POHVA

Development of ground improvement process (POHVA1)

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Confidentiality: Public

Report's title		
Development of ground improvement process (POHVA1)		
Customer, contact person, address		Order reference
TEKES, VTT, Finnish Road Administration, Destia, Nordkalk Oyj, City of Espoo, Finnsementti Oy and Suomen Maarakentajien keskusliitto.		TEKES 40250/05, 1188/31/04
Project name		Project number/Short name
POHVA1		1109
Author(s)		Pages
Leena Korkiala-Tanttu; Markku Juvankoski; Petri Valasti		19
Keywords		Report identification code
deep stabilization, piling, ground improvement, geophysics, resistivity sounding, site investigation, risk, machine automation		VTT-R-11157-07

Summary

This report is an English summary report of the Finnish research report VTT-R-10654-07.

Confidentiality	Public

Espoo 27.12.2008
Signatures   Signatures

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Distribution (customer and VTT)
TEKES, VTT, Finnish Road Administration, Destia, Nordkalk Oyj, City of Espoo, Finnsementti Oy and Suomen Maarakentajien keskusliitto.

Preface

The project 'Development of ground improvement process' (POHVA) started on the 1.5.2005. The primary objective of the POHVA study on ground improvement automation has been to develop a comprehensive automation system suitable for ground improvement (deep stabilisation) and piling. The automation system covers site investigation, the associated processing and analysis process, and a production control system for ground improvement work (in this study deep stabilisation and piling work). The study has been divided into two parts with the first phase (POHVA I) focusing on the management of subsurface information related to deep stabilisation and piling, as well as the requirements for production development imposed by this. POHVAI was finished at the end of 2007. The second part, which will focus on the automation of piling machines as well as deep stabilisation machines, started in the autumn of 2007 and is expected to be completed in 2010.

The POHVAI project was done by VTT, the University of Oulu and the Technical University of Helsinki together with Sito Oy. The project leaders were Markku Tuhola (1.5.2005 – 31.12.2006) and Leena Korkiala-Tanttu (1.1.2007 – 31.12.2007). The researchers were: Petri Valasti, Markku Juvankoski, Hans Rathmayer and Jouko Törnqvist from VTT, Rauno Heikkilä & Mika Jaakkola from Oulu University, Asko Aalto from Helsinki University of Technology. Besides them Juha Liukas from Sito Oy participated to the 3D design studies.

Ilkka Vähäaho from the city of Helsinki was the chairman of the steering group. Other participants of the steering group were: Kari Kuusipuro (Nordkalk Oyj), Matti Lahti (Finnish Road Administration), Jouko Murto (Lemcon Oy), Seppo Roos and Anniina Mattsson (Destia), Pia Rämö (Finnsementti Oy), Harri Tanska (City of Espoo) and Osmo Rasimus, Marko Kivimäki, Kari Hiltunen and Ilkka Jussila from Tekes. Other experts in the management group were Harto Räty, Heikki Kukko and Kalervo Nevala.

The authors wish to thank the members of the steering group and financiers for their support and information provided.

Espoo 27.12.2007

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1 Introduction

1.1 Objectives of study

The primary objective of the POHVA study on ground improvement automation has been to develop a comprehensive automation system suitable for ground improvement (deep stabilisation) and piling. The automation system covers site investigation, the associated processing and analysis process, and a production control system for ground improvement work (in this study deep stabilisation and piling work). The study has been divided into two parts with the first phase (POHVA I) focusing on the management of subsurface information related to deep stabilisation and piling, as well as the requirements for production development imposed by this. However, the study of piling has been of a "light" nature because piling will be addressed in more detail in the POHVA II project. The first part of the project will end at the end of 2007. The second part, which will focus on the automation of piling machines as well as deep stabilisation machines, started in the autumn of 2007 and is expected to be completed in 2010. A parallel primary objective has been to develop the management of information on subsurface properties and variation for the needs of risk assessment. The focus in risk assessment has been the uncertainty of predicting the quality of stabilisation.

1.2 The present state and possibilities of column stabilisation

The current operating process for column stabilisation is mostly at the 2D level. This two-dimensional platform applies to both quality control and the outcome of the work. At present, the image of the soil created for the purpose of stabilisation is insufficient and is based on point-type sounding. Sounding will of course be required for determining layers of soil in the future as well, but the subsoil model created by the designer is inaccurate, and this also applies to the representation of stabilisation characteristics (i.e. chemical continuity, continuity of drilling resistance). The actual process of choosing a binding agent is also vague. Stabilisation tests are typically carried out on a small number of levels (such as at two depths), and combined samples are used that do not represent the partial layers. The actual process of investigating deep stabilisation is still undeveloped and should be made more systematic.

The uncertainty associated with soil information is also reflected as an uncertainty factor in design. Simplifications and assumptions have to be applied to the soil layer model during the design. For simplicity, the quantity of binding agent is usually specified as constant for the entire length of a column. In this case, the weakest layer determines the quantity of binding agent, which means that the column becomes 'too good' on average. On the other hand, sections that is stabilised too well cause a problem because it is laborious to drive piles through them. This also calls for the possibility to adjust the quantity of binding agent at different depths. At present, the designer often specifies the target strength but the contractor determines the actual design – the quantity and even the type of binding agent – to be used.

Incoherent procedures are also reflected in the outcome of the work. Of course, subsurface conditions also contribute to an uneven result. Mixing work is affected by the amount of mixing, the rate of rise of the mixing tool, and the number and shape of the blades, as well as interruptions and blockages in the binding agent feed; the quality of the top section of the

column is also affected by the pull-out of the mixer close to the surface. With regard to quality control, the quality of the column is not monitored sufficiently. However, the SFS-EN standard of execution for deep stabilisation systematises the execution and documentation of stabilisation work.

