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COMPARISON OF THREE SMALL-SCALE DEVICES FOR THE INVESTIGATION OF THE ELECTRICAL CONDUCTIVITY/RESISTIVITY OF SWELLING AND OTHER CLAYS

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Abstract—Electrical measurements are used in various fields of geoscience and technology, *e.g.* gas/oil exploration or landslide-barrier monitoring. Although clays are amongst the most conducting geomaterials their electrical properties are not yet fully understood. For example, in a recent high-level-radioactive-waste repository large-scale test, a bentonite barrier was monitored geoelectrically. To facilitate interpretation of the results, the reasons for the observed differences in the electrical conductivity must be understood (*e.g.* changes in water content, temperature, salinity of pore water, *etc.*). To improve understanding of the electrical properties of clay minerals, *in situ* measurements must be combined with laboratory measurements. *In situ* measurements allow the characterization of the material in its natural state and laboratory measurements, for small sample amounts, allow the user to vary relevant parameters systematically such as water content, temperature, the salinity of the pore water, or even the cation population if swelling clay minerals are present. *In situ* measurements using different electrode distances, from m to cm range, proved that small-scale investigations are essential because of small-scale material heterogeneities. In the laboratory, all the relevant parameters mentioned above can be controlled more easily for small sample amounts. In the present study three different small-scale devices (SSM1–SSM3) were compared. The geometry factor, *K*, was determined both by calculation and by a calibration against solutions of different conductivity. Calculated and measured geometry factors were in good agreement. SSM1 and SSM2 – both with four pin-shaped electrodes – were found to be particularly applicable for *in situ* measurements. SSM2, with point contacts at the tips of the pins, was considered to be an improvement over SSM1 because the effects of both water content and temperature gradients (which are particularly relevant near the surface) were less pronounced using SSM2. SSM3, in which the contacts are placed at the bottom of a 4.5 mL trough, proved to be useful when systematically varying all of the parameters influencing the electrical properties in the laboratory.

Key Words—Electrical Conductivity of Clays, Electrical Resistivity of Clays, Smectite, Swelling Clay Minerals, Bentonite.

INTRODUCTION

Measurement of the electrical properties of clays is used in various fields of science and technology. As an example, electrical measurements are made for gas/oil exploration in drill holes. The electrical properties are also used for exploration of clay raw materials and water resources.

The electrical conductivity (*EC* = 1/electrical resistivity, *ER*) of clays is known to depend on 'volume conductivity' (≈water content) and 'surface conductivity' (≈diffuse double layer, DDL). The total electrical conductivity depends, therefore, on the DDL and the arrangement of clay-mineral particles in relation to each other (Tabbagh and Cosenza, 2006; Mojid and Cho, 2006; Garcia and Bazán, 2009).

Amongst all the clay minerals, swelling clay minerals (smectites) are known to play a special role in the electrical properties of clays and soils (Waxman and Smits, 1968). Their contribution to electrical conductivity is attributed to the mobility of the exchangeable cations in the interlayer. The tangential mobility (within the interlayer) of the exchangeable cations has been reported by many studies, *e.g.* Weiler and Chaussidon (1968) and Ishida *et al.* (2000). The reasons for differences in the electrical properties of clay minerals and clayey materials, however, are not yet fully understood (*e.g.* Kaufhold and Penner, 2006). For example, little is known about the effect of the variability of clay minerals (particle size, charge distribution, chemical composition, partly soluble admixtures, microstructure, *etc.*) on the electrical properties. The layer-charge density (Lagaly, 1994), the smectite content (Kaufhold *et al.*, 2002), the variable charge (Kaufhold and Dohrmann, 2013), and the cation exchange capacity (CEC) probably have an influence also.

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To fill this gap, the differences in the electrical properties of clays need to be studied under well defined conditions which can be provided by a small-scale laboratory device allowing parameters to be varied, including water content, temperature, salinity of the pore water, texture, and type of clay mineral. For example, Taioli *et al.* (2006) published a report on a small-scale laboratory device but admitted that it may not be applicable to clay minerals and/or clayey soils. On the other hand, the electrical properties can be measured *in situ* in a flow-through cell to investigate the effect of permeation of solutions. Examples of such devices were presented by Slater and Lesmes (2002) and Binley *et al.* (1996).

Large- and medium-scale *in situ* or field measurements of the electrical properties are conducted routinely either by logging in a bore hole or at the surface. In both cases either galvanic methods (direct contacts) or inductive methods can be used, as described by Schulmeister *et al.* (2003). An electrode device was developed (Veris® 3100, Veris Technologies, Salina, Kansas, USA) which can be towed by a car or by hand for mapping soils. The inductive EM38 device (Geonics Ltd, Mississauga, Ontario, Canada) can be used for situations involving approximately the same scale. Both devices provide comparable values (Suddeth *et al.*, 1999). The heterogeneity of clays in the open pit is commonly on a smaller scale, however. A small-scale investigation of the electrical properties of soils (Igel, 2007) addressed the analytical challenges resulting from the small scale.

The aim of the present study was to assess the applicability of three different small-scale devices with respect to the systematic investigation of the electrical properties, both *in situ* and in the laboratory.

GEOELECTRICAL BACKGROUND

All electrical measurements of geomaterials (rocks, stones, *etc.*) require a minimum of four electrodes. Two of them, usually labeled A and B (or C1 and C2), respectively, are used to insert a current into the material to be investigated. The other two, labeled M and N (or P1 and P2, respectively) probe the resulting potential difference (voltage). For small-scale measurements, the current needs to be small to avoid overstressing the resistivity meter but also to prevent unwanted heating or electrochemical reactions at the electrode–soil/clay interfaces. The resistivity/conductivity of the material results from the relations illustrated in equations 1 and 1a.

$$ER\ [\Omega\mathrm{m}] = K\ [\mathrm{m}]\cdot U_{\mathrm{MN}}\ [\mu\mathrm{V}]/I_{\mathrm{AB}}[\mu\mathrm{A}] \tag{1}$$

$$EC\ [\mathrm{S/m}] = 1/ER = 1/K\cdot I/U \tag{1a}$$

The factor K depends only on the geometry of the measurement device and is, therefore, referred to as a ‘geometry’ or ‘configuration’ factor; it has units of m. The K factor must be determined for each measurement device, calculated based on either the geometry or calibrated by materials of known resistivity, *e.g.* salt solutions.

