Vibration Monitoring in Tunnelling – Two Examples from Europe

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1. Keywords
Vibration monitoring, hazard management, blast pattern control, modern instrumentation, rockburst prevention, tunnel based seismic survey, look ahead tunnel face

2. Introduction
Tunnelling in Europe often faces a lot of problems caused by vibrations or cases in which vibration monitoring can help and reveal hazardous zones. These problems are specific where tunnels are build: in close vicinity to existing tunnels under operation, in difficult geologic or hydraulic conditions, under high overburden or directly under plants, buildings and residential areas or inside dams. Most tunneling projects are accompanied by vibration measurements for the purpose of limiting the vibration impact from blast work, traffic and machine operations on installations and the neighbourhood, following national standards. But there are often higher demands for vibration monitoring.

In this paper the role of vibration monitoring in the tunneling hazard management system is pointed out and the consequences are drawn for a comprehensive monitoring. The technical aspect of vibration monitoring covers a wide range of applications – from induced tremors, passive seismic events at geologic inhomogenities, shock and vibrations from machinery, TBM and blast work, vibration impact on structures and people up to high frequency seismoacoustic events close to the tunnel as an early warning indicator prior to rock bursts. The modern task is not only to record and report vibration data, the task is to manage the information as a part of a safety management system.

3 Seismic and Vibration Hazard Management
For detailed tunnel planning, geological, geophysical and geotechnical surveys were conducted to fix depth, line and construction of the tunnel. Before tunnel construction begins, these investigations also reveal areas with potential risks as shown in the subsequent table.
Table 1: Some potential risks related to vibration monitoring

<table>
<thead>
<tr>
<th>Risk type \ construction</th>
<th>Conventional heading</th>
<th>Tunnel Boring Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological Risks</td>
<td>Weak rock class</td>
<td>Inflow of water/gas</td>
</tr>
<tr>
<td></td>
<td>Rock fall</td>
<td>Unexpected rock types</td>
</tr>
<tr>
<td></td>
<td>Break outs</td>
<td>Fault zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cavities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seizing of TBM</td>
</tr>
<tr>
<td>Geotechnical Risks</td>
<td>Instabilities</td>
<td>Rock burst</td>
</tr>
<tr>
<td></td>
<td>Stress conditions</td>
<td>Tubbing deformation or failure</td>
</tr>
<tr>
<td></td>
<td>Rock burst</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tunnel deformation</td>
<td></td>
</tr>
<tr>
<td>Safety Risks</td>
<td>People endangered in tunnel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>People endangered at surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bothered neighbourhood</td>
<td></td>
</tr>
<tr>
<td>Economic Risks</td>
<td>Down time</td>
<td>Liabilities</td>
</tr>
<tr>
<td></td>
<td>Repair / recover costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of TBM</td>
<td></td>
</tr>
</tbody>
</table>

Risk identification and management of unexpected risks results in a tunnel specific monitoring and risk reduction strategy. In this paper we present two examples for vibration monitoring with different objectives. The close range vibration monitoring is about high amplitude and high frequency measurements in a minimum distance of 1 m to a blast face. The objective is to limit the vibration impact on the surrounding strata to avoid break outs and fracturing of the surrounding weak geologic structures. The second example is about a rock burst early warning monitoring system which is also used as receivers for active seismic exploration of tunnel surrounding. Both examples are embedded in a specific risk management system. In a simplified manner it is shown in table 2:

