SAGE 2023-2025

Electrical resistivity studies for bentonite

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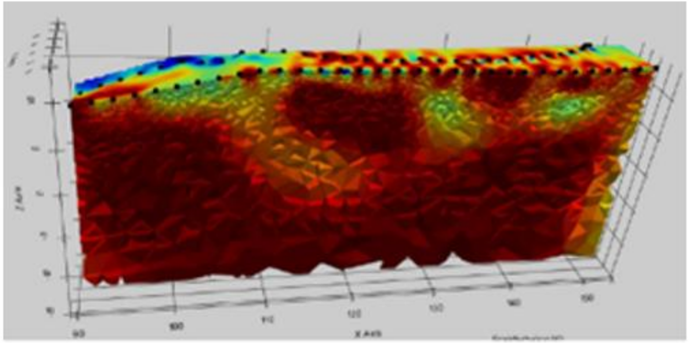
13/11/2025 VTT – beyond the obvious

Electrical Resistivity Tomography (ERT)

- Typically, ERT is used to investigate underground structures & provide information about geological, geotechnical, & hydrological conditions
  - Resistivity distribution can be used to differentiate between subsurface materials with differences in resistivities
  - Resistivity of a single material can vary by several orders of magnitude depending on the conditions, which makes qualitative analysis (e.g., water content) difficult

→ Need for research to understand the effects of different parameters on resistivity

VTT references
- Embankment dam investigations at hydropower plants
- Measurement applications for underground & surface mining sites
- Landfill site investigations
- Customized ERT measurement design and installation for Posiva's full-scale radioactive waste disposal system test (FISST)



ERT measurement cables and 3D underground visualization

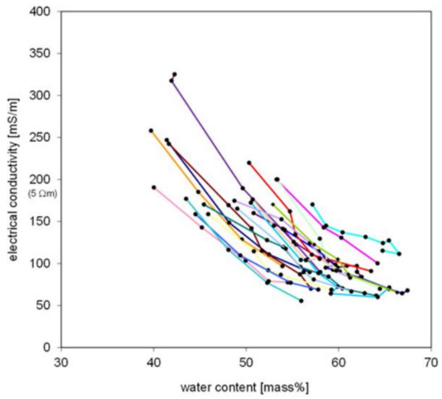
Electrical resistivity studies in SAGE

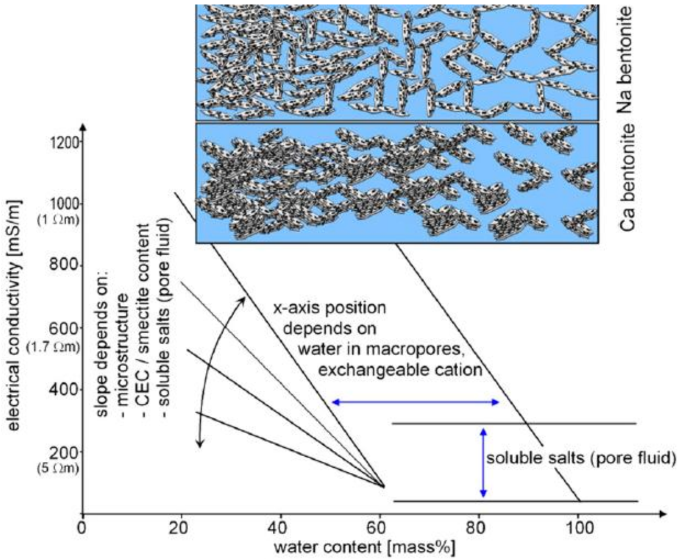
- In SAGE, the objective of the bentonite resistivity studies is to obtain quantitative data of the resistivity for different bentonite types in various conditions, from small-scale to larger-scale

  - In 2023, resistivity measurements for small cylindrical bentonite samples
  - In 2024, electrical resistivity tomography (ERT) measurements using multi-electrode arrays on small cylindrical bentonite samples during saturation. Comparing the results with XCT studies
  - In 2025, additional resistivity measurements for small cylindrical bentonite samples. Further development of ERT measurement system. **To be done**: ERT measurements during saturation of a bentonite sample and comparison of results with XCT studies.