The K factor for four-point electrodes placed at the surface of an infinite half space depends only on the distances r_i between the current electrodes and the potential electrodes (equation 2; *e.g.* Telford *et al.*, 1976). An infinite half space is the earth below when standing on the ground and a full space exists when buried deep in the ground with earth above and beneath.

$$K_{\text{half-space}} = 2\pi/(1/r_{\mathrm{AM}} - 1/r_{\mathrm{AN}} - 1/r_{\mathrm{BM}} + 1/r_{\mathrm{BN}}) \tag{2}$$

In the present study, the Wenner arrangement was used which means that all electrodes were arranged linearly with equal distances. In this case equation 2 is reduced to equation 3

$$K_{\text{half-space}} = 2\pi a \tag{3}$$

where a is the distance between electrodes (cm)

Equations 2 and 3 are valid for point electrodes, which means that the insertion depths of the electrodes are much smaller than the distance between them. This condition is rarely fulfilled in the case of small-scale arrangements.

If point-shaped electrodes are not placed at the surface but at a certain depth, t, then the geometry factor depends on both the separation a and the depth t and the following equation (4) can be used:

$$k(a,t) = 4\pi/\left[1/a + 2/\sqrt{a^2+4t^2} - 1/\sqrt{a^2+t^2}\right] \tag{4}$$

MATERIALS AND METHODS

To measure the electric resistivity (ER)/electrical conductivity (EC) the ‘4-Punkt-light’ measurement device, developed and distributed by Dipl. Geol. E. Lippmann (LGM company, D-94571 Schaufling, Germany), was used. The electrical current is adjusted to 0.1, 1, or 10 μA and the resulting voltage (in μV) of both of the inner electrodes (M, N) is displayed. The measurements are conducted at a constant frequency of ~10 Hz.

Small-scale *in situ* electrical measurements were conducted in several German open pits with different types of clay: Bentonite (Hallertau, Bavaria: Kaufhold *et al.*, 2003), ceramic clay (Westerwald, Rhineland-Palatinate: Kaufhold and Penner, 2006), and marine (brick) clay (Sarstedt and Vöhrum, Lower Saxony and Friedland, Mecklenburg-Western Pomerania).

Samples of each of the different clays were collected at the exact point of measurement and sealed carefully in plastic bags to determine the water content by oven drying at 105ºC in the laboratory. In addition, the smectite content was determined either based on CEC data (Meier and Kahr, 1999) or by the methylene-blue

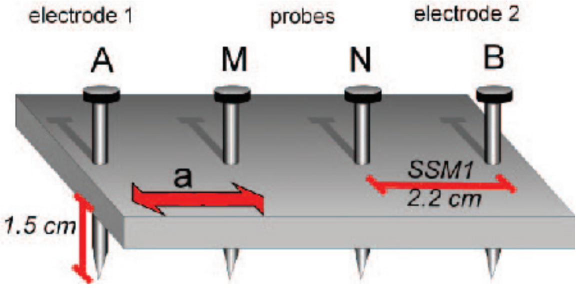

Figure 1. Schematic representation of the small-scale Wenner arrangement SSM1.

method. Both methods should be considered critically as discussed by Kaufhold and Dohrmann (2003).

Three different devices were used and are described below.

SSM1 (small-scale measurement device 1)

The first small-scale, *in situ* measurements were conducted to compare the electrical properties of bentonites with their mineralogical composition, *i.e.* the smectite content (Kaufhold *et al.*, 1998, 2003; DE 19839531). The aim was to use the data for quality control in bentonite mining. Measurements were performed in the open pits (*in situ*) on fresh and on smooth surfaces. The partially dried surfaces were removed with a shovel and measurements were performed quickly (within 1 min) to avoid drying effects. The temperature was recorded simultaneously. The electrodes were arranged according to Wenner, as described above (Figure 1). The distance between electrodes (*a*) was varied from 30 to 2 cm. The 2 cm device was termed SSM1; data shown in the present study were measured with *a* = 2.2 cm.

In a first approach, the distance between the electrodes (*a*) was 30 cm. This device was not applicable in the clay open pits because of: (1) the heterogeneity of the clay in this scale (cm–dm); (2) the difficulty in producing an even surface; and (3) the unavoidable occurrence of cracks between the electrodes. Therefore, *a* was decreased. In a second approach, *a* was varied from 2 to 6 cm (Figure 2). In this case the point electrode condition was obviously not fulfilled and the mutual interference between the electrodes was taken into account by calculating an appropriate *K* factor. Appropriate *K* factors for small-scale measurements were used, making use of a theorem of electrostatics which allows the user to approximate the electric field of a thin stick by the known electric field of an elongated half-ellipsoid, as derived by Igel (2007). His solution requires the numerical solution of an elliptical integral. Rücker and Günther (2011) developed an even more versatile 'Finite-Element' approach, which enables the model calculation of virtually any shape of the electrodes. The application requires intensive computer resources. According to Rücker and Günther (2011) however, the *K* factor of the complete electrode model of cylindrical electrodes is met quite closely by the *K* factor of point electrodes placed at a depth of ~60% of the length of the actual electrodes. Equation 4 with $t = 0.6 \cdot L$ was used to calculate the *K* factors of SSM1 (L = length of the electrode).