The stabilisation machine is controlled by routines that are partly manual and partly automatic. The principle of "constant binding agent feed" leads to binding agent consumption exceeding the actual need. Depth-wise control of the column machine during operation and the associated work-time documentation are insufficient. The conditions may make the mixing result weak, resulting in an inhomogeneous column. All in all, integration of the overall operating process for column stabilisation has been limited. Site investigation, the stabilisation design, column stabilisation, quality control and verification of actual quality have proceeded as more or less separate processes.

1.3   Networked operating process for ground improvement

The networked operating process for ground improvement (Figure 1) will in future consist of initial data measurements, associated processing and analysis, geotechnical 3D design, simulation of the work process and virtual design, as well as automatic work control. Networked automation for earth construction requires the management of the data that is needed and created in the different stages of the overall process. This refers to defining the information content and transfer format for data produced and required in the different stages of work. Defining the information content makes it possible to appropriately arrange data in a database from which it can be easily retrieved using specified search criteria. The subsystems of the networked operating process must produce documents that are well defined in terms of the information content and structure, and which adhere to an agreed standard and can be transferred between subsystems and corporate information systems as easily as possible.
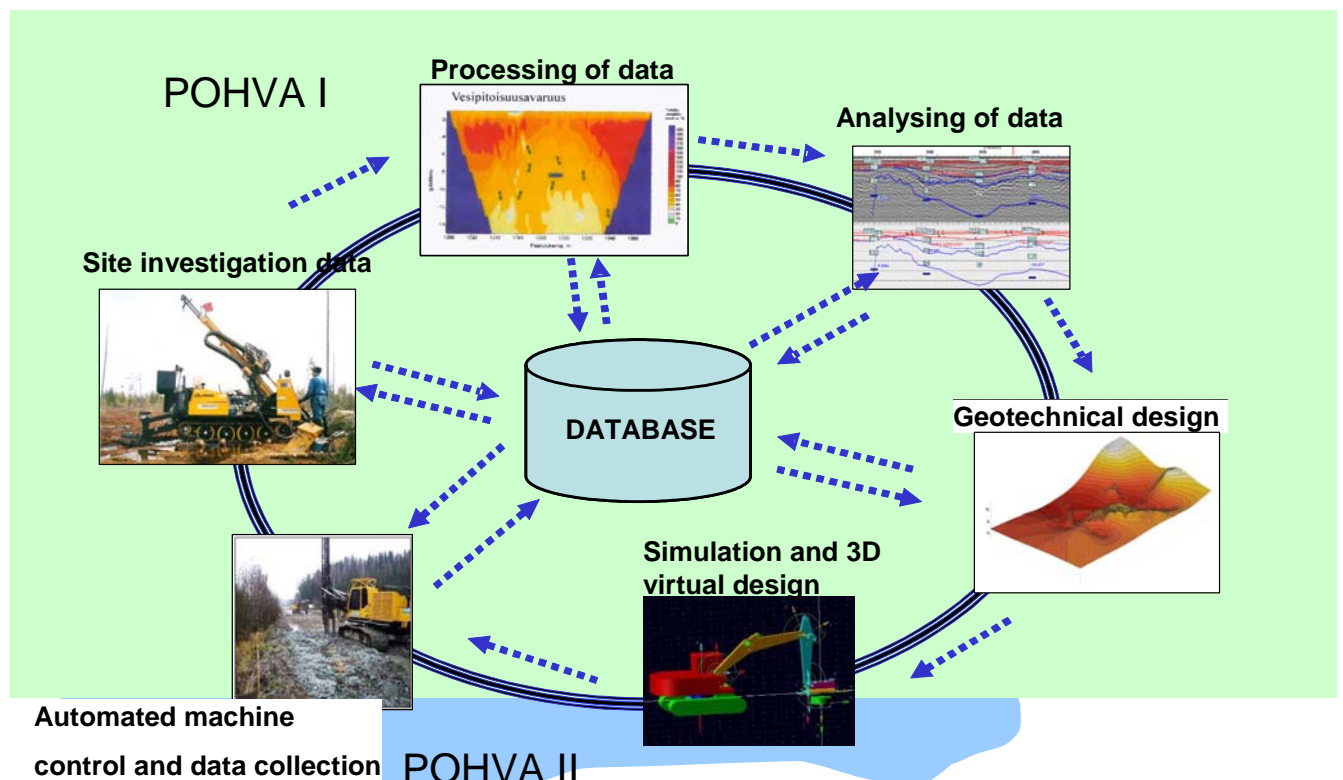

Figure 1. The networked operating process for ground improvement.

The POHVA I project aimed to make column stabilisation an integrated process: a continuous 3D subsoil model (layer boundaries, clay properties) and water content space (clay, gyttja) are created using electrical resistivity sounding and point-specific measurements, sampling and site investigations (sounding). The designer and the field technician for the electrical resisitivity work closely co-operate when creating the subsoil model.

Using the 3D model, the designer designs and optimises the field of columns to be stabilised (area to be stabilised, required number of columns, lengths and diameters of columns, distances between columns) to fulfil the requirements for settlement, bearing capacity and stability. The design software converts this information directly into control input data for use by an automatic stabilisation machine. After this, the 3D control of the automatic machine (operating coordinate system, positioning system, sensor system, overall kinematics, actuator control) takes over the responsibility for creating the column according to the design.

Actual data from the stabilisation work is measured continuously during the mixing (mixing tool position, quantity of binding agent supplied and actual mixture as a function of depth), and the execution process is automatically documented. Continuous measurement and documentation make it possible to assess the column-specific strength in real time and compare it with the target. In principle, it is possible to attach instrumentation to the mixing tool that will provide feedback on real-time measurement data and make it possible to further adjust the quantity of binding agent on a column-specific basis during the work.