Table 2: Simplified hazard management system for the two examples in this paper

<table>
<thead>
<tr>
<th>Hazard management Feature</th>
<th>Close range monitoring – blast tunnelling</th>
<th>Monitoring and Exploration – TBM tunnelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard and risks</td>
<td>Rank 1: definite problem break outs, cracking, instabilities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rank 2: potential problem Endangered staff and equipment</td>
<td></td>
</tr>
<tr>
<td>Organisation</td>
<td>Defined responsibilities, reporting to builder and construction supervisor, warning and alert recipient list and reaction comply with EU standards</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Defined responsibilities, reporting to builder and construction supervisor, warning and alert recipient list and reaction comply with EU standards</td>
<td></td>
</tr>
<tr>
<td>Operational Management</td>
<td>Monitoring the whole blast work, additional sensors at affected installations, visual inspections, re-plannings due to changes, weekly meetings and reporting on site, recommendations for risk reductions, decisions on</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monitoring in areas with large coverage and increased stress conditions, on-line monitoring at all times, campaign based active seismic surveys, regular meetings and reportings and development of geological and</td>
<td></td>
</tr>
</tbody>
</table>
3. First example - Limiting blast impacts and controlling blast patterns at Bigge Reservoir, Germany

To reduce costs by simplifying the blast pattern, reducing the vibration impact, enhance the fragmentation and lowering the quantities of explosives details on the ignition sequence and the blasting itself have to be analysed. These data can be derived by close-up shock- and vibration measurements.

The monitoring results provide essential information for improvement of the applied blasting procedure in particular, as well as broaden the general data base for further predictions.

We present example data from close-up monitoring of blasting during a tunnel drift towards and inside a reservoir dam. This methodology was also applied in multiple dam projects in Europe where inspection tunnels were driven by blast work along the dam bedrock interface. Data shown are from a tunnel driven into a dam at the Bigge reservoir in North-Rhine Westfalia, Germany. In this example the emergency outlet of the dam was modernised, which included the installation of new pipes and, in particular, a new shut-off valve and globe valve. The valve installation required a new and larger chamber. It was also necessary to build a new, 65-metre long access tunnel since the existing service galleries and shafts were too small for the new installations. This is a good example for very precise and careful blasting with no overbreak and minimum impact on structures and buildings.

The new Austrian tunnelling method with calotte driving was used for the excavation. The challenge for the tunnel drift and, in particular, the excavation of the new valve chamber were both in close proximity to vibration sensitive installations (e.g. existing valve chamber, outlet pipes, basement sealing of the dam) and in difficult local geological conditions in respect of tunnelling. The local geology consists of highly fractured clay and sandstone layers. The rock is highly tectonically stressed, water bearing and also weathered at larger depths. These circumstances required careful planning of the blasting procedure, putting strong limitations on vibration emissions in order to:

- Limit further fracturing of host rock
- Avoid activation of rock movements on existing faults and fractures
• Protect existing installations
• Protect basement sealing of the reservoir dam above from being fractured.
• Ensure precise excavation to reduce overbreak.

3.1 Blasting procedure

The requirements mentioned above were used as constraints in model calculations resulting in guidelines for a very careful blasting procedure:

• Maximum shot distance of 1 m
• Maximum charge of 400 g per detonation stage
• Optimised drill and blasting pattern
• Ground velocity should not exceed 200 mm/s at 1 m distance from blast hole to limit fracturing of host rock.

The blast monitoring can be sub-divided into 3 phases. Phase 1 refers to test blasts to elaborate the blasting pattern and fine-tune the blast sequence. Phase 2 refers to the tunnel drift and phase 3 to the excavation of the valve chamber.

3.2 Monitoring concept

A monitoring scheme consisting of two mobile sensors moving with the excavation front and 3 fixed sensors was applied to test and verify the predicted blasting behaviour. The distribution of the sensors is shown in figure 1.

The two mobile sensors were placed inside a borehole of 1 m depth at 1 m and 2 m distance from the excavation face. The main task for these sensors was to document the near field vibration field and thus the effectively emitted seismic energy from the blast.

Two fixed sensors were installed directly on the outlet pipes to directly monitor the induced vibration of the pipes. One sensor was placed inside an exploration borehole at the tunnel axes to monitor the far field vibrations as well as the impact on the basement seal of the reservoir dam. All installed sensors were 3-component velocity transducers.

