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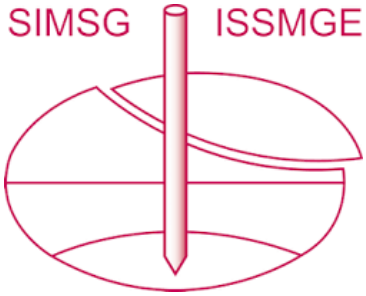

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Geophysical characterisation of marine and quick clay sites: field and laboratory tests

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ABSTRACT: Quick clay is a highly sensitive, post-glacial marine clay characterized by a remolded shear strength of less than 0.5 kPa. Such deposits pose a serious geohazard in Scandinavia and North America and need to be delineated in detail. Therefore, there has recently been a considerable amount of work published on the use of geophysical methods for their mapping. Two of them, especially electrical resistivity but also seismic measurements are tested for their consistency. In situ and laboratory measurements of resistivity and shear wave velocity (V_s) were acquired to characterise two clay sites in Norway. At the first site, resistivity changes are monitored while salt is artificially diffused in a quick clay deposit. Three successive ERT (electrical resistivity tomography) surveys and R-CPTu (resistivity CPTu) were acquired around the diffusion wells to monitor the salt plume over time as resistivity is closely related to pore water chemistry. At the second site, an ERT and seismic survey were carried out to characterise a non-sensitive clay deposit. In addition, resistivity and V_s were measured on high quality block samples. These laboratory data combined with the field data enable a study of how resistivity and V_s correlate to salt content in clay. The primary aim is to better employ geophysical methods for quick clay site characterisation.

1 INTRODUCTION

The Scandinavian post-glacial marine clays are deposited in marine environment during and after the last ice age, entrapping pore water of high salt content (~30-35 g/l) in the voids. Leaching of the pore water by meteoric groundwater flow has diluted the pore water salinity in some clays to less than 5 g/l. At low salt content the repulsive forces between the clay particles increase, and the structure easily collapses and the clay minerals float in their own pore water. The salt content in quick clays is often less than 2 g/l (Torrance 1979). The most reliable method to confirm quick clay is sampling and index testing in the laboratory to measure the remolded shear strength and sensitivity. However these tests are costly for systematic quick clay hazard zonation. As resistivity is closely correlated to the pore water salinity in clays, and quick clay is indicated by higher resistivity than low-sensitive clay, ERT is a suitable approach. Indeed, its use for quick clay mapping has increased during the last decade, also thanks to recent advances in the data acquisition (protocols and instruments) and processing tools.
Based on 2D ERT models Solberg et al. (2012) proposed the following ranges of resistivity for Norwegian clays:

- unleached marine clay: 1-10 Ωm
- leached, possibly quick clay: 10-80/100 Ωm
- dry crust clay, slide deposits, coarser material like sand and gravel and bedrock: >100 Ωm

However, increasing numbers of case studies reveal that this resistivity range is often influenced by local conditions. ERT is however considered as a useful mapping tool for landslide risk assessment at comparably lower costs than extensive drilling (e.g. Pfaffhuber et al. 2013, Bazin et al. 2014). Here, the limitations of the technique is considered by comparing resistivity values obtained with ERT, borehole logging and laboratory measurements. Furthermore, MASW (multichannel analysis of seismic waves) has also been used successfully to characterise Norwegian clays (e.g. Long & Donohue 2010). Since the V_s is directly connected to the small-strain shear stiffness G_{max} ($G_{max}=\rho V_s^2$, where ρ is the density in kg/m^3), it seems reasonable to investigate the effect of quick clay on V_s. The velocity change due to the removal of the salt content is expected to be weak and possibly within the measurement error (Donohue et al. 2012, Sauvin et al. 2014). Here, the measurement accuracy is considered by comparing V_s measurements obtained with MASW, borehole logging and laboratory tests.