1.4   Purposes and limits of the study

In summary, the purpose of the study has been to develop and produce process parts and turn them into an integrated system
- for refining subsurface information for deep stabilisation (and piling) into design control data for product strength (bearing capacity for piling),
- for optimising the product manufacturing parameters (quantity of binding agent, mixing, driving),
- for converting the product strength (bearing capacity) control data into the format required for machine automation, and
- for steering earth construction towards industrial production: an automated 3D control process increases the efficiency of the work and substantially improves quality; the 3D control process developed for stabilisation machines is also applicable to other earth construction machines such as pile driving machines, bench drilling machines, excavators, etc.

As to the limitations of the POHVA project, it should be noted that the project has not addressed:
- the significance of the mixing tool
- quality control methods in situ
- conventional strength tests on laboratory samples
- the wet method of deep stabilisation, or
- the service life and durability (long-term durability) of stabilised columns.

The general starting point for the study project has been to transfer information on the topography and properties of the soil into 3D design models and production control for earth construction, and to further transfer the actual data of the product, including quality data, to a

database. The indicator quantities, conversion algorithms, control quantities, measurement techniques and machines vary by earth construction technology.

2 Development of site investigation methodology

2.1 Development of resistivity sounding for deep stabilisation

The POHVAI project focused in particular on the development of an electrical resistivity sounding method for the needs of deep stabilisation. The study aimed at developing a model for the relationship between measured resistivity and water content in clay deposits. Measured resistivity is the combined effect of several factors that often cannot be separated into components. A particular problem with clay deposits is that general conductivity models assume that electricity is only conducted in pore liquid, but clay minerals are electrically conductive as such and this must be taken into account when converting resistivity into the water content. On the other hand, the parameters for the model of choice should be as simple as possible. Taking these factors into account, a decision was made to use extended Archie's law for converting measured resistivity into water content values.

To determine a 3D image of the soil using resistivity sounding, line measurements of resistivity are carried out on-site to provide 2D cross-sections of resistivity along the lines. An inversion is applied to the cross-sections, and they are combined into a single 3D graph consisting of 1 m^3 blocks. Each block has a resistivity value ρ, and the inverse of this is conductivity σ. Using extended Archie's law, the saturation S was first resolved for each block. Together with the product of porosity, this provides a volume-based water content that can be further converted to a weight basis using density information.

The calculated water content values and corresponding resistivity values were used to create a calculated resistivity-water content conversion curve. This was compared to the resistivity-water content curve obtained using the same resistivity values but replacing the calculated water content values with values determined in a laboratory. At the Vanttila site, water content values were also measured using a radiometric measurement device.

A comparison between the water content values determined using resistivity sounding and the values determined in a laboratory revealed that the water content values obtained from the model were approximately 20 percentage points lower than the laboratory measurements. With the exception of this difference in levels, the water content values measured in the laboratory and those obtained from the model followed a similarly shaped exponentially decaying curve as a function of resistivity. A level adjustment was applied to the models, which eliminated the difference between the water content values obtained from the model and those measured in the laboratory. After this, the exponential decay function was inserted into the adjusted water content values using the least squares method. The level adjustment provided good results, with the coefficient of determination exceeding 98%.

Inversion is a standard operation in the processing of geophysical measurement data. Inversion looks for a resistivity distribution that will optimally minimise the sum of squares for the differences between measured and calculated resistivity values. The minimum is sought in an iterative process by gradually modifying the resistivity distribution. Once there is no change or the sum of squares starts to increase, the iteration is stopped and the result from the previous round is stored. The resistivity structure obtained in this way will optimally

minimise the sum of squares of the differences and is therefore considered to be the "true" resistivity distribution, the structure that best explains the measurement result.

The inversion process may involve geological *a priori* information on the area, making the resulting resistivity distribution correspond to the actual distribution even better. Typical *a priori* information includes information on layer boundaries and layer structures obtained by sounding or seismic methods (Loke, 2004). In the POHVAI project a controlled inversion was applied to the Vanttila test site using boundary information obtained from Sito. The magnitude of the improvement depends on the geology of the area, the measurement configuration and the choice of inversion parameters. The improvement provided by controlled inversion of the data obtained from the Vanttila test site remained in the order of a few percentage points.

An alternative to the above is to carry out an empirical water content conversion directly on the water content values of samples, assuming that the samples represent the entire area. This type of empirical conversion, which was carried out for the Äijänpelto test site, is accurate in principle because it directly places measured resistivity values against water contents measured in a laboratory. The disadvantage is that this type of empirical curve is usually difficult to represent as a function; instead, spline matching with cubic polynomials has to be used.