The curves (Figure 2) show a slight increase in *ER* depending on the distance between the electrodes, which may be related to near-surface material heterogeneities or vertically variable parameters such as temperature and/or humidity. Interestingly, curves of different shapes were observed. In some cases, perfect linears were observed but some curves, particularly of open pit 2,

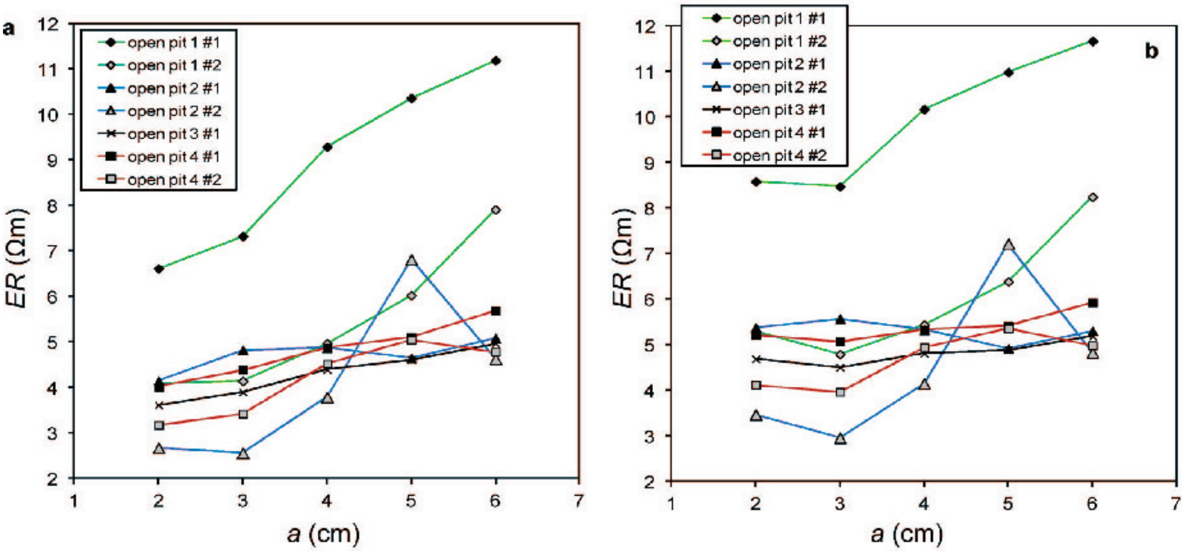

Figure 2. Dependence of apparent electrical resistivity (*ER*) of Bavarian bentonites on the distance of electrodes before (a) and after (b) *K* factor correction.

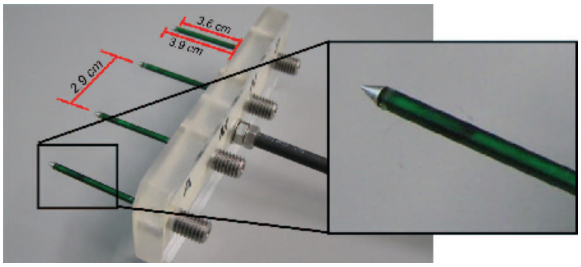

Figure 3. Photograph of the alternative device (SSM2) with real point electrodes (a = 2.9 cm).

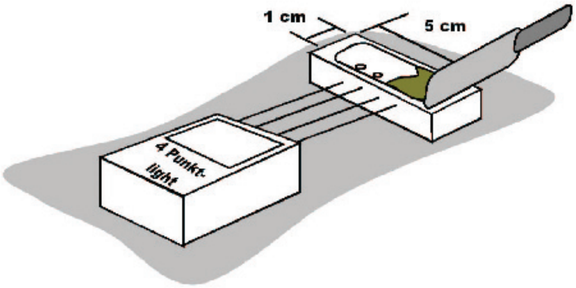

Figure 5. Schematic representation of the 4.5 mL small-scale laboratory measurement device (SSM3). The clay is smeared into the trough using a spatula.

indicated the lateral heterogeneity of the clay even on a small scale. Therefore, the smallest reasonable scale was selected. A distance (a) of 2 cm results in a length of the measured area of 6–10 cm and collecting the material which was penetrated by the electrodes results in a sample mass of 10–20 g, which is a typical amount of clay sample used in the laboratory for characterization after homogenization by grinding. Technically, a, the distance between the electrodes, may be decreased, but this would involve distances smaller than that commonly used in the laboratory. The distance between the electrodes and probes (a) should, therefore, be ~2 cm and for practical reasons was fixed at 2.2 cm.

SSM2 (small-scale measurement device 2)

Because of the lack of real point electrodes of SSM1 (Figure 1 and discussion thereafter), a different device was tested (Figure 3). The cylindrical part of the electrodes was surrounded by insulating plastic and only the tip of the electrode was in contact with the clay.

The conducting tips of the electrodes of SSM2 were intended to be surrounded entirely by rock to simulate point electrodes. The depth of the point electrodes of SSM2 was ~3.75 cm (average depth of the conductive pin). To calculate the K factor of SSM2, both the variable a and the depth t must be considered (according to equation 4). For a given electrode a, the K factor increases with depth of submersion of the point electrodes (Figure 4). For t = 0, the factor starts with the 'half space' value $K_0 = 2\pi a$ and at depths $t >> a$ it reaches the upper limit of the 'full space' value $K_\mu = 4\pi a$.

For measurements using SSM2 with a = 2.9 cm and t = 3.75 cm, the calculated geometry factor was K_{SSM2} = 0.328 m.

SSM3 (small-scale measurement device 3)

To investigate systematically the correlation of clay properties with electrical parameters, a further small-scale measurement device was developed in the shape of a small trough (Figure 5). To measure the electrical properties, the sample must be ductile (plastic) because it is smeared on the electrodes which are arranged at the bottom of the small trough (4.5 mL). The trough was made of insulating plastic, the electrodes were of steel and arranged according to Wenner. Care must be taken with respect to drying after smearing the clay gel in the trough. The measurements were performed quickly enough that no significant drying had occurred. Smearing the gel into the trough took ~5 s and after a few more seconds a stable value was obtained, noted, and ~1 mL of the material was used to determine the water content by oven drying (a dried and weighed cup

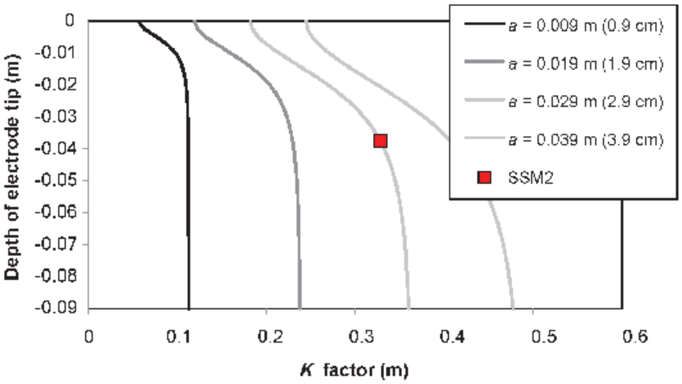

Figure 4. Calculation of the K factor for different electrode separation distances, a, and depths, t. The square represents the SSM2 parameters (a = 2.9, t = 3.75 cm).

was waiting on the nearby balance). The temperature was also a crucial factor influencing the electrical conductivity. All materials and the measurement devices were, therefore, carried out in a laboratory with constant temperature (22ºC).

