Geoelectrical monitoring of the tunnel boring at lot H3-4, section Kundl/Radfeld-Baumkirchen

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Introduction

For the tunnel construction at lot H3-4 in the Inn Valley, Austria, a tunnel boring machine (TBM) was used which was stabilized by a bentonite shield. In the case of increased hydraulic permeability of the sediments, the bentonite suspension could be blown out and, as a result, an uncontrollable collapse of the ground could happen, even a damage of the TBM. As no method was known at this time to control the spreading of the bentonite suspension from the surface, a methodological investigation should test high resolution 2D geoelectrical measurements for monitoring the tunnel boring. This technique was the most promising one because on the one hand the geological conditions in the Inn Valley were suited for resistivity measurements (the water level is close to the surface, and cohesive and non-cohesive material can change in short distance) and on the other hand it could be presumed that there is a contrast in resistivity between the bentonite and the pore liquid.

Investigation programme

A comprehensive investigation programme has been carried out, comprising the following phases:

- Test measurements for the selection of the most suitable electrode array

  These measurements should help to determine which electrode array would provide the best results with regard to robustness, time consumption, and resolution at the planned exploration depth (Wenner-α, Wenner-β and Schlumberger-array were tested).
- Reference measurements along the tunnel section

  This recording of the resistivity conditions before the passage of the TBM provides information about the geological situation and reference data for comparison.
- Measurements at the positions of escape shafts

  As bentonite suspension was used for the construction of the escape shafts, such measurements should investigate the influence of the bentonite suspension on the geoelectrical data. At the same time, the influences of installations on geoelectrical measurements should be determined.
- Measurements during and after the passage of the TBM

  The final goal of the investigations was the monitoring of the passage of the TBM and the detection of changes after the passage.

Altogether more than 5000 profile metres were measured.

Results of the investigation

Assessment of the electrode arrays

The measurements at very different conditions have shown that the Wenner-α-array produces the most reliable data under disturbed conditions. In the case of undisturbed, layered conditions the results of the different arrays are very similar and here the Wenner-α-array requires the least expenditure of time. When Wenner-α- and Wenner-β-data were acquired, a joint inversion of both data sets could improve the resolution.

For the exploration depth of 15 m to 30 m (the depth of the tunnel), an electrode spacing of 5 m was the optimum with regard to resolution and required measuring time.

Results of the reference measurements

The reference measurements along the tunnel route provided a very detailed picture of the different sediments in the ground. These geoelectrical results displayed the complicated sedimentation in the Inn Valley better than the drillings alone. The three vertical resistivity sections in figure 1 show material changes at short distances (the profiles have only a distance of 10 m to each other) – low resistivities (green to yellow) correlate with cohesive material and high resistivities (red to purple) correlate more to sandy or gravelly material or to reduced water content (e.g. near the surface). Thus, such areas with high resistivities in deeper ground indicate areas of possibly increased hydraulic permeability.