Line measurements carried out at the test sites included resistivity measurements and induced polarisation measurements. The measurements were carried out using Abem Terrameter equipment and the Wenner alpha configuration. At the Vanttila site, the actual resistivity values calculated for each block of the inversion area (1 m x 1 m x 1 m) have been combined into one block representing the entire area (Figure 2). In Figure 2, the resistivity distribution is presented as vertical 2D sections. The figures clearly indicate a thinning of the clay layer towards the southern end of the area where the resistivity values are high.
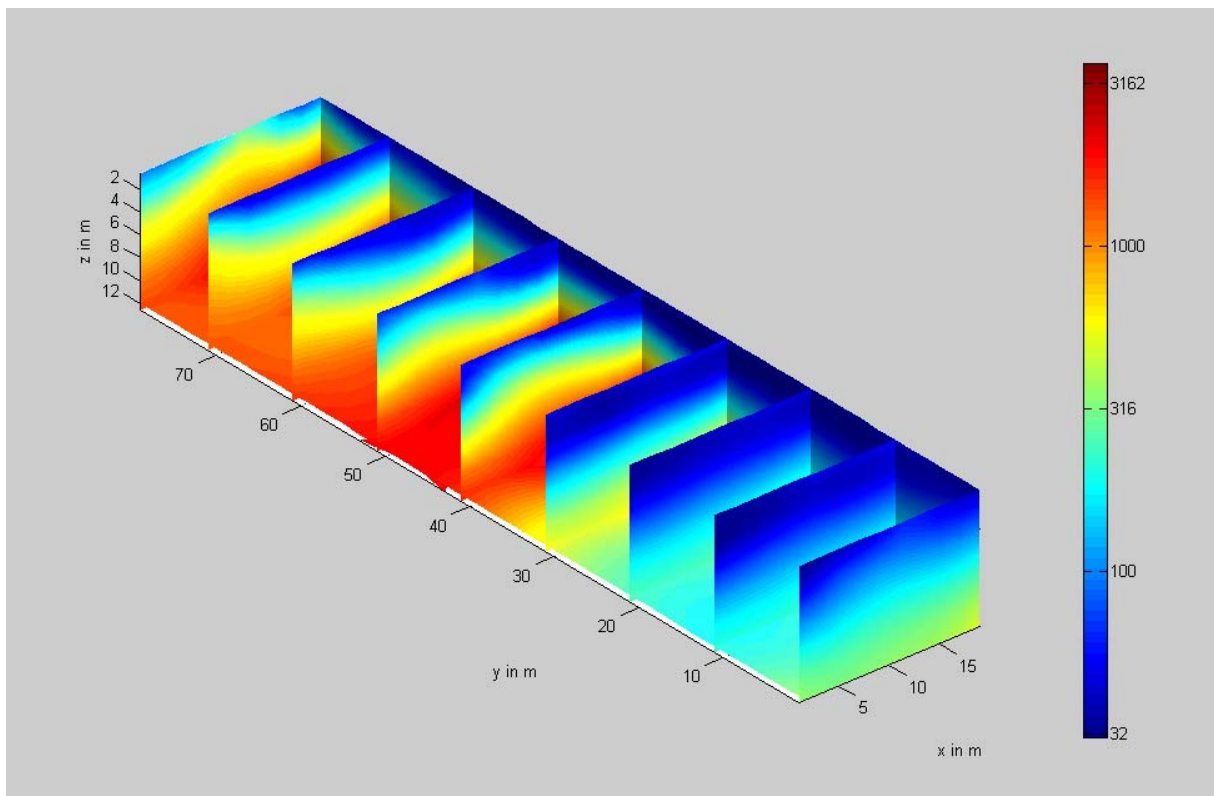

Figure 2. The resistivity distribution in vertical 2D sections.

2.2 Other geophysical measurement methods studied

Site investigation methodology was studied in relation to deep stabilisation and piling. With regard to piling, it is essential that the locations of the bearing boundaries are known. In this respect, the study focused on conventional seismic methods. Conventional seismic methods are based on the reflection and refraction of an acoustic wave from boundaries at which the acoustic impedance – that is, the product of the seismic wave velocity and the density of the medium – changes. P and S waves are used for refraction and reflection sounding when the typical quantities to be determined are the depths of the boundaries and the thicknesses of the layers between them. In Finland, topsoil seismics have been almost exclusively based on refraction sounding, on the one hand because refraction sounding is easier to interpret than reflection sounding, and on the other hand because the high-frequency waves required for reflection sounding become rapidly attenuated in topsoil layers.

The accuracy of seismic methods will often be less than that of traditional sounding, but the boundary between moraine and topsoil, and that between topsoil and rock, can usually be determined quite easily.

The success of mass stabilisation can be investigated using the SASW method. The method has been used in Sweden (Dahlin et al. 1999) for determining improvement in the strength of a site mass-stabilised with lime. In column stabilisation the integrity of a column can be verified using a downhole method based on the propagation of an S wave.

3 Development of stabilisation tests

The methodology for laboratory stabilisation tests has not been standardised in Finland. For this reason, the handling of samples, mixing of binding agent, construction of samples, storage and testing may substantially differ between different laboratories. At the HUT Laboratory of Soil Mechanics and Foundation Engineering, the most problematic areas have been sample mixing and compaction (Aalto, 2006).

The POHVA I project included the development of an index testing method for stabilisation tests. The index testing method development and the associated testing programme were planned and implemented at the Helsinki University of Technology Laboratory of Soil Mechanics and Foundation Engineering in 2005–2006. The work consisted of developing an index testing method for measuring the stabilisation of soil material, as well as its application to the stabilisation of different soil types under laboratory conditions. The developed index testing method was used to investigate the effect of the water-binding agent ratio, the quality of the binding agent, the humus content, storage time and storage temperature on the one-axial compression of stabilised soil.

The objective of developing the index testing method was to create a stabilisation testing method that would be as fast as possible and allow easy and quick variation of different quantities and qualities of binding agents (and types of soil), taking into account the problems of the mixing and compaction technique referred to above.

The prototype developed for index testing eliminated the layering of samples. The efficiency of mixing – that is, the homogeneity of mass – is represented by the averages of internal deviations within the index testing series, which were usually in the order of 4...7% with

slightly different combinations of binding agent and soil material, with the exception of one mixture of pure lime and viscose clay for which it was approximately 19%.

The one-axial compression strengths determined using the standard testing method (28 d / 6 °C) were approximately one-quarter (19…35%) of the compression strengths determined using the index testing method (7 d / 23.5 °C). All in all, the index testing method seems to be a promising method for determining functional binding agents quickly and inexpensively. The method can also be used for preliminary estimates of the quantities of binding agent needed (Aalto, 2006).

