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REVIEW PAPER

Exploration of Tunnel Alignment using Geophysical Methods to Increase Safety for Planning and Minimizing Risk

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Abstract Engineering geophysics provides valuable and continuous information for the planning and execution of tunnel construction projects. For geotechnical purposes special high-resolution geophysical methods have been developed during the last decades. The importance of applying geophysical methods in addition to usually used geological and geotechnical exploration techniques is increasing. The main goal is to achieve an accurate and continuous model of the subsurface in a relative short period of operation time. The routine application of engineering geophysical methods will increase in the coming years. Due to the high acceptance of engineering geophysics at construction sites, much wider application of geophysical investigations is expected. The combination of different methods—geophysics, geology, and geotechnics as well as the so-called joint interpretation techniques—will be of essential importance. Engineering geophysics will play an important role during the three phases: geological investigation, tunnel planning, and execution of tunnel construction. If hazards are well known in advance of a tunnel project the safety of workers will essentially be increased and geological risks will be minimized by means of successful and interdisciplinary cooperation.

Keywords Line investigation · Karst cavities · Geophysics · Seismics · Tomography · Elastic parameters · Strain

1 Introduction

Tunnel construction depends especially on a qualitative and quantitative description of the underground conditions. Engineering geology and hydrogeology offer a number of methods in order to investigate these conditions with the desired precision. These methods (e.g., DIN 4020, DIN 4021, SIA 199, EC: ENV 1991) are generally recognized to be state of the art and they are regulated in a wide range of standards. Geological studies generally imply the adoption of near-surface mapping along exposures or the use of deep drillings with core recovery and analyses. However, even within intensive and expensive investigations of the foundation soil, distances between drillings can easily range between 50 and 200 m. Furthermore, in the case of detailed explorations of deeper targets, i.e., crossing waters or deeply located tunnels, boreholes are drilled more than 1,000 m apart. Therefore, to overcome uncertainties in the description of physical properties determined from a few drillings only, the importance of geophysical investigations is increasing due to the fact that these methods yield continuous information along profiles or about the complete area under investigation of relevant physical subsoil properties.

2 Possibilities to Apply Engineering Geophysics

The investigation of subsoil conditions is always important when buildings are created on the surface or built into the soil. Especially for tunnel constructions, planners and

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supervisors need very detailed and comprehensive information about the subsoil where they plan to drive the tunnel. Comparable to a medical case a detailed examination with, e.g., radiographs, is essential for the preparation of an operation. No responsible doctor would perform an operation without having this urgently needed information in advance. Otherwise, disregard of these precautionary investigations would result in a kind of Russian roulette. The same holds for engineering: a wrong diagnosis due to a lack of information can cause immense damage.

The procedures of applied geophysics (engineering geophysics) were developed during the last 20 years, based on the classical applications in coal, oil, and natural-gas exploration. Based on these developments today's possibilities to apply geophysics in tunnel construction projects are various and supply the engineer with a range of information about the structure of the subsoil. Using geophysical measurements it is possible to obtain relatively quickly a model of the structure and physical properties of the subsurface along a line (profile) or—by the combination of several profiles or rather a planar assembly—a three-dimensional picture of the underground. The application of geophysical methods is used to determine the physical characteristics of the inaccessible underground without touching the subsoil to a larger extent (Lenz et al. 1997; Althaus and Räkers 1998; Althaus et al. 2000).

The physical characteristics change according to the lithological, structural, and mechanical changes in the underground, so that they can be detected with geophysical techniques if physical changes reach values of certain significance. After applying filter and evaluation procedures the subsoil can be described by models. In order to obtain a correct estimation of the possibilities of geophysics (Räkers et al. 1996) and also to prevent overreliance on geophysical methods, the following statements can be made:

- A complete transparent underground cannot be produced by geophysical investigations.
- Geophysical experiments are indirect procedures and should be combined with direct investigations (e.g., drillings) and calibrated with these.
- Conceptual formulations and subsoil models have to be discussed between the geotechnical consultant and the geophysicist before any measurement starts.
- It depends on the experience of the geophysicist to find the most reasonable geophysical method or its combination with others in economic and technical terms with appropriate consideration given to the desired application.

Considering these statements, engineering geophysics yields valuable additional information to the standard subsoil investigations and helps to implement the planning and investigation steps in an economical and technically optimized way. Therefore, the geophysical investigation program has to be designed for the problems to be investigated. Usually, geophysical investigations will consist of a number of different techniques and procedures. A selection of the most important engineering geophysical procedures are presented in Table 1.

Table 1 Frequently applied engineering geophysical methods with measured variables and their targets

Methods	Targets	Parameter	Geophysical methods/techniques
Seismics	Layers, loosening, cavities, change of material, faults, obstacles	Elastic parameter	Reflection seismics Refraction seismics Borehole seismics (tomography, VSP) Surface wave seismics Vibration monitoring
Gravity	Cavities (e.g., dolines, gallery) and inclusions	Density	Measurement of the relative mass attraction
Magnetics	Iron, ores, minerals, masonry, refuse dumps	Susceptibility	Measurement of the total magnetic Earth's field/measurement of the gradient
Geoelectrics	Layers, change of material, groundwater, cavities, metal, sewers, contamination	Electric resistivity	Electric sounding/tomography
Electromagnetics	Layers, change of material, groundwater, cavities, metal, sewers, contamination	Electric resistivity	Electromagnetic induction transient electromagnetics/magnetotellurics
Radar	Layers, change of material, inclusions, obstacles, sewers	Electric resistivity	Electromagnetic reflection
Borehole measurements	Layers, water saturation, porosity, groundwater flow, cavities, loosening	Elastic parameter, density, susceptibility, electric resistivity	e.g. caliper, γ- and n radiation, γ-γ-(density)-log, full-wave-sonic-log, SP-log, televiewer

VSM vertical seismic profiling

Depending on the geotechnical and geological questions and on the required resolution, data-acquisition parameters of the used geophysical method need to be adapted. Due to acquisition parameters large-scale measurements can be carried out to investigate depth ranges of several kilometres and small-scale measurements to investigate near-surface conditions at depths down to a few meters only. Geophysical applications in tunnel projects are not only used for planning purposes but also during the construction phase. An overview of the two stages is given as follows:

- Planning Stage
  - Investigation of the bedrock structure (e.g., boundary between different rock horizons, layer thicknesses or geological anomalies)
  - Investigation of cavities (e.g., karst cavities, mining structures)
  - Recognition of obstacles (e.g., buildings, pipelines)
  - Derivation of the geotechnical parameters in terms of density and deformability of the rock mass
  - Investigation of the water level or extended water-bearing strata
  - Investigation of contaminated areas

The results of geophysical applications during the planning state offer a cost-effective and purposeful arrangement for further and more detailed investigations. The recognition of obstacles is of crucial importance for the planning of the building procedures. Additionally, the following tasks have to be performed at the construction stage:

- Construction Stage
  - Measurements to look ahead of the tunnel face;
  - Quality assurance (e.g., when executing a concrete slab below the water table, sealing membrane, friction piles in water-filled excavations);
  - Vibration measurements to determine the effects on human beings and buildings. With knowledge of the influencing parameters the method for tunnel driving can be optimized.