The *K* factor of SSM3 could not be calculated because of the complex geometry. It deviates in two senses from the idealized point solution of equation 3: (1) the electrode buttons are not small compared to the electrode distance; and (2) the small volume of the trough imparts notable boundary conditions instead of the infinite half space.

Although the effect of this complex geometry could, in principle, be treated by a 'Finite-Element' modeling procedure, the best way to determine the applicable *K* factor in this case is experimental calibration with liquids of well known conductivities.

Calibration

The *K* factor can be calculated but ideally is determined empirically by calibration. To calibrate, a set of different solutions with different ionic strengths was used. SSM3 was calibrated with 4.5 mL of each solution but investigating the solutions with SSM1 and SSM2 turned out to be a challenge. In a first approach, a 5 L cup containing the different solutions was used and the electrodes were inserted as in a clay or soil. However, the ratio of the results of parallel measurements with all three SSMs obtained in the laboratory did not match with the ratio obtained from parallel measurements in the open pits (real half space). Therefore, in a second attempt, a 70 L vessel with 50 L of the different solutions was used and was adequate. The distance of the measurement location in the water bath to the walls was 25 cm and the distance to the bottom was ~35 cm. These distances were required to mimic a real half space. The room temperature was 22ºC and the temperature of the solutions was 25ºC. The reference conductivity of the solutions was measured with a calibrated laboratory conductivity meter (conductometer HI 9033 HANNA) which is applicable for solutions. The laboratory calibration started with tap water (commonly 18 Ωm as confirmed by the reference conductivity meter). As explained above the M-N voltage was measured with all devices and the reference value (measured with the conductivity meter) was also recorded. Different ionic strengths were adjusted by adding a defined amount of NaCl. All data are summarized in Table 1 and the calibrations are given in Figure 6. The pure water value measured with SSM3 was expected to be affected by traces of clay and salt on the surface of the plastic trough. These traces could not be removed by washing and so this value was not considered in the determination of the calibration factor.

The *K* factors for SSM1 and SSM2 were calculated based on equation 4. In the case of SSM1, with $a = 2.2$ cm and $L = 1.6$ cm, the equivalent depth of point electrodes

Table 1. Raw data and calculated calibrations for all three devices.

	T (ºC)	Conductometer			SSM1 (10^4 nA)			SSM2 (10^4 nA)			SSM3 (10^2 nA)		
50 L lab. water	25	[µS/cm]	[mS/m]	[Ωm]	[µV]	[V/A]	*K* [m]	[µV]	[V/A]	*K* [m]	[µV]	[V/A]	*K* [m]
0.02 mol/L (58 g NaCl/50 L)	25	531	53.1	18.8	946	94.6	0.20	547	54.7	0.34	543	5430	0.0035
0.04 mol/L (+58 g NaCl/50 L)	25	2880	288	3.5	193	19.3	0.18	105	10.5	0.33	136	1360	0.0026
0.06 mol/L (+58 g NaCl/50 L)	25	5030	503	2.0	115	11.5	0.17	61	6.1	0.33	84	840	0.0024
0.1 mol/L (+116 g NaCl/50 L)	25	7015	701.5	1.4	77.2	7.72	0.18	42.5	4.25	0.34	55.7	557	0.0026
0.2 mol/L (+290 g NaCl/50 L)	25	11240	1124	0.9	51.9	5.19	0.17	27.4	2.74	0.32	33.8	338	0.0026
	25	22000	2200	0.5	27.5	2.75	0.17	14.8	1.48	0.31	18.6	186	0.0024

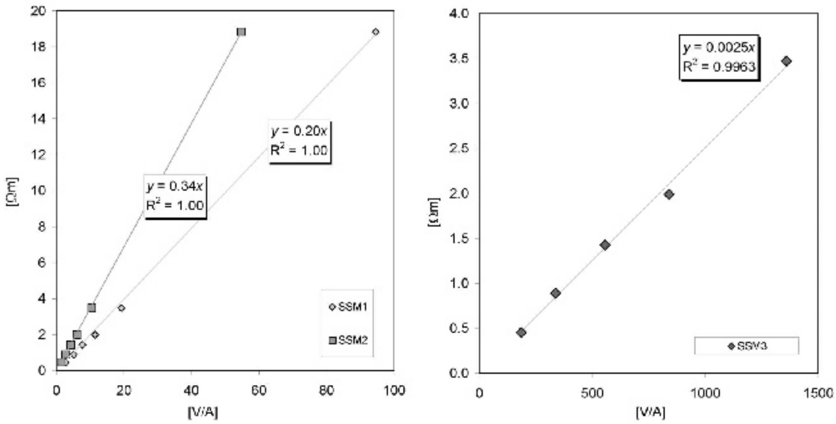

Figure 6. Calibration curves of all three devices.

becomes t = 0.96 cm and the calculated result is K_{SSM1} = 0.174 m. This corrected value is ~26% greater than the improper surface-point electrode approximation from equation 2. The experimental calibration of SSM1 (Table 1 and Figure 6) correspondingly yields K = 0.18 m (average value) and K = 0.20 m (derived from the slope in Figure 6), thus confirming the approximation algorithm. For SSM2, the calculated K value (0.33 m) was in particularly good agreement with the 0.34 m value determined empirically, probably because of the presence of point electrodes which are easier to consider quantitatively. This does not apply to the calibration point measured for tap water (the largest *ER*), which in all cases fails to follow exactly the trend evident from the other calibration points.