4 Database of stabilisation tests

4.1 Contents of database

A stabilisation test database containing 3,435 lines of information on stabilised samples was compiled in connection with the POHVA project. There are 14 "soil types" in the database. The soil types of the samples are clay (laSa, liSa, ljSa, saLj, some samples designated only Sa), silt (Si, saSi, ljSi, siLj), gyttja (Lj) and peat (Tu). Some soil types have no designation at all. The soil types used in the samples originate from 73 different sources. There are a total of 34 binding agents. Some of the binding agents are identical in principle, with only the mixing ratios differing, while some are mixtures for which the composition is not precisely known. The properties of the samples have been determined at different times in many different laboratories over a period of almost 17 years. Some of the samples are conventional cylindrical stabilisation test samples, some are prism samples and some are pill samples made in connection with the POHVA study. At best, the database contains almost 30 items of data associated with a sample, ranging from geotechnical properties to geochemical properties and location data. However, not all properties have been determined for a majority of the samples, as a result of which there are a lot of "holes" in the stabilisation database.

Due to the vast spectrum of variables and other circumstances presented above (sample size, etc.), it is not possible to determine universal interrelations for the stabilised samples. The most common binding agents were chosen for further processing: cement, cement+lime and lime. This provided 808 observations of shear strength for cement, 646 for cement+lime and 309 for lime. However, these groups still contain "holes" with regard to several properties. Examined as a whole, the stabilisation tests have not been carried out in accordance with any uniform procedure. In addition to the dimensions of the test samples, there has been great variation in the storage times and temperatures.

Looking into the future, the reliability of the database could be improved if it were possible to conduct the stabilisation tests in one single laboratory. However, this is not practically possible. Uniform instructions for determining the properties (starting with the pH measurement) and carrying out stabilisation tests would help in improving reliability but will not completely solve the issue.

4.2 Modelling of shear strength by linear regression

This study has created statistical models for the shear strength of stabilisation by soil type when the binding agent is either cement, a 1:1 mixture of lime+cement or lime. The τ models for shear strength are linear multi-variable models of the form

$$\tau = a_1 x_1 + a_2 x_2 + ... + a_3 x_3$$

in which the coefficients a_i are constants determined in connection with fitting the model.

It must be noted that linearity specifically refers to the linearity of the coefficients; the variables may include nonlinear terms such as powers x^2 or logarithms $\ln(x)$. Shear strength was explained by the quantity of binding agent (kg/m^3), water content (%), water-cement ratio, pH, clay content (%), humus content (%) and equivalent time. Equivalent time refers to a quantity describing the time-temperature of a sample, defined as a function of storage temperature and storage time. The use of equivalent time instead of ordinary time clearly homogenised or reduced the scatter of predicted values obtained from the models.

The coefficients of determination R^2 for the models (with all three binding agents included) using conventional stabilisation tests were 64% on average (range 32…83%), and R^2 corrected was 52%. With index tests, the corresponding R^2 value was 76% on average (range 62…96%) and R^2 corrected was 72%. The mean error of estimate specified as a percentage was 66% for conventional tests and 49% for index tests.

A graph of each model has been plotted with diamond symbols in the coordinate system of calculated and measured shear strength (example in Figure 3). The same coordinate system shows the residual (grey dashed line) or the difference between measured shear strength and shear strength obtained from the model, which would be zero in an ideal case. The graph also shows the confidence interval for the average at a confidence level of 95% (interval limited by the red curves), as well as the prediction interval for individual observation values at a confidence level of 95% (interval limited by the blue curves).
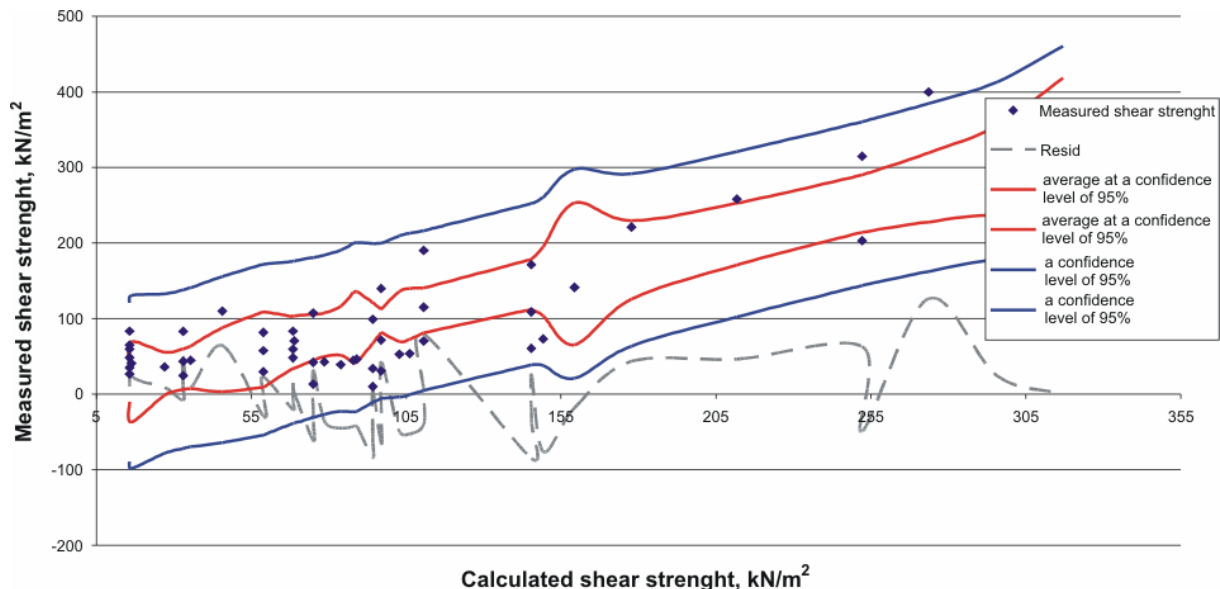

Figure 3. Calculated (laskettu) and measured (mitattu) shear strengths, fat clay; an example.