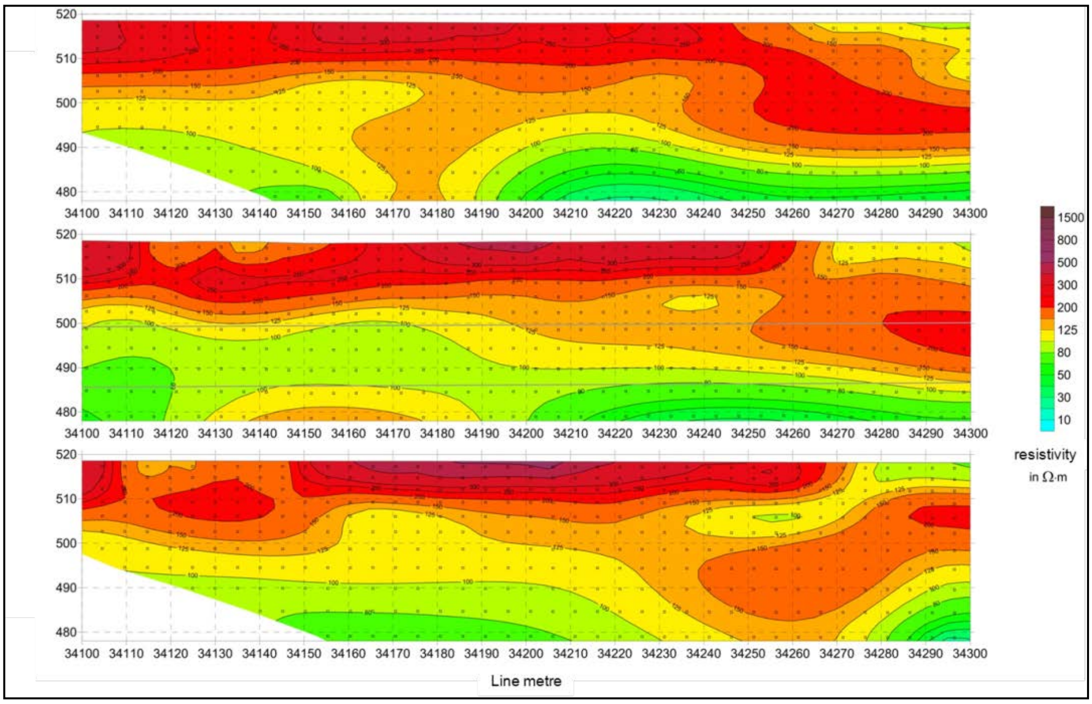

Fig. 1: Vertical sections of the calculated resistivity distribution along three parallel profiles (the middle is above the planned tunnel, the others 10 m left and right of it).

When five parallel profiles were measured, the data could be inverted in 3D. This kind of interpretation provided the best picture of the sedimentation along the tunnel route but it required a lot of computer capacity to build a sufficiently detailed model of the ground. Figure 2 presents different views at the resulting resistivity model. The three-dimensional variation of the sedimentation can clearly be seen. Choosing a presentation of the resistivity model as an iso-surface (like on the right side in figure 2), it is even possible to predict where the TBM will pass areas with increased hydraulic permeability.