Electrical resistivity of bentonite

- The magnitude of the electrical resistivity can be related to several properties of bentonite, such as:
  - Water content/Degree of saturation
  - Porosity/Dry density/Microstructure
  - Ionic concentration (salinity)
  - Mineral composition
  - Temperature

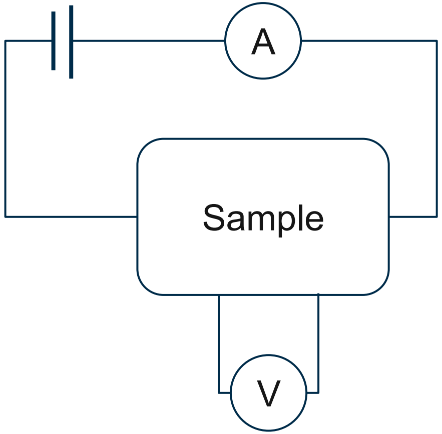




Figures: Kaufhold, S., Dohrmann, R., Klinkenberg, M. & Noell, U. (2015): Electrical conductivity of bentonites. Applied Clay Science 114, pp. 375-385.

Definition of the electrical resistivity measurement

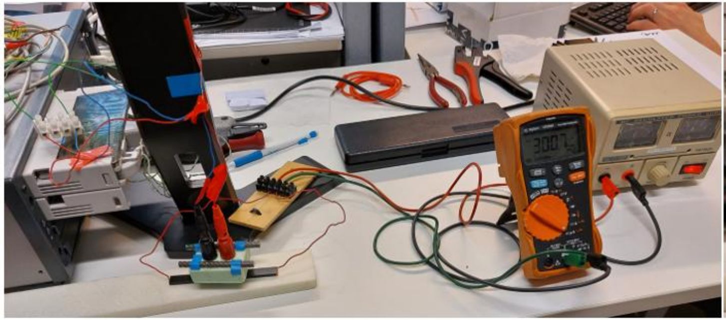
- The electrical resistivities (or conductivity) are commonly measured using the four-probe method
  - A known current is supplied to a sample through current electrodes at the ends of a sample
  - A voltage drop (potential difference) is measured between potential electrodes which are located between the current electrodes
  - With the calculated resistance and known dimensions of the sample and the measurement setup, resistivity can be calculated

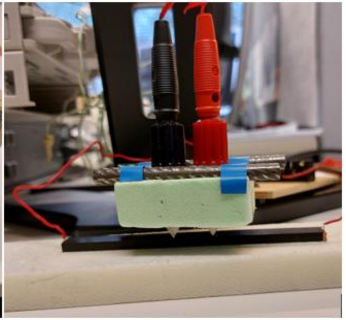


$$\rho = \frac{R \times A}{d} \qquad R = \frac{\Delta U}{I}$$

Method calibration of the resistivity measurement

- The electrical resistivity measurements of the bentonite samples were conducted using the ABEM Terrameter LS2 device (ABEM Instrument AB)
- Prior to the bentonite resistivity measurements, accuracy of the ABEM Terrameter LS2 device in the laboratory scale measurements was tested utilizing a standardized measurement setup to measure the resistivity of conductive plastics (ISO 3915:2022).