The application of the first two steps in the construction stage will avoid unexpected events during the building execution (e.g., finding obstacles which cannot be detected from the surface, or the occurrence of defects in a deep excavation).

3 Combination of Methods and Involvement of Direct Exposures

In previous chapter the most important geophysical methods are listed in Table 1 and the possible fields of application are described. The potential of geophysics substantially increases by using a combination of different methods. The following examples of successful and economic method combinations can be mentioned:

- Seismic reflection and refraction methods in addition to gravity for the investigation of alluvial fills and karst cavities
- Geoelectric and seismic reflection techniques for hydrogeologic questions
- Ground-penetrating radar (GPR), gravity, and seismic reflection methods for the localization and characterization of fault zones

Furthermore, an important step for a successful investigation on tunnel alignment is the ability to create geophysical models of the area of interest. This step is often called calibration. Direct investigations (drillings, etc.) always supply exact, but only very local, information. However, geophysics supplies physical parameters, which are regarded as integral values over a wider surface or a larger volume. The first step for investigating a tunnel site is the planning and performance of a geophysical program with interpretation of the results. Accordingly, an optimized drilling program is needed. Finally, the drilling results are used to calibrate the geophysical results and to generate the desired geotechnical model.

4 Seismic Methods

4.1 General Information

Seismic methods use information from elastic waves to generate a model of complex underground structures. The important parameters for wave propagation are the wave velocities in the different layers and the densities of the materials. The underground affects the propagation of seismic (elastic) waves by mechanisms such as reflection, refraction, diffraction, absorption, and dispersion (Fig. 1).

In engineering geophysics seismic waves are generated artificially, e.g., by explosives, hammer blows, vibrators, accelerated weight drops, implosions or other seismic sources. In water, systems such as a sparker, boomer or airguns are applied. For the recording of seismic wave's geophones, accelerometers or hydrophones are used. The data-acquisition parameters are adapted to the special situation, respectively. Seismics is usually carried out along profile lines, i.e., two dimensions (2D). For spatial investigation of the underground a laminar measuring setup of the source positions and receiver locations is necessary, which results in a three-dimensional (3D) insight into the underground.

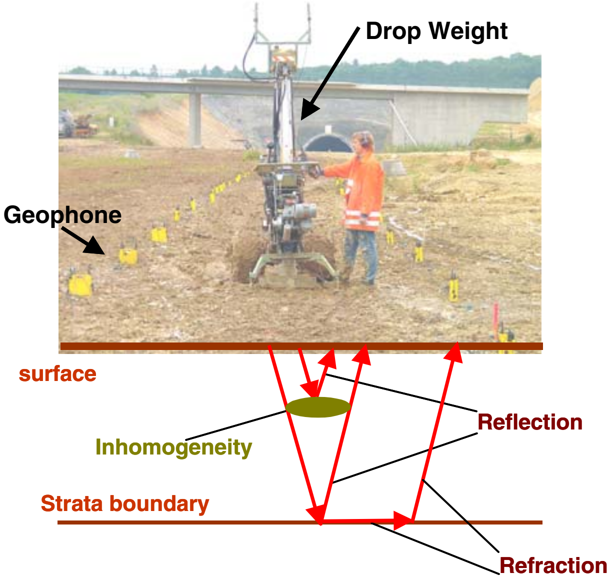


Fig. 1 Seismic principle for high-resolution investigation of subsoil conditions

The seismic display definition is subdivided into the vertical and the lateral resolution. The vertical resolution, e.g., the resolution of boundaries of the beds, especially depends on the frequency content of the seismic signals and of course on the signal-to-noise ratio of the registered wave field.

Generally the following formula applies:

$$v = \lambda f$$

with:

v wave velocity (m/s)
λ wavelength (m)
f frequency (Hz).

Usually, the range between one-quarter and one-half of the wavelength is defined as the vertical resolution. Hence, with a seismic wave velocity of 300 m/s in the near-surface underground and with a signal frequency of 300 Hz the wavelength is calculated to 1 m. Thus, the maximal vertical resolution is about 0.25–0.50 m.

The lateral resolution is defined as the minimal lateral extension of an object that can be resolved. The signal that is emitted from a certain point and recorded at a receiver originates from a constructional interference from a broader zone along the reflecting boundary (Fresnel zone). When the distance between two reflecting points is smaller than the radius of the Fresnel zone, no differentiation between the two points is possible.

The radius r of the Fresnel zone depends on the seismic velocity v, the dominating frequency f (Hz), and the travel time t (usually measured in seconds):

$$r = \frac{v}{2}\sqrt{\frac{t}{f}}.$$

Under optimal conditions the radius of the Fresnel zone reduces to one-quarter of the wavelength. Thus, high frequencies (small wavelengths) are needed for a high resolution of the underground. Since higher frequencies are attenuated more strongly than lower frequencies underground it is necessary to find an optimal balance between signal energy and frequency content.

