Electrical tomography monitoring of the excavation damaged zone of the Gallery 04 in the Mont Terri rock laboratory: Field experiments, modelling, and relationship with structural geology

Dominique Gibert a,⁎, Florence Nicollin a, Bruno Kergosien a, Paul Bossart d, Christophe Nussbaum b, Agnès Grislin-Mouëzy a, Frédéric Conil a, Nasser Hoteit c

a Géosciences Rennes (CNRS UMR 6118) and GdR FORPRO (CNRS-ANDRA G788), Université Rennes 1, Bât. 15 Campus de Beaulieu, 35042 Rennes cedex, France
b Geotechnisches Institut AG, Gartenstrasse 13, 3007 Bern, Switzerland
c ANDRA, Scientific Direction and Geomechanics Department, 92298, Chatenay-Malabry, France
d Federal Office of Topography, Swisstopo, Seftigenstrasse 264, 3084 Wabern, Switzerland

Received 22 July 2005; received in revised form 2 March 2006; accepted 8 March 2006
Available online 5 May 2006

Abstract

The excavation of the new G04 gallery in the Opalinus clay of the underground rock laboratory at Mont Terri offered a unique opportunity to perform an electrical monitoring experiment of the evolution of the excavation damaged zone (EDZ) during the progression of the excavation. An electrode array was installed near the end of the first section of the gallery in order to monitor the evolution of the EDZ at the restart of the excavation works. Data sets acquired at different time intervals show conspicuous changes of the electrical resistivity. Forward modelling of a data subset indicates resistivity variations from 6 Ω m for undamaged Opalinus clay to 45 Ω m in the most damaged zones. Comparison with geological observations shows that the resistivity changes are strongly controlled by the local tectonics and by the bedding in the rock formation.

© 2006 Elsevier B.V. All rights reserved.

PACS: 41.20.Cv; 62.20.Mk; 91.25.Qi; 93.30.Ge
Keywords: Electrical tomography; EDZ; Mont Terri; Radioactive wastes

1. Introduction

Among the different rock formations aimed at being used for radioactive waste disposal, argillaceous forma-
tions are particularly studied for their remarkable confinement and self-sealing properties (Meier et al., 2000). To investigate the suitability of waste disposal in these formations, a number of organisations dealing with radioactive waste disposal have initiated the Mont Terri Project in 1995 and the construction of the Mont Terri Underground Rock Laboratory (URL) in a Mesozoic shale formation constituted by the Opalinus clay. Now there are 12 organizations joining the project, these are: ANDRA (France), BGR (Germany), CRIEPI (Japan), GRS (Germany), HSK (Switzerland), ENRESA
A recent study by Kruschwitz and Yaramanci (2004) shows that wave methods also provide useful information. In a non-destructive and low-cost method, electrical impedance tomography has the advantage of being a non-destructive and low-cost method which allows to easily investigate large volumes of the EDZ. Other experiments that have already used geo-electrical measurements in the Mont Terri are: VE (Ventilation Experiment) designed to monitor the EDZ evolution during the excavation of G04. This resulted in heavy constrains both on the time schedule and on the technical aspects of the experiment. The G04 gallery was located at the southern end of the URL and is aimed at providing the URL with numerous additional experimental facilities (Fig. 1). The first section of the gallery is oriented in a NW–SE direction with its axis making an angle of 20° northward with respect to the bedding strike. This section was excavated in the so-called shaly facies (see Nussbaum and Bossart, submitted for publication, for details) during the Spring 2004 and over a total length of 80 m (20 m for the start niche and 60 m for the G04 gallery). A detailed plan view of the excavation stages is given in Fig. 2. After the completion of the excavation of the first 20 m, we proceeded to the installation of the experimental electrical tomography setup within a few days of July 2004 during which we also performed a whole set of measurements. These first data are of a particular importance for the entire experiment since they constitute the data set representative of the initial state of the geo-electrical structure of the EDZ before the restart of the excavation.

