Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)
 ISBN 978-1-138-38865-9

Contribution of continuous geophysical measurements to the success of tunnelling

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ABSTRACT: Today, many geophysical methods are available, which support the exploration of a tunnel route before tunnelling commences. Some have also been used during tunnelling for many years. Among them, seismic methods account for the largest share in both the number of tunnel applications worldwide and the success rate of contributing to geological exploration.

Since deep and long tunnels harbour considerable geological uncertainties, continuous measurements are increasingly becoming urgent to obtain a complete forecast. It is precisely these tunnels that are being driven by more powerful TBMs, which require a smooth and fast course of all measurements on the job site. Moreover, flexible operation and analysis of results is required. Modern systems are mastering these requirements more and more. Case studies are presented in which operational as well as data-analytic aspects are compared and discussed. Likewise, new trends in the interaction between tunnelling and geophysics will be presented.

1 INTRODUCTION

Site investigations ahead of the tunnel face by means of geophysical methods are increasingly becoming an essential part of the risk management process for the last 20 years. The tunnelling industry has already identified the potential of these usually non-destructive methods that valuably contributes to the assessment of the ground conditions and to the provision of an interpretative reporting.

Among available methods being used nowadays, two groups can be identified: alternative geophysical techniques emerging in the tunnelling sector, mostly electromagnetic techniques, and techniques already mature for the sector and successfully used in many working sites. Seismic methods have established as the frontrunner offering a wide range of data acquisition techniques, data processing types and result visualization tools. Tunnel seismic has undergo a recurrent development accompanying the tunnel industry for several years and adapting to its demanding requirement. With the advent of the industry 4.0, new horizons are being opened, hence more effective data collection, higher amount and faster data transfer, and fancy data analysis technique are expected. Therefore, existing modern seismic technologies should cope with newer requirements as well as with new trends in the tunnelling industry. For instance, in operational terms, the use of TBMs for long and deep tunnels is more and more preferred. In terms of data analysis, a reasonable question would be how we can get more useful information from all data that are being collected. These situations pose new challenges to tunnel seismic.

Continuous seismic measurements look for optimising both data acquisition process as part of the operative work flow while tunnelling and the rapidness in providing reliable geological predictions for the next tens of meters ahead of the face. In the case of TBM drivage an additional issue is related to the type of seismic source being used. Due to technical and operative constrains, the use of explosive might be restricted. In that case, impact sources surge as an alternative to be considered. Beside this operational aspect, continuous measurements allow for gradual detection of relevant geological target coming ahead. Such targets however, may not always lay directly in front of the drivage but they may run sub-parallel to the tunnel excavation. If seismic data from continuous measurement is available, it should be possible to process and evaluate this data in a special fashion to prospect not only targets ahead but laterally located around the tunnel excavation.

2 OVERVIEW OF SEISMIC METHODS

This paper focuses on seismic methods, because seismic reflection imaging is the most effective prediction method due to its large prediction range, high resolution and ease of application on a tunnel construction site. When using the information of the full seismic wave field propagating through the ground, seismic properties such as seismic velocities and their derived elastic parameters such as Poisson's ratio or stiffness present valuable information to characterise the ground.

There are nowadays several seismic methods being applied during mechanised tunnelling. The operation of the Integrated Seismic Prediction (ISP) methods is possible during normal TBM operation; meaning measurement preparation occurs while the TBM advances and measurement itself is done during ring-building and stand-by times avoiding long TBM downtimes. Here, an impact source generates both body and surface waves, whereas the surface waves is being converted at the tunnel face to an S-wave propagating towards discontinuities in the ground and being reflected (Borm et. al. 2003).

The TSWD-method has been developed for seismic exploration ahead of the tunnel face during TBM tunnelling where the cutting process of the TBM itself is used as the source of seismic waves ensuring a continuous seismic monitoring without hindering the drilling and driving operations (Petronio et al. 2003).

A meaningful alternative is Tunnel Seismic Prediction (TSP) - a rapid, non-destructive and highly sophisticated measuring method and system especially designed for underground construction works. The TSP method was firstly introduced to the underground construction market in 1994. With the use of the latest technology of the TSP 303 system, true 3-D data processing tools and presenting parameters of rock characterisation ahead of the face in three dimensions is available.