The following seismic methods can be used successfully for the exploration of tunnel alignments (Fig. 2) depending on the exploration goals and accessibility:

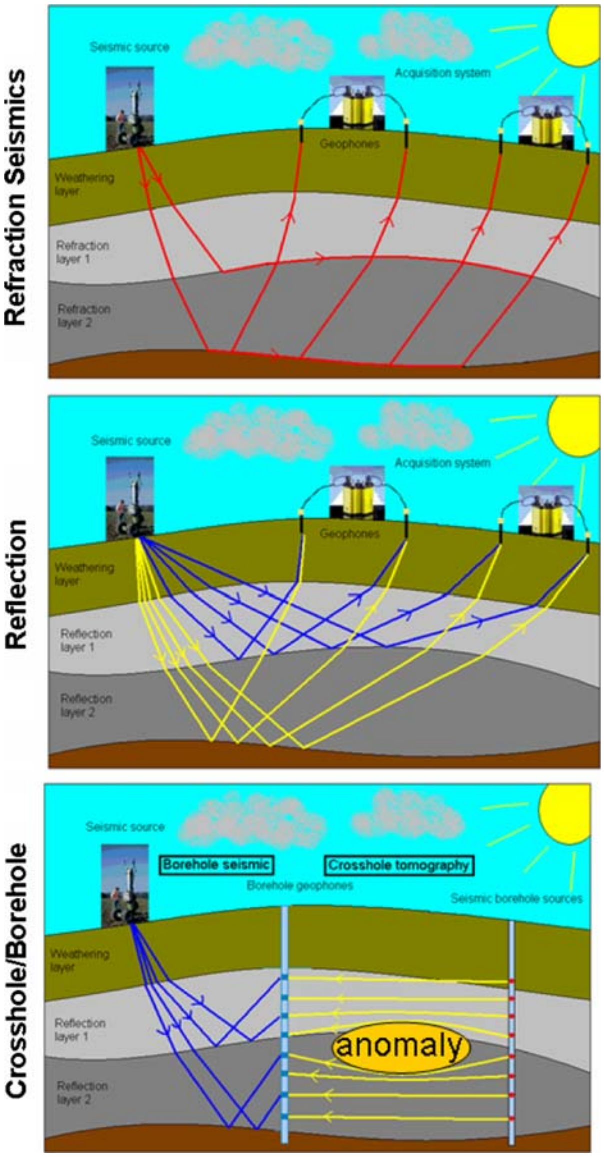


Fig. 2 Basic variants of applied seismics (seismic refraction, reflection method, borehole seismics)

- Reflection seismic method
- Refraction seismic method (standard, CMP, tomography)
- Well shooting (VSP, tomography)

Within the seismic data different waves types are measured, which are interpreted with respect to the given task:

- Compression waves (P-wave)
- Shear waves (S-wave, SH, SV)
- Surface waves (Rayleigh wave, Love wave)
- Disturbing waves/noise (air waves, electrical influences, traffic noise, etc.)

Apart from the effects described above (reflection, refraction, diffraction, etc.), there is the need to consider those seismic waves which have the ability to change their modes at the boundaries between different media (e.g., from P- to S-wave). Further information can be found in Baker (1999), Evans (1997) or Yilmaz (2001).

4.2 Reflection Seismics

The reflection seismic method is based on processing reflected waves that have been generated at the surface and recorded after traveling through the underground. At boundaries or at inhomogeneities in the underground, where the seismic impedance (i.e., the product of velocity and density) of a material changes, a part of the energy of these waves is reflected.

To determine seismic velocities and to optimize the relation between signal and background noise, seismic waves are recorded with a number of geophones, which are arranged in constant distances along a line. The data acquisition usually takes place according to the so-called roll-along/end-on procedure. This means that the source point is located at the beginning or end of an active geophone profile and moves the spread in front or behind. With the help of the distances between the source location and the geophones and with determined travel times of these waves (i.e., the time the wave needs to travel from the seismic source to the reflecting boundary of the bedrocks and back to the geophone) the depth to the reflecting boundary of the bedrocks (the distance to the reflecting object) can be calculated. A resulting travel time curve is shown in Fig. 3.

The portion of the energy reflected at a layer interface (or at an object) depends on the ratio between the seismic impedances on both sides of the interface. During seismic reflection data processing the seismic traces are sorted according to the common mid points (CMP) between the source and receiver positions in the field. After applying dynamic corrections (e.g., velocity corrections) the amplitudes of the traces are summed up (stacked) so that at each CMP a stacked trace of all contributing records is generated. The resulting CMP stacked section corresponds to a registration, with which both the source and geophone apparently are positioned at the same location, namely the CMP. Due to the fact that several seismic traces are assigned to one CMP, so-called multiple coverage is obtained. The advantage of a multiple coverage compared with single trace measurements is an improved signal-to-noise ratio and thus higher quality and accuracy of the results. The principle of sorting the traces in CMP gathers is shown in Fig. 4.

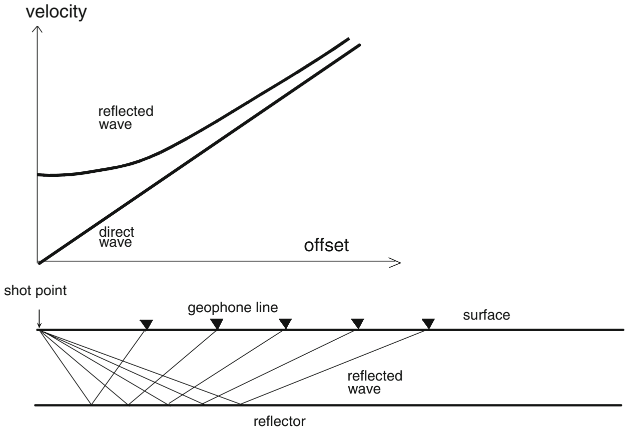


Fig. 3 Shapes of the ray paths and travel time curves of reflected seismic waves

The final result of reflection seismic data processing is a so-called seismic reflection stacked section.

