Seismic prediction ahead of tunnel constructions using tunnel surface-waves

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Abstract

To increase safety and efficiency of tunnel constructions, online seismic exploration ahead of a tunnel can become a valuable tool. We developed a new forward looking seismic imaging technique to e.g. determine weak and water bearing zones ahead of the constructions. Our approach is based on the excitation and registration of tunnel surface-waves (TS-waves). These waves are excited at the tunnel face behind the cutter head of a tunnel boring machine and travel into drilling direction. Arriving at the front face they generate body-waves (mainly S-waves = ”RS”-waves) propagating further ahead. Reflected S-waves are back-converted into tunnel surface-waves (”RSSR”-waves) and can be recorded by geophones mounted on the tunnel wall. Using 3D Finite Difference modeling, an analytical solution of the wave equation in cylindrical coordinates and field data acquired at the Gotthard massive (Switzerland) we investigated the propagation characteristics of tunnel surface waves in terms of dispersion and polarization. Understanding the excitation and propagation of TS-waves is the key for developing processing and imaging techniques for our seismic look ahead prediction in tunnel constructions.

Introduction and RSSR method description

With the increasing number and complexity of tunnel constructions, exploration of the geology ahead of the tunnel face during the tunnel construction progress is becoming more important. By the help of the gathered exploration data, measures to stabilize weak zones or water invasion can be taken early. Common seismic exploration use body waves to image geological structures ahead of the tunnel. These methods face technical difficulties to place source and receiver at the working front. Avoiding this by exciting body waves behind the tunnel boring machine (TBM) suffers from low wave energy which propagates in the favored direction ahead of the tunnel. Our approach uses tunnel surface-waves (Rayleigh-waves) rather than body-waves which are excited behind the TBM. Thus they do not interfere with the tunnel construction. Since these tunnel surface-waves travel parallel to the tunnel axis and convert mainly to S-waves (RS-waves) when reaching the tunnel front, much of the excited wave energy propagates ahead of the tunnel. S-waves beeing reflected at heterogeneities (RSS-waves) and back converted to tunnel surface-waves (RSSR-waves) can be used to image the geological structure ahead of the tunnel [1]. A principal sketch of the RSSR wavepath is displayed in Figure 1.

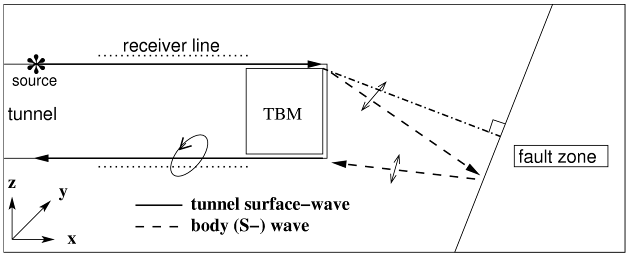

Figure 1 : Wavepath of a surface-wave- to S-wave conversion at the tunnel front (taken from [1]).

In more detail, snapshots of the P- and S-wave field gained by 3D-Finite Difference modeling illustrate the RSSR-wave propagation (Figure 2, T = 1 ms – 30 ms) : a seismic source (e.g. seismic hammer or vibrator) excite body-waves and surface-waves (T = 1 ms). By definition of waves traveling at plane air-rock interfaces, they are called Rayleigh-waves. While the body-waves spread out into the formation, Rayleigh-waves propagate parallel to tunnel axis (T = 7 ms). When reaching the edges of the tunnel front (T = 12 ms), the Rayleigh-waves generate body-waves (mainly S-waves). Thus, the tunnel face can be regarded as a new source exciting waves in favored directions. At geological structures (weak zones, heterogeneities,...) the converted S-waves are reflected (T = 20 ms) and back converted to Rayleigh-waves when arriving the tunnel (T = 30 ms). After dispersion correction and stacking the recorded RSSR arrivals, we can calculate the distance between tunnel front and reflector. Nevertheless, one single RSSR measurement can not provide any information about the spatial orientation of the structure. This can be given by continuous measurements, while the tunnel construction progresses.

Started as a modeling study, the RSSR method has been successfully proved its practicability in various field data sets [2]. As a result the current research focuses on parameter optimization and development of imaging methods to both making the the RSSR method more robust during the field work and improving the data interpretation.