3.3 Monitoring Equipment

DMT equipment from Germany was used in both examples. The Summit Monitoring and the new Summit M Vipa series of 24-bit networking seismographs with 24-bit technology allows to detect weakest signals (see example 2) as well as very high amplitudes with the same instrument. The network capabilities of the system was used to set up the local vibration monitoring networks.

Main features of these instruments are:

- Easy to use, Colour graphic display, lightweight, ruggedised
- Long duration internal battery (> 5 d)
- 24 bit technology and frequency range up to 5 kHz
- 2 GB internal memory, unlimited external storage via USB port
- Noise monitor
- Internal GSM modem for Remote access (mobile or internet)
- Internal serial, VipaNet and LAN for Easy setup of networks
- International standards implemented

These seismic shock and vibration recorders (figure 1) are designed for autonomous outdoor use with various sensors – typically surface or borehole sensors.
Regarding the sensors, the high mechanical stress both from the blasting itself and from the daily installation / deinstallation procedure requires ruggedized equipment. Moreover, the measurement task very much exceeds the sensor requirements of normal engineering standards with respect to frequency range from 10 Hz to 2000 Hz and measuring range from 0.001 mm/s and exceeding 2000 mm/s.

### 3.4 Analysis of Monitoring Results

According to the monitoring concept, the signal of all installed sensors was simultaneously recorded for each blast. It can be clearly recognized that the recording of the near-field sensors allows distinguishing each individual detonation. Analysis of the near field signals provided the following characteristics:

- The impulse length of individual detonations is between 15 ms and 35 ms at the near field sensors.
- Detonation timing was chosen in order to have only little overlap of single charges and thus clearly separating the maximum amplitudes of the individual detonations.
- The dominating frequencies are in the band between 100 and 400 Hz.

In total, 205 blasts were carried out during the excavation of the tunnel and the valve chamber. Only 35 exceeded the vibration limit of 200 mm/s (see table 3). In most cases, only a single detonation step of the blast sequence was responsible for the higher vibration emission. Each blast with vibration emission above the 200 mm/s limit was carefully analysed and the blasting pattern was modified, if necessary.

<table>
<thead>
<tr>
<th></th>
<th>BL1 m</th>
<th>BL2m</th>
<th>KB02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average amplitude [mm/s]</td>
<td>115</td>
<td>86</td>
<td>25</td>
</tr>
<tr>
<td>Recording with max amplitude &lt; 200 mm/s</td>
<td>83.6 %</td>
<td>93.9 %</td>
<td>98.4 %</td>
</tr>
<tr>
<td>Number of recordings with max amplitude &gt; 200 mm/s</td>
<td>30</td>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

A typical first approach for the analysis of vibration data is simply to determine separate blast hole vibrations in the seismogram and their magnitude of vibration.
3.5 Optimisation of blasting procedure

The aim of the optimisation of the blasting sequence in this project was the equalisation of the emissions of all detonations to prevent single detonations from causing unnecessarily high vibrations and thus, dominating the overall emission level. Provided that inaccuracies of the blast installation are limited, high vibration emissions will correspond to higher force of the blast hole. Adding additional auxiliary holes to the sequence could relieve critical areas.

Figure 2 shows an example record and the corresponding blasting pattern. The individual detonations can be clearly identified in the record. Three detonations are marked in the record, which significantly rise above the average vibration level. The three increased emissions relate to blast holes in the corner region indicating that the applied force was too high in that region. Auxiliary blast holes were added to the pattern to reduce the emission level.

![Figure 2. Identification of individual blast holes emitting abnormally high vibration and correlation to blast design.](image)

4 Second example - Combined seismic monitoring and exploration, Brenner Tunnel Project, Italy

This second example describes a combination of active and passive seismics in a support tunnel of the Brenner tunnel project on the Italian side of the Alps. Passive seismics applied as a high frequency seismic monitoring system is used as an early warning system to protect against rock bursts. Active seismics is conducted to explore the structure of the surrounding strata and the geologic conditions ahead the tunnel face. The work is currently conducted in an early stage and some first results are shown.