The two marine clays included in this paper were deposited after the last glaciation about 10.000 years ago, and they are in the Trondheim (Dragvoll site) and

Oslo (Onsøy site) areas. These two sites have been investigated in connection with research projects and are well characterized. However the three types of measurements (ground-based geophysics, borehole logging, and laboratory) do not all exist for the two sites. Dragvoll clay is low saline, with a remolded shear strength of less than 0.1 kPa, while Onsøy clay has a high salt content and a remolded shear strength from 2 to 6 kPa.

2 QUICK CLAY SITE: DRAGVOLL, NORWAY

2.1 *Research site*

The NTNU research site at Dragvoll is located 156 m above current sea level and the clay deposit is up to 40 m thick (Fig. 1 upper). To investigate the effect of potassium chloride (KCl) on geotechnical properties, six salt wells filled with KCl were installed in January 2013 (Helle et al. 2015). Vertical 63 mm diameter pipes allow the salt to diffuse into the quick clay layer from 4 to 8 m depth. They are regularly refilled with granular KCl to maintain a high concentration (~4 mol/kgw). R-CPTu around one of the salt wells and ERT surveys were carried out to inspect the migration of the salt plume.

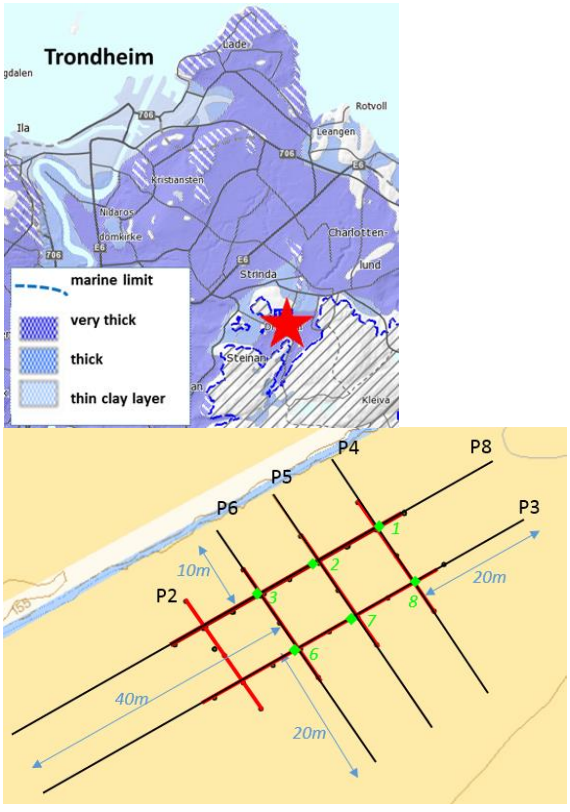

Figure 1. Upper: Dragvoll site. Lower: The ERT survey before salt-well installation is illustrated in thick red lines while the two later surveys are in thin black lines. The salt wells are numbered in green (1, 2, 3, 6, 7, and 8).

2.2 *ERT surveys*

2.2.1 Monitoring surveys

Six ERT profiles with varying electrode spacings (0.25, 0.5 or 1 m spacing) and varying lengths (20, 40 or 80 m long) were acquired once before installing the salt wells, and twice after (Fig. 1 lower) to monitor resistivity changes over time (time-lapse). The surveys were performed with a 12-channel Terrameter LS recording unit (ABEM 2010). The multiple gradient array was chosen for the acquisition protocol, it has been designed for use in multichannel systems (Dahlin & Zhou 2006) and is optimal for this instrument. The penetration depth was 3.8, 7.2 and 15.6 m depending on the electrode spacing. Datasets acquired with different electrode spacings but along the same line were concatenated to improve the model resolution. The raw data were inverted with software RES2DINV (Loke 2016) to obtain the model resistivity distribution. The following options were chosen for the inversion: half unit cell spacing, manual removal of noisy data points, smooth inversion with reduced side-block effects, and time-lapse resistivity inversion between consecutive surveys.