The K value of SSM3, however, due to the even more complex geometry, would be much more difficult to calculate and hence had to be determined empirically (0.0025 m).

In addition to the different solutions, clays or soils could also have been used for calibration. This could be important because of the different interface of the electrodes and the water compared to the electrodes and a solid (clay or soil). Theoretically, the K factor should depend only on the geometry. Strong evidence in support of the validity of the K factors determined with the solutions is the fact that the ratios of the values determined with all small-scale devices do not depend on whether a solid or a liquid is measured. In different open pits all three SSMs were used to measure the voltage necessary to maintain a specific current (*e.g.* 10 μA). The ratios of these values of the different SSMs were in good agreement with the ratios of the voltages determined in the solutions (which are listed in Table 1). No other materials were, therefore, needed as references.

RESULTS AND DISCUSSION

In situ measurements with SSM1 and SSM2

The plan was to use both devices for *in situ* determination of the electrical properties in open pits. SSM1 was used by Kaufhold *et al.* (1998) and Kaufhold *et al.* (2003) for the investigation of more than 200 different Bavarian bentonites. Based on these measurements, an empirical relation between *ER*, water content, and temperature and in turn a complementary method for quality control were established. Later, investigations of the Westerwald ceramic clays also proved a strong correlation between the *ER*/water content ratio and the CEC (smectite and smectitic layers content in mixed-layer minerals: Kaufhold and Penner, 2006). The clays in the present study, however, are dominated by low-CEC clay minerals (kaolinite, illite), which provide a more or less CEC-independent contribution to conductivity which explains the slightly lower *ER* values compared to the CEC and water content of the Bavarian bentonites (Kaufhold and Penner, 2006). The disadvantage of this method, however, is that a fresh surface has to be produced because the water content of the bentonite at the surface is smaller than within or even decreases during the measurements. Moreover, the temperature is known to affect the measurement and the temperature gradient is significant near the surface. Note, for quality-control purposes, no measurements of surfaces exposed to the sun were taken. These problems can be overcome to some degree by using device SSM2 because of the distance of the clay volume determining the electrical signal from both gradients (water content and temperature). To test both methods and investigate the compatibility, parallel measurements were conducted in different clay open pits (Figure 7).

Both devices (SSM1 + SSM2) are applicable in clay open pits with plastic/ductile clay. Note that neither can be used in the case of clayey material containing a network of small calcite or gypsum veins because these veins isolate the conducting clay. Such circumstances were found in some of the bentonite mines of Milos, Greece, but generally are rare. In principle, both devices could have been used as a reference measurement device for the present study. A typical measurement scenario is shown in Figure 8. Note that the temperature was also recorded to enable further interpretation of the data.

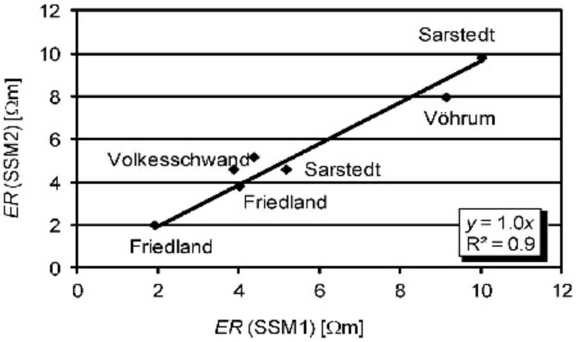

Figure 7. Comparison of SSM1 and SSM2 by means of seven parallel measurements in four different clay deposits.

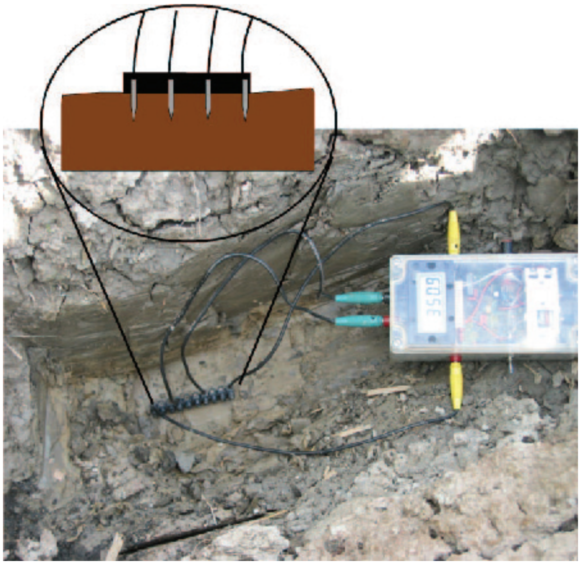

Figure 8. *In situ* measurement of electrical properties using the SSM1 device. At the same location, samples were also taken to determine water content and the temperature was measured.

Laboratory measurements with SSM3

The electrical properties of clays are known to depend on the water content, among other parameters (including the CEC). The small-scale laboratory device SSM3 permits investigation of this relation over a wide range of water contents (Figure 9). The water content (Figure 9) represents the so called 'mineralogical water content' (mass of water desorbed by drying compared to the initial total mass). Accordingly, a common clay with 90 wt.% water is a suspension (90 wt.% = 90 g water and 10 g clay). The 'technical water content' of this suspension would be 900%. Comparing literature data, the type of water content must be considered. To record the curves, the clays were mixed with excess water first. Values representing different water contents were then recorded stepwise and by slow drying of the clay gels and smearing them into the 4.5 mL plastic trough (SSM3). Therefore, the curves are discussed starting with large water contents and proceeding to smaller values. The curves shown (Figure 9) can be subdivided into three branches and these may be explained by the schematic model shown in Figure 10. The first branch, at large water contents (roughly >70 wt.%), reflects the electrical properties of a clay suspension which differs from a gel in that water forms the matrix and the clay particles are dispersed in the water matrix. At water contents of <60 wt.% (in most cases a clay gel) the properties start to depend on the clay particle interactions (and contacts) because the clay particles are expected to form the matrix (percolation theory; *e.g.* Kesten, 2006). For water contents of 30 to 60 wt.% a linear electrical conductivity range was observed (2nd branch). Because the conductivity–water relation is apparently linear in this range, considering the conductivity rather than the resistivity is reasonable. Note that in this linear range the electrical conductivity only increases if the conductivity of the pore water is significantly less than the conductivity of the clay minerals. In turn the electrical conductivity increases because (1) the smaller amount of (electrolyte poor)

