Prediction ahead of the tunnel face by seismic methods—pilot project in Centovalli Tunnel, Locarno, Switzerland

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Introduction

In planning the construction of a tunnel, a geological prognosis is necessary. The reliability of the prognosis is directly related to the amount of information available from surface geology, drillholes and geophysical surface investigations.

During the excavation phase the tunnel engineer requires detailed and quantitative information about abrupt changes in rock quality and formation boundaries lying ahead, and these cannot always be obtained from surface investigations. In particular, in the case of a thick overburden, this information has usually to be gathered from the surroundings of the tunnel by drilling boreholes into the formation from the tunnel itself. If the geological structure is complex, a large number of such boreholes is necessary, leading to costly delays in tunneling progress.

Recent developments are aiming to use non-destructive geophysical exploration techniques for prediction purposes. Apart from seisics, radar has been applied successfully in non-conductive crystalline rock (Blümling et al. 1992). Such methods may contribute to a saving in the number of boreholes which would normally have to be drilled from the tunnel wall or face. Notable in this case is the efficiency of tunnel seismic methods, which can provide a range of up to several hundred metres and good resolution independent of rock type.

During the construction phase of the Centovalli railway tunnel a sequence of in-tunnel seismic surveys was carried out for the first time. The first aim was to determine the thickness of the gneiss overburden, i.e. the distance to the rockhead boundary at the top of the gneiss, which runs parallel to the tunnel profile. Above this boundary, lie partially unconsolidated moraine deposits. The second aim was to detect any zones of heavily weakened gneiss rock ahead of the tunnel face, which would require appropriate measures to be adopted for further excavation. Another goal of the pilot project was to test in-tunnel seismic methods in order to develop and optimize the techniques for future routine operations.

In-tunnel seismic methods

Over the last decade, borehole seismic methods have been developed for hydrocarbon exploration. In particular it has been advocated that vertical seismic profiles (VSPs) could be used during the drilling phase to carry out a prognosis ahead of the drill bit (Balch et al. 1982). If one compares a tunnel with an oversized drillhole, it is evident that seismic profiles analogous to VSPs in vertical boreholes can be acquired in horizontal tunnels. It is also possible to acquire seismic reflection profiles along the axis of a tunnel.

Figure 1 shows the principle of these two techniques. The VSP mode is suitable for exploring the rock formation ahead of the tunnel face and the reflection mode for investigating the surroundings of the tunnel.

In the VSP mode, illustrated by the set of raypaths labelled 1 in Fig. 1, the seismic waves are generated by firing a small charge in a sidewall shothole (c. 100 g, 4 m depth). The distance between shothole and tunnel face is typically about 100 m. The seismic waves travelling in the direction of the tunnel face and the later-arriving reflections from the formation are received by a spread of highly sensitive accelerometers laid out between the tunnel face, or tunnel boring machine, and the shothole. In spite of the rough environmental conditions in the excavation area, single-component receivers fixed by their spikes to the tunnel wall provide a simple way of recording. Three-component downhole receivers would considerably enhance the quality of the recorded data but, in addition to the increase in field effort, there is a big risk of losing costly equipment in collapsing receiver holes (Sattel and Gelbke 1987). Normally, a receiver spacing of 2 m is sufficient to avoid spatial aliasing for frequencies lower than 800 Hz.

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Fig. 1. Prediction ahead of the tunnel face by seismic methods: (a) Combined acquisition using reflection- and VSP-mode. (b) VSP-mode measurement and data interpretation.
Fig. 2. Centovalli tunnel project: (a) situation map showing section of seismic profiles, (b) cross-section through the line of the tunnel showing the location of profiles I, II, III.

The signals from the accelerometers are digitally recorded. During the subsequent data processing, the direct and reflected wavefields are separated such that the latter only contains reflections from the area ahead of the tunnel face. As the seismic velocity of the rock is known from direct wave arrivals, the distance between the tunnel face and discontinuities ahead is determined from the traveltimes of the reflections. In general, zones of weak or crushed rock generate good reflections at their boundaries with the intact rock mass.

In the seismic reflection mode, illustrated by the set of raypaths labelled 2, the same receiver spread is used. Here the seismic signals are generated along the tunnel wall in the vicinity of the receivers, using very small charges in short sidewall shotholes (c. 30 g, 1 m depth). The reflection data are then processed by conventional methods including common midpoint stacking to enhance the signals. The result will be a stack, or a migrated stack, which indicates the lateral offset of reflecting discontinuities to the tunnel axis.

Profiles of both types described above provide quite comprehensive data from the region all around the tunnel face, and are applied in a common field operation. Including preparation work, the field operation for one
100-m profile acquired in both modes takes about 12 hours. The data processing can be completed in a similar period providing results within a 24-hour period. The information can then be used to decide on appropriate measures for continued tunnelling.