One selected resistivity profile is presented in Figure 2. The data fit is very good (RMS = 0.96% at iteration 4). The top is marked by a ~1 m thick dry crust layer. The clay is very homogeneous and typical of leached clay (ρ ~ 50 Ωm). The clay thickness is greater than the penetration depth (15 m). One selected time-lapse resistivity change, almost 3 years after salt-well installation, is presented in Figure 3. The ERT monitoring is not able to detect any conductive anomalies near the salt wells. Only a strong elongated anomaly is observed in the first 1.5 m, due to the seasonal water table fluctuations (Fig. 3 inset).

2.2.2 Resolution tests

To illustrate the resolution of the ERT survey, a synthetic test was carried out. The synthetic model is displayed in Figure 4 and contains several geological units with three different resistivities: a 1 m thick resistive dry crust (ρ = 150 Ωm), a background typical of leached clay (ρ = 50 Ωm), three conductive salt wells between 4 to 8 m depth (ρ = 0.3 Ωm). A synthetic data set is obtained by perturbing the theoretical solution of the forward problem with 5 % Gaussian noise using RES2DMOD package (Loke 2002). It is computed assuming a multiple gradient array with 81 electrodes at 1 m spacing, which is the geometry of a real survey.

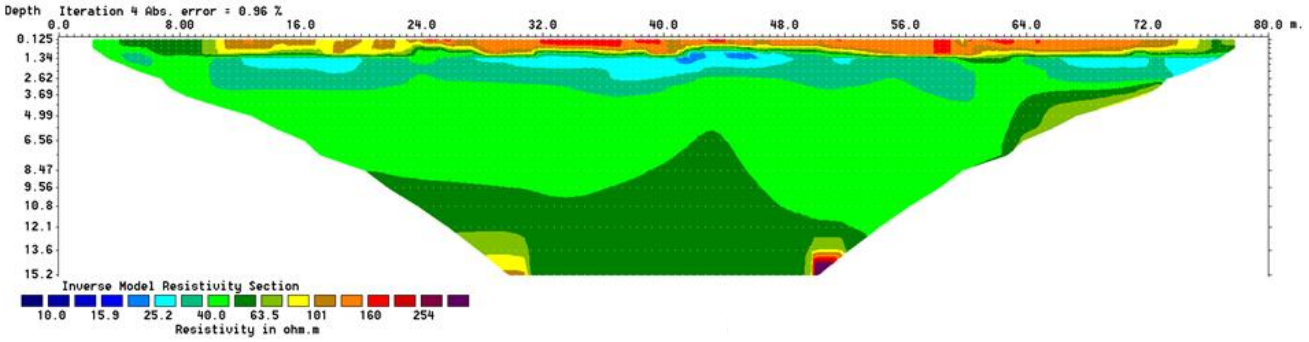

Figure 2. Representative ERT depth section (profile P3).

