Field-Scale Quality Control of Lime-Cement Pillar in Conductive Clay Using Electrical Resistivity Tomography

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Summary

Ground improvement with lime-cement pillars is becoming increasingly common in the Nordic countries for exploitation of areas with poor stability. However, there is no non-destructive method for quality control of the ground improvement. Significant changes in the electrical properties after mixing of the binders make electrical resistivity tomography (ERT) a potential method. In connection with lime-cement pillar trials for the Västlänken project in Gothenburg, Sweden, a series of different single borehole ERT measurements were performed. Three cases are compared in this paper: untreated ground, treated uncured ground and treated cured ground. The raw data pseudosections show a significant general drop in resistivity between the untreated and treated uncured data sets, while the curing process increase the resistivity significantly close to the borehole. Full 3D inversions have been carried out for all three cases. In model space the cured pillar is still causing a clear increase in resistivity around the borehole, while the decrease between the untreated and uncured case is less obvious than in data space. With the large contrast between the untreated and the treated uncured in data space it was expected to be visible in model space, improved inversion methods and settings could help resolve this.

Introduction

Ground improvement with lime-cement pillars is becoming increasingly common in the Nordic countries for exploitation of areas with poor stability. The stabilization method leads to economical savings compared to alternative methods, furthermore it is beneficial from an environmental point of view and a sustainability perspective as it minimizes transport and reduces use of natural resources. However, there is need for improved and spatially comprehensive quality control methods of the ground improvement. Today, quality control methods involve core drilling or complete exposure by digging (after curing) which are both costly and destructive methods. The quality control aspect can generally be divided into two steps, where the first step is carried out directly in connection with the ground improvement to check if the entire intended volume has been treated, or if there are zones which need additional treatment. It is of utmost importance to construct pillars according to design since gaps in continuity can severely compromise the intended mechanic and hydraulic properties of the ground. The result of ground improvement is also affected by the type of soil, the type of binder, and the parameters used in the production (e.g. binder composition). The second quality control step involves determining the spatial continuity and mechanical properties of the treated subsurface after curing.

This paper focuses on the first step where the control needs to be done in direct connection to when the stabilization being carried out, so that fixes can be done while equipment and crew are in place and before the binder has cured in treated parts of the volume. At this stage, little stability growth has occurred since the binder has not cured yet, and thus seismic methods are unsuitable. The electrical properties, however, can change drastically when binders are mixed into the soil (Dahlin et al., 1999; Lindh et al., 2000). Electrical resistivity tomography (ERT) is therefore an interesting option for mapping which parts of the subsurface that has been processed and identify zones that need to be supplemented. Mooney and Bearce (2017) has shown that the true diameter of jet columns can be estimated within 5% in a range of 0.9 to 2.5 m. However, for this to work in routine application the method must be further developed and adapted so that it becomes sufficiently robust and easy to handle in the demanding environments. Furthermore, the results of the quality control need to be reported promptly in a form that allows for direct feedback to the contractor at site.

Ground improvement and in-situ field measurements

Test measurements with single borehole ERT were carried out in connection with the lime-cement pillar trials for the Västlänken project in Gothenburg, Sweden. The pillars were constructed down to around 20 meters depth by SMG (Soil Mixing Group) using their dedicated equipment (Figure 1, left) and KC50/50 compound, targeting 50 or 80 kg/m^3 of the binder. The objective of the tests was to assess if ERT can be used as quality control method for lime-cement pillar ground improvement. A slotted PAH pipe (inner and outer diameter of 51 mm and 63 mm respectively, slots widths of 0.3 mm) was inserted in the centre of the lime-cement pillar immediately after construction to provide a path for inserting an electrode string into the centre of the pillar. The pipes were installed with the help of a Geotech 605 to push them into the centre of the pillar directly after the mixing tool had been removed (Figure 1, middle). ERT measurements were made using a multi-electrode borehole cable with take-out spacing 0.5 m that was inserted into in slotted pipes (Figure 1, right) and the pipes were filled with tap water to ensure enough electrode contact. The instrument used was an ABEM Terrameter LS2 with a multiple gradient array sequence. The field measurements were carried out at three different stages in the lime-cement pillar process:

1. Before ground improvement - Untreated ground.
2. At ground improvement - Treated, uncured ground.
3. After ground improvement - Treated, cured ground.

