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An automatic method for data processing of seismic data in tunneling

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ABSTRACT

We present a new method for the prediction of the discontinuities and lithological variations ahead of the tunnel face. The automatic procedure is applied to data collected by seismic reflection surveys, with the sources and sensors located along the tunnel. The method allows: i) to estimate an average value of the wave velocity; ii) to detect the discontinuities for each source point; and iii) to analyze and plot the number of superposing estimates for each node of the domain. The final result can be interpreted as the probability to detect a discontinuity at a certain distance from the tunnel face. The method automatically estimates the peaks in the seismograms that can be related to a reflection. On the base of this process, the method only requires the source–receiver geometry and the data acquisition parameters. The procedure has been tested on synthetic and real data coming from a seismic survey on a tunnel under construction. The results indicate that the method runs very fast and it is reliable in the identification of lithological changes and discontinuities, up to more than 100 m ahead of the tunnel face.

1. Introduction

The prediction of the geological risk during tunnel construction is still a challenge: detection of faults and other geological features affecting the work in front of the tunnel is highly desirable for safety and engineering reasons.

In the last decades, different methods have been proposed in order to solve this problem (e.g. Kneib and Leykam, 2004; Kneib et al., 2000; Sattel et al., 1992). Most of them are based on seismic investigations of the rock ahead of the tunnel face; substantial differences among the methods consist to perform the geophysical survey in tunneling with TBM or with conventional drilling and blasting technique. Chang and Yu (2005) discuss some methods for geological explorations in tunnel when using a TBM (Tunnel Boring Machine). In particular, the simplest technique is the pilot hole drilling, which is able to advance for 30 m in 2 h, but it is not always representative of the effective rock characteristics and, moreover, it cab be complex to interpret the drilling performance, in order to define a geological model. The LDHD (Long Distance Horizontal Drilling) permits instead a direct inspection of the rock cores, needing however a long break of the tunneling activity. Horizontal sonic logs in small diameter boreholes, drilled ahead the tunnel front, are a good compromise between the need to reduce the time of no activity and reliability in detection faults and discontinuities (Godio and Dall'Ara, 2012).

A different approach is given by the geophysical methods, mainly based on the reflection seismic. Differently from the survey in open field, the prediction of lithological changes or rock discontinuities in a tunnel is a critical problem, mainly because the sensors and the sources cannot have a large spatial coverage. Therefore, ad hoc techniques must be developed.

The most common approach is based on the concept of ellipsoids (Ashida, 2001; Ashida and Koichi, 1993), where the two foci coincident are with a source–receiver pair; this concept permits the detection of the main reflectors, which are defined as the tangent planes to all the ellipsoids.

Some methods are based on the tomographic approach; this aims to image the rock volume around the tunnel using seismic attribute, like the wave velocity or the reflectivity (Tzavaras et al., 2012; Yamamoto et al., 2006). Basically, in the travel time tomography, the space domain is meshed in pixels (2D model) or voxels (3D model) according to the expected resolution, a velocity model is assumed, the ray-paths between the sources and the receiver are calculated. The inversion problem is usually solved by iterative algorithms, where the whole space domain is evaluated, trying to minimize an objective function of the synthetic and experimental travel times. The maximum reliable imaging distance is dependent on the attenuation of the rocks encountered (hard rock corresponds to low attenuation) and also on the S/N.

One of the most diffused techniques is the TSP (tunnel seismic prediction), strictly derived by Vertical Seismic Profiling. The data processing method is an advanced migration imaging technique making full use of both kinetic and dynamic characteristics of seismic waves, that is, both travel time and amplitude (Baldi et al., 2006).

More recently, Tzavaras et al. (2008, 2012) processed the data acquired in the Gotthard base tunnel by using the 3D versions of the KPSDM (Kirchhoff Pre-Stack Depth Migration), the FVM (Fresnel Volume Migration) and the RIS (Reflection Image Spectroscopy).

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The Tunnel Seismic Tomography (TST) is a tunnel seismic prediction technology developed by the Chinese Academy of Sciences (Yonggui et al., 2006). Data processing integrates seismic migration imaging, velocity scanning structural grain analysis and travel time inversion imaging. The seismic migration imaging obtains the positions of the reflection planes in front of the tunnel face, the reflection strength and the velocity distribution.

Another approach is the Three-dimensional Reflection Tomography (TRT), which uses advanced algorithms for rapidly imaging subsurface cavities and structures that exhibit significant changes in velocity or attenuation, based on the reflected waves. The excitation is produced by sledgehammer strokes or by a magneto-strictive source driven by a swept frequency signal (Yamamoto et al., 2006).

Contrarily to TRT, the True Reflection Underground Seismic Technique (TRUST) uses explosives detonated from small boreholes in the tunnel face or side wall (Benecke et al., 2008). The sensors are placed in "listening boreholes" drilled into the rock at about every 50 m.

Other techniques have been developed when TBM is adopted as seismic source. Swinnen et al. (2007) propose a technique for the seismic imaging from a TBM by using a method based on short focussing operators optimized in a least-square sense.