Figure 5 shows an example of such a section with interpreted reflecting horizons along a line investigation over a planned tunnel. Due to the fact that reflected amplitudes are limited only to that range, where interfaces are present an interrupted reflection can be interpreted as a disturbance in that special layer interface. On the basis of calculated seismic velocities the positions of reflecting horizons (horizontal lines in Fig. 5) and of faults or

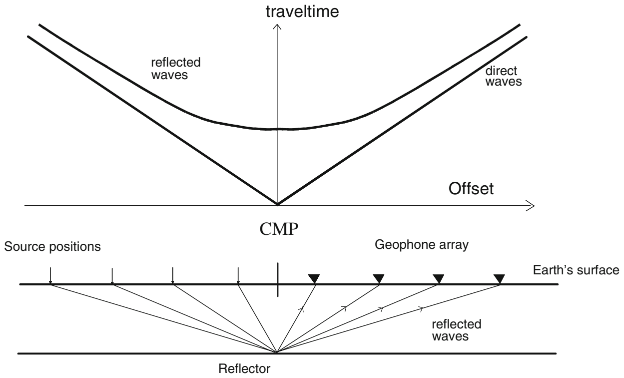
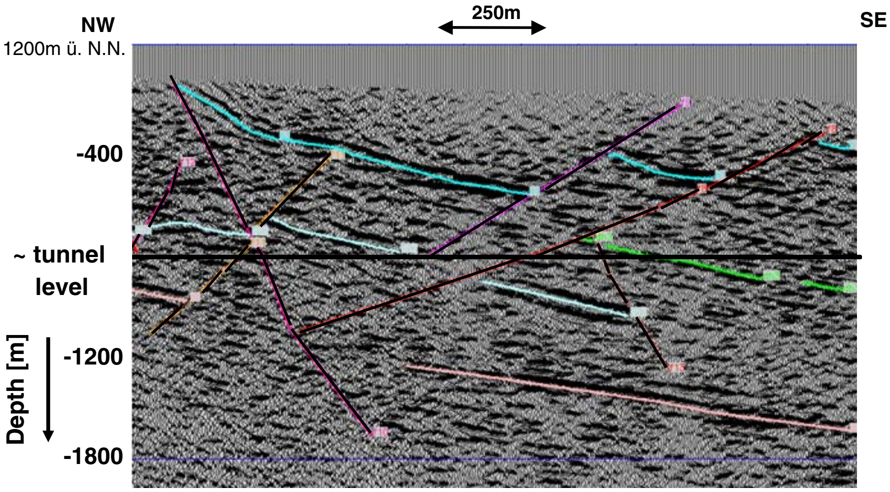


Fig. 4 Shapes of the seismic ray paths and travel times in a CMP gather

Fig. 5 Example of a seismic stacked section with interpretation of an exploration for the Koralm tunnel between Graz and Klagenfurt (Austria)



disturbances (vertical colored lines in Fig. 5) can exactly be identified within the reflection seismic stacked section. Together with drilling results each reflecting horizon can be assigned to a geological layer interface, in which also the individual disturbance (faults, leachings, interstratifications, etc.) can be identified.

4.3 Refraction Seismics

4.3.1 Standard Refraction Seismics

If the underground is characterized by increasing seismic velocities (e.g., change of elastic modulus) with increasing depth, seismic waves travel along layer interfaces, if they dip with a certain angle onto a boundary. In such a case, parts of the seismic energy are permanently radiated back (refracted) to the Earth's surface. Thus, the refracted waves are recorded by geophones located at the Earth's surface. The travel times of the refracted waves are determined and the seismic velocities are calculated with respect to the depth of each layer.

Figure 6 shows the principle of the refraction seismic method, the ray paths of the seismic waves underground, and their travel time curves. It can be recognized that at a certain distance refracted waves appear as the first arrivals because they are faster than the direct waves. Therefore, refracted waves overlap the direct waves although their travel distances are much higher. Calculating the reciprocal gradients of the travel time curves the velocities of the seismic waves (direct and refracted) are determined. The extension of the travel time curve of refracted waves back to the source position determines the so-called intercept time (Ti). By knowing seismic velocities and intercept times standard refraction seismic methods [generalized reciprocal method (GRM), wavefront method, intercept time method] provide a velocity-depth model of the underground. Seismic velocities are assigned to different materials and thus, a velocity-depth model displays the material properties of the underground structures.

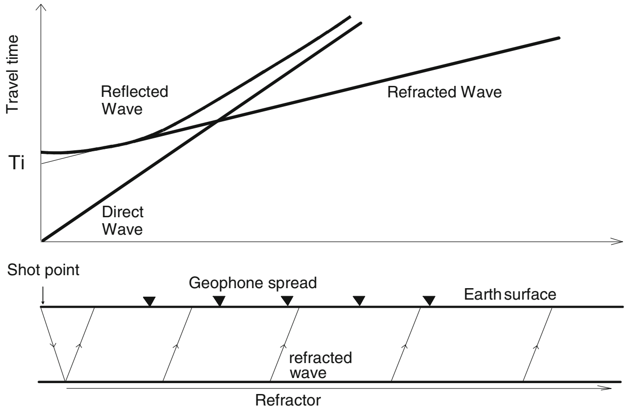


Fig. 6 Principle of the refraction seismic method: ray paths and travel time curves

Figure 7 shows the result of a standard refraction seismic processing. The calculated thicknesses of layers (areas of constant velocities) are represented with reference to the topography of the Earth's surface above sea level. Each layer displays a characteristic velocity which is related to the elastic modules of underground materials. By means of the standard refraction seismics the stratigraphy of the underground can easily be determined.

4.3.2 CMP: Refraction Seismics

A method to improve the signal-to-noise ratio of refracted waves is common-midpoint (CMP) refraction seismics (Orlowsky et al. 1998). Applying this technique, the shallow underground is described using all information (amplitude, frequency, phase characteristics) of the wavetrain, following the first break (first-break phase). Thus, the layering can be determined, and additionally locations of

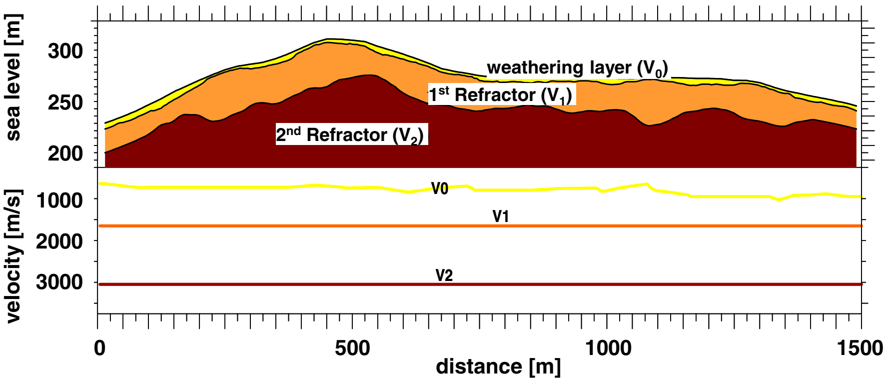


Fig. 7 Typical result of standard refraction seismics for the exploration of a tunnel; the layered structure at depth becomes obvious

disturbances such as faults, weak zones, and clefts can be detected. This information is of great importance when, for example, investigating underground water migration paths, which often follow faults or weak zones. In CMP refraction seismics the roll-along method is used for data acquisition. Thus, the recorded seismic data can be simultaneously processed with reflection seismic techniques to describe deeper underground structures.