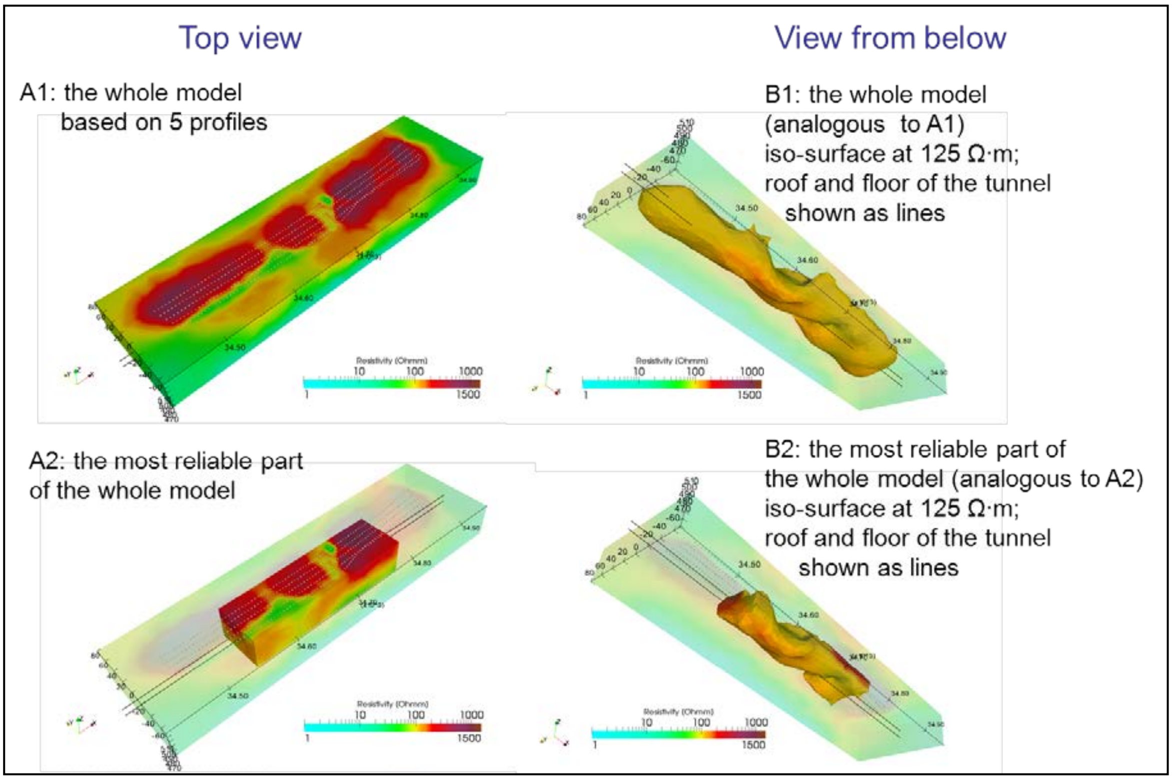

Fig. 2: Different views at the 3D model of the calculated resistivity in an area where five parallel profiles were measured (the electrode positions are marked by grey dots at the surface).

Results of the monitoring

The most interesting question was, of course, if the progress of the TBM and the spreading of the bentonite suspension could be monitored. To answer this question, an almost continuous measurement of the resistivity was carried out over about a week during the passage of the TBM. Some exemplary results of that investigation are shown in figure 3 as resistivity sections after inversion. The uppermost section presents the resistivity conditions before the arrival of the TBM (picture A: reference measurement in Nov 2007). The first measurement while boring on 10 March 2008 (picture B) shows principally the same resistivity distribution like the reference measurement, but two changes can clearly be seen: the resistivity left of the marked position of the cutting head of the TBM is much lower due to the spreading of the bentonite. Right of the cutting head a resistivity maximum is developing. As this maximum always occurs at this position (see also pictures C and D), it is assumed that this is an artefact caused by the influence of the steel wheel of the cutting head. With the progress of the tunnel boring the resistivity section changes accordingly. There are no indications for an uncontrolled spreading of the bentonite (the tunnel boring runs without any problems at this time). However, the results of the resistivity sections indicate that the bentonite is sinking downwards with time. These measurements proved impressively that a monitoring is possible by the technology applied.