2.1 *Continuous seismic methods*

Continuous seismic methods can be an effective component of many site characterisation investigations. One of the primary benefits of continuous seismic measurements is to increase spatial sampling density so that background and anomalous conditions can be identified early in the investigation. As with all geophysical methods, seismic methods are limited in depth penetration, i.e. the range of the target depth. As the target becomes deeper meaning further away, the resolution of geophysical measurements decreases. Due to larger volume sampling or wave signal attenuation, the contrast between the target and surrounding materials needs to be even greater. At some point, a discrete localised target, such as a cavity, may be more difficult or impossible to detect at distances greater than 100 meters ahead of the face. (Fig. 1). However, as the excavation advances, the target gets closer and a better resolution or imaging will be possible by continuous measurements.

Recently, a new concept for continuous seismic exploration while excavation has been introduced, Tunnel Seismic Prediction while Excavation, TSPwE® (Dickmann et al. 2018). By deploying three pairs of receivers along each tunnel wall and blasting a minimum number of shots for a given face position (Fig. 2), 3-D images are generated and updated every 10 to 15 meters, depending on the advance rate. This methodology brings some advantages when prospecting geological features as the cavity example mentioned above. In this case, detection shortcomings due to the distance of the target at early stages, such as wave signal attenuation, penetration depth and lateral resolution are counteracted by continuously calibrating the 3-D results while getting closer to the target. Moreover, since the largest reflection signals are based on the cavity (largest contrast), higher accuracy should be expected during automatic data processing.

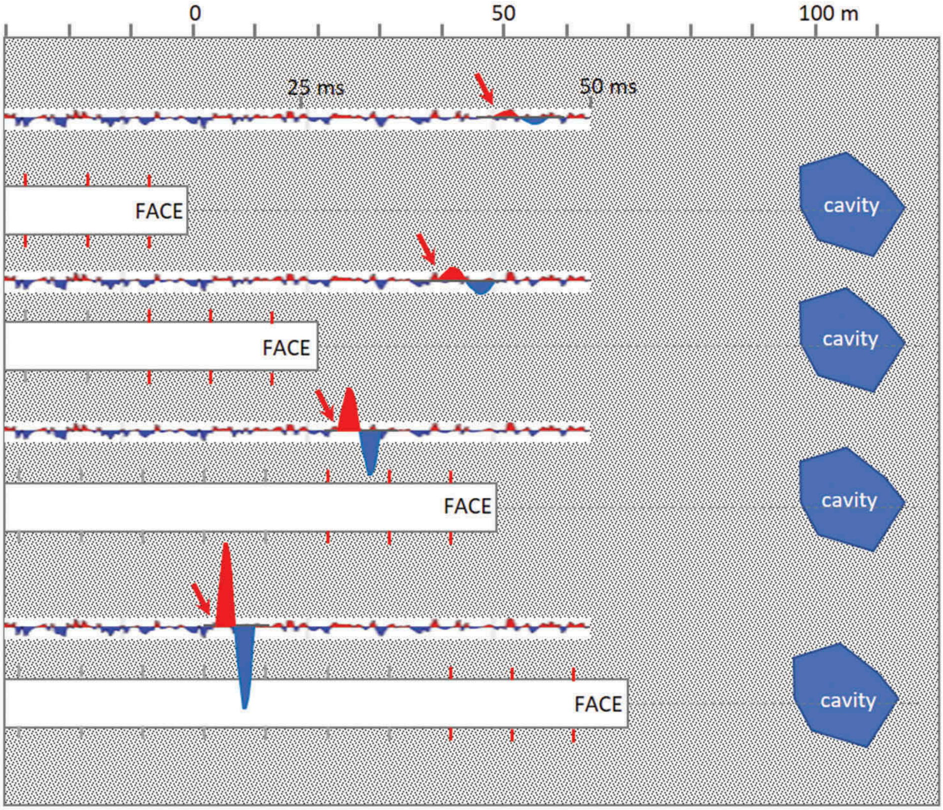

Figure 1. Tunneling at four different stations while heading towards a cavity. At the upper station, the cavity is about 100 m ahead of the face and the seismic signal reading of the reflection at the cavity is hardly recognizable (refer to red arrow at approx. 40 ms). When approaching the cavity while measuring seismic reflection signals from source points behind the tunnel wall, the signal becomes stronger and significant.