CMP refraction seismics is usually applied in combination with the generalized reciprocal method (GRM; Palmer 1986). This joint application is possible because of the close relationship between the two methods in their kinematical description. To maintain the advantages of the roll-along technique in data acquisition for the combination of both methods, the refraction seismic data must be treated in such a way that it can be used simultaneously by CMP refraction seismics and by GRM. GRM needs records of forward and reverse data. Thus, the data must be sorted as shot-receiver gathers and as receiver-shot gathers to obtain the raw data for a GRM analysis. For CMP refraction seismics, the data is sorted in CMP offset gathers. The results of the GRM analysis are used to determine optimum stacking velocities and integration boundaries for a partial radon transformation in the inversion process of CMP refraction seismics so that local irregularities of interest can be detected and identified. Figure 8 shows the results of CMP refraction seismic data processing. The topography of the Earth's surface and the wave fields of two explored refractors, in each case related to sea level, are shown in Fig. 8a. In this section, many disturbances are identifiable with perpendicular throws of 3 to approximately 20 m. Figure 8b shows the interpreted structures of Fig. 8a. In contrast to the results of the standard refraction seismic method (Fig. 7), both the stratigraphy and the complete tectonics of the near-surface underground are determined.

4.4 Refraction Tomography

Refraction tomography is an extension of the standard refraction seismic method. Applying refraction tomography a continuous increase of seismic velocities with increasing depth in each layer is considered which is caused by the corresponding stress increase. Furthermore, differences of seismic velocities within a single layer (and thus different degrees of disturbances or changes of the elastic modulus) are analyzed with the help of refraction tomography. Refraction tomography is applicable to both compression waves (P-waves) and to shear waves (S-waves).

Layers with constant seismic velocities are only an approximation and display a first-estimate model which usually differs from real underground conditions. Due to different degrees of disturbances or the presence of

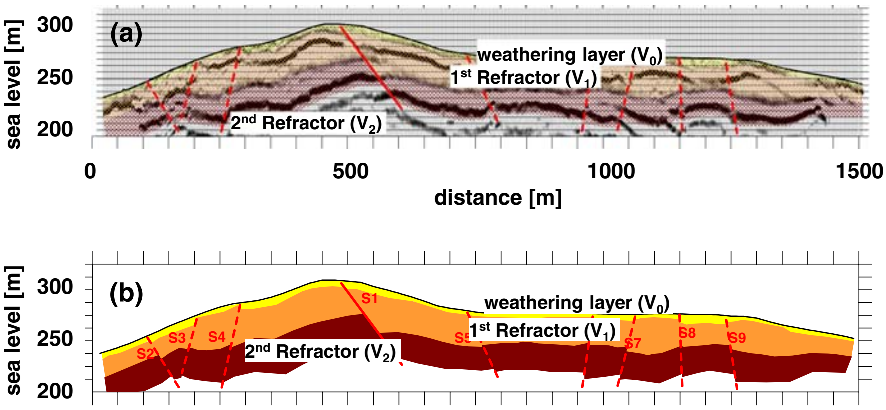


Fig. 8 The results of processed CMP refraction seismic data from preliminary exploration of a tunnel alignment (**a**). The *refractor* is represented as a complete wave field. Locations of disturbances (faults) can be recognized on the basis of the shape of the phases. An interpretation of the results is shown in (**b**). The tectonics of the underground structure becomes clear

inclusions of foreign materials, the seismic velocities within layers can vary significantly. In particular cavities, weathered rock or erratic blocks show either a reduction or an increase of seismic velocities in comparison with the surrounding material.

Applying refraction tomography, special requirements have to be met during the data-acquisition process. The field geometry is comparable to parameters used in standard refraction seismics or CMP refraction seismics along line profiles. However, a substantially higher measuring effort has to be made. The geophone and source point spacing have to be selected much smaller, in order to achieve a significantly higher coverage of refracted waves in the underground to calculate a continuous seismic velocity distribution. In the case of standard refraction seismics, travel time curves, which comprise a number of determined travel times, are allocated to a single layer. In contrast to this, refraction tomography associates to each single travel time a velocity value in a certain depth and at a certain lateral position. The determined velocity field calculated from the travel time's results in a continuous velocity-depth model of the investigated subsurface.

Figure 9 shows a result of refraction tomography processing displayed as a continuous velocity-depth profile. In contrast to the standard refraction seismic method no discrete layers need to be associated for the structure of the subsurface. In Fig. 9 a relative reduction of the seismic velocity can be recognized between distances of 50 and 70 m along the profile and at depths between 10 and 18 m. This kind of low-velocity zones cannot be resolved by the standard seismic refraction method. An allocation of velocity values to rock parameters is possible on the basis of calibration drillings.

4.5 Surface Wave Seismics

When exciting seismic waves at the Earth's surface, in addition to P- and S-body waves, surface waves with relative strong amplitudes are generated. Surface waves are differentiated into Love and Rayleigh waves. Love waves show a displacement which is horizontal and perpendicular to the direction of wave propagation, whereas Rayleigh waves show vertical particle motions. The energy of the surface waves propagates mainly horizontal and is generally bounded to the Earth's surface. Thus, surface waves have relative strong amplitudes at the surface, which decrease exponentially with increasing depth. Therefore, surface waves are usually used for the investigation of anomalies in the near surface.

The most important nature of surface waves is their dispersion character, i.e., the propagation velocity described as a function of frequency. Oscillations with large wavelengths (low frequencies) are influenced by a larger depth range than oscillations with short wavelengths (high frequencies). Due to the relative low propagation velocity the wavelengths of surface waves are relative short, and thus the resolution of structures in the near-surface underground is relative high when applying surface wave analyses. Therefore, for example, polluted areas and their lateral demarcation disruptions in the near-surface underground as well as cavities, erratic blocks, manmade hazards, etc. can be detected with relative high accuracy.