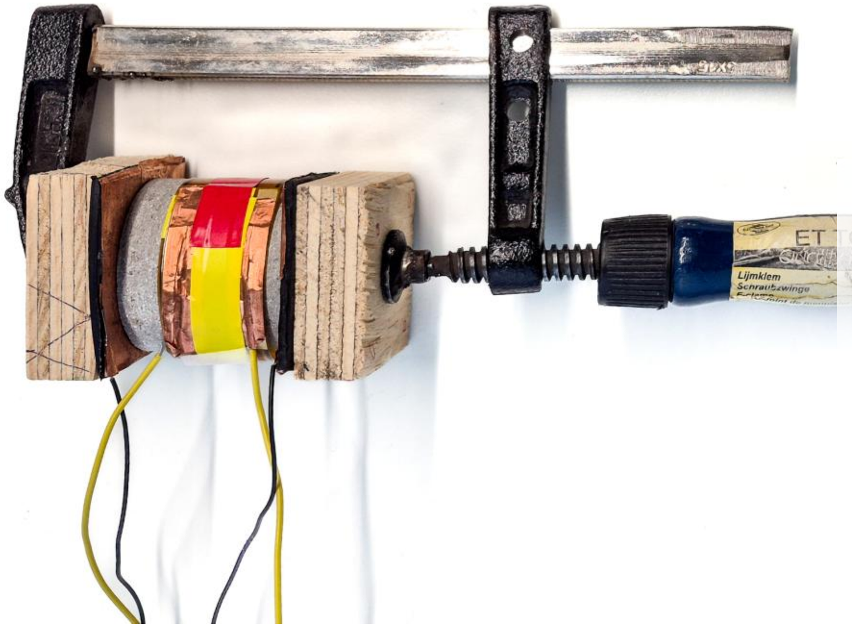




Calibration test results for conductive plastic sample

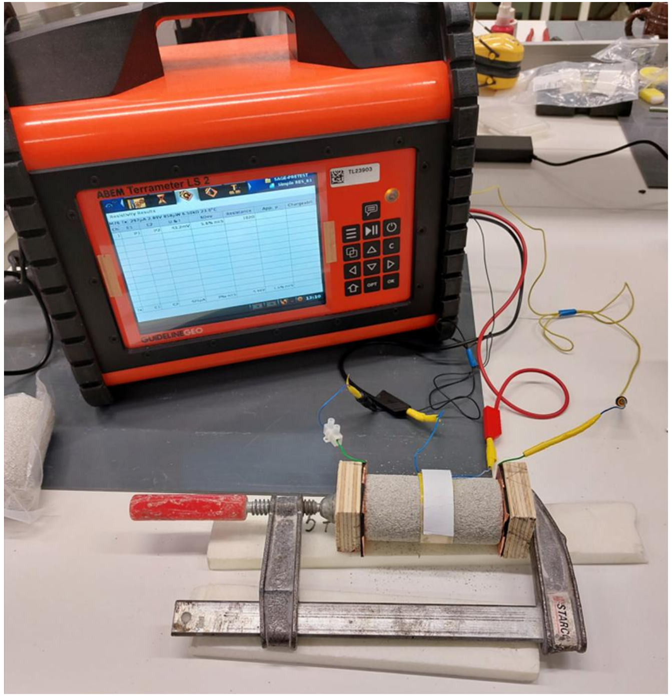
Method	Resistivity (median) (Ωm)
Calibration setup	0.1851
ABEM instrument	0.1849

Pre-tests and the measurement setup of bentonite resistivity measurements



Electrical resistivity measurements of SAGE bentonite samples

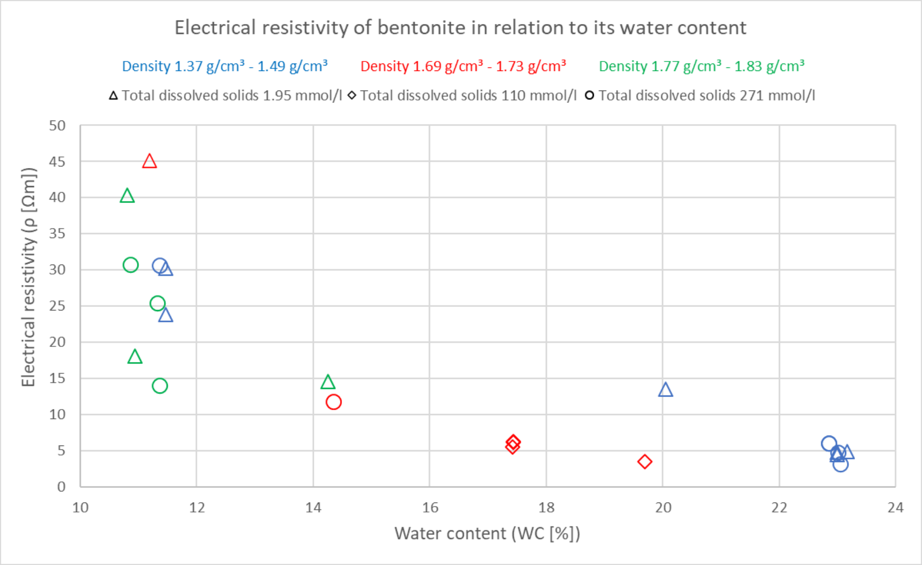
- Measurements for 24 bentonite samples
  - 6 measurements per sample (three positions for the potential electrodes and two current flow directions)
  - Samples:
    - 10 Na-bentonite (Wyoming) samples
    - 7 Na-Ca-bentonite (Georgia) samples
    - 7 Na-bentonite (Bulgaria) samples