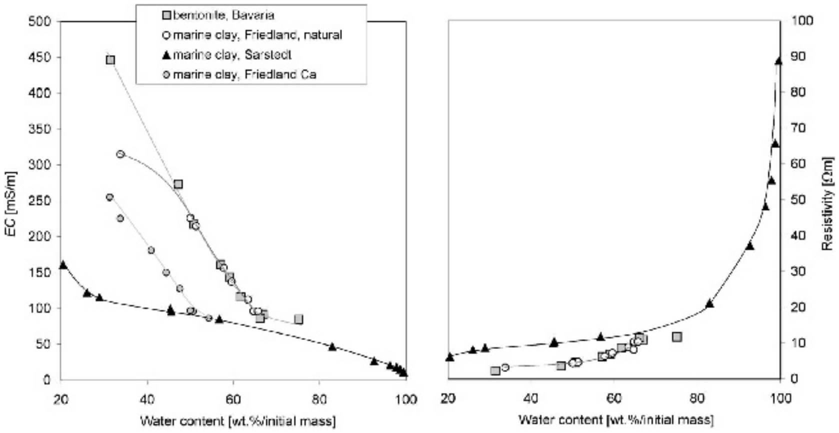

Figure 9. Dependence of the electrical conductivity and electrical resistivity on the water content of three different clays. The Friedland clay was investigated in its natural form (Na^+) and after exchange of the Na^+ by Ca^{2+}.

water and the larger amount of clay minerals and (2) the increased number of clay-particle bridges. Each clay reaches the plastic limit (at an individual water content) and hence cannot be smeared further without the formation of cracks and/or voids. These values were not considered further but represent the 3rd branch. No values are presented because of the macroscopically evident occurrence of cracks. The electrical properties would then depend more on the compaction caused by smearing the clay than on material properties. The maximum electrical conductivity is expected to correspond to water saturation.

Examination of the water content (*WC*)–*EC* curves obtained by SSM3 actually allows for the comparison of the *EC* values of different clays, *e.g.* the marine Friedland clay with bentonite from Bavaria. Interestingly, the natural Friedland marine clay had a larger *EC* value than the bentonite even though it had a significantly smaller CEC (Friedland = 30 meq/100 g, bentonite = 70 meq/100 g). According to Waxman and Smits (1968) the CEC is expected to affect the *EC* significantly. If CEC is to be the dominant factor then the bentonites should have shown much larger *EC* values than the Friedland clay. This unexpected result may be due at least partly to the type of exchangeable cation. The smectites (free smectite + smectitic layers of mixed-layer minerals) of the Friedland clay were dominated by exchangeable sodium, which contributes significantly to electrical conductivity because of the larger mobility of the Na^+ compared to Ca^{2+} and likewise the fact that more cations are present in the case of Na^+ in the interlayer (two permanent negative clay charges are compensated either by one Ca^{2+} or two Na^+ cations). After Ca^{2+} exchange of the Friedland smectites an electrical conductivity was observed as expected (less than that of the bentonite which is commonly dominated by Ca^{2+} and Mg^{2+}).

The aim of most of the measurements of the electrical properties is to rank different materials according to their conductivity or resistivity. The data presented (Figure 9) reinforces the idea that such a ranking cannot be made without defining a reference water content. For example, the Bavarian bentonite had a smaller conductivity value at 60 wt.% water than the Sarstedt clay at 20 wt.% water. Note that in the field, *i.e.* in a drill core or an open pit, the water content of the clays may vary depending on the ambient conditions.

To improve the comparability of the conductivity of different clays, defining a constant reference water content (*e.g.* 50 wt.%) or stating the slope or the *y* intercept of the linear part is suggested (Figure 10).

SSM3 could also be used in the open pit, although this may not be necessary. Regardless, to further test the applicability of this device, parallel measurements were performed with SSM1 and SSM3 in three different clay open pits (Figure 11).

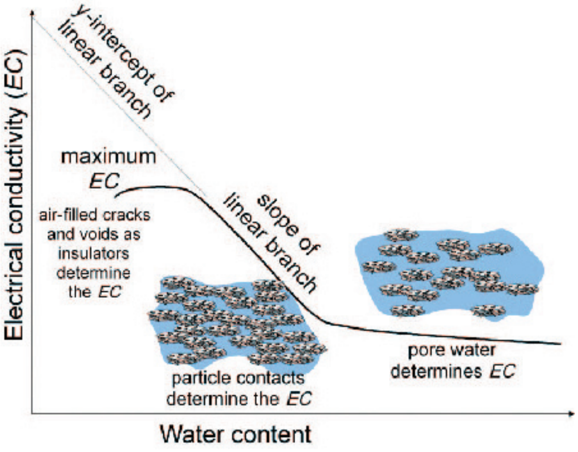

Figure 10. Model explaining the typical *WC–EC* curve of clays.

First, SSM1 was used. Then, the plastic clay was smeared into SSM3 and the resistivity was measured. Finally, a sample was collected and sealed carefully for water-content determination in the laboratory.

A satisfying correlation was found (Figure 11) which proves the applicability of SSM3 for both *in situ* and laboratory investigations. However, the resistivities obtained with SSM3 were systematically larger than those measured with SSM1. This may be explained by the fact that smearing the mostly relatively dry materials leaves some voids which causes an increase in the resistivity. Therefore, SSM1 and SSM2 are preferred for *in situ* measurements.