In order to suppress any electrical shortcut, the metallic fibbers normally used to reinforce the shotcrete layer have been replaced by plastic fibbers in the 20-m-long start niche in May 2004. In September, at the beginning of the excavation of the G04 gallery, a further 15-m long segment of the gallery was also shotcreted with plastic fibbers. In the same way, no steel reinforcement was placed in the concrete floor in the same segment of gallery. In order to eliminate the changes produced in September by the filling of the 2 gaps kept to install the floor electrodes, an insulating plastic sheet was placed in the voids before pouring the concrete (Fig. 3). By this way, these new volumes of concrete have no geo-electrical effects, and the comparison between the data sets obtained at different dates is made easier. The profile of the gallery has the classical horseshoe cross-section and is circular in its upper part with an average diameter of 5.1 m. The shotcrete layer has a thickness between 10 cm and 35 cm, with an average of 15 cm.

The electrode array consists of three rings of electrodes completed by one horizontal line located on the south wall of the gallery 1.1 m above the floor level. As shown in Fig. 3, the rings of electrodes are placed near the gallery face to best monitor the evolution of the EDZ at the restart of the excavation. Ring 1 is located at about 1 m from the gallery face and ring 2 is 50 cm apart toward the entrance of the gallery. Because of the great probability of a total destruction of rings 1 and 2 at the restart of the excavation works, we decided to place ring 3 at a safer place, 4 m away from the gallery face.
Each ring counts 32 electrodes with a constant angular sampling around the gallery. Excepted for the floor where the profile of the gallery is far from circular, the distance between electrodes is almost constant with \( \Delta s \approx 55 \text{ cm} \). The horizontal line counts 17 electrodes with \( \Delta s = 50 \text{ cm} \), 3 of which being common with the three rings. The 110 electrodes are stainless steel rods with a diameter equals to 8 mm. The electrodes were placed through the following procedure: 1) a 16-mm drilling of the shotcrete covering the walls of the gallery is done and the thickness of the shotcrete layer is measured; 2) an 8-mm drilling of the clay is done over a depth of 5 cm; 3) each electrode is individually cut at its right length and its part crossing the shotcrete is covered with insulating tape in order to restrict the electrical contact with the clay; 4) once cut and insulated, the electrode is hammered to enter the small-diameter hole drilled in the clay; 5) epoxy resin is injected in the drilled shotcrete in order to secure the electrode; and 6) the electrode is connected to a coaxial wire. Finally, all wires forming the electrode array of either a ring or the horizontal line are driven to a common control box and connected to a standard multipin plug in order to allow easy future measurement operations.

In September 2004, at the restart of the excavation works, no important damages occur and most of the electrode array remained available. However, in October, an important failure of the shotcrete layer happened and the whole horizontal line of electrodes was destroyed as well as several electrodes of rings 1 and 2. Further shotcreting of the gallery walls was necessary to stop the failure and, when the excavation of the gallery was finished at the end of November, we proceeded to repairing the rings of electrodes. Unfortunately, the horizontal line was heavily destroyed to be repaired and we decided to abandon it. Interestingly, when repairing the electrode array, we observed that several electrodes had been folded at right angle during the shotcrete failure without being removed from the clay in which they remained embedded. This shows that, once drilled to receive the electrodes, the clay converged and strongly fixed the electrodes. At the start of December, after repairing the electrode array, we proceeded to a whole series of measurements 1 day before the excavation of the entrances of the EZ-B and HG-A niches (Fig. 1).

2.2. Measurement procedure

The equipment used in these experiments consists in an ABEM SAS4000 resistivity meter operated with an ES464 multi-electrode switcher which may be connected to an ensemble of 64 electrodes. The electrode switcher may be arbitrarily configured to allow for any choice of the \( A \) and \( B \) electrodes used to inject the electrical current \( I \) and the \( M \) and \( N \) electrodes where the electrical potential \( \Delta V \) is measured. In the present study, we discuss the results obtained with a circular adaptation of the classical Wenner configuration where the electrodes are equally spaced and placed according to the sequence \( \{A,M,N,B\} \). A total of 161 measurements results from this configuration. Other non-standard electrode configurations, not discussed in the present paper, have also been used in order to augment the tomographic data set. Complementary small-scale geo-electrical soundings with an electrode spacing of 10 cm have been done to measure the electrical resistivity \( \rho \) values of the shotcrete layer. We obtained \( \rho \) values \( \approx 1000 \Omega \text{ m} \).