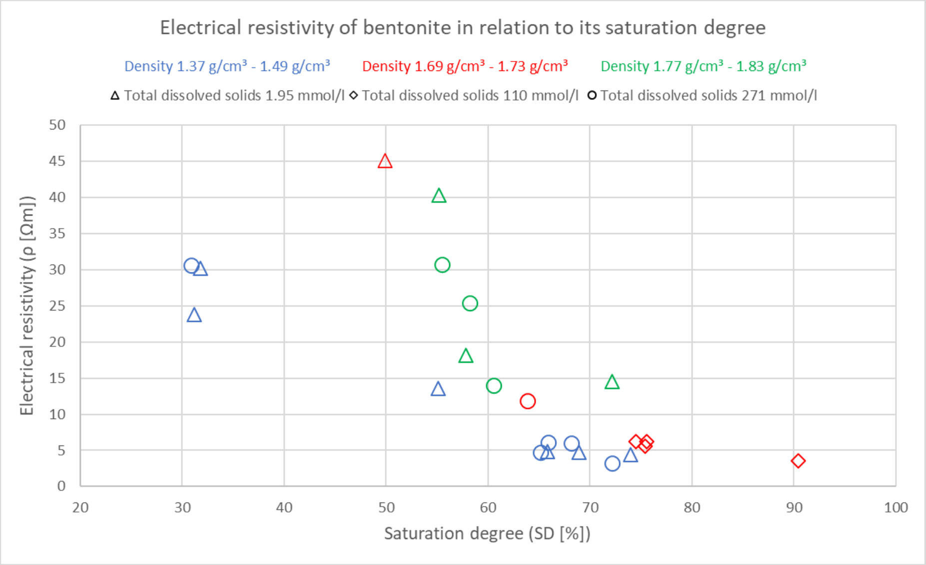


Electrical resistivity measurements of SAGE bentonite samples

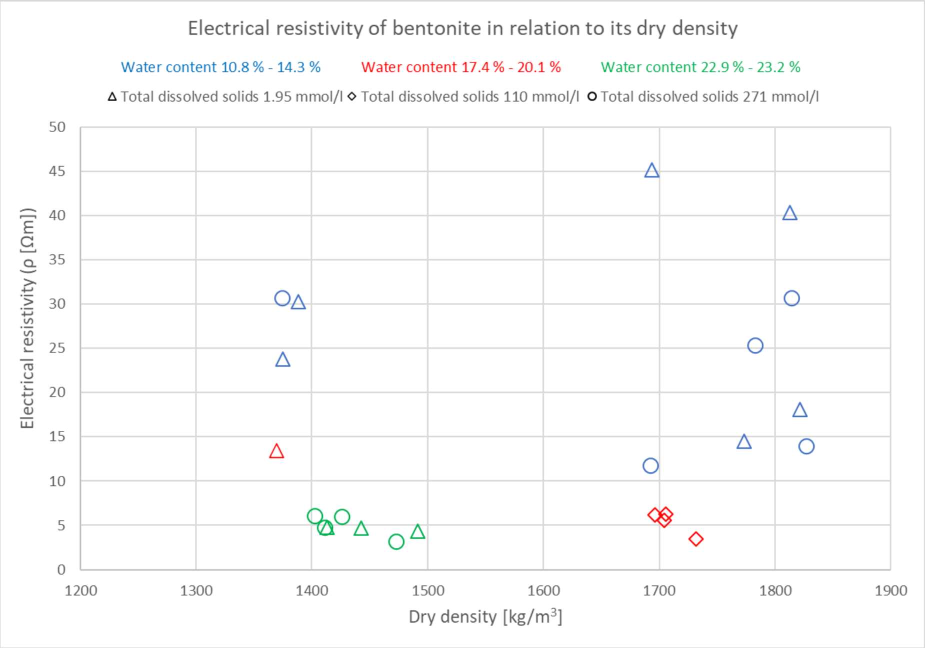
Sample No.	Bentonite	Water content %	Dry density (kg/m^3)	Saturation degree (%)	Total dissolved solids (mmol/l)	**Electrical resistivity (ohm*m)**
1	Na	23	1443	69.0	1.95	**4.65**
2	Na	23	1492	74.0	1.95	**4.33**
3	Na	10.95	1822	57.9	1.95	**18.06**
4	Na	11.48	1375	31.2	1.95	**23.73**
5	Na	11.48	1389	31.8	1.95	**30.20**
6	Na	11.37	1374	30.9	271	**30.66**
7	Na	23.05	1472	72.2	271	**3.18**
8	Na	11.37	1827	60.6	271	**13.97**
9	Na	11.37	1825	60.4	271	**3.25**
10	Na	19.7	1732	90.5	110	**3.46**
11	Na-Ca	10.82	1813	55.2	1.95	**40.28**
12	Na-Ca	10.86	1814	55.5	271	**30.71**
13	Na-Ca	17.44	1705	75.4	110	**5.49**
14	Na-Ca	17.44	1696	74.5	110	**6.11**
15	Na-Ca	17.44	1706	75.6	110	**6.18**
16	Ca	20.06	1370	55.1	1.95	**13.47**
17	Na-Ca	23.18	1413	65.8	1.95	**4.77**
18	Na-Ca	23.01	1411	65.1	271	**4.75**
19	Ca	11.19	1694	49.9	1.95	**45.11**
20	Ca	14.26	1774	72.2	1.95	**14.47**
21	Ca	11.33	1782	58.2	271	**25.40**
22	Ca	14.35	1693	63.9	271	**11.77**
23	Ca	22.85	1426	68.2	271	**6.03**
24	Ca	22.85	1402	65.9	271	**6.06**