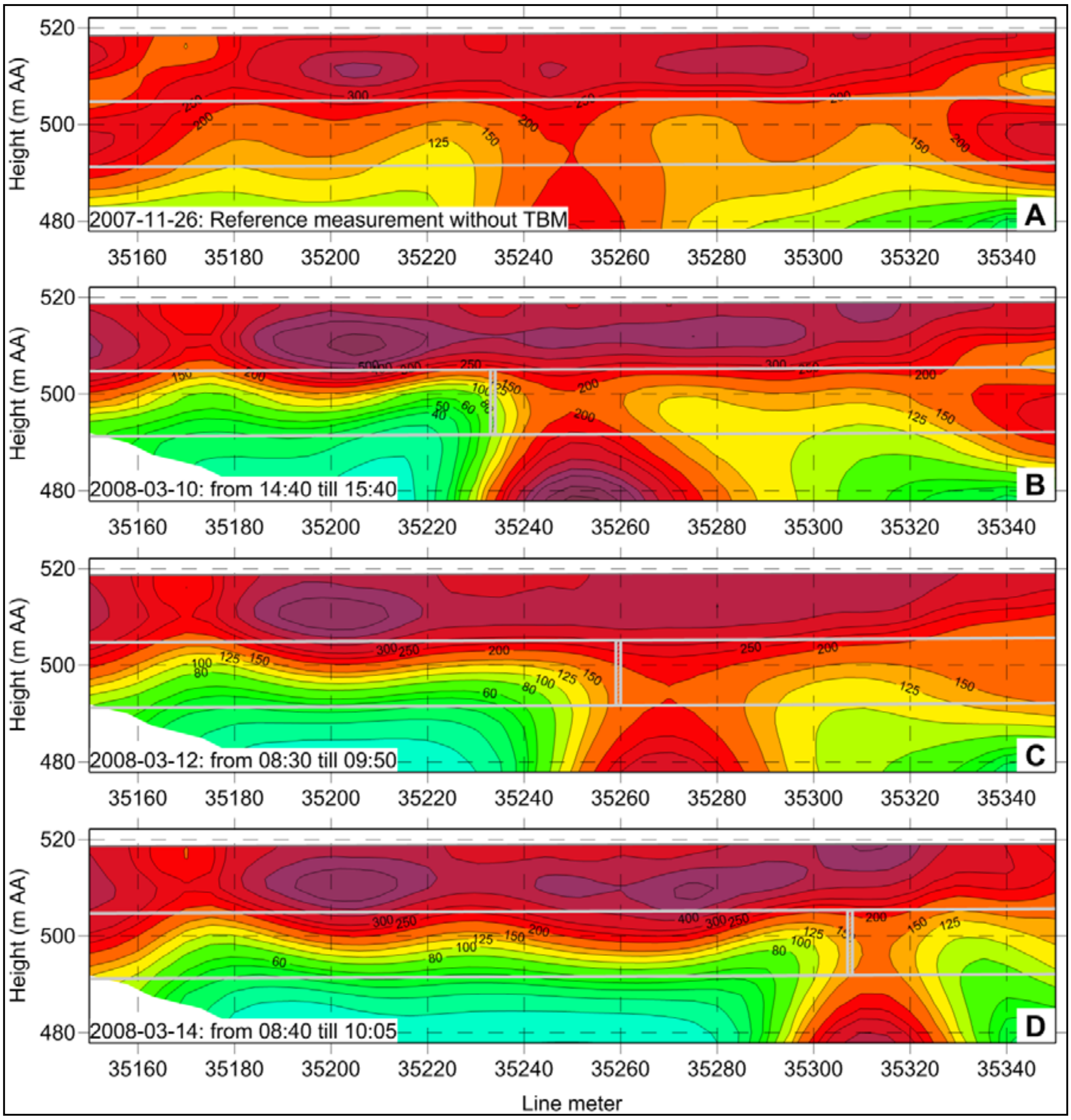

Fig. 3: 2D resistivity sections at different periods of time during the passage of the TBM (the position of the cutting head is marked in the sections B to D).

An assessment of the changes on the basis of the pseudo-sections alone would be much more complicated and it is not expected that small extrusions of bentonite can be detected only by the interpretation of measured differences without inversion.

The detectability of an uncontrolled extrusion of bentonite could not be checked during this monitoring. But this was possible at a position of the tunnel route where, after the maintenance of the cutting head during the restart of the TBM, bentonite was blown out to the surface resulting in a sinkhole. The resistivity measurements could not be done directly above the sinkhole for safety reasons. Therefore two profiles 10 m apart were measured after this event.
The result at one profile is shown in figure 4 – the reference measurement on top and the resistivity section after the outflow below. The resistivity in the depth range of the tunnel is clearly reduced after the passage of the TBM due to the bentonite spreading into the ground. The position of the sinkhole region is also clearly marked at 34780 m by a local range of low resistivity.

But it can also be seen that in the area where the bentonite extruded to the surface the resistivity in the depth range of the tunnel is remarkably higher than in the areas before and behind. This example demonstrates that even local events of extreme bentonite spreading can be detected by 2D resistivity measurements, in particular, when reference data are available.