So far (March 2005), five measurement campaigns have been done in July, September, October, December 2004, and January 2005. A total of about 40 000 measurements have been done, most of them for both electrical resistivity and chargeability. The measurement procedure consists of
injecting a square-shaped alternating current $I$ in order to suppress any polarisation effect onto the electrodes. The electrical potential $\Delta V$ is synchronously measured to eliminate electrical noise and enhance the signal-to-noise ratio. Repetitive measurements have been performed in order to check for the reliability of the data. Three different resistivity meters have been used during the five measurement periods, and we have performed a calibration of all devices with a common reference resistor. The only noticeable instrumental bias (approx. $+0.8 \, \Omega \, m$) present in the data sets was for those obtained in January 2005. Although the resistance of the electrode contacts may have changed from one time interval

Fig. 2. Plan view of the G04 gallery showing the different stages of the excavation process. The electrode arrays are located at the level of the red marker placed at the end of the start niche of G04.
from another, the very high impedance of the resistivity meter ensures that the potential measurements remain unbiased. In fact, no outliers eventually caused by contact defects were detected in the data sets.

3. Pseudo-sections of electrical conductivity

3.1. Geometrical construction of pseudo-sections

The data discussed in the present paper are presented as pseudo-sections of the apparent resistivity \( \rho_a \). Let us recall that pseudo-sections must not be seen as true tomographic cross-sections but, instead, should be considered as a natural manner to display measurements of the electrical resistivity by spatially ordering the data as a function of the electrode positions. An intuitive and natural way to spatially arrange the data is to simply consider that, the larger the angular distance between the \( A \) and \( B \) current electrodes, the larger the radial depth of the region representative of the measurement would be. Both the distance between the \( M \) and \( N \) potential electrodes and their position relative to \( A \) and \( B \) also control the depth range corresponding to the measurement. Although empirically established, this simple rule allows for a first glance at the electrical resistivity distribution provided small resistivity contrasts are assumed. This last condition is satisfied in the EDZ where the electrical resistivity varies by less than one order of magnitude. For resistivity contrasts spanning several orders of magnitude, the patterns displayed by pseudo-sections should be more cautiously considered because of complicated non-linear effects.

The computation of pseudo-sections involves geometrical factors \( K \) which convert the measured electrical resistance \( \Delta V/I \) into the apparent resistivity \( \rho_a = K \Delta V/I \). This conversion is such that, for a medium with a constant resistivity \( \rho \), the apparent resistivity is such that \( \rho_a = \rho \). This implies that the geometrical factors must properly account for the geometry of the experiment.

Theoretical expressions are available for flat half-space geometry and classical electrode arrangements like the Wenner one used in the present study. The circular geometry involved in the gallery of course strongly departs from a flat geometry and we used

\[ A \text{ and } B \text{ current electrodes, the larger the radial depth of the region representative of the measurement would be. Both the distance between the } M \text{ and } N \text{ potential electrodes and their position relative to } A \text{ and } B \text{ also control the depth range corresponding to the measurement. Although empirically established, this simple rule allows for a first glance at the electrical resistivity distribution provided small resistivity contrasts are assumed. This last condition is satisfied in the EDZ where the electrical resistivity varies by less than one order of magnitude. For resistivity contrasts spanning several orders of magnitude, the patterns displayed by pseudo-sections should be more cautiously considered because of complicated non-linear effects.} \]

The computation of pseudo-sections involves geometrical factors \( K \) which convert the measured electrical resistance \( \Delta V/I \) into the apparent resistivity \( \rho_a = K \Delta V/I \). This conversion is such that, for a medium with a constant resistivity \( \rho \), the apparent resistivity is such that \( \rho_a = \rho \). This implies that the geometrical factors must properly account for the geometry of the experiment.