The measurements for treated, uncured ground (stage 2) were carried out in immediate connection with the construction of the lime-cement pillars and for treated, cured ground they were carried in the same PAH pipe 36 days after construction. In addition, the measurement for untreated ground was for practical reasons carried out in a separate PAH pipe close by. The PAH pipe casings reached different depths ranging between 15 and 17 meters depending on the installation method and on the local conditions (Table 1).

Figure 1 *Documentation of the field installations and measurements: mixing tool with 80 cm diameter (left), installation of slotted PVC-pipe (middle) and installed ERT-cable (right).*

Table 1 Summary of some relevant features of the datasets.

Dataset	***Stage***	***Top (m)***	***Bottom (m)***	***Extent (m)***	***Datapoints***
Untreated	*1*	*-1.6*	*-17*	*15.5*	*568*
Treated, uncured	*2*	*-1.6*	*-17*	*15.5*	*606*
Treated, cured	*3*	*-1.0*	*-15*	*14*	*468*

Figure 2 shows the resulting pseudosections from the measurements for one lime-cement pillar and for the untreated ground. The pseudosection measured in untreated soil exhibits apparent resistivities around 1 Ωm along of the surveyed depth, but in the top few meters it reaches up to 4 Ωm. The higher apparent resistivities close to the surface are most likely caused by the fill material, whereas the deeper part reflects the resistivity of the natural formation. The pseudosection measured after mixing in binder shows distinctly lower resistivities (approximately a factor of two), with apparent resistivities down to below 0.4 Ωm.

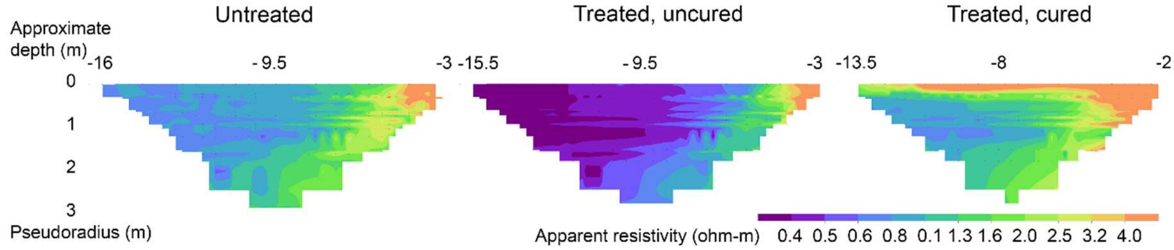

Figure 2 *Pseudosections for the datasets measured for untreated ground (left), treated ground before curing (middle) and treated ground after curing (right). Note that the right side of the pseudosections correspond to the top of the vertical electrode array and that moving down in the pseudosection corresponding to increasing the radius of the measured volume.*

Inversion of field data and resitivity models

As described in previous section, the measurements were made as single borehole ERT, and a cylindrical zone of approximately 80 cm in diameter with change in resistivity is anticipated as result of the binder mixing. Following this, a radially symmetric model could be appropriate, but also a full 3D inversion should be able to produce similar results, though radially symmetric inversion would be less underdetermined. Presently available inversion software does not, however, routinely support 2D inversion with cylindrical coordinates. There are available 1D "doughnut" inversion software e.g. AarhusInv and a 2D radial inversion could be constructed e.g. in the BERT/GiMli package. However, such inversion would present a special case of the actual 3D inversion problem and would only be suitable for tomography of single lime-cement pillars which themselves present a special case and are uncommon at construction sites. For these reasons, full 3D inversion has been carried out for the datasets presented in the previous section. Inversion of the acquired field data was carried out in BERT/GiMLi v. 2.2.9 (Günther et al., 2006; Rücker et al., 2017) as 3D inversions for a 32 segment cylindrical parameter space with radius of six meters and length of 20 meters. Individual meshes where constructed for each inversion due to geometry differences between the three datasets, especially due to the differences in the electrode array depth and extent. Mesh refinement were carried out around the electrode nodes with 10% of the electrode spacing. The inversions were carried out with robust data and blocky model constraints, isotropic weighting and L-curve optimization of the regularization and data error estimates of 1% and 10^{-6} V voltage error. The blocky model constraints and isotropic regularization were used to accommodate the expected sharp model contrasts between treated and untreated ground. All inversions converged with χ^2 below 1.

