11, 12, 13]
- hybrid seismic method [14]
- spectral analysis of surface waves [15, 16, 17]
- multi-channel analysis of surface waves [18]
- continuous surface wave system [2, 19]
- refraction microtremor [20, 21]
- borehole seismic method [22]
- vertical seismic profiling [22, 23]
- seismic tomography [22, 23]
- electrical resistivity method [24, 25, 26, 27, 28]
- spontaneous potential method [24, 29, 30]
- induced polarization method [24, 30]
- electrokinetic probing [31]
- ground penetrating radar [32, 33]
- transient electromagnetic method [34]
- VLF method [35]
- magnetotelluric method [36]
- radiometric method [30, 37]

3 Examples of the use of geophysical methods in underground engineering in Croatia

In Croatia, a series of research works and consequently practical uses of geophysical methods have been successfully implemented in engineering practice as will be shown further on.

a) Seismic refraction method

The seismic refraction method is based on the analysis of artificially created seismic waves that are generated from the surface. Those waves travel to a particular depth and return to the surface after refraction at the boundaries of layers with different seismic velocities. Fig. 1a shows the procedure for data acquisition, whereas Fig. 1b shows the time – distance diagram of first arrivals, which following further treatment, result in a distribution of longitudinal P velocities at a depth along the investigated profile. Velocities v_0 to v_4 imply wave velocities in corresponding layers. A number of methods were developed to interpret the measurement results with the most commonly used method being the Generalised Reciprocal Method (GRM) [6], Delta-t-V Method [7], and the Diving Wave Tomography [8].



(a) (b)

Figure 1 Seismic refraction method: (a) data acquisition, (b) time – distance diagram of first arrivals [14]

The refraction profile of the allocation of P velocities based on depth shown in Fig. 2 represents the result of investigation works at the location of the future power station at Koprivnički Ivanec using the seismic refraction method [38].

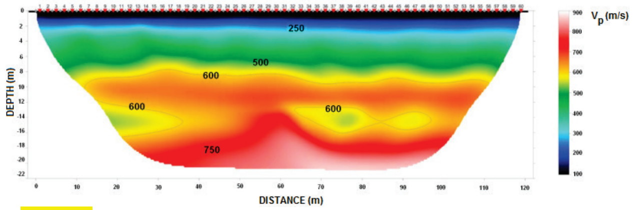


Figure 2 Refraction profile from the Koprivnicki Ivanec location [38]

The seismic refraction method has successfully been used in determining the stiffness of carbonate rock mass in Croatian karst [39]. Intensive measurements of rock mass deformation in Croatian karst, occurring due to construction works, has shown that measured values as a rule are much greater than the values gained from calculations. Traditionally, input parameters used in such calculations include stiffness acquired from direct correlations with existing rock mass classifications [40, 41]. However, the presence of a number of karstified zones with increasing depth can be established by comparing the velocity of longitudinal P waves with the respective depths where they are measured. In that way, it is possible to establish a direct link between the velocity of longitudinal P waves and at particular depths the variable stiffness characteristics of fragmented rock mass. On the basis of this the expression for determining rock mass rigidity in Croatian karst has the following forms:

$$E_{\mathrm{m}} = ID_{\mathrm{m}} \cdot GSI^2 \cdot v_{\mathrm{p}}^2, \tag{1}$$

where E_{m} is the stiffness in GPa, *GSI* geological strength index in % and v_{p}, the velocity of longitudinal waves in km/s. $\mathrm{ID_m}$ designates the deformation index for rock mass (in the range 0 ÷ 1).

During construction of protection pit for the garage at the Kantrida swimming area in Rijeka, measurements of horizontal and vertical deformations of rock mass were carried out using a vertical inclinometer and sliding deformeter Using seismic refraction method, profile of longitudinal wave velocity in the garage is determined, as shown in Fig. 3.