Theoretical expressions are available for flat half-space geometry and classical electrode arrangements like the Wenner one used in the present study. The circular geometry involved in the gallery of course strongly departs from a flat geometry and we used...
specific geometrical factors derived from a numerical modelling of the circular geometry.

Fig. 4 explains how the pseudo-sections presented hereafter are constructed. For the symmetrical Wenner electrode array with a constant interval of size $a=BN=NM=MA$, each measurement is assigned to a point $P$ located at a radial distance $a$ from the wall of the gallery and at an angular position passing through the middle of the potential electrodes $M$ and $N$. The assumed circular geometry of the gallery is clearly not verified in the lower part of the walls and on the flat floor. This produces geometrical distortions and biased apparent resistivity because of the use of the circular geometrical factor $K$. However, these distortions and bias remain constant and they cannot explain the temporal variations observed among the data sets recorded at different time intervals.

3.2. Results

Fig. 5 shows the pseudo-sections of apparent electrical resistivity $\rho_a$ corresponding to the main stages of the excavation process. The measurements done in October 2004 are not displayed because of their sparsity resulting from the important damages produced by the excavation on the electrode array. When repetitive measurements were available, we checked that the corresponding pseudo-sections were identical up to the measurement noise which is less than several percents. All sections display apparent

![Fig. 5. Pseudo-sections of apparent resistivity computed from the measurements performed on the three rings of electrodes at different stages of the excavation. The thickness of the pseudo-section annulus relative to the diameter of the gallery is arbitrary. The orientation of the pseudo-sections is the same as in Fig. 3, i.e. North is on the right side. July=initial state corresponding to Fig. 3, September=measurements done about 3 weeks after the restart of the excavation, December=reference state 1 day before excavation of the EZ-B and HG-A niches shown in Fig. 1, January=pseudo-sections obtained after the excavation of the entrances of the EZ-B and HG-A niches.](image-url)
resistivity contrasts spanning almost the same range $2.5<\rho<16\ \Omega\ \text{m}$. As can be observed, the pseudo-sections of the nearby rings 1 and 2 look very similar while those for ring 3 appear quite different.

As can be seen on Fig. 5, the pseudo-sections of both rings 1 and 2 show conspicuous changes in the apparent resistivity. These changes are particularly important between July and September with an enlargement of the high-resistivity region at the top of the gallery. Less-important changes of the electrical resistivity may be observed in rings 1 and 2 in December and January. The evolution of ring 3 appears quite different from the other two rings, with an overall decrease of the apparent resistivity and no important increase of the high-resistivity regions. Because of the proximity of ring 1 to the face of the gallery in July 2004, a part of the resistivity increases observed between July and September may be due to the retreat of the face. However, if present, these changes should have an invariant circular geometry, a property clearly not shared by the most important resistivity changes observed in ring 1.

### 4. 2.5D direct geo-electrical modelling

#### 4.1. Method

In order to check for the reliability of the pseudo-sections shown in Fig. 5, we performed some direct geo-electrical modelling of the data corresponding to ring 1. Let us emphasise that this modelling does not result from an inverse problem (e.g. Gibert and Virieux, 1991; Pessel and Gibert, 2003) but, instead, has been done through a trial-and-error iterative direct modelling approach.

For the present modelling, a circular 2.5D forward problem was used. The 2.5D geometry assumes that the resistivity structure does not vary in the third direction perpendicular to the modelling plane which contains the $\{A,B,M,N\}$ electrodes. The 2.5D geometry assumed in the present study was certainly not satisfied in July 2004 for ring 1 which was about 1 m away from the face of the gallery. Indeed, at that date, the damaged zone was not yet fully developed, and the medium located on the western side of ring 1 was actually more conductive than assumed in the modelling. This conductive zone reduces the differences of electrical potential measured between the $M$ and $N$ electrodes, giving lower apparent resistivities. In practise, the 2.5D modelling will then be biased toward lower resistivities.