Field operations and results

Both methods of seismic profiling described in the previous section were applied as a pilot project during construction of the Centovalli railway tunnel. This tunnel was built to replace the existing railway track through Locarno city centre.

Figure 2 shows a vertical section through the tunnel where the seismic acquisition profiles were laid out. This section, located about 1140–1305 m away from the tunnel entrance at San Antonio has an overburden of 70–100 m and was excavated conventionally using explosives. The rock mass was characterized as migmatitic gneiss with a rugged upper boundary overlain by unconsolidated material which mainly consisted of moraine.

If a buried valley filled with moraine were encountered unexpectedly, especially if it intersected the tunnel axis at a low angle, it would pose a severe hazard for the mining work and endanger the tunnel itself. With a thin overburden, as in this case, there would also be a danger of ground subsidence in the city area of Locarno.

Because the geological investigations only provided qualitative indications about the depth profile of the gneiss–moraine boundary, it was decided, in close consultation with the authorities involved, to carry out a sequence of combined seismic profiles. It was planned to overlap the successive acquisition profiles to reproduce in part the results of the previous ones.

Profile I

A first seismic spread was laid out at 1140–1304 m along the tunnel (Fig. 2) after the face had reached 1305 m. Because the gneiss–moraine boundary was expected to be about 50 m above the tunnel axis, dipping to the south, the receiver spread was placed on the upper part of the right wall of the tunnel in order to obtain the desired directional sensitivity. Our experience has shown that the tunnel cavity considerably reduces the sensitivity to reflections from interfaces beyond the opposite tunnel side, unless the dominant wavelength of the signal is greater than the diameter of the tunnel.

The shotheoles (depth 1.5 m) for acquiring data in the reflection mode were drilled into the lower part of the right tunnel wall; the two shotheoles for the VSP-mode (depth 4 m) were drilled in the same manner at 1150 and 1230 m.

Seismic data were acquired during a weekend working break without giving great problems. Nevertheless, a significant part of operation time was taken up by searching for receiver positions with good acoustic coupling. Additionally, the shotheoles showed poor stability in the weathered gneiss rock and had to be flushed or re-drilled in many cases. The operation was finished after a period of 30 hours. The quality of the recorded data was relatively good considering the difficult field conditions.

The processing, following immediately after the

Table 1. Summary of seismic predictions, modifications to tunnelling techniques, and features proved by tunnelling

<table>
<thead>
<tr>
<th>Operation</th>
<th>Prediction by seismics</th>
<th>Tunnelling techniques</th>
<th>Proved by Tunnelling</th>
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<tr>
<td><strong>Profile I</strong></td>
<td>Height of rockhead c. 25 m at tunnel face. No prediction ahead. Projecting the rockhead boundary along the line of the tunnel implies that the boundary intersects the tunnel around 1372–1387 m.</td>
<td>None</td>
<td>Improving rock quality from 1305 m. Now steel reinforcement necessary from 1220 m.</td>
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<td>17 March/1305 m</td>
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<td><strong>Profile II</strong></td>
<td>Height of rockhead approx. 20 m at tunnel face. Zone of weak rock in the vicinity of the face 1337–1342 m. A pronounced zone of weak rock predicted around 1372–1387 m.</td>
<td>Intersecting the first zone of weak rock (1337–1442 m) the excavation length was reduced to 1–1.5 m. From 1359 m every 5 m prediction boreholes of 6–10 m length were drilled ahead of the face.</td>
<td>The zone of weak rock predicted was found from 1337–1342 m. Steel reinforcements were necessary for further tunnelling. The second zone of weak rock was found as predicted at 1372–1387 m. This zone was very intensively fractured and contained weathered rock of very poor quality with respect to stability.</td>
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<td>8 April/1334 m</td>
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<tr>
<td><strong>Profile III</strong></td>
<td>Height of rockhead approx. 16 m at tunnel face. From 1442–1458 m a pronounced zone of weak rock is predicted. The distance to rockhead increases again from 1390 m. The predicted weak zone at 1442–1458 m is interpreted as a very weak zone within the gneiss.</td>
<td>Reduced length of excavation (1–1.5 m).</td>
<td>From 1390 m no further steel reinforcement was necessary. From 1440 m a sudden change to poor rock quality was observed. Further inclusions of unconsolidated material were getting more frequent. Moraine was finally reached at 1450 m.</td>
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<td>26 May/1414 m</td>
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acquisition, yielded the results which are listed in Table 1. As expected, the stack obtained from the reflection-mode data (Fig. 3) showed a reflection which could be interpreted as the top of the gneiss rock, i.e., the gneiss-moraine boundary. It can be seen from Fig. 4 that the radial offset between the tunnel axis and this boundary is considerably smaller than had been expected from extrapolation of the available geological data.