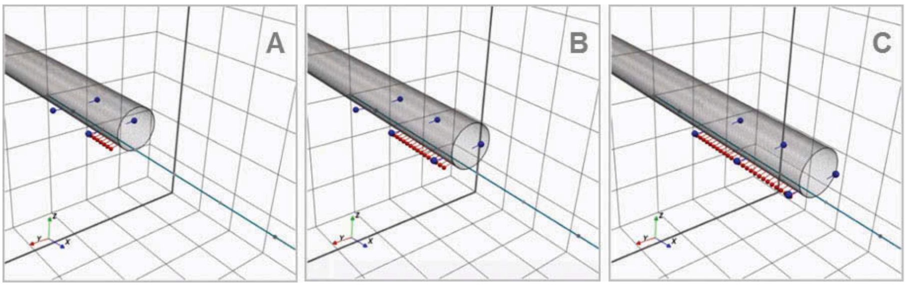

Figure 2. Concept of TSPwE®: tunnel seismic prediction commences after deployment of four receivers (blue dots) (A). Shooting in small boreholes along the side wall happens along with heading. (red dots in A, B and C). After about 10 to 15 meters a third receiver pair is deployed (B). After 20 shots along the side wall, the rear receivers are being deployed as front receivers (C).

2.1.1 *Addressing operational aspects using continuous seismic*

Continuous seismic measurements can be done in both conventional and mechanised tunnelling. In conventional headings, explosives are being commonly used as the seismic source. In mechanised tunnelling however, the use of explosive as a seismic source poses an important restriction since it is not necessarily available at site or not available at all. Additionally, due to licensing restrictions and safety regulations, the use of explosive or selection of conventional tunnelling as the excavation method is slowly decreasing in some countries, as for instance in China. Under this scenario, the use of TBM is expected to increase in the upcoming years.

To cope with this scenario, the use of an alternative impact source together with continuous measurements is foreseen. A sledge hammer, an electronically controlled mechanical hammer or actuator can then be employed as the impact source. Similar as explosive sources, impact sources also generate body waves that travel through the rock mass and are reflected at discontinuities. The signal transferred to the medium by this type of source presents different characteristics with regards to signal amplitude and frequency range and compared to those generated by explosives. In addition, the total energy transferred into the rock mass is much lower. Consequently, the penetration depth and the achievable seismic resolution for detecting a given target must be evaluated.

Figure 3 shows the TSP layout and comparison of 3-D distribution of the P-wave velocity for single measurements performed in a test tunnel. TSP data was acquired using a mechanical hammer at 18 "shot" positions (Fig. 3a). In total, 103 blows were performed (5 to 6 blows) per shot position. Hammer data was stacked at each position to increase the Signal-to-Noise