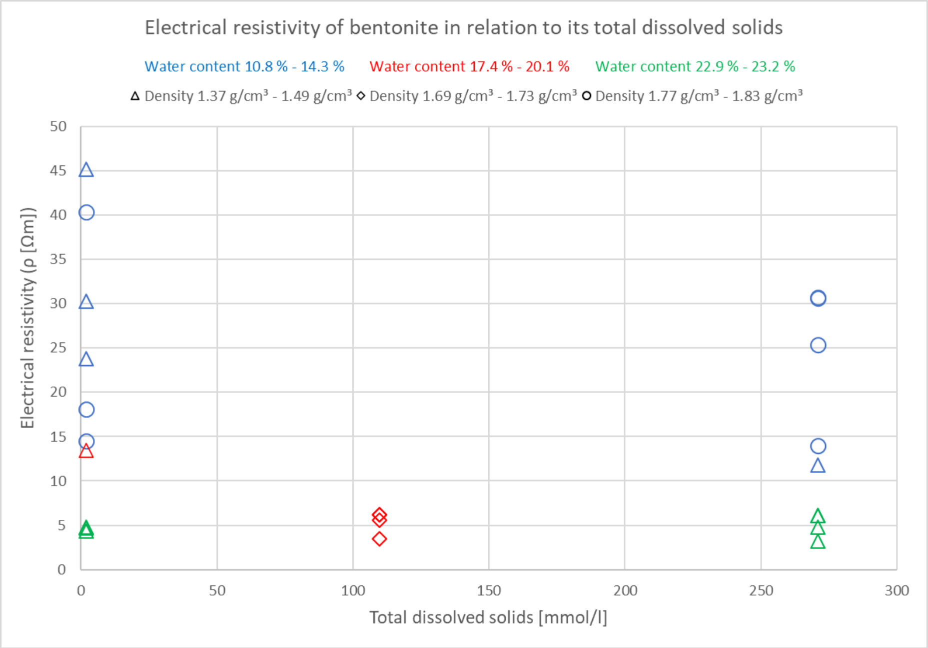
Electrical resistivity measurements of SAGE bentonite samples