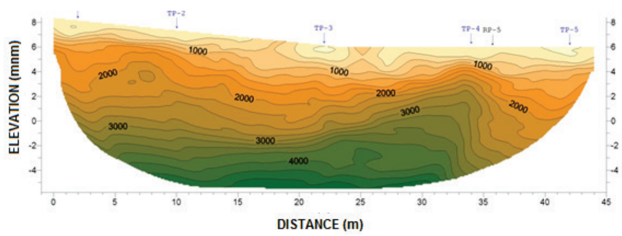


Figure 3 Refraction profile on location of garage of swimming pool Kantrida [42]

Aided by FLAC software, the horizontal and vertical displacements at various depths were calculated using four different models. Model 1 used an expression proposed by Serafim and Pereira (1983) [43], Model 2 the expression proposed by Hoek, Carranza-Torres and Corkum (2002) [44], Model 3 the expression provided by Hoek and Diederichs (2006) [45] whereas Model 4 the expression (1) adapted to the characteristics of rock mass in Croatian karst. The acquired results for all four models are also compared to the measurement results shown in Fig. 4 from which it is evident that the proposed model for rock mass stiffness (Model 4) shows a smaller deviation from the measured values than what is the case for other models obtained using correlations with rock mass classifications [39].

Also noted is the particular significance if one takes into account that the 50 % of Croatian landmass is in karst [46, 47] and that this type of stiffness model, based on longitudinal wave velocities, is a good basis for stress-strain analysis in the field of rock engineering in Croatia.

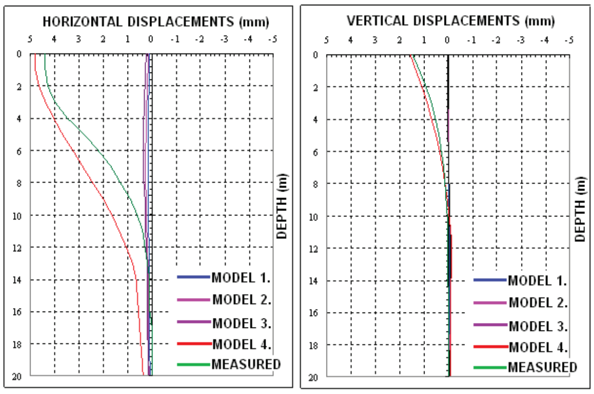


Figure 4 Comparison of measured and calculated horizontal and vertical displacements [39]

Gazdek et al. [48] give an interesting example of using seismic refraction method for verification of the quality of ground improved with vibro stone columns. The surveying location was the KTC Shopping Centre in Krapina. Changes in the volume and compaction of incorporated gravel resulted in changes of the ground density and stiffness prior to and after incorporation of the vibro stone columns, and such changes are adequately distinctive for their probing using longitudinal P waves.

b) Hybrid seismic method

Seismic refraction method, which analyses refracted waves, and seismic reflection method, which analyses reflected waves, have their advantages and disadvantages. The weathering zones, typical for karst regions, are successfully registered using refraction method, and provide significantly better results at smaller depths. Reflection method however has an advantage at deeper investigations when identifying a fault, fissure systems and caverns. The hybrid seismic method unites independently acquired results from seismic refraction and reflection into a unique profile, allowing geologists and geotechnicians a better insight into engineering-geological profile under investigation [14].

The technique using the hybrid seismic method, which includes the overlapping of refraction and reflection profiles, is used in the scope of investigation works for the requirements of residential building foundation design in Dubrovnik [49]. The investigation results are shown in Fig. 5, where Fig. 5a represents refraction profile, Fig. 5b represents reflection profile and Fig. 5c represents hybrid seismic profile generated by overlapping profiles from Fig. 5a and Fig. 5b. The line of velocity at 1600 m/s, Fig. 5c, represents the boundary between fragmented and compacted limestone. This boundary extends along the whole profile at depth of about 20 m. At the reflection profile section, karstified zone was registered with chaotic dispersion of reflected waves, which is interpreted as a tectonic zone with an emphasized fault.