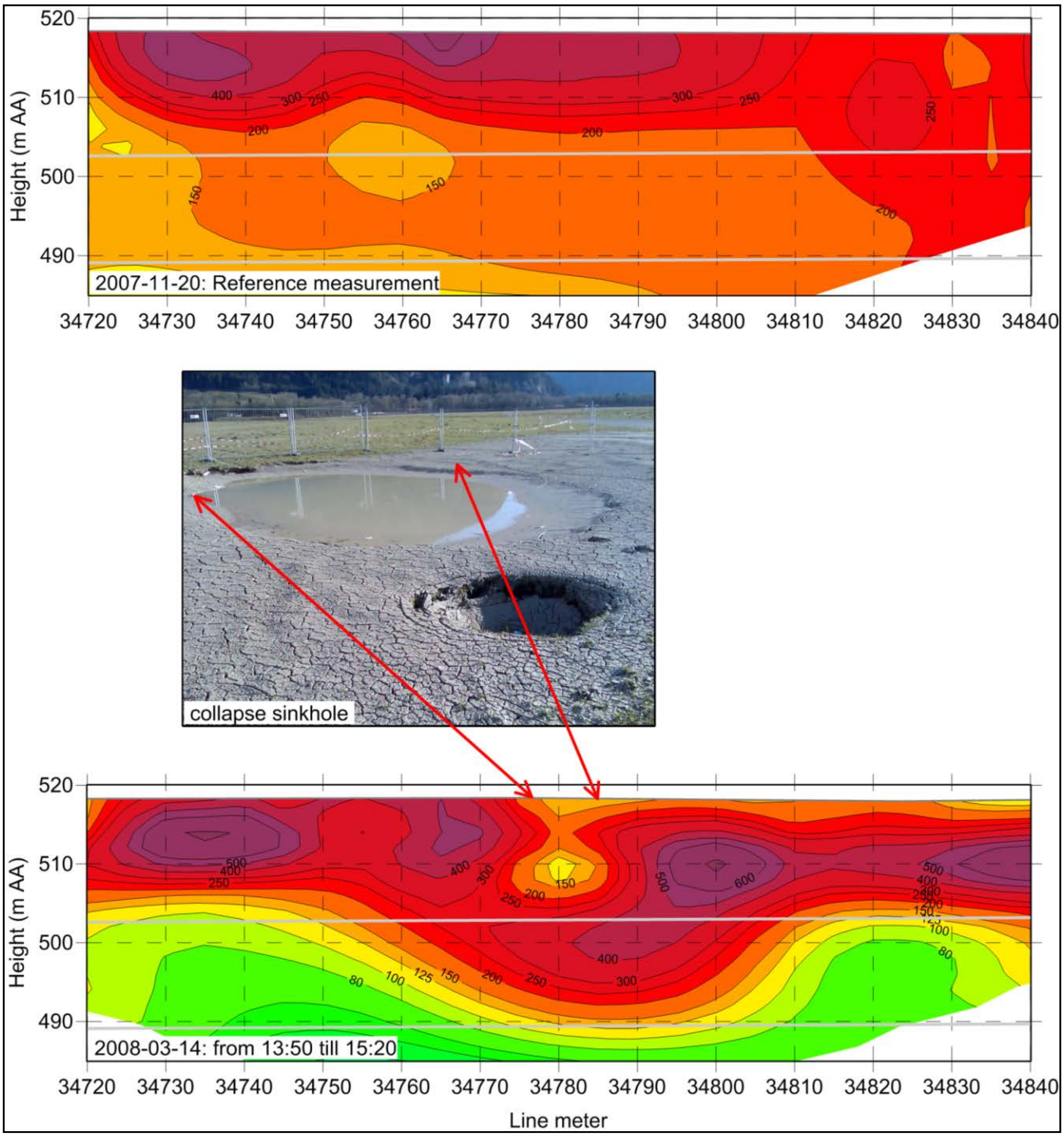

Fig. 4: 2D resistivity sections before and after the passage of the TBM; after maintaining the cutting wheel, bentonite was blowing out when restarting the TBM.

Conclusions

The very comprehensive methodological investigations regarding the monitoring of the tunnel boring in the sediments of the Inn Valley by 2D geoelectrical methods allow the following conclusions to be drawn:

- Geoelectrical measurements before the passage of the tunnel boring machine (TBM) could describe the partly complicated geological conditions more detailed than the results of drillings alone.
- The best interpretation of these reference measurements was achieved by 3D-inversion on the basis of five parallel 2D-profiles.
- According to the results achieved, it can be estimated that such a geoelectrical monitoring is useful for a maximum depth range of 15 m to 25 m to the top of the tunnel.
- Finally, this methodological investigation could prove that for tunnel boring with a bentonite shield the selected geoelectrical technique:
    - can provide information about the spreading of the bentonite suspension into the surrounding rock,
    - can detect local events as e.g. in the case of the sinkhole.

The one-week measurement on the central profile just above the route of the TBM showed the feasibility of the applied techniques for the monitoring of the tunnel boring but also the necessity to improve the technology of the measurement. Such improvements could be the acceleration of the measurement itself (e.g. by the application of multi-channel instruments) and the development of ‘online’-interpretation and imaging tools which would allow the recognition of an uncontrolled spreading of the bentonite suspension almost in real-time.