Electrical resistivity measurements of SAGE bentonite samples





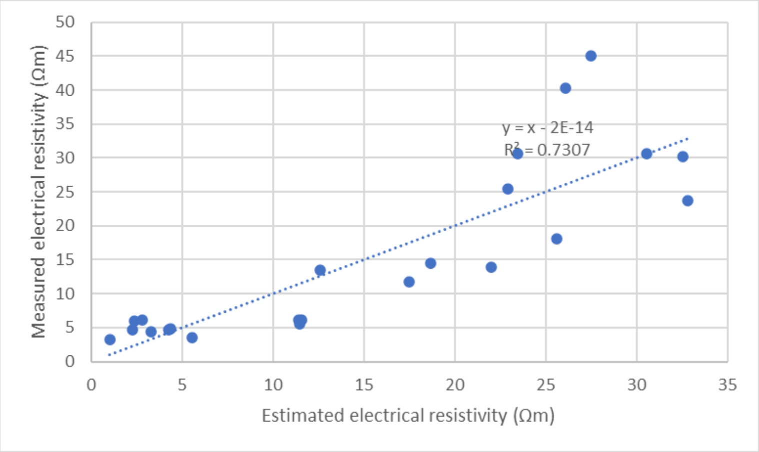
Statistical analysis

- Linear regression with the least squares method
  - Coefficients (m) can be estimated for the variables, which can be used to determine estimates for electrical conductivity.

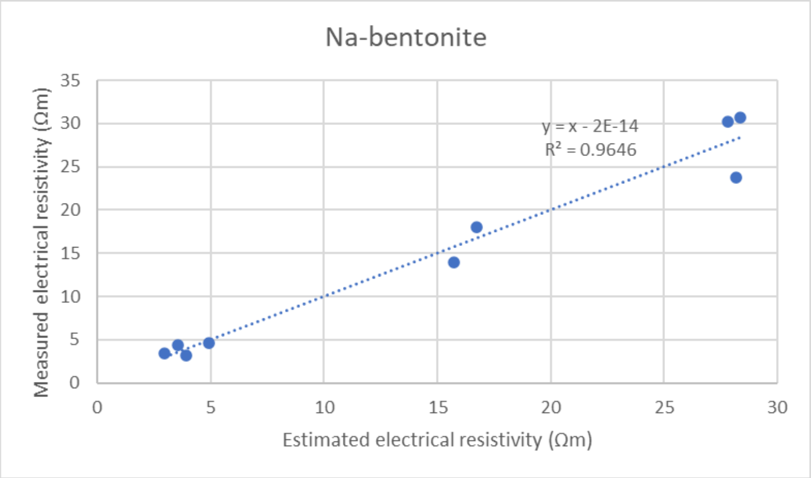
$$y = m_1 x_1 + m_2 x_2 + m_3 x_3 + b$$

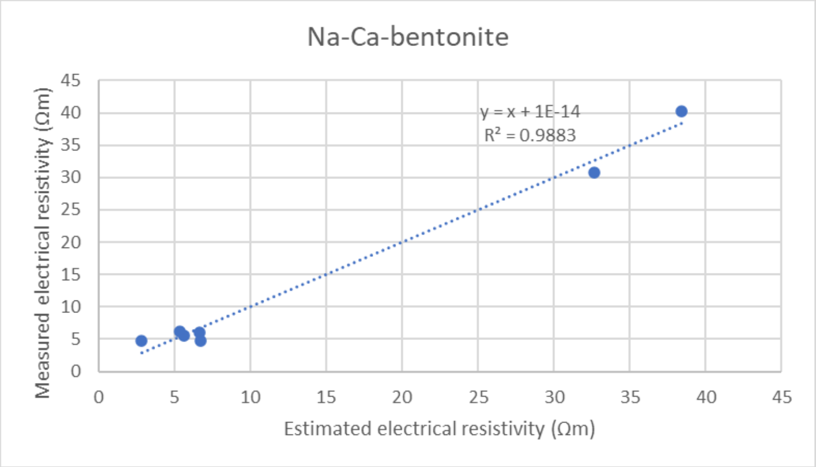
Table 6. Regression statistics (m_x=coefficients of the independent x-values: total dissolved solids, dry density and water content; se_x=standard error of the independent x-values, the constant b, and the y estimate; R_2=the coefficient of determination; F=the F statistic; ss_{reg}=the regression sum of squares; ss_{resid}=the residual sum of squares.