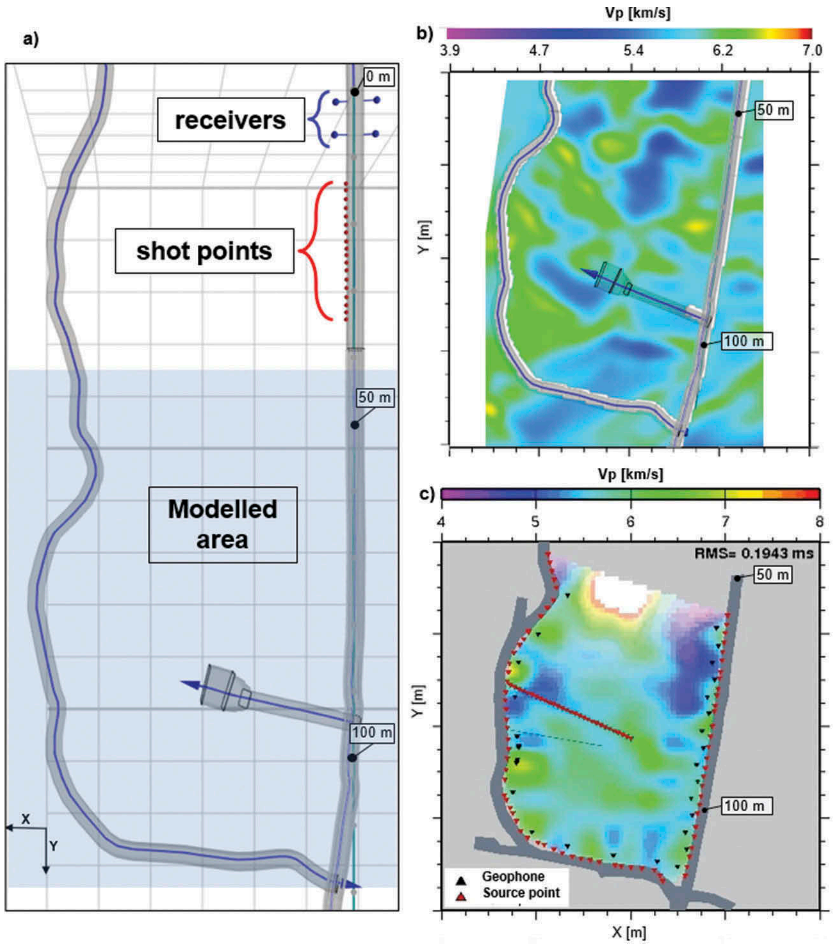

Figure 3. a) Position of receivers and shot points of the TSP layout and modelled area in blue. b) 3-D P-wave velocity distribution obtained from the TSP data on modelled area in plane-view. c) 2-D P-wave distribution obtained from seismic tomography (modified from Richter, H. 2010).

Ratio (SNR). Stacked data was then processed by the standard processing workflow of the TSP software. The control data correspond to seismic tomography acquired along three surrounding galleries as shown in Figure 3c. In this case, seismic tomography is set as the benchmark since resolution achievable by this method is expected to be higher. It must be point out that the 2-D tomography results used for the comparison already existed from former surveys. TSP data was processed independently, i.e. with own input parameters for seismic data processing and modelling.

Figures 3b and 3c depict the P-wave velocity distribution for the TSP results and seismic tomography, respectively, throughout the modelled area as indicated by the blue square in Figure 3a. The area starts approximately 10 meters ahead of the last shot point of the TSP layout and extends about 80 meters in the longitudinal direction (Y). In the lateral direction (X), the model spans about 25 meters from the tunnel axis where the seismic measurement was done. In general, the results are in satisfactory agreement, the prevailing modelled P-wave velocity estimated by both techniques varies around 6 km/s (green). Although some differences are present, important features or velocity anomalies are evident in both results. For instance, the high velocity zones at the top/centre and surrounding the left tube in the tomography are also noticeable in the TSP results. Similarly, the largest low velocity zone (blue) at the top, surrounding the right tube, are also reproduced by the TSP results although slightly shifted to the left. Towards the bottom gallery, results differ slightly more. A relevant aspect is the magnitude of the contrast in each result. In the seismic tomography results, the velocity contrast between the rock prevailing velocity and the anomalies is apparently higher. In turn, although the spatial distribution of the anomalies indicated by the TSP results match the tomography, the contrast is somehow lower particularly for the high velocity zones. This might be due to different input parameters in data processing of each methodology as for instance the initial value assigned to the average P-wave velocity for each model, 5.4 km/s and 5.7 km/s for the tomography and the TSP, respectively. Influence of other input parameters can also not be disregarded.

This benchmark attempt indicates that the TSP results coming from data acquired using hammer blows is reliable for the first tens of meters ahead of the seismic layout, in this example up to around 80 m. Considering this, the use of mechanical hammer for continuous measurements is feasible. As mentioned above, the TSPwE concept implies updating 3-D results in short spatial intervals, every 10 to 15 meters ahead of the face which will lay within a reasonable range for this type of source. Moreover, since the data density will increase by using up to 6 receivers and optionally by using two shot lines, the accuracy and reliability of models coming from data acquired using impact sources should considerably improve.

2.1.2 *Extending data analytics in continuous seismic*

One advantage of using continuous seismic relies on the gradual detection of targets as the tunnelling progress approaches to it. Certainly, it is preferable to obtain early indicators of the presence of unfavourable structures to further explore them and the risks associated to them. In many cases, unfavourable structures are not ahead and vertically oriented but rather they run parallel or subparallel to the tunnel, i.e. horizontally layered. In the worst scenario, this feature will intersect the tunnel at some future stationing resulting in possible hazardous situations, e.g. water ingress, collapses from the crown, etc.

Seismic data acquired within a tunnel contain useful information coming from a 3-D space around the tunnel. Depending on the type of data analysis, structures ahead of the tunnel face or surrounding the tunnel can be modelled. Such data analysis can be referred to as processing to tunnel side or side processing. Side processing of TSP data coming from standard acquisition procedure, i.e. sporadic or periodic measurements, present limitations related to the lateral resolution due to the length of the seismic layout. Hence, only a limited portion of the potential layer (reflector) will be detected compared to the actual length of the geological feature extending horizontally. By using continues measurements such limitation can be partially overcome because each portion of the target feature are continuously imaged (Fig. 4).