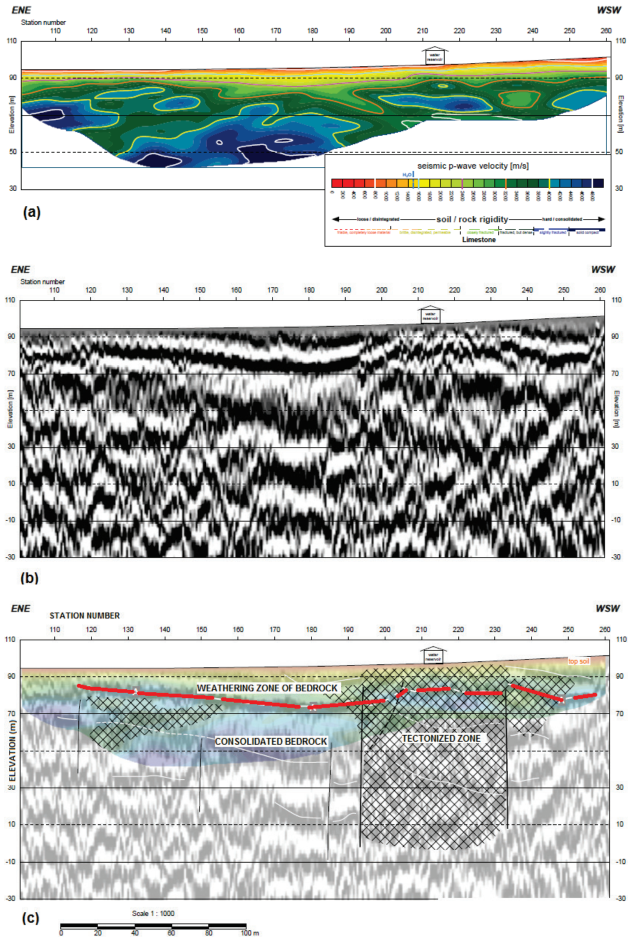
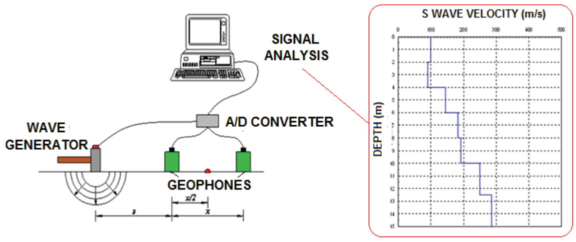


Figure 5 Investigation for the purpose of residential building foundation design: (a) seismic refraction profile, (b) seismic reflection profile, (c) hybrid method interpreted profile [49]

c) Spectral analysis of surface waves

A spectral analysis of surface waves (SASW) is a non-destructive geophysical method for determination of the velocity of S waves and is exceptionally useful in determining the elastic modulus of various materials at very small strains, as well as in determining changes of such modulus with respect to depth. The method is based on the dispersive characteristics of Rayleigh's R waves and the fact that R waves at different wavelengths or frequencies propagate to different depths. Geophones are placed in predefined intervals, Fig. 6a, and they measure arrival time of the wave velocity generated by a vertical mechanical impulse on the terrain surface. Then, a Fourier analysis is carried out on the gathered signals, whereby the signal is transformed from the time into the frequency domain [15, 16, 17]. As the velocity of the surface wave R is a good indicator of the velocity of an S wave, further analysis gives a result in the form of shear velocity with respect to depth, as shown in Fig. 6b. The profile of the S wave velocity can determine the stiffness-depth profile.



(a) (b)

Figure 6 SASW: acquisition equipment (a), S velocity profile (b)

The procedure of SASW method can successfully carry out investigations of the average increase in stiffness of ground improved using jet grouting technique. An interesting example of the use of this procedure was shown by Kovačević et al. [17] on the example of the St. Kuzam Tunnel where, during excavation, a collapse of the rock mass occurred in the northern tunnel pipe covering a 35-metre length. In order for the successful continuation of excavation works, improvement was made to the mechanical characteristics of the collapsed material. The improvements were carried out using the jet grouting technique. The quality control program for ground improvement included borehole profiles (drillings along with sampling) and SASW surveying, which provided the ability to determine the stiffness characteristics of the ground prior to and after improvement to the collapsed ground area. The ratio of ground stiffness following the improvements and prior to the ground improvement represented an average degree of ground improvement using jet grouting. Positions of the borehole profiles and SASW profiles are shown in Fig. 7.