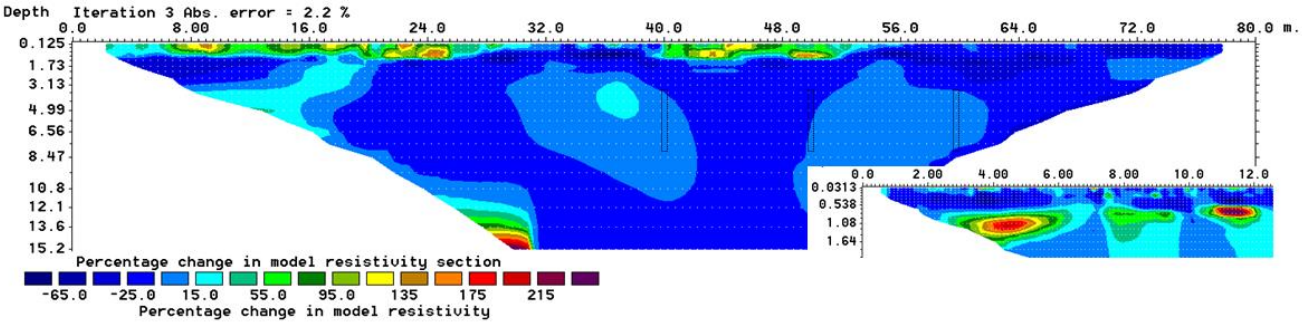

Figure 3. Time-lapse resistivity changes along P3. The inset shows a shallow profile illustrating seasonal variations.

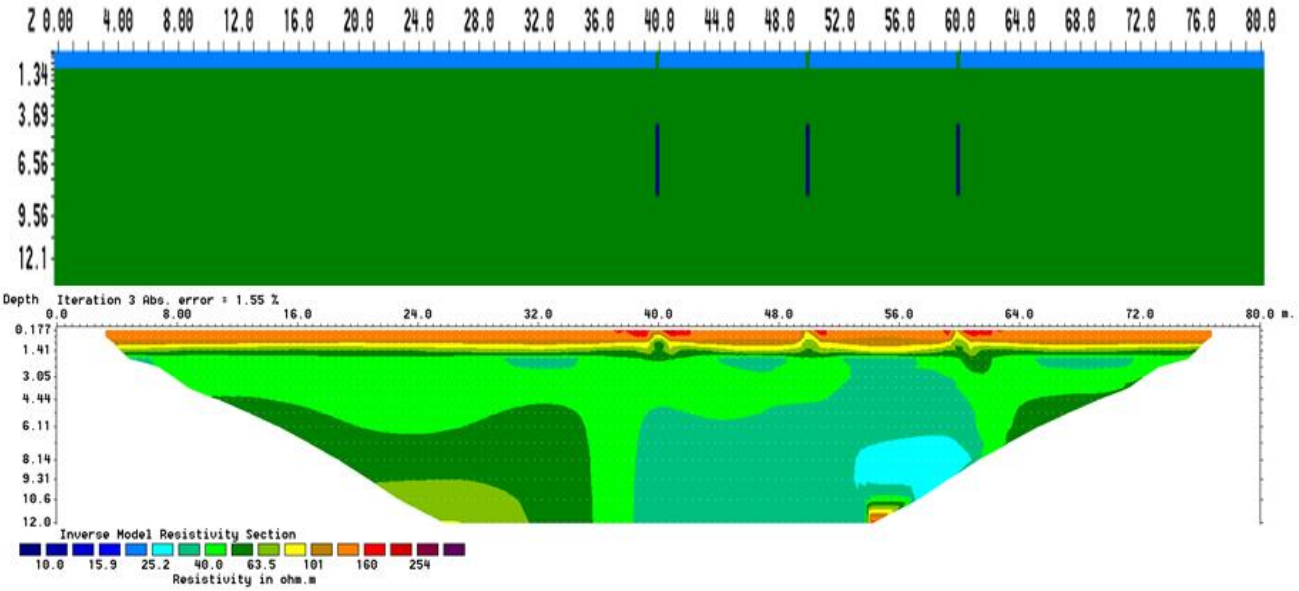

Figure 1. Resolution test: the synthetic model is shown at the top while the recovered resistivity model is shown at the bottom.

This synthetic data set is then inverted with RES2DINV using similar parameters as for the real datasets. The data fit is already good (RMS = 1.5 %) after 3 iterations. The synthetic response shows that dry crust layer and the average resistivity are well retrieved. However the narrow salt wells are not detected and instead the inverted model images a 20 m wide conductive anomaly. This illustrates the low resolution at depth of the surface-based ERT method and its inadequacy to detect slim salt plumes below 4 m depth. Cross boreholes surveys would be recommended for such a target.