4.3   Utilisation of results from previous stabilisation study

A previous extensive stabilisation study (Kukko & Ruohomäki, 1995) developed models for the compression strength of stabilised clay in which the compression strength is determined as a function of the water-binding agent ratio as the sum of a term representing the submicron fraction of the clay and a term representing the square of the humus content. The coefficients

associated with these terms had been determined on the basis of the observation data at that time. In this connection, the model was fitted to the shear strength values of materials stabilised with cement and lime-cement that were used in the index tests. The coefficients obtained from the study differ greatly from the terms obtained in the previous study due to factors such as the different strength levels provided by the test types. However, the fitting procedure can be used for creating a site-specific shear strength model, for example, if a sufficient number of laboratory tests are available.

4.4   Factors affecting stabilisation and strength

The stabilisation test database was also used to determine which factors affect the strength of stabilisation obtained. The binding agent used in Finland is cement or lime, or a mixture of them, usually in a 1:1 ratio. A mixture of cement and lime is the most common binding agent because it provides better strength than pure lime and it also works adequately in humus-containing clay layers. The presence of lime usually improves the homogeneity of the column compared to just cement-based binding agents. In addition to these, ground blast furnace slag, fly ash and similar industrial by-products can also be used, particularly in soil types such as sulphide soil that may otherwise exhibit poor stabilisation.

The strength obtainable on-site depends on many factors, such as the soil, its quality and water content, the binding agent, its quantity, the mixing tool, its speed of rotation and rate of rise. In the short and long term, the strength obtained by a binding agent can also be weakened by substances or conditions in the soil that are detrimental to binding. Reasons for poor compression strength have included high humus content and a low pH of the soil material. Both of these factors usually have an impact in sulphide soil as well.

4.5   Significant factors for different binding agents

Cement: When the binding agent was cement and all observations (age approx. 30 days) were studied, the pH did not seem to come up in particular as a strength-affecting factor. The most significant factors contributing to shear strength would seem to be the humus content, sensitivity, conductivity and salt content. According to the most uniform series of samples available, the most significant factors were again the humus content, as well as the shear strength of the soil, the sensitivity and quantity of the binding agent. The effect of the salt content almost disappeared. In spite of the apparently great dependency shown in the sounding images, the correlations R^2 between the more significant factors and shear strength are weak and not more than 0.26.

Lime-cement: When the binding agent was lime-cement, the pH did not seem to come up in particular as a strength-affecting factor. The most significant factors contributing to shear strength would seem to be the humus content, the shear strength of the soil, the sensitivity, conductivity and the salt content. According to the most uniform series of samples available, the most significant factors were again sensitivity, conductivity and the cation exchange capacity. The effect of the salt content almost disappeared. The pH value has no effect between the poorest and strongest columns in terms of shear strength.

Lime: When the binding agent was lime, the pH did not seem to have any significant effect on strength, at least on the basis of this material. Also, in this instance, the most significant factors would seem to be the humus content, sensitivity, conductivity and the salt content. When a fairly complete series of observations is included, the most significant remaining

factors affecting strength with lime are the humus content, sensitivity, conductivity and the salt content.

Of the different factors, the clearest effect is related to sensitivity. Strength increases with increased sensitivity for all binding agents.

5 Contaminants detrimental to stabilisation

Cement is currently used as the binding agent or a component of the binding agent for almost all stabilisation, which means that the contaminants and detrimental factors are principally the same as those for concrete construction.

With regard to chlorides contained in soil and water, as well as other chemical stresses, the values presented in the standards on concrete (Betoninormit, BY50, 2004) can also be considered guide values requiring consideration with regard to stabilisation. Particular attention must be paid to this if there are harmful chemicals in the soil and the water flow rate in the soil is high.

Acids and sulphates may particularly impact on the success of stabilisation. Acids will corrode cement stone compounds because cement stone is alkaline. Sulphuric acid is more harmful than other acids because its reaction products, i.e. sulphates, also cause swelling damage in concrete. Seawater presents a special condition with regard to sulphate damage because the chlorides in seawater can mostly prevent the concrete-damaging effect of sulphates. Blast furnace slag will also clearly improve the sulphate resistance of concrete if its proportion in the binding agent is at least 70%. This is due to the fact that blast furnace slag does not contain C_3A, which reduces the formation of ettringite as a result of sulphates (BY32, 1992). It is uncertain whether the formation of ettringite will cause problems in ordinary stabilised columns because the porosity of columns is supposedly high enough to allow the formation of ettringite without weakening the column (Janz & Johansson, 2002).

Certain salts, such as ammonium and magnesium salts, will also react with hydroxide ions and reduce the pH value (Janz & Johansson, 2002).

The long-term durability of stabilisation is particularly impaired if substances harmful to stabilisation are initially present in the soil or if moving water, particularly soft water or water with a low pH value, is able to affect stabilisation either in its entirety or through water-conducting layers. Particular attention must be paid to the quality of stabilisation and the homogeneity of columns at such sites because discontinuities in columns are a particular risk for the long-term durability of stabilisation.

6 Strength obtained through stabilisation in the laboratory and on-site

The shear strength obtained through stabilisation on-site is usually lower than that obtained with samples in a laboratory. The difference is mostly due to more efficient mixing of the binding agent and soil material in the laboratory. For the purposes of practical design, the strength obtained in the laboratory must therefore be reduced to the strength obtained on-site. In principle, the magnitude of the correction coefficient is affected by the same factors

affecting the strength obtained on-site. The effects of various factors have been itemised to a varying degree in the different instructions.