The surface above a given tunnel with low overburden, e.g. with subsea tunnels, gives an ideal situation for validating the applicability of side processing to TSP data acquired using

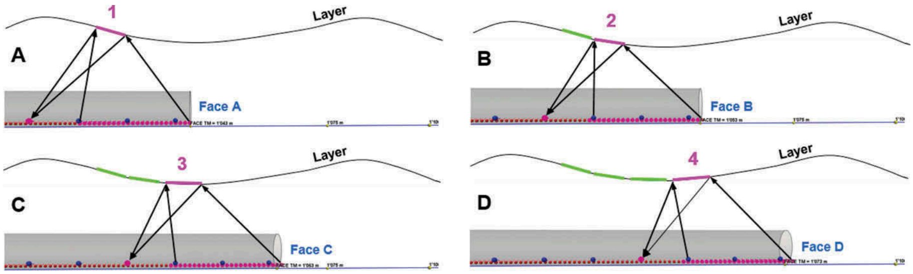

Figure 4. Schematic representation of side processing of data acquired using the TSPwE concept. The capital letters A, B, C and D indicate various tunneling stages with their respective face positions (advance from left to right). The red and green segments lying on the layer represents the modelled segment by current and previous side investigations, respectively. As the continuous data acquisition advances, the layer is continuously modelled.

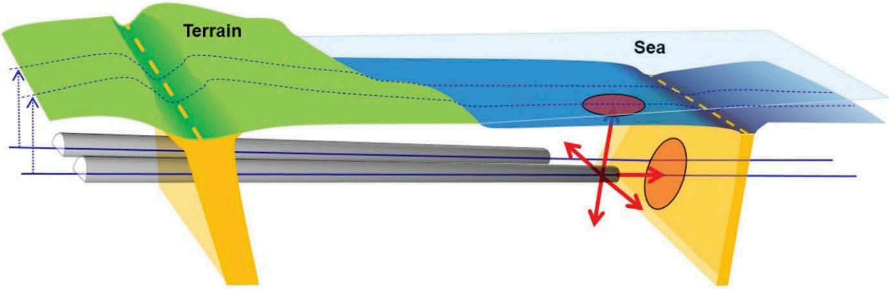

Figure 5. Schematic representation of subsea tunnels showing the terrain and sea surface as well as the seabed. Surface delineation (blue dotted lines) as well as detecting other structures (red arrows with imaging planes) are of interest for the project.

the continuous approach. Figure 5 schematically shows such a situation in a subsea tunnel. The surface may also be deemed as a formation change, a discontinuity, or any other significant geological structure presenting sufficient rock physical property contrast. As depicted in this picture, the surface above the two tubes will be imaged by seismic measurements done within the tunnels.

Figure 6 shows the longitudinal view of the 3-D migrated sections from two single TSP measurements done in parallel tubes for such a scenario upon the geological forecast. Although the measurements were carried out in different tubes and not strictly following the TSPwE concept, it resembles very well the significance of continuous measurements. For the sake of simplicity both results are projected into the same plane located at the middle of the tunnel axes.

A migrated section represents the real spatial position or distribution of reflective rock zones along the section, hence the intensity of the colouring (red or blue) indicate zones of high reflectivity or in other words areas with significant rock condition changes. White colouring denotes no reflectivity. In section Face A (left), two major features are identified, the most significant corresponds to a strong reflectivity zone smearing vertically up to the surface. This zone matches very well the weakness zone inferred in the geological forecast (dotted red line behind the section). Towards the surface, the reflection zones tend to bend following the contact between the hard rock and the deposit material. In this example, the proximity and magnitude of the weakness zone strongly dominates the migrated section. In turn, section Face B shows the highest reflectivity directly around a section of the tunnel, possibly due to the presence of a significant Excavation Damaged Zone (EDZ), and at a small portion nearby the