2.3 *R-CPTu survey*

A resistivity module is attached to a conventional CPTu: the probe is 80 cm long with 4.4 cm diameter and holds four ring electrodes. Two outer rings, 20 cm

apart, inject a current while two inner rings measure the voltage (Fig. 5 right). R-CPTu readings are therefore small-scale compared to ground-based geophysics. Several R-CPTu logs acquired in October 2015 (2 years and 9 months after wells installation) around one of the salt wells (from 50 cm to 1.5 m away) clearly illustrate how far and in which direction the salt plume has migrated (Fig. 5 left). The maximum resistivity reduction due to the increased salt content goes from 50 to 8 Ωm. Further analysis of the R-CPTu profiles are presented in Helle et al. (2016). The resistivity depth profiles extracted from the two perpendicular ERT profiles (P3 and P4) are also shown for comparison. They are in very good agreement with the resistivity values obtained with the R-CPTu. However, they fail to detect the resistivity reduction near the salt well, as already noticed in Figure 3.

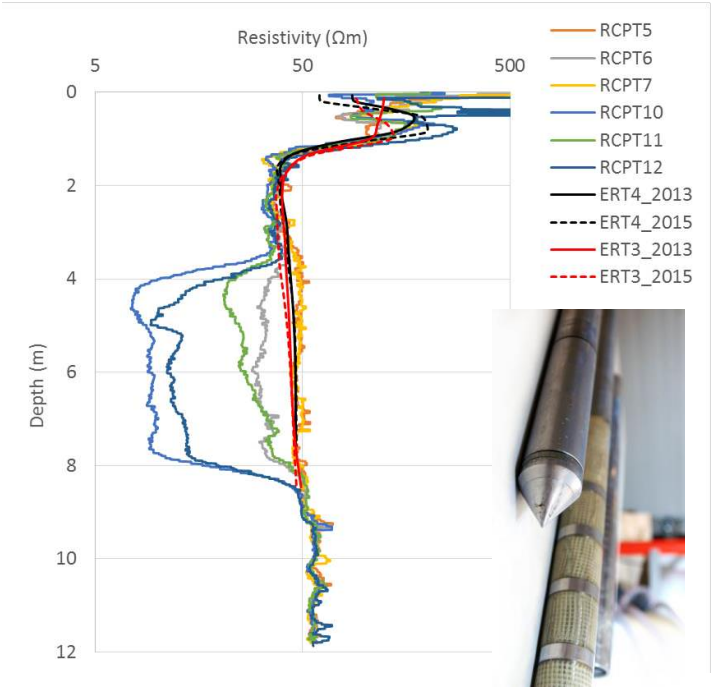

Figure 2. Left: R-CPTu and ERT depth profiles around well 8 during the salt diffusion test in Dragvoll. Right: R-CPTu tool.

3 LOW-SENSITIVE CLAY SITE: ONSØY, NORWAY

3.1 *Research site*

Onsøy is located within the marine clay deposits in SE Norway close to the town of Fredrikstad (Fig. 6). The area is near present sea level. NGI has been using this site for research testing for several decades because of the high thickness (up to 44 m) of the clay deposit and its highly uniform nature.

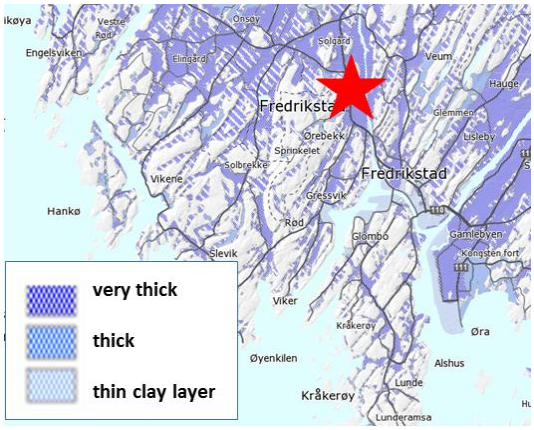

Figure 6. Onsøy site, Norway.