**Profile II**

Extrapolation of the gneiss-moraine boundary observed on reflection profile I would intersect the line of the tunnel in the region of 1372–1387 m. Therefore a second seismic profile was started after the excavation of only another 29 m, with the tunnel face at 1334 m. Using the experience gained from profile I, the recording spread was shortened (1239–1333 m) and the shotholes...
were lined with PVC casing. These measures reduced the time taken for data acquisition by about 30% and improved the data quality at the same time.

The processing of the reflection-mode data resulted in a stacked section which reproduced the results from profile I where the two profiles overlapped. For the continuation of profile II, the reflection interpreted as the gneiss-moraine boundary showed a gentler dip down towards the line of the tunnel (Fig. 4).

The processing of the VSP-mode data gave additional
useful information from the area ahead of the tunnel face. In the VSP section the most distinct reflection could be interpreted as a zone of very weak rock, approximately 10 m thick, at a distance of approximately 40 m ahead of the tunnel face (Fig. 4). In fact, on subsequent excavation the tunnel hit the predicted zone at 1372 m where the rock mass was characterized as very strongly fractured and altered gneiss (mechanically disturbed migmatite) containing some regions of unconsolidated material. From 1387 m onwards, the quality of the rock mass improved considerably (Table 1).

Profile III
As the gneiss-moraine boundary had not been intersected when the tunnel profile had reached 1414 m, a third seismic profile was carried out to make a further prediction. For data acquisition the same parameters were used as in profile II with the spread laid out from 1319-1413 m (Fig. 2). Profile III was finished without problems giving data of good quality. Using the experience from the previous profiles, the acquisition efficiency increased considerably and took only 12 hours.

The processing of the reflection-mode data gave results which could be correlated with those from profile II in the overlapping part of profiles II and III. Furthermore, the stack showed a reflection which indicated a steeper descent of the gneiss-moraine boundary, as shown in Fig. 4. The minimum height of the boundary, of about 10 m, was found in the neighbourhood of the zone of very weak rock (1372-1387 m). Further on, a rise in the gneiss-moraine boundary was observed on the seismic data, associated with better rock quality in the excavated region.

The processing of the VSP-mode data provided a section (Fig. 3) showing a distinct reflection which was interpreted as the beginning of a further large zone of very weak rock at 1442 m. The start of the zone was predicted at a distance of 28 m ahead of the actual position of the tunnel face (Fig. 4). The subsequent excavation showed a sudden decrease in rock strength at 1440 m and then an increasing amount of unconsolidated material. Finally at 1450 m the gneiss-moraine boundary was encountered (Table 1). For this reason a further prognosis with the seismic methods was not necessary.

Conclusions
Previously, a prognosis of the rock consistency ahead of a tunnel face could be obtained only by drilling a considerable number of probing boreholes from inside the tunnel. Detailed information about the rock quality, fracture zones and interfaces requires coring of these boreholes, which is time-consuming and restrictive for the other tunnelling work. Percussion drilling with the tunnelling equipment takes considerably less time but requires a lot of experience to detect a change in rock quality by observation of drilling progress and cuttings analysis. For that reason it was advisable to apply geophysical methods to obtain complementary information, with the objective of saving time-consuming and costly drilling operations.

In spite of the complex geological structure in the vicinity of the Centovalli railway tunnel, the prognosis of the extremely weak zones in the gneiss rock mass ahead of the tunnel face, as well as the mapping of the dipping boundary between the gneiss rock and the underlying unconsolidated sediment (moraine), was successfully achieved by means of the combined seismic profiling methods described above. For future projects these methods promise to be suitable for a prognosis ahead of the tunnel face, because the actual tunnelling work is hardly, if at all, affected by the seismic measurements in the tunnel.

In particular, if tunnel boring equipment is in operation, unexpected encounters with zones of very poor rock quality can be avoided, increasing the safety and the performance of tunnel boring considerably. Precise detection of such zones is very important if a great mass of overlying rock is present. Large deformations can then occur in the vicinity of the boring head with the potential danger of the tunnel boring machine becoming stuck.

For future routine operations, the seismic methods should be developed and optimized. For data acquisition, the mechanical contact of the receivers and the rock has to be improved in order to obtain better resolution in the seismic results. Data processing should be speeded up considerably using an on-site computer in order to make a prognosis in time and to adopt the relevant techniques for continued excavation. This holds especially for tunnel boring with high performance, i.e. more than 10 m progress per day.

A reliable prognosis ahead of the tunnel face, in combination with modern high-pressure grouting of weak rock zones ahead, makes the whole operation much safer, especially for the construction of deeply buried tunnels.

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References