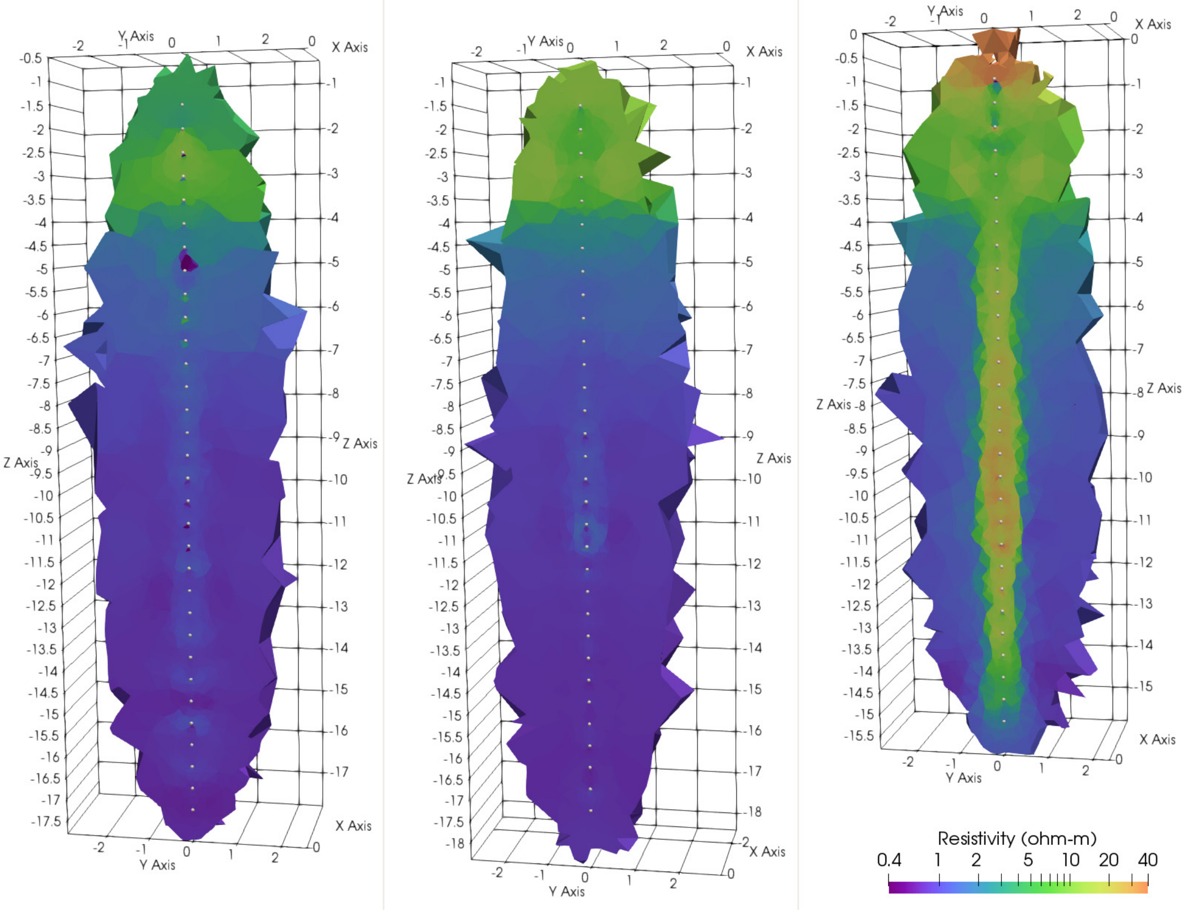

Figure 3 *Inversion model resistivity and subsurface electrodes corresponding to stage 1, 2 and 3 from left to right: before, at and after curing. The position of the electrodes is shown as white spheres. Note that the visualizations are limited with a lower coverage threshold of 1 to exclude elements with lower resolution*