The TSWD (Tunnel Seismic While Drilling) makes use of the vibrations produced by the cutting head of the TBM as seismic source (Bruckl et al., 2008; Petronio and Poletto, 2002; Petronio et al., 2007). The process includes the noise separation in remote seismic data and the cross-correlation between the reference signal at the source and the data acquired by sensors. The main advantages with respect to the previous methods are the acquisition of real-time information about the rock characteristics ahead of the TBM, without stopping it during the excavation.

Our approach is a fully automatic method based on an automatic detection of the reflection events, once analyzed all the signals recorded by an array of sensors. The space domain in front of the tunnel is subdivided in many pixels; the procedure is able to find the nodes of the domain that can be considered as reflection points; finally, by taking into account the information derived from all the sources, a map of probability to detect a change of acoustic impedance is represented. At this stage the velocity model is based on a simple regression analysis of the travel-times of the direct waves and refracted waves in the close to the tunnel wall.

At first, an idea of the geometrical representation of the problem under study is given, with a particular attention to the concept of ellipsoids.

In order to check the method efficiency, we discuss the results on a 2D synthetic model, generated using a commercial software. Successively, a seismic investigation conducted in a tunnel under construction is analyzed to point out the performance of the methodology, even in terms of computational effort.

The method has been tested in tunneling using simple source, such as hammer strokes, but further implementations are still in progress in order to develop new strategies for extending the application in tunneling using TBM.

2. The conceptual model

2.1. General idea

A seismic investigation in a tunnel has substantial differences with respect to the classical surveys based on the seismic reflection, because the zone in which the sensors are located is very limited, usually close to the tunnel face. Indeed, they are placed on tunnel walls, in order to detect the waves generated at the source point and reflected back by the discontinuities; reflections occur in regions characterized by a contrast of impedance with respect to the embedded material. A typical configuration of sources/receivers is shown in Fig. 1.

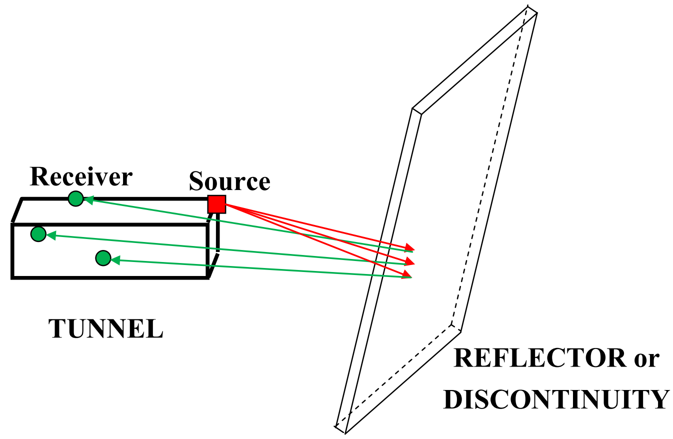

Fig. 1. Typical survey in a tunnel: the reflection of the seismic waves generated by the source (red square) is generated by the discontinuity; the reflected waves are recorded by the sensors placed on the tunnel walls (green circles).

Let us simply consider the ray-tracing theory: since the receivers can be distributed elsewhere on the tunnel walls, the reflections from a single source point do not result in a single point but in a determined region called reflection zone.

In Fig. 2, the representation of a 3D investigation is depicted. The slope of discontinuity, with respect to the vertical and horizontal axes, is characterized by the angles α and γ respectively.

The wave generated in the source S is back-scattered by the discontinuity in the point P, the angle ϑ depends both on the discontinuity slope and relative positions between P and S. The reflected wave reaches the tunnel at the sensor placed in the point R.

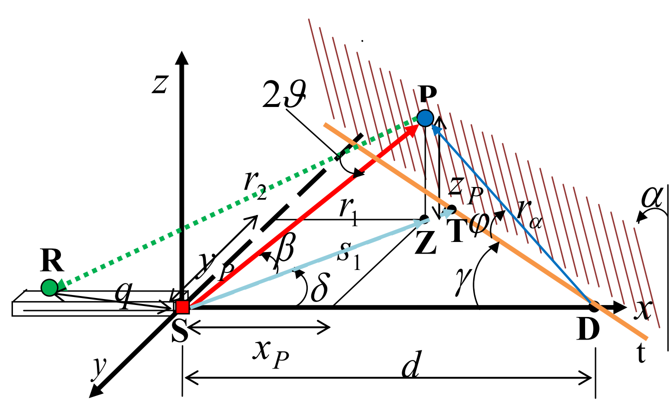

Fig. 2. Geometric illustration of the problem in three dimensions. The discontinuity plane is indicated with thin brown lines. The red continuous line represents the direct wave, while the green dotted line represents the reflected wave. The most important parameters introduced in the figure are:

- S: source point
- P: reflection point, indicated by the coordinates x_P, y_P and z_P
- R: position of the sensor considered
- α: inclination of the discontinuity respect to the axis z
- γ: inclination of the discontinuity respect to the axis x
- r_1: path of the direct wave generated in S
- r_2: path of the wave reflected in P
- D: point in which the tunnel will cross the discontinuity
- d: distance between the tunnel face and the discontinuity
- ϑ: wave incident angle (equal to the reflection angle)
- q: distance between the sensor and the source point.