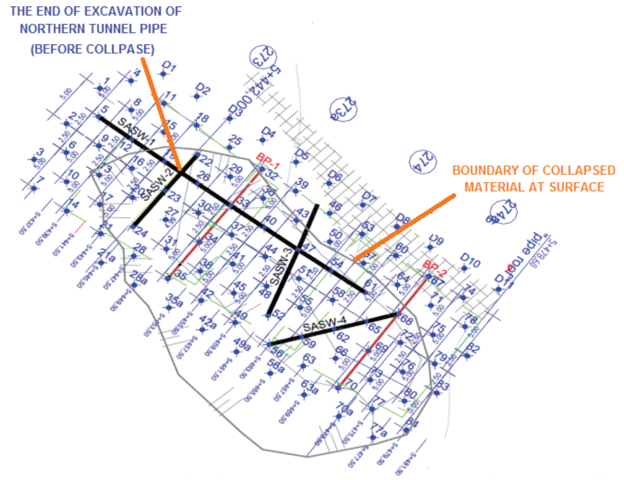
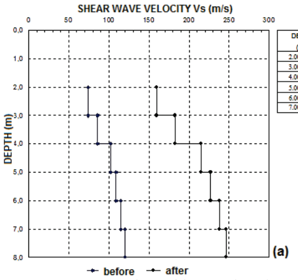


Figure 7 Situation of soil improvement with positions of SASW profiles [17]



DEPTH (m)	Vs before (m/s)	Vs after (m/s)	G0 before (MPa)	G0 after (MPa)	E0 before (MPa)	E0 after (MPa)	E0 after / E0 before	E0 after / E0 before
2.00-3.00	74	160	10,4	48,6	27,1	126,5	4,67	AVG
3.00-4.00	86	183	14,1	63,6	36,5	165,4	4,53	
4.00-5.00	102	215	19,8	87,8	51,4	228,4	4,44	4,41
5.00-6.00	109	227	22,6	97,9	58,7	254,6	4,34	
6.00-7.00	115	238	25,1	107,6	65,3	279,8	4,28	
7.00-8.00	120	246	27,4	115,0	71,1	298,9	4,20	

(b)

SASW PROFILE	AVERAGE IMPROVEMENT
1	4,41
2	4,31
3	4,66
4	5,03

(c)

Figure 8 Results of investigation with SASW method: (a) velocity of S – waves (m/s) with depth (m) before and after improvements for profile 1 with (b) calculated average degree of improvement, and (c) values of average degree of soil improvement for all profiles [17]

It was shown that the average improvement of stiffness ranged from 4,31 to 5,03, Fig. 8.

Further excavation of the tunnel pipes could continue, after it was proven that the degree of improvement was adequate.

d) Multi-channel analysis of surface waves

The theoretical background of the method described as a multi-channel analysis of surface waves (MASW) is equivalent to the SASW method. In comparison to the SASW method, which uses a wave generator and only two geophones, the MASW measurement equipment comprises a generator and a series of geophones, as shown in Fig. 9, hence data acquisition can be carried out much quicker.

Investigations using the MASW method were carried out in terms of the extensive investigation works at the location of the future port on the Danube River in Ilok [50]. Following the acquisition and analysis of data, the resulting profile showing the velocity distribution of surface S waves is shown in Fig. 10.

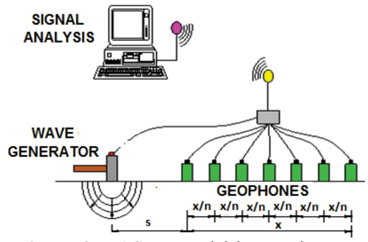


Figure 9 MASW acquisition equipment

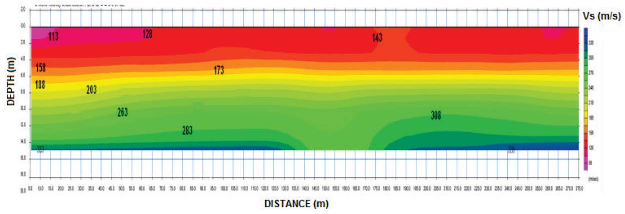


Figure 10 MASW profile from the future Ilok Harbour location [50]

Based on correlations of the velocity of surface S waves and ground stiffness at small strains, the profile allowed the determination of values for the elastic parameters of ground at the respective location, necessary for the design phase, as shown in Fig. 11.