It is relatively simple to distinguish between surface waves and body waves (P- and S-waves) in seismograms due to the fact that surface waves are much slower than body waves and they have relative strong amplitudes. These characteristics allow exact velocity determination of surface waves in distinguished frequency ranges. Knowing the velocities in the selected frequency ranges, velocities can be assigned to a certain depth range of the underground. This method is usually applied to maximum depths of about 15 m depending on the geological situation in the exploration area. During the analysis process of surface wave propagation, maps of the velocity distribution for different frequencies (and thus for different depth levels) of the surface waves are generated.

For analyzing surface waves, single-shot seismograms and so-called constant-offset (CO) sections are usually used. CO sections are displays of seismic traces in which the distances between the source locations and the geophones are kept constant. Inhomogeneities detected in CO sections represent a first indicator of anomalies in the

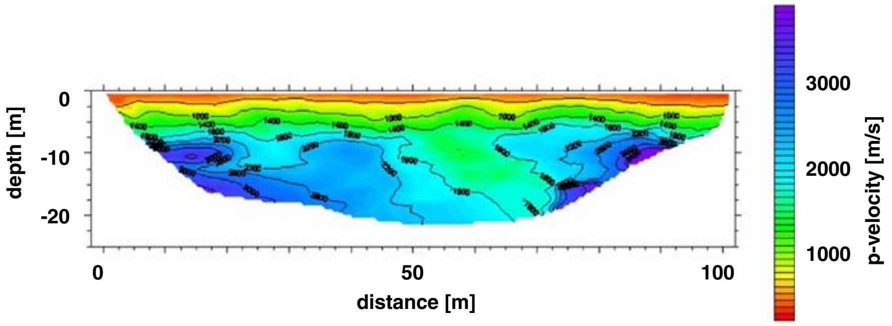


Fig. 9 Result of a refraction tomography in the area of the planned high-speed railway line. A low-velocity zone can be recognized at distances between 50 and 70 m at depths of 10–18 m

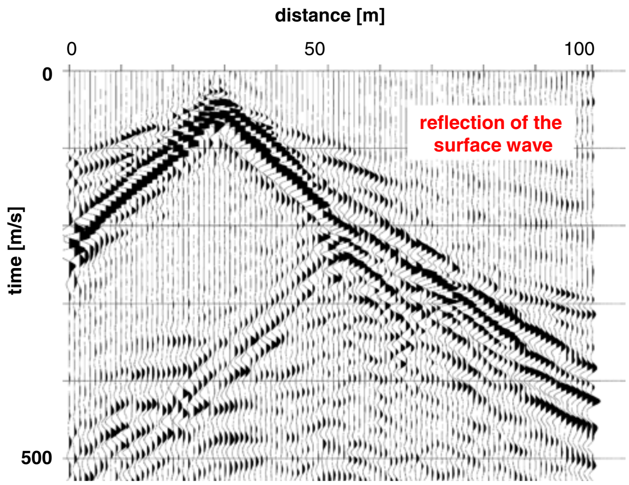


Fig. 10 Example of the analysis of surface waves to map anomalies in the near-surface underground

near-surface underground and thus these locations are used for intensified analysis of the surface waves of single-shot sections. Single-shot analyses include an intensified determination of the dispersion characteristics, the identification of locations where the dispersion changes (inhomogeneities) in the underground, the determination of amplitude changes, and a detection of the reflections of the surface waves at near-surface anomalies. Figure 10 shows an example of a single-shot analysis of surface waves with respect to anomalies in the near-surface underground. The surface waves are reflected at an obstacle at a depth of 3 m.

4.6 Seismic Tomography

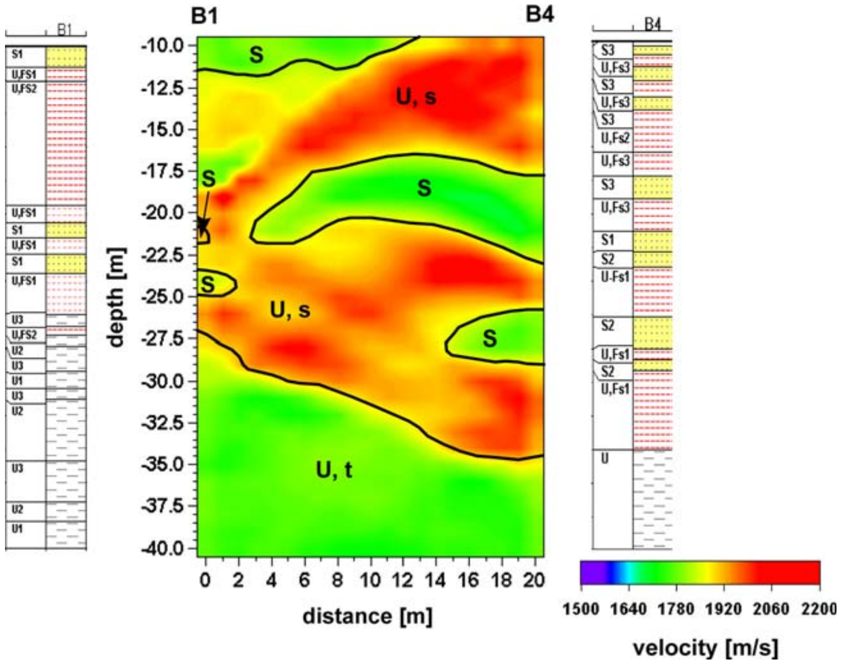
Applying seismic borehole tomography usually results in a display of the P-wave velocity distribution in a plane of the area between two boreholes (i.e., the source and the receiver boreholes). With specially adapted seismic sources and receivers high data quality can be received without damaging the boreholes during data acquisition. To explore the plane between two boreholes in detail the data-acquisition technique and the field layout have to provide the possibility to analyze wave propagation in all directions (every possible wave path and ray angle). Each travel time of a seismic wave which propagates from the source position to the receiver location depends on the propagation velocity of the seismic wave in the material between the boreholes.

Figure 11 shows a result of a seismic tomography between two boreholes (B1 and B4) in an area dominated by sand and clay. To interpret the results additional information of geotechnical and geophysical borehole measurements were used, so that velocity values could be assigned to special soil types. Without the results of seismic tomography the interpretation of the existence and distribution of sand lenses would not have been possible.