For the 2.5D geometry, the computation of the electrical potential in the modelling plane may be reformulated as a sequence of 2D forward problems solved for a range of spatial wave numbers taken in the direction perpendicular to the modelling plane (e.g. Pessel and Gibert, 2003). This results in a huge reduction of both the memory storage and the computing time. Both the circular geometry and the irregular meshing of the model are accounted for by renormalising the variable electrical conductivity in the Poisson equation to be solved. By this way, the standard MUDPACK (Adams, 1989, 1991) multigrid finite-differences algorithm may be used with a Cartesian square mesh.

The meshing is divided into two domains: an inner domain and an outer one. The inner domain consists is an annular area extending from the wall of the gallery to a depth of 3.2 m. A Neumann boundary condition is applied at the inner boundary corresponding to the wall of the gallery. This condition physically imposes that no electrical current flows across the wall of the gallery, excepted at the $A$ and $B$ electrodes where a prescribed current is injected (generally 100 mA). Because of its high resistivity $\rho$ values $\approx 1000\ \Omega\ \text{m}$ with respect to the

---

**Fig. 6. Resistivity models derived from the pseudo-sections of ring 1 shown in Fig. 5. The radius of the outer boundary equals 5.7 m, and each concentric layer has a thickness of 40 cm. The orientation of the cross-sections is the same as in Fig. 5, i.e. North is on the right side. July=initial state corresponding to Fig. 3, September=3 weeks after the restart of the excavation, December=reference state 1 day before excavation of the EZB and HG-A niches shown in Fig. 1, January=model obtained after the excavation of the entrances of the EZ-B and HG-A niches.**
one of the Opalinus clay, the shotcrete layer is mainly insulating and it is not included in the model. The outer domain extends from the exterior boundary of the inner domain to a large distance of 26 m where a Dirichlet boundary condition holds. This condition physically means that at a sufficient large distance from the gallery, the electrical potential is not significantly disturbed and may be zeroed. It was checked that only negligible perturbations of the electrical potential occur at distances larger than 10 times the radius of the inner boundary where the electrical current is injected. Hence, the outer boundary may safely be considered as an equipotential surface and the Dirichlet constrain may be applied at this limit of the numerical model. The outer domain is assumed homogeneous with an electrical conductivity whose value may be changed in the modelling. The inner domain is aimed at representing the EDZ and may have a spatially variable electrical resistivity. This domain is divided into 8 concentric layers of equal thickness (40 cm). Each layer is divided into 16 angular sectors of equal size. This makes a total of 129 cells where the electrical resistivity may arbitrarily be fixed.

The manual modelling strategy follows a layer-stripping approach. First, the model is given a constant resistivity. Then, the innermost layer of the inner domain is given resistivities such that the data corresponding to shallow depths in the pseudo-sections are correctly reproduced. The resistivities of the innermost layer are progressively copied in the other concentric layers and adjusted to reproduce the whole data set. Several dozens of trial-and-error modellings are sufficient to obtain a resistivity model that reproduces the data within an acceptable misfit range of about 10%. This procedure was applied for each data set, each time starting with a constant resistivity model.

4.2. Results

The resistivity models obtained for ring 1 are shown in Fig. 6, and their misfits are displayed in Fig. 7. The misfits are obtained by subtracting the synthetic data (i.e. potentials) given by the model from the experimental data set. Whence, positive misfits are representative of too-low resistivities in the model while positive misfits are for too-high resistivities. The adjustment of the models was done not only by searching for the smallest as possible global misfits but also by searching for misfits with as identical as possible patterns from one time interval to another. By this way, we produced a set

![Fig. 7. Pseudo-sections of the misfits corresponding to the resistivity models of ring 1 shown in Fig. 6. The misfits are defined as the experimental data minus the synthetic data derived from the models which have been manually adjusted in order to produce very similar misfit patterns. Orientation of the cross-sections is the same as in Fig. 5, i.e. North is on the right side.](image)