3.2 *Seismic survey*

Six MASW profiles were carried out in 2005 using a RAS-24 seismograph and Seistronix software. A sledgehammer was used as a source and 4.5 and 10 Hz vertical geophones were planted every 1 or 2 m. Data processing was performed by selecting dispersion curves from a phase velocity-frequency spectra, generated using a wavefield transformation method (Park et al. 1999). V_s models were inverted with the software Surfseis using the least squares approach of Xia et al. (2003). In addition, three V_s borehole logs were acquired in 1984 using the Univ. of British Columbia S-CPTu (Eidsmoen et al. 1985, Lunne et al. 2003) and in 2004 by the Univ. of Massachusetts (Landon 2007). The V_s depth profiles are depicted in Figure 7.

3.3 *ERT survey*

A 80 m ERT profile with 1 m electrode spacing was acquired in 2016. The profile was positioned as close as possible to where the block samples were collected for direct comparison with laboratory data. The survey was performed with the same instrument and same data processing work flow as in Dragvoll. The resistivity profile is presented in Figure 8. The data fit is very good for (RMS = 2.5 % at iteration 4). The top is marked by a ~1 m thick dry crust layer. The clay appears very homogeneous and extremely conductive (ρ ~ 1Ωm). The clay thickness (44 m) is much greater than the penetration depth (15 m).

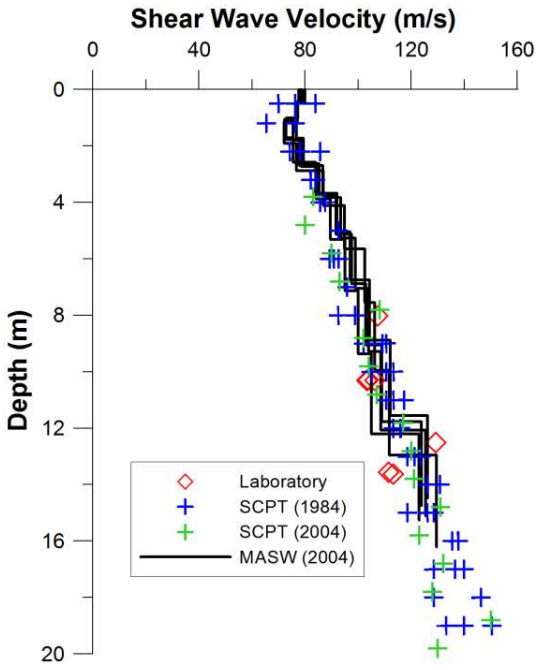

Figure 7. V_s depth profiles in Onsøy.

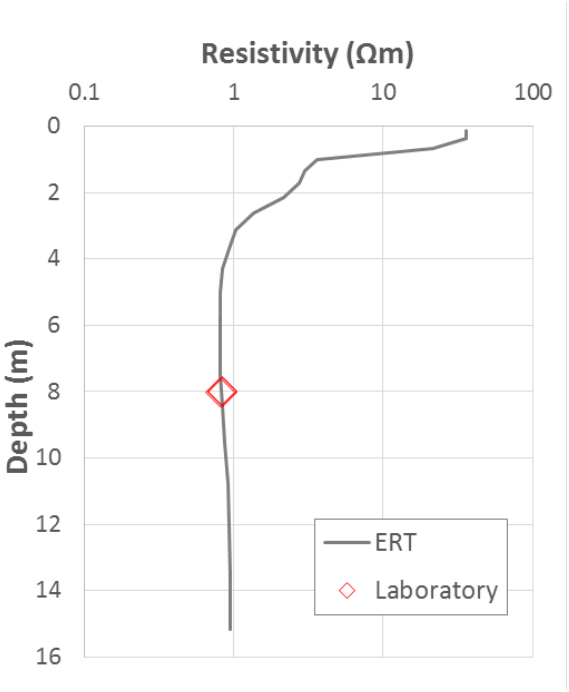

Figure 9. Resistivity depth profile in Onsøy.