4.7 Vertical Seismic Profiling

Additional information for the calibration of seismic surface measurements can be gathered using the vertical seismic profiling (VSP) technique. In VSP experiments, usually source points are located at the Earth's surface,

Fig. 11 Result of seismic tomography showing the distribution of sand lenses between boreholes B1 and B4 after calibration of the velocities based on information from geotechnical and geophysical borehole measurements



generating signals which are recorded in vertical drilling. Source and receive positions can also be exchanged. Using the VSP technique, an identification of seismic reflectors and the corresponding velocity distribution of seismic waves is possible. Thus, VSP measurements are especially applied together with reflection seismic investigations for the calibration of reflecting horizons and their corresponding depths. Furthermore, structures below the borehole bottom can be explored in more detail compared with reflection seismic measurements at the Earth's surface alone. VSP measurements support the results evaluated from all other seismic measurements performed at the Earth's surface so that it is advisable always to use surface seismic methods together with the VSP technique.

4.8 Calculation of Geotechnical Parameters

Propagation velocities of different wave types together with densities are correlated with elastic parameters of underground structures. The correlation is described with the following formula:

$$\begin{aligned}
&\lambda = \rho\left(v_{\mathrm{P}}^2 - 2v_{\mathrm{S}}^2\right)\\
&\mu = \rho v_{\mathrm{S}}^2\\
&K = \rho v_{\mathrm{P}}^2 - \tfrac{4}{3}\mu = \lambda + \tfrac{2}{3}\mu\\
&\sigma = \left(v_{\mathrm{S}}^2 - \tfrac{1}{2}v_{\mathrm{P}}^2\right)\big/\left(v_{\mathrm{S}}^2 - v_{\mathrm{P}}^2\right)\\
&E = 2v_{\mathrm{S}}^2\rho(1+\sigma)
\end{aligned}$$

with

λ	Lamé constant
μ	shear modulus (Lamé constant)
K	compression modulus
σ	Poisson's ratio
E	dynamic elastic modulus
ρ	density
v_{p}	P-wave velocity
v_{s}	S-wave velocity.

From these formulae it can be recognized that seismic velocities are directly influenced by the elastic parameters of the rock mass. Material changes lead to a change of the velocities and thus, vice versa, detected velocity changes are a hint of changing properties in underground structures.

However, to calculate elastic parameters of underground materials it is necessary to determine both P- and S-wave velocities. Since P-waves have the highest propagation velocity, they appear as the first arrivals in seismograms, and therefore their velocity can easily be determined. However, S-waves with lower propagation velocities are more difficult to identify. Therefore, special data-acquisition and processing techniques are needed for the generation and identification of S-waves. Special sources which generate especially S-waves and which prevent P-waves have been developed in past decades. Furthermore, to record S-waves, receivers with three recording components (two horizontal and one vertical component) have to be used. Applying the refraction tomography technique, it is possible to generate velocity models for both P-waves and S-waves. In connection with borehole measurements seismic velocities can be directly correlated to measured densities so that the distribution of the dynamic elastic modulus can be calculated from the formulae above.

5 Case Studies

5.1 Seismic Investigations for a High-Speed Railway Line in the Alps

In a region of a planned high-speed railway line in the Alps, extensive seismic investigations were carried out. Goal of the geophysical investigations was the geological exploration of those areas which may influence the stability of the planned tunnel. High-resolution seismic investigations gave information about the structures in the near-surface underground as well as at greater depths. The focus of the exploration was the detection of possible fault zones in the depth range of the planned tunnel at a level of approximately 400 m above sea level. Since the surface of the exploration area exceeded 1,600 m above sea level the exploration depth for the geophysical surface methods was about 1,200 m. Applying high-resolution seismic methods the geological conditions at the depth of the tunnel were investigated appropriately. With a combination of several seismic methods the geological and tectonic conditions in the underground (see Fig. 5) was obtained. In the interpreted seismic profile, reflection horizons are specified and tracked along the section. Disturbances can clearly be recognized. Applying the CMP and the standard refraction seismic methods the thickness of the surface layer as well as the depth and the gradient of the changes from block debris to crystalline rock were identified. Together with the results of geological mapping and borehole geophysics a general model of near-surface and deep structures was developed successfully.

5.2 Estimation of Rock Properties for a Line Investigation in Austria

During the approval stage of a tunnel project, in connection with the redevelopment of an old tunnel in Austria, geological and geotechnical exploration methods were used in addition to refraction seismics and radar methods, in order to explore the invert, the crown, and the sidewalls of an exploration tunnel. By integrating geological, geotechnical,

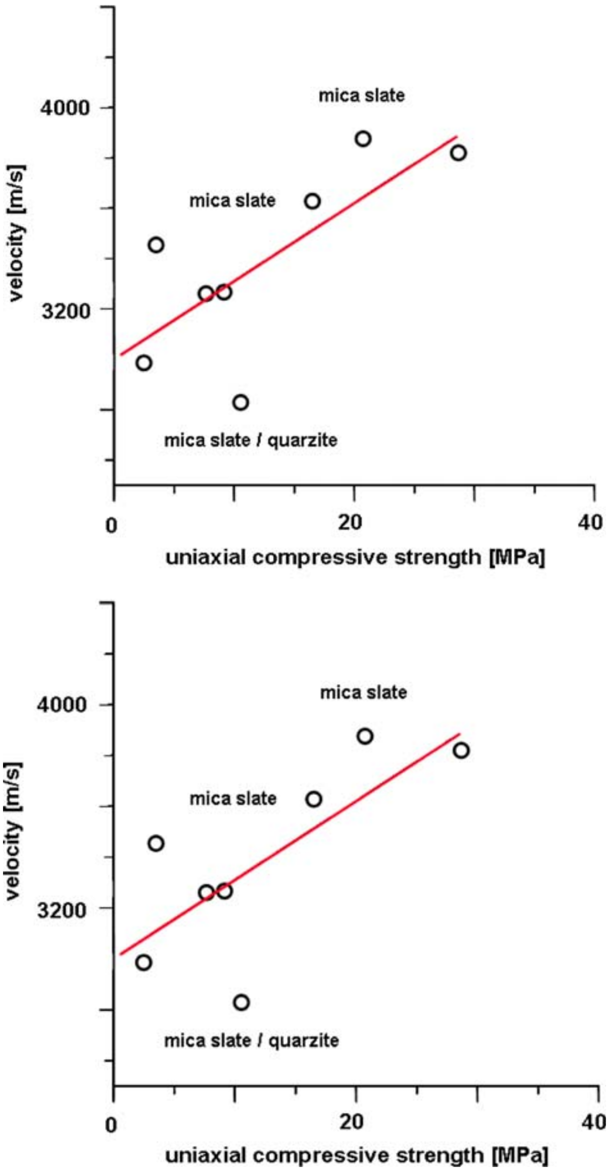


Fig. 12 Comparison between seismic velocities and the uniaxial compressive strength of the mica slate, which was determined by uniaxial laboratory measurements