![Fig. 8. Pseudo-sections of the apparent resistivity corresponding to the resistivity models of ring 1 shown in Fig. 6. Orientation of the cross-sections is the same as in Fig. 5, i.e. North is on the right side.](image)
of models with almost identical defects so that changes from one model to another are made more significant. The pseudo-sections of the apparent resistivity produced by the geo-electrical models of Fig. 6 are shown in Fig. 8 where one can observe that the models reproduce the main apparent resistivity anomalies present in the data. Interestingly, the resistivity models do not show an increase of resistivity with the circular symmetry expected to be produced by the retreat of the gallery’s face. This confirms the fact that the important resistivity increases observed in the data may safely be attributed to the EDZ expansion.

5. Discussion

5.1. Ring 1

We begin the discussion with ring 1 which, as expected, experienced the most important changes between July and September after the excavation of the G04 gallery. Indeed, both the relevant pseudo-sections (1JUL and 1SEP in Fig. 5) and the resistivity models show an important development of the high-resistivity region located at the top of the gallery (i.e. from 9 to 12 o’clock). However, as can be checked in Fig. 9 (1SJ) which shows the pseudo-sections of the difference between data sets, almost the entire EDZ region has a resistivity increase excepted at the floor where the resistivity slightly decreases. It cannot be excluded that this latter phenomenon is produced by a water input in the gaps (Fig. 3) which remained open during 4 months and where the Opalinus clay was exposed to the very high relative humidity of the ambient atmosphere during the Summer months. Interestingly, the largest increase of resistivity occurs in the outer part of the EDZ. This may be explained by the fact that, as the gallery progressed, the radius of the damaged zone enlarged as did the anomalous stress field. When comparing the pseudo-sections 1SEP and 1DEC of

![Fig. 9. Pseudo-sections of the differences between successive data sets for rings 1, 2, and 3. The orientation of the pseudo-sections is the same as in Fig. 5, i.e. North is on the right side. July=initial state corresponding to Fig. 3, September=measurements done about 3 weeks after the restart of the excavation, December=reference state 1 day before excavation of the EZ-B and HG-A niches shown in Fig. 1, January=pseudo-sections obtained after the excavation of the entrances of the EZ-B and HG-A niches.](Image)
September and December, one observe that the resistivity increases in two curved and opposite regions with a quite symmetric shape visible in the difference 1DS in Fig. 9. The resistivity changes (1JD in Fig. 9) observed between December 2004 and January 2005 after the excavation of the HG-A and EZ-B niches only occur on the north wall. This latter resistivity increase is probably due to the excavation the EZ-B niche whose axis makes an angle of 65° with respect to the gallery axis and has its east wall located at about 1 m from ring 1. Although its entrance is also located at about 1 m from ring 1, the excavation of the HG-A niche did not produce significant resistivity changes. This may probably be explained by the fact that the axis of this niche is at a low angle of 23° with respect to the gallery axis.

The resistivity models obtained for ring 1 (Fig. 6) are compatible with the interpretation drawn from the pseudo-sections. However, a more quantitative analysis may be done for both the resistivity values and the spatial extension of the resistivity domains. In particular, the background resistivity $\rho = 6 \, \Omega \, m$ in the outer domain and in some cells of the outermost concentric layers of the inner domain, a rather low value which falls near the lower end of the resistivity interval $8 \leq \rho \leq 16 \, \Omega \, m$ measured for undamaged Opalinus clay by Kruschwitz and Yaramanci (2004).