Parameters influencing the electrical properties

The dependence of the electrical properties on the water content has been explained above. The *WC-EC* curves recorded with SSM3 were obtained by drying a clay gel or a suspension. The pore-water composition

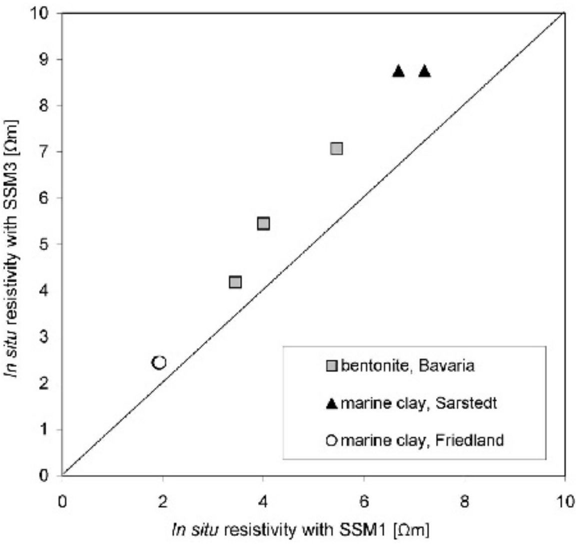

Figure 11. Comparison of the results of SSM1 and SSM3 when applied *in situ*.

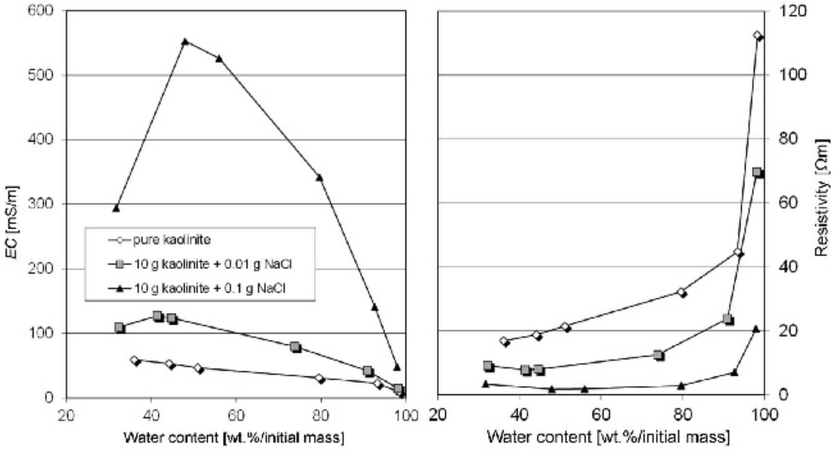

Figure 12. SSM3 measurements of the electrical properties of kaolinite to study the effect of soluble minerals.

and in turn the volume conductivity were, therefore, variable. For soils or sediments, however, a constant salinity of the pore water is commonly considered. This should not reflect reality because in a clay or clayey sediment a certain amount of soluble minerals is present and the amount of water depends on external factors (*e.g.* humidity, rainfall, groundwater level, *etc.*). Hence, the water-soluble minor component ratio is variable and determines the volume conductivity. To assume a certain type and amount of soluble mineral in the sample is more realistic (*e.g.* 0.1 wt.% NaCl, 1 wt.% calcite, *etc.*). In the case where carbonates and/or gypsum, which are partly soluble in water, are present, the pore-water composition depending on the variable water content is even more complex because the pore-water composition depends on the solid/liquid ratio. In turn, this determines the amount of soluble carbonate/gypsum. On the other hand, using the small-scale laboratory device also allows measurement of the *WC–EC* curve with constant electrical conductivity of the pore water. In this case, different suspensions, gels, or dry pastes must be prepared using different amounts of one solution. This was not investigated in the present study, however. Instead, the *WC-EC* curves of kaolinite with different amounts of soluble phases (model substance halite) were measured (Figure 12).

A further example of the usefulness of different small-scale devices is the investigation of the effect of preferred orientation (texture) of clays on the anisotropy of the electrical properties. In four open pits (Westerwald, Bavaria, Friedland, Sarstedt), measurements were performed both perpendicular and parallel to the bedding (Figure 13). At Westerwald, Bavaria, and Friedland no differences between perpendicular and parallel measurement results were observed. The clay minerals of these materials, therefore, were believed to be arranged more or less randomly and fine bedding was assumed to be absent.

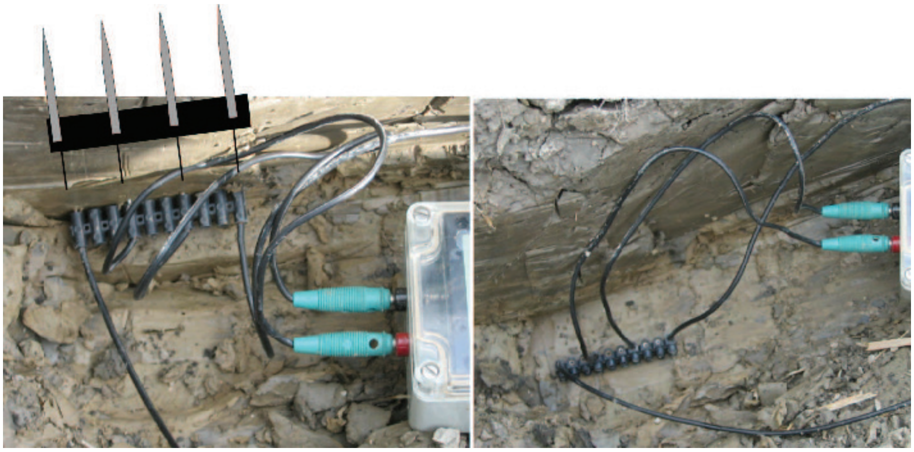

Figure 13. Photographs of parallel and perpendicular *ER* measurements using SSM1.