Table 1 Determination of soil stiffness from MASW results [50]

MASW 16 -02						
(WAVE GENERATION LOCATION : 88.0 m)						
DEPTH	S WAVE VELOCITY	POISSON COEFF.	P WAVE VELOCITY	SOIL DENSITY	SHEAR MODULE	ELASTICITY MODULE
d (m)	V_S (m/s)	ν	V_P (m/s)	ρ (kg / m^3)	G_0 (MPa)	E_0 (MPa)
0.0 - 1.4	141	0,35	294	1800	36	97
1.4 - 3.1	136	0,35	283	1800	33	90
3.1 - 5.2	149	0,35	310	1800	40	108
5.2 - 7.6	191	0,35	398	1800	66	177
7.6 - 10 .4	272	0,35	566	1800	133	360
10.4 - 13.5	284	0,35	591	1800	145	392
13.5 - 15.0	317	0,35	660	1800	181	488

e) Electrical resistivity method

By measuring the electrical resistivity of various ground compositions or rock masses, zones of different electrical resistivities can be identified. These zones provide the basis for making conclusions on the geological structure of investigated terrain. In Fig. 11 is shown that the ranges for certain types of ground and rock mass can vary quite largely. The success of investigations will depend primarily on the differences in material resistivities, because the greater the differences, the more precise interpretation results can be expected.

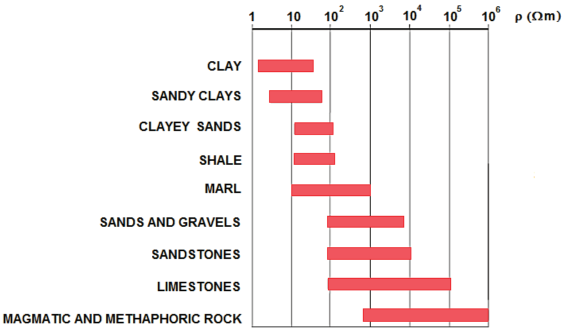


Figure 11 Ranges of electrical resistivity for certain materials [24]

Up until the 1990s, the use of the electrical resistivity method involved the use of one-dimensional methods for horizontal profiling and vertical sounding. This was followed by the development of a two-dimensional and three-dimensional electrical probing, i.e. electrical tomography [25, 26], which today is the most commonly used amongst all electrical methods. The electrical tomography provides a more exact image of electrical resistivities of the underground. Theoretically, 3D surveying of electrical resistivity can be more precise and more exact than 2D surveying, but at this moment 2D surveying is an economical compromise between acquiring exact results and maintaining surveying costs relatively low [27]. During the investigation, Wenner's, Schlumberger's, two-electrode or dipole configuration of electrodes are used. Often, for surveying requirements sophisticated multi-electrode systems are used that allow full automatic measuring of resistivity, and carrying out a large number of measurements in a relatively short time. As a result of investigation using 2D electrical tomography, apparent resistivities are obtained which are shown in the form of so-called pseudosections [28], which represent the underground cross-section obtained by marking the apparent resistivities exactly under the centre of the electrode configuration at a depth proportional to the electrode spacing.

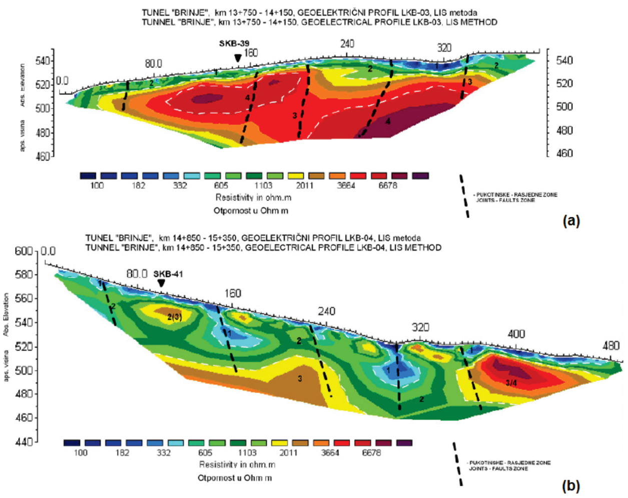


Figure 12 Electrical resistivity method – Approach cutting of tunnel Brinje: (a) north approach cutting, (b) south approach cutting [51]

Investigation using an electrical profiling technique was successfully carried out in the area of the north and south portal of the Brinje Tunnel located on the Zagreb-Rijeka Highway [51]. In the area of the northern approach cutting, in accordance with presumptions caverns without fillings were detected which significantly increased electrical resistivity in the rock mass area, as shown in Fig. 12a. At the southern portal, as shown in Fig. 12b, zones possessing lower electrical resistivities were registered, indicating a poorly fragmented rock mass with localities or pockets and discontinuities filled with clay.