3.4 *Laboratory tests*

A major difficulty in soil geotechnics is to retrieve undisturbed samples that maintain the clay structure. NGI has been using a specially designed block sampler from the Univ. of Sherbrooke Québec (Lefebvre & Poulin 1979) since 1982. Tests on block samples show that they are of high quality (Karlsrud & Martinez 2013). Specimens from Onsøy block samples, with a diameter equal to 71 mm and height ~70 mm, were mounted into specially modified triaxial cell, then incrementally and anisotropically consolidated to their in-situ stress. Three resistivity and seven V_s measurements were acquired longitudinally. Laboratory data points are compared with the V_s and the resistivity depth profiles in Figure 7 and in Figure 9. The agreement with ground-based geophysics is very good, probably thanks to the homogeneity and isotropy of the clay layer.

4 CONCLUSIONS

As all geophysical techniques, ERT depth sections suffer from some methodical limitations. The weakness illustrated at Dragvoll is the lack of resolution at depth. Nonetheless, the comparison between ERT, R-CPTu and laboratory data confirms the good agreement between 2D profile, borehole and sample resistivity data. Hence, the ERT method is satisfactory in accuracy (property to measure the right resistivity). It is however weak in resolution (property to detect small-scale anomalies) at depth and synthetic modeling is for that reason advisable to design an effective survey geometry.

MASW models suffer from similar weaknesses. Nonetheless, the comparison between MASW, S-CPTu and laboratory data confirms also a good

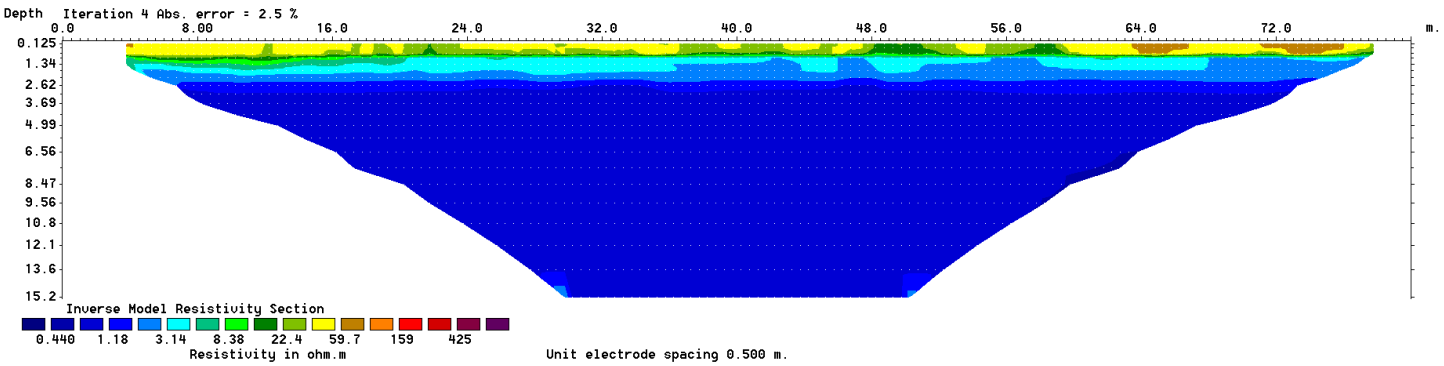

Figure 8. ERT depth section in Onsøy.

agreement between seismic profiling, borehole and laboratory bender element measurements. Hence the V_s method is also satisfactory in accuracy (property to measure the right velocity) thanks to the clay homogeneity and isotropy. Further work is however necessary in order to quantify the velocity change due to leaching for quick clay applications (Gribben et al. 2016).

5 ACKNOWLEDGEMENTS

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