The geophones for active and passive measurements are located in small drill holes. One monitoring section consists of 3 boreholes which located in the circumference 120 degrees apart. Each 50 meters of the tunnel position (refer to Figure 2) a monitoring section is located. The boreholes are about 2 m deep with a typical
diameter of 42 mm. Special one- or three-component sensors (geophones or accelerometers) are placed in the boreholes and coupled to the rock by a clamping mechanism. The boreholes are damped to avoid recording of acoustic noise. For active seismics the seismic signals are generated by small explosives in boreholes placed every 5 m along the tunnel axis. The required load of the explosive charge depends on the geological conditions and the overall background noise level which will be determined at the beginning of the system installation with a source testing. The system presented in figure 3 covers a tunnel part of about 150 m with three receiver boreholes (upper tunnel position, lower left position and lower right position) at four tunnel positions each 50 m apart from each other.

Figure 3: Measuring principle of the SUMMIT Monitoring installation

The seismic measurement of 150 m tunnel line without drilling is about 1.5 hours. While the active seismic exploration is carried out during the maintenance intervals, the rockburst monitoring is running in continuous mode. The data are collected in the central DMT Summit Monitoring unit and sent accordingly to a computer outside of the tunnel where the monitoring data is stored, processed and distributed and displayed automatically.

4.1 Seismic Exploration

The data of the active seismic exploration is recorded approximately two times per week in standard maintenance intervals. Approximately The 'look ahead' distance depends on several factors, i.e. the source strength, the rock formation, the material change of reflectors and the strike of reflectors with respect to the tunnel route. If, for example the load of the explosive charge which can be used is limited, the exploration distance is restricted by the possible source strength. Usually in compact rock 20-50 g of seismic explosive charge is sufficient to obtain reflections from distances of up to about 150 m. The data is transferred to the computer server and directly sent to the processing centre via internet. The results are sent back to the server within 24 hours and can directly be transferred to the tunnel information system to be involved in the decision making process.
4.2 Rockburst Monitoring

The continuous data recording produces seismic data 24 hours per day. The data can be transferred to the computer server station via memory card or - if available on the site - online via wire or fiber optic cable. At the beginning of the measurements, noise tests are made to characterize the overall seismic noise level from the construction activities. With the result of these investigations, threshold values are defined for the rockburst events to be monitored by the system. Different criteria are possible. These criteria can be the number of events above a certain amplitude (or energy) level within a certain rock volume or the amplitude (or energy) level of a single (strong) event. Alarm criteria and corresponding threshold values are implemented via software interface and can be adjusted anytime if necessary. All seismic events above the predefined noise level are detected automatically and localized accordingly. Figure 4 shows the rockburst data from a tunnel project in the Alps. The seismic events are displayed in projections on the horizontal and vertical plane in a range of 20 m around the tunnel wall. Obviously the events are clustered in some regions, which might indicate activities to occur along existing zones of weakness or increased pressure on the walls or tubbings.

Figure 4: Data presentation of the pressure induced events close to a tunnel in the south Alps

4.3 OUTLOOK

The outlook for the different purposes of tunnel monitoring is better knowledge of circumstances, enhanced procedures and increased safety. This can be achieved by modern seismographs which overcome the limitations of the past, e.g. in dynamic range, frequency range and network capabilities.

Another future outlook is the seismic recognition method ahead of the face (TRUST). This new approach combines geological, geotechnical and results from active and passive seismic survey to investigate areas ahead and around tunnel face. In this context vibration monitoring is embedded in tunnel exploration. The combination enhances the acceptance of the investigation method, additional valuable information is provided for tunneling engineers and is part of the hazard management system.