and geophysical interpretation of all data, the structure and disturbances of regions in the near field of the tunnel were explored. The high-resolution radar method provided a continuous structure profile along the invert, the crown, and the sidewalls and gave an indication of disturbances. By using the high-resolution refraction seismic method the invert of the tunnel could be explored and the seismic velocity of the rock mass below the ballast could be measured. The quality of the rock mass and the degree of disturbance around the tunnel was evaluated by correlating seismic velocities with the surrounding rock properties. The results are shown in Fig. 12.

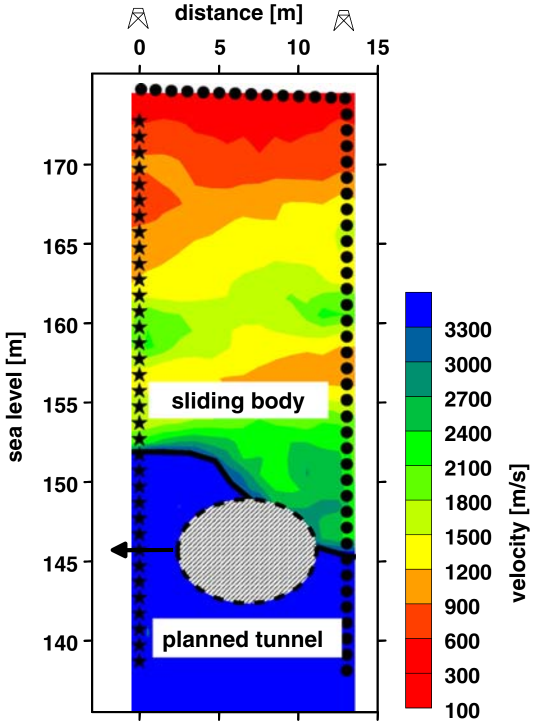


Fig. 13 Result of seismic tomography for a road tunnel to map a slide body

5.3 Line Investigation of a Tunnel Crossing a Landslide

Figure 13 displays the results of seismic tomography for the line investigation of a road tunnel. Two adjacent boreholes were drilled with depths of about 35 m having a distance of 13 m. Locations marked with stars and points in Fig. 13 display the position of sources and receivers in the boreholes. It can be recognized that a Devonian landslide body was precisely detected. The course of the planned railway alignment contacted this unstable area so that, based on the tomography results, the course of the tunnel was moved approximately 30 m into the solid Devonian rock mass in order not to be tangent to the landslide body.

5.4 Line Investigations for a New High-Speed Railway Line in the Southern Part of Germany

For the investigation of the underground along a new high-speed railway line in the southern part of Germany a combination of the three geophysical methods, seismic, geoelectric, and microgravity (joint interpretation) was applied. Seismic and geoelectric methods were used for modeling the lithologic and tectonic structures as well as for calculation of the corresponding depths of detected anomalies, which were filled and unfilled cavities, subsidence, surface disintegrations, karstifications, and deep-ranging

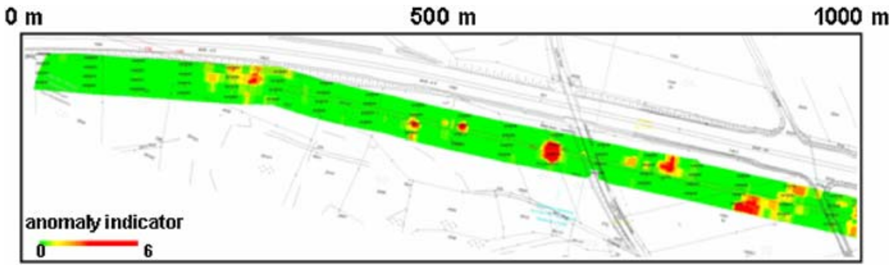


Fig. 14 Map of the anomaly factor calculated by joint interpretation of various geophysical methods in an area of a high-speed railway line

dolines. However, since unfilled cavities due to karstifications were the main problem for the stability of the high-speed railway line the microgravity method was applied to detect those locations where a mass deficit (and thus a cavity) in the underground was to be expected. A seismic velocity reduction at special locations in the underground together with high electric resistivities was an additional hint of the existence of cavities in the underground. Thus, the information of a mass deficit in the underground, low-velocity areas, and high resistivity were collected together (joint interpretation) to calculate the so-called anomaly indication factor (anomaly factor), which took high values at those locations with high likelihood of the occurrence of a relevant cavity. The anomaly factor values were gathered and displayed on a map of the investigated area. Locations with a high anomaly factor (red areas) were opened with drillings and if necessary the cavities were filled with concrete suspension to stabilize the railway line. The result of this procedure is presented in the map of Fig. 14. The results of the geophysical explorations demonstrated the advantages of the joint interpretation technique using the information of all applied methods. A very good correlation between the results of the joint interpretation and the corresponding drillings to fill the detected cavities was recognized. Thus, not a single but a combination of several geophysical methods was the only instrument that could ensure a complete result. The geological characteristics of the underground depend on various parameters. Anomalies appear at those locations where one of these parameter changes. It is impossible to determine all geological parameters by applying only a single method. Using the joint interpretation technique, even more abnormalities can be described and characterized very precisely. With respect to the given karst problem, the combination of three different independent geophysical methods in addition to geotechnical drillings was the optimum procedure to stabilize the underground.

6 Conclusions

Engineering geophysics provides valuable and continuous information for the planning and execution of projects. The application of geophysical methods in addition to usually applied geological and geotechnical exploration is necessary to achieve accurate and continuous models of the subsurface in a short time schedule. To achieve optimum benefit from geophysical investigations it is necessary to apply these methods:

- After intensive discussions between geologists engineers and geophysicist
- At an early stage of the project.

Thus, engineering geophysical methods will become an important part of planning and execution of an engineering project, with safety planning being essentially increased and risk being minimized by means of successful and interdisciplinary cooperation.

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