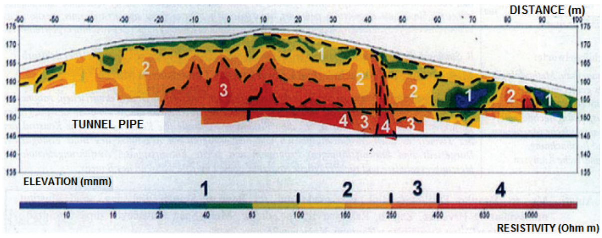


Figure 13 Electrical resistivity method – Tunnel 'Sv. Marko' [52]

The electrical resistivity method was also carried out on the St. Mark Tunnel location, which is situated on the Zagreb-Rijeka Highway [52]. The tunnel comprises two tunnel pipes and is characterised by a relatively small overburden at only 22 m. Fig. 13 indicates the geotechnical media determined on the basis of electrical resistivity of the ground and rock mass at the respective location. The geomedia consists of sandy clay (geomedia 1), a mixture of clay, sand, silt and sandstone fragments (geomedia 2), fully disintegrated dolomite (geomedia 3), and compact dolomite (geomedia 4).

f) Ground penetrating radar

Ground penetrating radar (GPR) provides a high-image of dielectric characteristics of subsoil or rock mass from a depth of a few centimetres to tens of metres. Investigation is based on a transmitter that utilises short electromagnetic waves directed into the subsoil or rock mass. When the wave encounters an obstacle in the underground, part of the energy is reflected back to the receiver, which then processes it, thereby creating a continual profile of electrical properties of the material. The frequency of the electromagnetic wave determines two surveying parameters: depth and resolution. The greater the frequency the better the resolution but less investigation depth and vice-versa. The procedure for investigation using ground-penetrating radar is shown in Fig. 14.

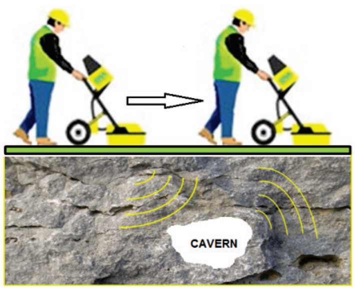


Figure 14 Investigation with Ground Penetrating Radar method

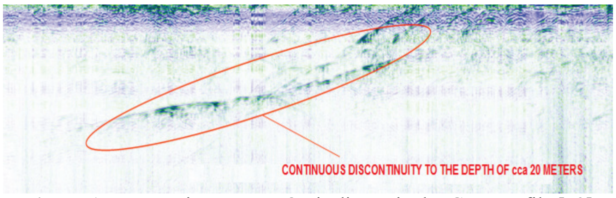


Figure 15 Reservoir space on Omisalj terminal – GPR profile [53]

Investigation using ground penetrating radar was carried out in the investigation area of the reservoir area for crude oil and the oil derivatives at the Omišalj Terminal on Krk [53]. Fig. 15 shows a ground penetrating radar profile, where the settings of the measurement equipment is set so as to distinguish depths greater than 25 m, all with the aim of determining the continual discontinuity that extends to a depth of 20 or so metres. Having inspected all the surveyed profiles, it was ascertained that the rock mass was in places very fragmented, with a series of identified faults and cavities.

4 Conclusion

Geophysical methods are non-destructive methods that are increasingly being used in engineering practice. The main reason lies in the economic and time savings when compared to conventional surveying, primarily borehole investigations. However, geophysical methods are still used in combination with borehole works, because in that way a more complete image is obtained and much better possibilities in interpreting geological structures of the investigated area. It is actually in this area of underground engineering that their greatest use is to be found – from defining the type of layers of the investigated area, to determining the depth of the bedrock, groundwater table, rock mass cavities and caverns, etc. Furthermore, an increasing application of geophysical methods is directed towards determining the physical-mechanical parameters of subsoil or rock mass that are of great importance for construction projects in urban areas where the construction of underground structures causes ground or rock mass displacement, which has a significant impact on nearby structures. Therefore, in Croatia, following world trends through a series of research works and practical applications, geophysical methods are implemented in the field of underground engineering.

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