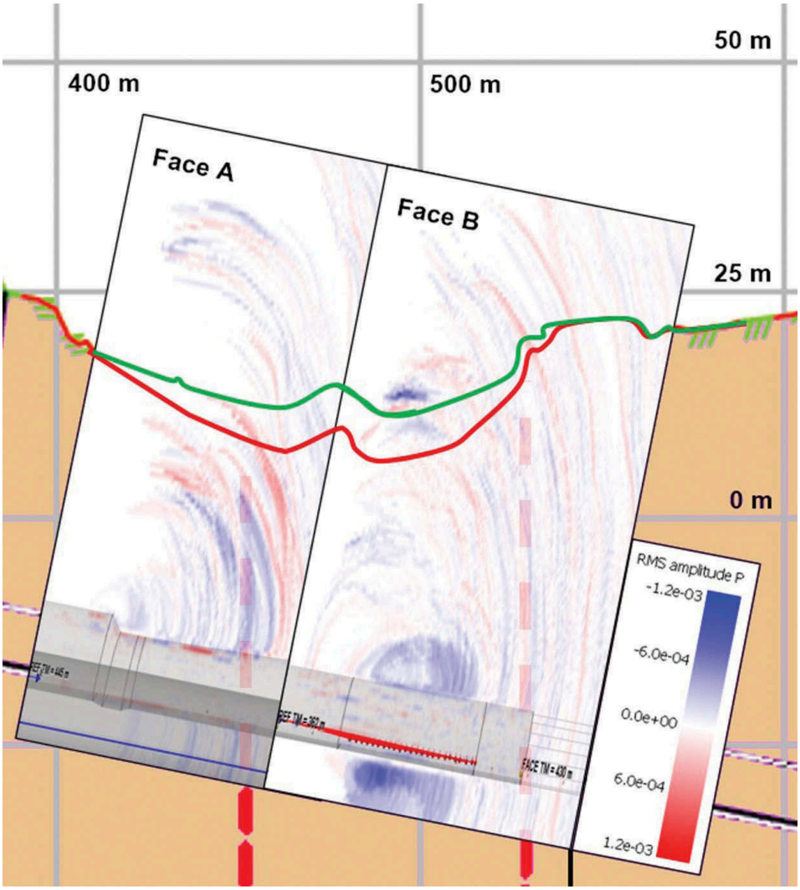

Figure 6. Two migrated sections of the P-wave component analysis upon geological forecast of seismic investigations in a subsea tunnel. Each section was obtained from periodical seismic measurements. Red and green lines represent the contact between hard rock and deposit material and the surface, respectively.

surface. Because of the upward dip of the surface towards the right, unfortunately, it is not possible any longer to obtain reflections that make possible to image the contacts along the entire section. In any case, evaluation of these periodic seismic measurements already gives insights into the potential of using a combined approach of continuous investigation and special data analysis as side processing.

2.2 *Benefits and contribution of tunnel seismic*

Considering the common high uncertainty of the geological forecast for a tunnel project, any variant of tunnel seismic together with probe drilling and geological documentation will help in validating and refining the geological forecast. Selection of the more suitable seismic technique for a given project should be done following an evaluation of the capabilities and limitation of each methodology available and site requirements. If TSP is considered as the right option, various measurement schemes can be followed: sporadic, periodic and continuous (Fig. 7). Then, it is the tunnel engineer's decision on the right selection of the best approach for the project.

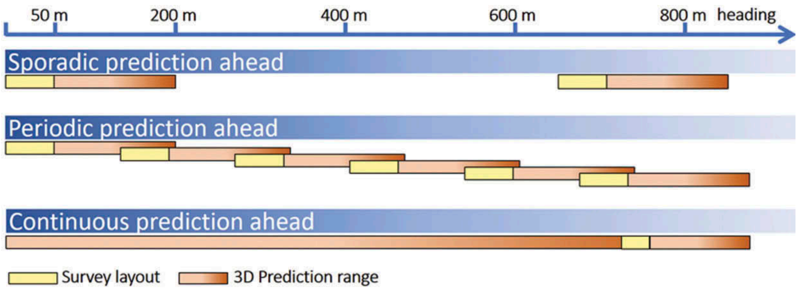

Figure 7. Top: Sporadic measurements may be carried out, when only specific sections of the tunnel course shall be investigated. Middle: A better than sporadic approach is the periodic prediction, where a new measurement is to be done before the previous investigation range exceeds. Bottom: a continuous prediction delivers data while excavating and updates a predictive model quasi continuously in short intervals of about 10 meters.