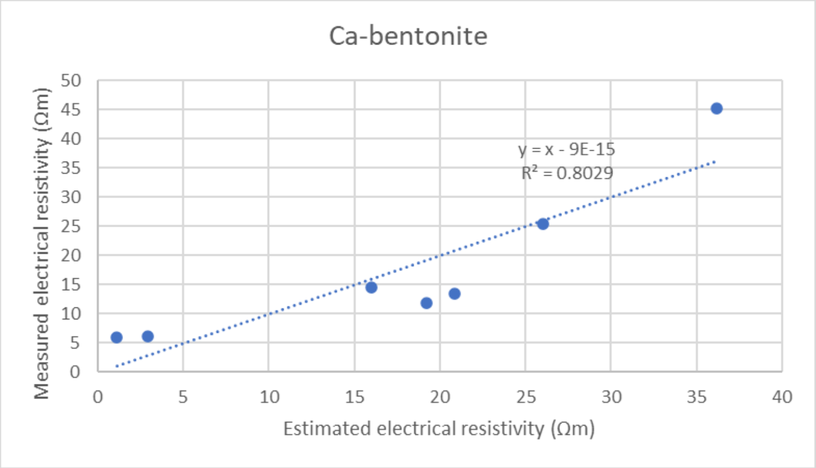
Total dissolved solids	Dry density	Water content	
m_3 = -0.009427	m_2 = -18.9188041	m_1 = -2.369056	b = 86.0511556
se_3 = 0.0122209	se_2 = 10.059581	se_1 = 0.3524546	se_b = 19.788979
R^2 = 0.730704066	se_y = 7.1286215		
F = 17.1847838778	df = 19		
ss_{reg} = 2619.850096	ss_{resid} = 965.527647		



Statistical analysis of different bentonite types







Statistical analysis

Table 4. Estimation of effects of independent variables on the electrical resistivity, based on the coefficients from the regression analysis.

Water content		Dry density		Total dissolved solis	
m_1	-2.369056213	m_2	-18.91880411	m_3	-0.009427497
Change in value (%)	Change in electrical resistivity (Ωm)	Change in value (g/cm^3)	Change in electrical resistivity (Ωm)	Change in value (mmol/l)	Change in electrical resistivity (Ωm)
2	-4.738112426	0.05	-0.945940206	20	-0.188549936
4	-9.476224852	0.1	-1.891880411	40	-0.377099873
6	-14.21433728	0.15	-2.837820617	60	-0.565649809
8	-18.9524497	0.2	-3.783760822	80	-0.754199745
10	-23.69056213	0.25	-4.729701028	100	-0.942749682
12	-28.42867456	0.3	-5.675641234	120	-1.131299618
14	-33.16678698	0.35	-6.621581439	140	-1.319849554
16	-37.90489941	0.4	-7.567521645	160	-1.50839949
18	-42.64301183	0.45	-8.513461851	180	-1.696949427
20	-47.38112426	0.5	-9.459402056	200	-1.885499363
22	-52.11923669	0.55	-10.40534226	220	-2.074049299
24	-56.85734911	0.6	-11.35128247	240	-2.262599236
26	-61.59546154	0.65	-12.29722267	260	-2.451149172
28	-66.33357396	0.7	-13.24316288	280	-2.639699108
30	-71.07168639	0.75	-14.18910308	300	-2.828249045

- The water content of the samples had the greatest effect on electrical resistivity, dry density had some effect, and salt content had only a minor effect.

Statistical analysis

- Based on the regression analysis presented above, it is also possible to estimate the values of each independent x-variable, for example water content:

$$x_1 = \frac{y - m_2x_2 - m_3x_3 - b}{m_1}$$

- This approach could be used in electrical resistivity tomography analyses to determine the 3D electrical resistivity tomography of a bentonite sample during saturation. The electrical resistivity values of different parts of the sample or system could be converted into water content values/saturation levels.
- If new material is used, preliminary resistivity measurements must be performed in order to perform regression analysis for this material.

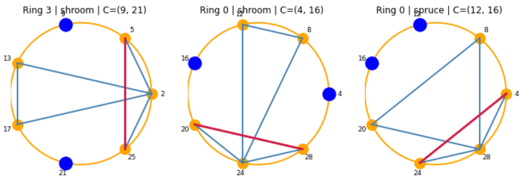
SAGE
ERT (Electrical Resistivity Tomography)