The present design instructions for deep stabilisation (FinnRa, 2001) present a **maximum correction coefficient value depending on the laboratory strength and the binding agent used.** When using lime-cement as the binding agent, the maximum correction coefficient is $\tau_{field}/\tau_{lab} = 1.0$ up to laboratory shear strength $\tau_{lab} = 120$ kPa and declines in an almost linear manner to the value $\tau_{field}/\tau_{lab} = 0.6$ when the laboratory shear strength reaches 330 kPa. Correspondingly, the correction coefficient values for other binding agents are $\tau_{field}/\tau_{lab} = 0.9$ ($\tau_{lab} = 120$ kPa) and $\tau_{field}/\tau_{lab} = 0.5$ ($\tau_{lab} = 330$ kPa). According to the design instructions for deep stabilisation, laboratory strength can only be used as such without a correction coefficient when the shear strength target for the columns is less than 120 kPa, the binding agent is lime-cement and the quantity of binding agent is increased by 10% from that used in the laboratory.

Site-specific or equipment-specific reduction procedures have also been developed for the reduction of shear strength, allowing the reduction factor to be estimated on the basis of the number of levels in the mixing tools, the natural shear strength of the soil and the rate of rise (Törnqvist & Juvankoski, 2003), or the shape of the mixing tool (Aalto 2002).

All in all, the reduction procedure presented in the design instructions for deep stabilisation (FinnRa 2001) can be considered a suitable basic reduction procedure when using shear strength models if no more detailed descriptions are available.

7 Risk assessment for the management of subsurface information

In connection with the development of shear strength models for stabilisation, defined 95% confidence intervals and 95% prediction intervals for the average have been presented. The prediction interval is more extensive and represents the range that will include the shear strength obtained from a test on the material in question with 95% probability. The confidence interval for the average is narrower.

For the purpose of design, the strength is estimated as a "conservative average". According to the European standard EN 1997-1, the conservative average is the average of a limited set of geotechnical parameters at a confidence level of 95% (the value will be below the average with a probability of less than 5%). If in question is the possibility of a local fracture, the conservative estimate for the lower limit is the 90% lower limit of the prediction interval.

If the lower limit of the 95% average confidence interval of the statistical evaluation is used for the assessment of strength, this introduces a small error but the result is on the safe side. If the shear strengths calculated for the stabilisation samples using a model specific to the soil type differ from the shear strengths obtained for the samples in stabilisation tests, the calculation model must be corrected by the ratio between the shear strength determined for the samples and the calculation result.

It is recommended that, if necessary, the 90% lower limit of the prediction interval is determined separately using scatter data determined on-site, because the distributions based on observation data will be as such excessively large. Water contents specific to each site and soil layer can be estimated on the basis of the electrical resistivity sounding to an accuracy of

at least ± 20 percentage points. The feed accuracy of the quantity of binding agent can also be estimated to be in the order of ± 5…10%, which means that, in kilograms, the variation in an average quantity of 150 kg/m^3 of binding agent is ± 7…15 kg/m^3.

8 Linking subsurface information to the design environment

8.1 Developing an additional module for the design software

The POHVA I project defined the requirements for using resistivity sounding and the boundary conditions for a data model and functionality in the design software. On the basis of the specification, the required prototype was implemented as an extension to the design software. The prototype was tested using actual material from sample sites.

The design software used in the project was the Windows-based Citycad. The 3D soil model used in Citycad is based on soil layers to which geotechnical and earth engineering properties can be attributed. For resistivity sounding, the software was supplemented with functionality for processing storing and visualising raw data. Furthermore, auxiliary functions were implemented for the interpolation and printing of sounding values. Figure 4 shows a few images of the Citycad version in use.
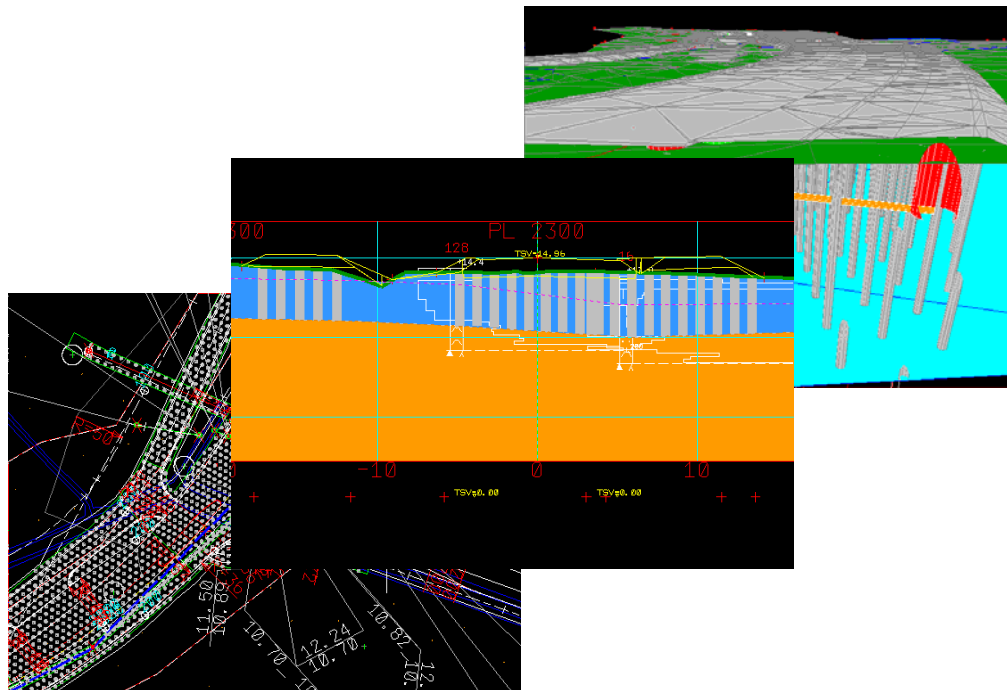

Figure 4. Design software Citycad.