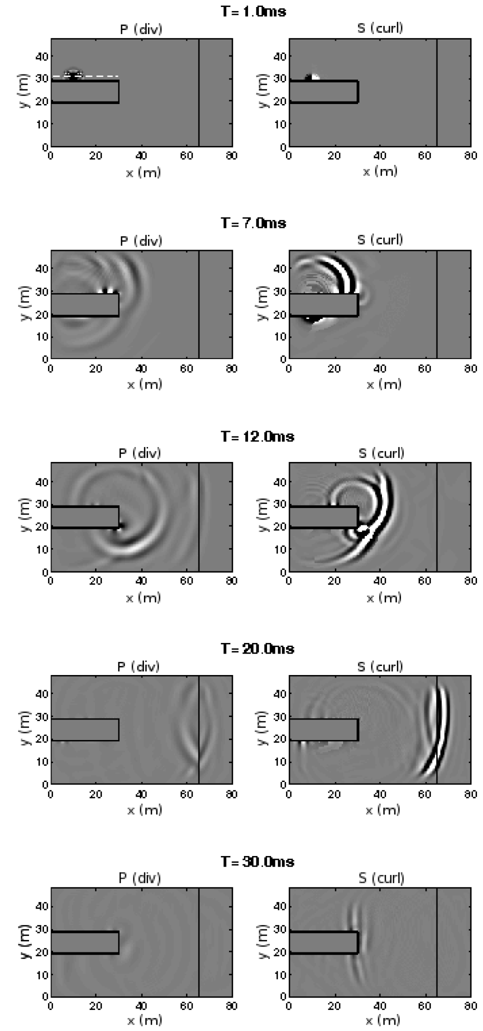

Figure 2 : 3D-Finite Difference simulation of RSSR-waves. The wave field was divided into P- and S-wave component and is displayed for different propagation times (taken from [1]).

ANALYTICAL SOLUTION

As described, crucial element of our method is the excitation of pure Rayleigh-waves. However the tunnel surface is curved and so we examined whether the definition of surface-wave at plane interface is working in our case, too. Based on Stilke, 1959 [3], the excitation and propagation of surface-waves by means of phase velocity and oscillation vector around a tube within a homogeneous space for cylindrical coordinates was investigated. An important criterion is the tube-diameter to surface-wave wavelength ratio w. At low w < 0.6, tunnel surface-wave velocity is significant lower than S-wave velocity and the surface-waves have large amplitude. Both are typical for Rayleigh-waves. With increasing w > 1.2, the surface-wave velocity is approaching the S-wave velocity of the host rock and the amplitude is converging to zero. Therefore, for w>1.2 the excited wavefield can be regarded as S-waves rather than typical Rayleigh-waves. In between 0.6<w<1.2 a transition between surface- and S-wave can be observed.

Field observations and FD modeling

To validate the relevance of the analytic solution, we investigated field data acquired by the GFZ Potsdam (Germany) at the Piora Adit close to the Gotthard Base Tunnel (Switzerland) [2] (Figure 3). By bandpass filtering (0-400 Hz and 400-800 Hz) the frequency spectrum was divided (Figure 3 c) and two data sets were created, which can be treated as two single measurements with each a different center source frequency. The tunnel surface-wave in the low frequency range filtered section (w ≈ 3.1) shows S-wave velocity and almost linear polarization normal to the tunnel wall (Figure 4 a and Figure 5 a). The properties are comparable to an S-wave. Increasing the bandpass frequency range (w ≈ 1.0) leads to slower propagation velocity and a more elliptical particle motion (Figure 4 c and Figure 5 c), typical for a Rayleigh-wave. The dependency of propagation velocity with respect to the center frequency of the measured data could be explained by dispersion effects, too. Therefore, common receiver gather with non-dispersive tunnel surface-waves were produced by 3D-FD modeling using a homogeneous full space and similar geometry. Bandpassfiltering in the same ranges shows comparable behavior of velocities and hodograms with increasing w. Thus they correspond very well to the Piora field data (Figure 4 b/d and Figure 5 b/d).

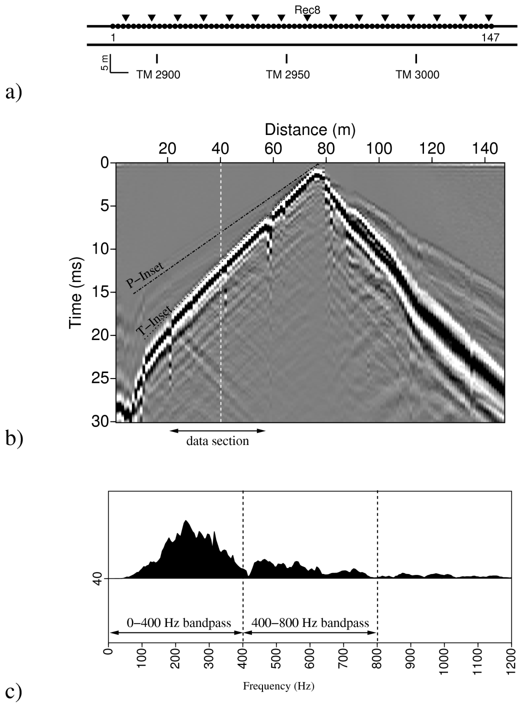

Figure 3 : a) Source and receiver geometry of the seismic survey in the Piora Adit. b) Common receiver gather of receiver 8. c) Frequency spectrum of trace 40.