In July, the high-resistivity domain is mainly restricted to radial distances $r \leq 1.6 \, m$ almost on the entire circumference of the gallery, excepted at the bottom (i.e. from 5 to 7 o’clock) and in two narrow sectors located in the upper-right (i.e. at 1 o’clock) and in the lower-right (i.e. at 4 o’clock) parts of the wall. The resistivities are found to vary from $9 \, \Omega \, m$ to $33 \, \Omega \, m$. In September, the resistivity domain extends up to radial distances $r = 3.2 \, m$ in the upper part of the gallery (i.e. around 12 o’clock) with resistivities as large as $38 \, \Omega \, m$. Again, these values are slightly lower than the ones found by Kruschwitz and Yaramanci (2004) for the damaged rock zones. The modelling also confirms an extension of the high-resistivity domain centred on 3 o’clock which now goes to $r = 2.4 \, m$ with a maximum resistivity of $24 \, \Omega \, m$. We also observe a moderate but significant extension of the resistive area centred on 8 o’clock. It is interesting to note that the resistivity of the innermost layers remains almost constant from July to September, indicating that the EDZ in the shallowest zones was probably fully formed by July and did not significantly evolved in September. The resistivity model obtained for the December’s data is identical to the September model. This is not the case for the January’s model where a significant increase of the resistivity was necessary in the middle part of the North wall (i.e. centred on 3 o’clock). This might correspond to an additional damage produced by the excavation of the EZ-B niche.

5.2. Ring 2

The pseudo-sections obtained for ring 2 look very similar to those for ring 1. This of course results from the proximity of both rings which are only 50 cm apart. However, several differences may be noted. First, the resistivity measured in July in the top part of the gallery appears significantly higher for ring 2 as can be checked by comparing pseudo-sections 1JUL and 2JUL. Indeed, pseudo-section 2JUL looks more like 1SEP as if more damage in the EDZ of ring 2 already occurred by July 2004. This may be due to a larger stress release resulting from the larger distance between ring 2 and the gallery face. This interpretation agrees with the moderate increase of resistivity observed in September relative to what is observed for ring 1 (compare 1SJ with 2SJ in Fig. 9). This again could indicate that less additional damage occurred in September on ring 2 because more was done by July 2004. At the present stage of this study, we cannot firmly establish this interpretation which needs quantitative geomechanical modelling. Also, we cannot rule out some effects due to a slightly different tectonic behaviour between rings 1 and 2.

5.3. Ring 3

The pseudo-sections of ring 3 show less-pronounced changes of the resistivity from what is observed for rings 1 and 2. This again may partly be attributed to the fact that the EDZ near ring 3 already experienced much of its damage by July 2004. Indeed, this ring is at about 4 m away from the gallery face, and we may expect that at such a distance the perturbing stress field is almost fully developed. However, we observe that the high-resistivity region at the top part of the gallery is far less developed than in the other two rings. From this point of view, it is important to notice that a reinforcement fibre rock bolt was placed precisely on ring 3 (the emerging end of this rod is visible on Fig. 3) and that it could have, as expected, stopped the evolution of the EDZ.
5.4. Correlation with geology

As can be seen in Figs. 5 and 9, the excavation of the gallery produced an evolution of the resistivity structure of rings 1 and 2 in the upper-left part (i.e. upper southern part) and in the southern wall of the EDZ. In this region the resistivity $\rho \approx 30 \, \Omega \, m$, a high value which may result from the combined effects of both fracturing and drying of the Opalinus clay. In September, this high-resistivity region is of a much larger extent, especially in the top part where high resistivities are modelled up to depths of 3 m for ring 1 (Fig. 6).

A detailed small-scale structural survey has been carried out during the construction of the Gallery 04 and of the HG-A and EZ-B niches. The resulting geological mapping centred on the rings of electrodes is shown in Fig. 10. This map shows the unfolded gallery wall and ceiling parts together with 3 structural profiles located near the geo-electrical profiles. Two main structural elements are visible: bedding planes and two sets of tectonic fractures. Whereas the first set is characterised by steeply and extended (>5 m) bedding parallel fractures, the second is characterised by moderately dipping and short (about 1 m) splay fractures. Both fracture systems are sealed and contain slickenfibres on their surfaces, indicating a NW-directed overthrust direction. The mean fracture frequency is about 1.5 fractures per meter. Not shown in this map are structures related to the excavation damaged zone (EDZ) such as extensile open fractures, open desiccation fractures, reactivation of bedding planes and breakout structures.