Objectives for 2024-2025

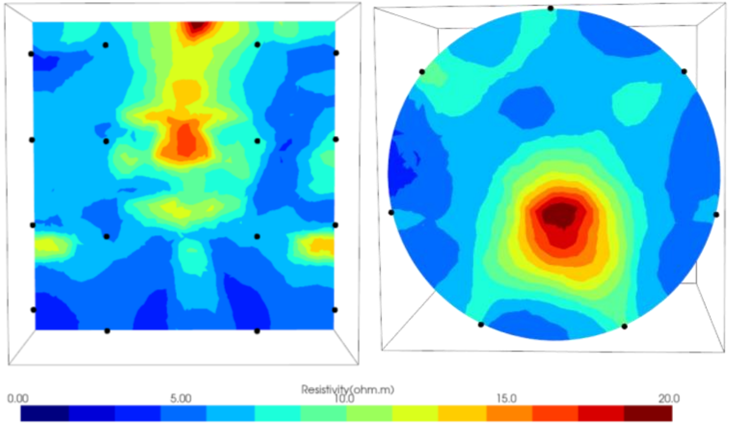
- The first objective for the years is to develop a methodology for lab-scale bentonite ERT
- The second objective is to use the measured bentonite resistivities to interpret bentonite properties from the ERT images
  - Knowing the resistivity dependency on the varied parameters (such as water content), the electrical resistivity tomography can be transformed to, for example, water content tomography.
  - The ERT measurement will be further calibrated by comparison to water content and density profiles that are analyzed post mortem.

T3.3 Electrical resistivity tomography

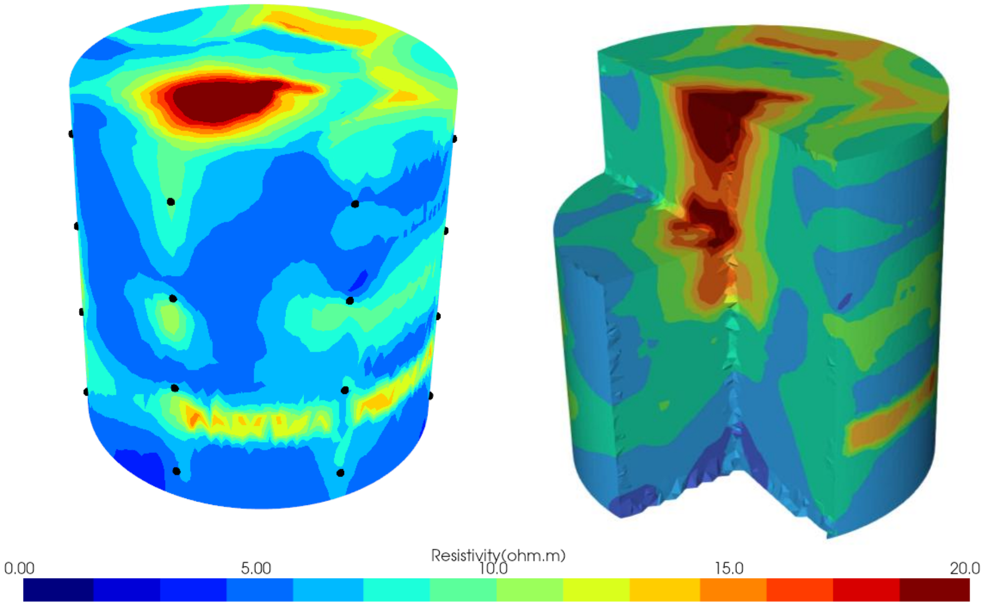
- 3D electrical resistivity tomography setup + calibration
  - The flexible circuit board was updated to have more electrodes (28 instead of 18)
  - Most electrode combinations measured with a total of over 4000 measurements
    - This decreased the influence of individual poor measurements
  - The new setup has been tested in the lab and results are promising! Resistivity range dropped from 1–10 000 Ωm to 1–30 Ωm
- Measurements designed for the XCT mould are scheduled by the end of 2025



Electrical resistivity tomography – pre-tests for cylindrical bentonite samples



ERT measurement from a bentonite sample with a drilled hole



Next steps

- Resistivity studies:
  - Need for more samples to create more accurate models: same material with different densities and water contents
  - Should resistivities of granular materials be measured? Is it possible?

- ERT studies:
  - Upscaling from cm-scale to dm-scale
  - Joint tomography with ERT + Xray for different bentonite materials
    - Joint inversion of both methods?

Thank you for your attention

Questions?