The resulting inversion models based on the three datasets are shown in Figure 3 as resistivity parameter volumes clipped in the center to visualize the core of the investigated ground (along the electrode array and the PAH pipe). Furthermore, the visualizations are limited with a minimum coverage threshold of 1 to exclude elements with lower resolution. All three models show higher resistivity (above 10 Ωm) values down to approximately 4 meters below surface. This is likely related to the anthropogenic fill material present at the site, whereas below this level marine clay is dominating as indicated by the lower resistivities. For the inversion model of the stage 1 (Figure 3, left) measurements in untreated ground there seem to be a slightly increased resistivity along the electrodes. This might be caused by the slotted PAH pipe which isolating properties likely has larger effects on the shorter electrode spacing which has the sensitivity focused at smaller radius. Contrastingly, this effect is less pronounced in the inversion model of the stage 2 measurements in treated, uncured ground (Figure 3, middle). This is possibly caused by the lowered resistivity from the mixing of the binder which could compensates the resistivity increase from the PAH pipe, though one could expect that the factor 2 difference in apparent resistivity of large part of the pseudosections would map more prominently into mode space. Finally, the third inversion model for the treated, cured case shows a clear high-resistive anomaly oriented along the electrodes which corresponds in diameter with the mixing tool and is a clear indication of treated geometry. The differences in resistivity within the treated volume could indicate different actual concentration of binder.

Conclusions and future work

The tests show that mixing of binder consisting of a 50%-50% lime-cement mix into the ground quickly reduces the formation resistivity so that there is a significant contrast compared to the untreated soil. This contrast in resistivity is clearly seen in data space while the expected difference in model space is less evident. The resistivity contrast is in accordance with and in support of the main hypothesis and while this contrast is also expected to be seen in model space improved inversion methods and settings could help resolve this. The result is particularly encouraging since one of the possible limitations of the approach could be the conductive clays that are common in and around Gothenburg. The tests also indicate that the data contain information related to variations in the degree of stabilisation along the pillars, which may be indicative of variation in diameter or amount of stabiliser along the pillar. However, in-situ verification information from the lime-cement is needed to conclude the actual suitability of ERT as a quality control method for ground improvement.

The measurements were made via a slotted plastic casing inserting into the centre of the pillars. A possible source of error could be that slotted pipe did not end up in the center of the pillar as, despite that it was inserted in the hole left by the mixing tool. It would have been desirable to use the soil mixing tool for installing the electrode string in order to reduce the risk of not ending up having it in the centre. Furthermore, using the stabilisation rig could eliminate the need of a separate geotechnical rig for the sensor installation, which could potentially reduce the cost, but a re-design of the electrode strings would be required. Additionally, it could be worthwhile to investigate a logging-like methodology where a stiff array of electrodes is used for measuring at several depths.

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References

Dahlin, T., Svensson, M., Lindh, P., 1999. DC Resistivity and SASW for validation of effeiciency in soil stabilisation prior to road construction, in: 5th EEGS-ES Meeting. https://doi.org/10.3997/2214-4609.201406466

Günther, T., Rücker, C., Spitzer, K., 2006. Three-dimensional modelling and inversion of dc resistivity data incorporating topography - II. Inversion. Geophys. J. Int. 166, 506–517. https://doi.org/10.1111/j.1365-246X.2006.03011.x

Lindh, P., Dahlin, T., Svensson, M., 2000. Comparisons between different test methods for soil stabilisation, in: ISRM International Symposium 2000, IS 2000.

Mooney, M.A., Bearce, R.G., 2017. Assessment of Jet Grout Column Diameter during Construction Using Electrical Resistivity Imaging, in: Grouting 2017. American Society of Civil Engineers, Reston, VA, pp. 42–51. https://doi.org/10.1061/9780784480809.005

Rücker, C., Günther, T., Wagner, F.M., 2017. pyGIMLi: An open-source library for modelling and inversion in geophysics. Comput. Geosci. 109, 106–123. https://doi.org/10.1016/J.CAGEO.2017.07.011