Table 1. Comparison of the three types of data measurement available for TSP. Excavation methods: mechanised or conventional. Production cycle means the workflow plan for the tunnel excavation and how TSP can be implemented.

Type of measurement	Excavation method	Seismic source	Production cycle	Downtime (min)	Prediction range (m)
Sporadic	all	explosive mechanical	independent	~60*	120 – 150 80 – 120
Periodic	all	explosive mechanical	integrated	~60*	120 – 150 80 – 120
Continuous	all	explosive mechanical	part of it	< 10	120 – 150 80 – 120

* Standard acquisition, if Multiple Shot Recording is used downtime reduces by 1/3.

Table 1 summarizes major differences and benefits for the three types of measurements available for TSP. The table may be considered as a support decision tool for the selection and implementation of TSP as the seismic prospection method.

3 NEW TRENDS OF GEOPHYSICS IN TUNNELLING

There are not seldom many methods used in underground construction projects, including geo-technical sounding and sampling, geophysics, environmental sampling and testing, hydro-geology and geotechnical laboratory testing. One of the biggest challenges is to make use of all the data during the interpretation and the modelling. The traditional way includes a lot of drawings, plots, diagrams, tables spread on desktops, walls, floors, screens etc. (Cracknell & Reading 2014). The digital world has evolved during the last 30 years and it does find a peak in industry 4.0 where data exchange has never been more essential than before and hence opens many new opportunities for joint interpretation. The GeoBIM concept suggests how to make use of these opportunities available today, state of the art geotechnical and geophysical data handling and workflow (Svenson 2017).

Once data exchange and joint interpretation becomes possible, a further step to artificial intelligence such as machine learning algorithms is made. Machine learning algorithms use an automatic inductive approach to recognize patterns in data. Once learned, pattern relationships are applied to other similar data to generate predictive models. Hence, there is much scope for the application of machine learning algorithms to the rapidly increasing volumes of geophysical data obtained by continuous measurements for geological mapping problems.

Machine learning approaches can be applied at different stages throughout the geophysical evaluation, ranging from raw data analysis by classifying and filling gaps, processing parameter adjustment (data mining) and ultimately on automatic interpretation which comprises predicting rock properties and extracting discontinuities from seismic data (faults, layers, etc). However, there are challenges for application of this technique in geophysical data mainly related to the amount, quality and non-uniqueness of geophysical data, the homogeneity of collected data and the dependency of the involved variables. Nevertheless, with increasing computational power and the experience already gained in application of machine learning in different field of geoscience, adaptation and rapid development for the tunnel industry is possible.

4 CONCLUSIONS

Beside the operative benefits provide by the execution of continuous seismic measurements, further data analysis can be done from a single dataset. While prediction ahead allows to tackle continuously geological structures ahead of the face that may pose a hazard to the excavation, specialized processing to tunnel side helps investigating subparallel structures that may intersect the tunnel along as the excavation advances. Since the same dataset is being used for both type of predictions: ahead and side, no extra job must be carried out in the tunnel once a measurement has been completed. The lateral resolution limitation of side processing due to the length of the TSP layout is until some extent overcome by employing the continuous measurement approach. This was demonstrated by analysing two datasets of single TSP measurements with the task of detecting the surface in a subsea tunnel.

The use of impact hammer for continuous measurements is also feasible. This is particularly important for TBM drivage where the use of explosive is restricted. By comparing TSP results of a sporadic measurement against results of high resolution seismic tomography in a test gallery, important insights about the penetration depth and resolution of the TSP results was possible. In this example, reliable results were obtained until about 50 meters away from the seismic layout. Considering that 3D results of continuous measurements are update every 10 to 15 meters as the excavation progress, the penetration depth achievable when using impact source should be fair enough for the integration of this type of source into the continuous seismic approach. Certainly, the use of a seismic source as an impact hammer in a TBM drivage should be well prepared. The impact hammer can be mounted in a suitable place of the TBM structure or could be mounted in an additional vehicle if there is enough space for accessing.

With these extended capabilities, tunnel seismic technologies like TSP, shows its versatility and recurrent development adapting to the new requirements and trends of the tunnelling industry. As these trends grow, implementation of alternative geophysical prospection technologies in tunnelling is expected to increase in the following years. Certainly, a combination of geophysical techniques may also be an attractive approach as a tool for further mitigate the geological risk still coming ahead or from the sides while tunnelling.

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