In order to better correlate the geo-electrical measurements with the EDZ structures, the stress situation has to be taken into consideration as well as the direction of the Gallery 04 relative to the bedding anisotropy (Bossart and Wermeille, 2003). In Fig. 11a, a stereographic projection shows that the gallery is subparallel to the bedding strike direction with a

Fig. 11. (a) Stereographic projection (lower hemisphere) showing the gallery axis (thick line N70) subparallel to the bedding strike direction (N60) and the maximum principal stress direction $\sigma_1$ oblique to the bedding plane. (b) Expected stress redistribution resulting from the excavation with the maximum tangential stresses on the upper right and lower left parts of the gallery. (c) Breakouts occur mainly on the upper left part of the gallery (i.e. SSE side) where the fabric, tangential to the walls, is not supported, and where tangential stresses are high. Only minor breakouts are observed on the lower right part of the gallery (i.e. NNW side) due to the blocking by the concrete invert.
difference of only 10°. The maximum principal stress, \( \sigma_1 = 6.5 \) MPa, is shown oblique to both the bedding and the tectonic fracture planes. The stress redistribution corresponding to this situation is shown in Fig. 11b with the maximum tangential stresses expected on the upper right and lower left of the gallery. The maximum values of these stresses clearly exceed the bedding and the tectonic fault strengths. Indeed, the maximum tangential-stress values are of the order of 3\( \sigma_1 - \sigma_3 = 3 \times 6.5 - 2 = 17.5 \) MPa, and the uniaxial compressive strength of undisturbed Opalinus clay is around 11 MPa. According to these data, Fig. 11c shows that the highest density of EDZ fractures and corresponding breakouts are expected to occur at locations where both the tangential stresses exceed the rock strengths and the bedding and fracture fabric are tangential to the tunnel wall. This is the case at the upper left and the lower right. This phenomena has been clearly observed in a nearby microtunnel with a perfectly circular section (diameter of 1 m) and oriented parallel to the bedding strike. During the construction of the Gallery 04, EDZ fractures and breakouts were clearly observed in the upper left, but not so much in the lower right, as shown in Fig. 11c. The reason for that may be twofold: 1) the concrete liner at the invert supports the anisotropic fabric, 2) the gallery is not strictly parallel to the bedding striking direction. Thus, a large EDZ zone has not been developed on the lower right.

When combining the findings of the geo-electrical measurements with the structural results, we can conclude that the breakouts at the upper left are clearly correlated with the relative high-resistivity values. Chronologically, the EDZ has formed during and soon after the gallery excavation. Later, a drying out process of this loosened zone may happen depending on the seasonal humidity of the gallery atmosphere. Thus, the observed high resistivity result from the combination of these phenomena acting at different time scales. The intense fracturing of this part of the EDZ increases the exchange surface and favours a preferential drying out and the formation of an unsaturated zone. This situation becomes quite clear in all the three circular geo-electrical profiles. A detailed understanding of the respective importance of these effects needs geomechanical modellings as could be done with the FLAC3D software (Brummer et al., 2003).

Many of the geo-electrical measurements show high-resistivity values in the middle part of the northern wall (i.e. at 3 o’clock) where tangential stresses are low, and where only a weak EDZ should form. The profiles of the structural map (Fig. 10) show that this part of the gallery wall is characterised by an increased tectonic fracture density with frequencies of 2–3 structures per meter. The high resistivities can therefore be explained by tectonic fractures which are sealed with calcite shear fibres.

**Acknowledgments**

This work benefited from invaluable help from the whole staff of the FORPRO GdR: Joël Lancelot, Annie Le Bauzec, Patrick Pinettes, and Patrick Verdoux. The field experiments have been greatly improved by the assistance of Nicolas Badertscher and José Métille from the MontTerri staff. This work is financially supported by the CNRS and ANDRA through the GdR FORPRO and corresponds to the GdR FORPRO contribution number 2005/02 A. Financial support of the experimental work at Mont Terri was provided by the NF-PRO European program. Detailed information concerning the Mont Terri URL may be found at http://www.mont-terri.ch.

**References**