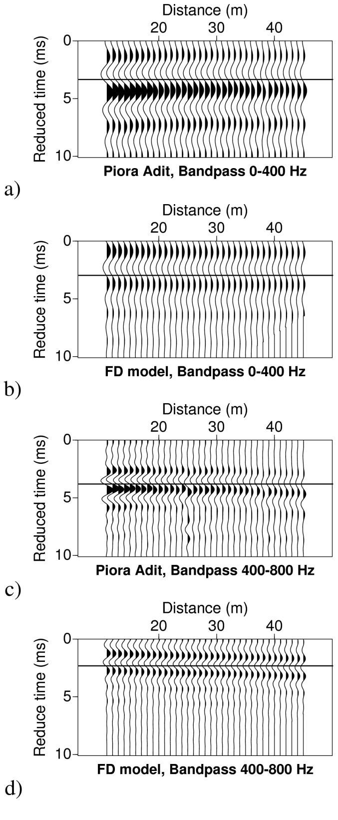

Figure 4 : Velocity reduced common receiver gather of a section of a) Piora data, bandpass filtered 0-400 Hz, b) FD modeled data, bandpass filtered 0-400 Hz, c) Piora data bandpass; a reduction velocity of 3100 m/s (S-wave velocity) was applied to all seismogram sections

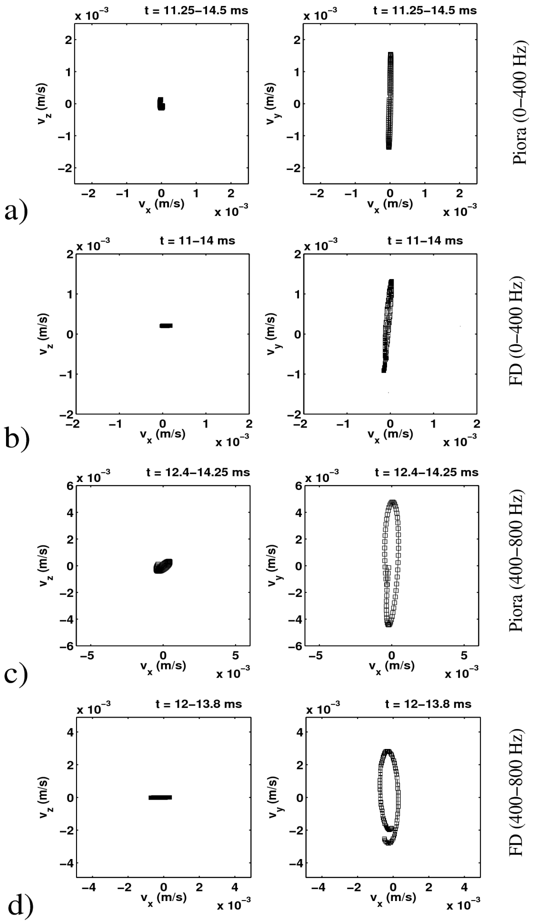

Figure 5: Hodograms extracted for different time intervals along the Trace 40 of the Piora field data. Particle velocity of tunnel surface-wave is shown in the x-y-plane and x-z-plane : a) bandpass filtered 0-400 Hz (Piora), b) bandpass filtered 0-400 Hz (FD model), c) bandpass filtered 400-800 Hz (Piora) and d) bandpass filtered 400-800 Hz (FD model).

Conclusions

We used both analytic solutions and numerical studies to describe the excitation of tunnel surface-waves with respect to the tube diameter to surface-wave wavelength ratio w. For a small w < 0.6 the tunnel surface-waves show propagation characteristics (velocity and particle motion) of Rayleigh-waves, whereas for large w > 1.2 they behave like S-waves. Advantage of pure Rayleigh-wave excitation are a better signal to noise ratio of RSSR-waves and the possibility of guiding the converted RS-waves in specific directions at the tunnel face (beamforming).

References

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[2] Lüth, et al., 2007, Seismic investigations of the Piora Basin using S-wave conversion at the tunnel face of the Piora adit (Gotthard Base Tunnel), International Journal of Rock Mechanics and Mining Science, doi.10.1016/j.ijrmms.2007.03.003.

[3] Stilke, 1959, Ueber seismische Oberflaechenwellen an einem Hohlzylinder im Vollraum (On seismic surface-waves along a tube in full space), Ph.D. thesis, TU Clausthal (in german language).