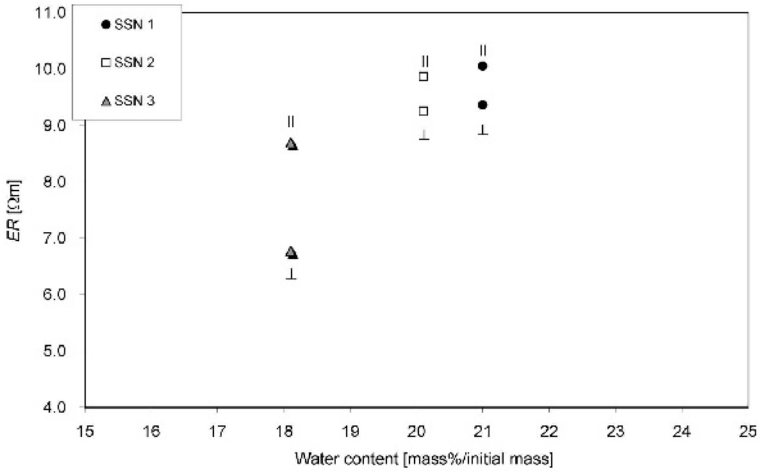

Figure 14. Investigation of the anisotropy of electrical properties at three sites in the Sarstedt clay deposit.

At the Sarstedt site, however, where macroscopically visible fine bedding occurs, the electrical behavior was different. A larger *EC* value was found when measuring perpendicular to the bedding (Figure 14). No proven explanation can be provided for this observation and further detailed investigations using SSM1 and SSM3 are required. Various interpretations are offered in the schematic Figure 15. On one hand, the insertion of electrodes parallel to bedding may cause some cracks because clays are known to break mainly parallel to the bedding. On the other hand, vertical insertion of the electrodes compresses the layers and might be expected to cause fewer microcracks.

Based on the assumption of fine bedding, the results observed may also be explained by the electrical short cut of layers with different conductivity in the case of perpendicular electrodes. This second model assumes that the fine bedding consists of a mixed layering of conducting (clay-rich) and more isolating layers (carbonate or quartz-rich), which is common in sediments. In the case of parallel insertion of the electrodes, the carbonate/quartz-rich layers would, to a certain extent, isolate the layer in which the electrodes are present. In contrast, electrodes inserted perpendicularly would shortcut the different conducting layers and, in a way, bridge the isolating layers. Most of the differences observed were not large (<1 Ωm) and different mechanisms are assumed to play different roles. Identification of the exact cause of these differences requires additional systematic investigations, ideally using SSM1 and SSM2, because the connecting effect would be small in the case of the second explanation and SSM2.

SUMMARY AND CONCLUSIONS

Three different small-scale devices (SSM1, SSM2, SSM3) were compared with respect to their applicability for both *in situ* and laboratory measurements of the electrical properties of clays. All devices were based on the Wenner arrangement and measurements were conducted with the '4-Punkt-light' apparatus. Variation of the electrodes and probes proved that a suitable distance, *a*, was ~2 cm (for technical reasons 2.2 cm was used). The volume determining the electrical properties in this case corresponded to the typical amount of clay sample investigated in the laboratory (after homogenization).

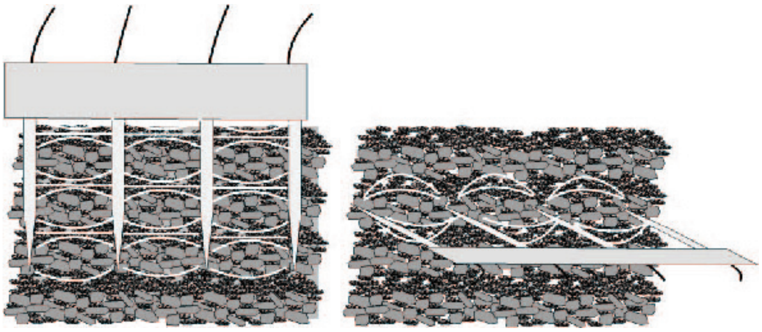

Figure 15. Model to explain the differences in parallel and perpendicular measurements.

The comparability of EC values measured *in situ* with parameters derived in the laboratory, such as the smectite content or CEC, is guaranteed. All three devices were calibrated against the same set of aqueous solutions. Interestingly, a volume of 50 L was required for the calibration tank in order to impede boundary effects from the walls. Using a 5 L tank only resulted in a different ratio of the electrical signals derived from the different devices compared to the ratio measured *in situ* with an infinite half space. Parallel to the experimental calibration, the *K* factors of SSM1 and SSM2 could be calculated analytically based on their geometry. Devices 1 and 2 were particularly applicable for *in situ* measurements whereas SSM3 was advantageous in the laboratory for the systematic investigation of some parameters affecting the *EC* of clays. SSM1 was used for complementary quality control throughout bentonite mining. One concern using this device was the direction of electrode insertion (parallel or perpendicular to bedding). Accordingly, in all open pits investigated in the present study, measurements were performed both parallel and perpendicular to the bedding. Only in one brick clay deposit (Lower Cretaceous clay in N. Germany, Sarstedt) was a significant difference observed. This requires further investigation. SSM2, with actual point electrodes, was considered to be an improvement over SSM1 because water content and temperature gradients which are particularly relevant near the surface were less pronounced using this device. SSM3, on the other hand, proved to be useful at recording the water content–electrical conductivity relation (*WC-EC* curves). All the clays investigated showed increasing *EC* (decreasing resistivity) with decreasing water content. Below water saturation of the clay, the *EC* values dropped because of the formation of cracks and voids. The curves measured suggested that comparisons of the *EC* values for different clays requires consideration of either a reference water content or, even better, the slope of the linear branch of the *WC-EC* curves. The effect of soluble phases (as minor constituents of the clays), which depend on the degree of drying and which determine the pore-water conductivity, was measured. Most of the clays were expected to contain <0.1 wt.% halite. Assuming a variable pore-water composition which can be described by the content of soluble phases (*e.g.* halite) in the dry state was more realistic than assuming a constant pore-water composition because the amount of water in soils and in sediments depends on the ambient conditions and, hence, is variable. Future work will be devoted to understanding the reasons for differences in the electrical properties of clays. The results of the present study (*e.g.* Friedland clay *vs.* bentonite) proved that the Waxman and Smits equation (Waxman and Smits, 1968) may be useful to explain the difference between sand, silt, and clay, but not to explain the differences between different clays.

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