The special characteristics of resistivity sounding include the high number and density of points and the associated measurement data. The interpretation program (which refers to a tool for the field technician and the person interpreting the results) produces the material in the format <l, s, z and values>. It was decided that this should first be modified to the established Road Administration format supported by the design software. With regard to data management, a decision was made to stick to the existing 'single point' data type that allowed the storage of the position, classification and three data values in connection with a point. However, this impacted on efficiency because the data type also includes other information

that is excessive with regard to sounding. However, the number of points was not considered excessively large as to make it inefficient.

The design software can produce surface data using measurement lines as well as boundaries between the earth's surface and interpreted soil layers using basic functions. However, the prototype was supplemented with an additional printing function. For each point in the voxel model, the function calculates the soil layer to which it belongs. In this context, the measurement points are referred to as voxels (volumetric pixels) to differentiate them from pixels processed on a 2D plane. Correspondingly, the term voxel model is used.

For the purpose of visualisation, the model can be presented in cross-sections, either as rectangles, a point-type object (centre point of a voxel) or a point-type object with a measurement value.

8.2 Testing of the software prototype and operating experience

The study involved resistivity sounding at two different test sites: Äijänpelto and Vanttila. Both sites are located in Espoo, and there was other supplementary site investigation data and surface data available for both. The resistivity interpretation results from the test sites were transferred to the Citycad design software using the processing module for soil resistivity sounding.

Soil interpretation was carried out at the measurement site, including the dry crust, the clay layer, the silt/moraine below the clay, and the rock surface. The interpretation program was provided with information on earth surface elevations at the measurement lines, and a corresponding topography correction was made to the interpretation program. The sounding points with resistivity values and preliminary water contents were read into the design software and converted to the VVJ coordinate system. The material was printed out from the design software so that the sounding points were associated with the interpretation of the soil layer they belonged to. In addition, the sounding points close to the sampling points and the corresponding water contents measured in laboratory tests were also provided. On the basis of this, the interpretation program provided sounding points with more precisely determined water content values.

According to the operating experience achieved, the interpretation of usable measurement data into a voxel model calls for special competence. It is important for the design process that the interpreted measurement data can be viewed and utilised, especially in design software that also provides all the other materials: the terrain model, soil model, site investigations and a pavement structural model, for example. However, design software does not necessarily provide all the features of the interpretation program or a program intended solely for the processing and visualisation of 3D point data. The reliability and smoothness of data transfer between programs is essential.

One of the challenges was that the interpretation program processed data in a local coordinate system bound to the measurement line, while design software usually operates in a global coordinate system. Particular attention should be paid to the preparation of a measurement plan for resistivity sounding.

From the designer's viewpoint, the voxel model provides valuable additional information to support conventional site investigations. For example, the area can initially be investigated with a more coarse sounding interval, and additional investigations can be guided on the basis of the electronic voxel model.

At the examined sites, all of the voxels in the model were equal in size (1 m x 1 m x 1 m), which may give the designer a wrong impression of the measurement accuracy as it deteriorates when it gets smaller. One of the data items to be interpreted could be sensitivity or reliability, which would provide the designer with information on where the measurement results are most reliable and where additional data is required. Resistivity sounding will clearly help in the focusing of site investigation and the interpretation of the soil model.

8.3 Proposal for design process

At present, a realistic starting point for the design process is that the interpretation program and the design program operate independently as tools for the appropriate experts. Data transfer is based on files. A measurement plan has to be drawn up before the resistivity sounding, and the measurement lines must be marked on-site in advance. Measurements from separate lines will be combined in a shared coordinate system in the interpretation program, most preferably in the global coordinate system used by the design software.

Topography correction can be performed either in the interpretation program or in the design software. The clearest practice would be to do this immediately in the interpretation program. If the surface models cannot be used directly in the interpretation program, the design software will provide earth surface heights at the measurement points. This will allow the immediate use of a uniform xyz voxel model for data transfer without additional conversions. Topography correction must be done in accordance with the surface formed by the points where the probes are located. Information on the origin and precision of the measurements must be associated with the measurement batches.

The design involves the processing, editing and storage of the basic materials, the terrain model and site investigations, as well as the interpretation of the soil model. The interpretation of resistivity sounding requires co-operation between the interpreting party and the designer. This also imposes requirements on the smoothness of data transfer.

With regard to design, the interpretation of sounding requires professional skills and is clearly the task of the field technician; the designer needs resistivity soundings that have already been interpreted. At the same time, conventional soil layer interpretation and co-operation between the interpreting party and the designer are required in order to specify the interrelationship between resistivity and water content in more detail.

8.4 Recommendation for data transfer

In the present situation, it is recommended that data transfer for resistivity sounding and other site investigation data be carried out using common text formats such as the Road Administration format. The parties should agree upon the applicable format at the very beginning of the project. In the future, a uniform, preferably international and XML-based, format should be agreed upon for data transfers associated with resistivity sounding. The specification of the model must take into account the work completed so far in the Inframodel project and in the Infra product information model that may be implemented. The report presents a recommended example for an XML-based format for resistivity sounding. The study also presented a recommendation on how stabilisation control data can be converted into a format required for machine automation.

9 Measurement techniques for automatic collection of quality data

At present, the positioning of column stabilisation is based on sticks that are separately measured and placed at the centre of the upcoming columns, as well as on the manual movement of the machine and positioning of the piling rig. The vertical control of the piling rig may be manual or automatic. In the future, machine movements could be automated so that it would be possible to position the piling rig automatically on the basis of the xyz data for the columns obtained from the column plan.

According to the stabilisation execution standards, a work record must be maintained that presents data such as the party carrying out the work, the date and weather, the numbering of the columns in accordance with the work plan, the top and bottom levels of the columns, the column positions based on post-measurement, as well as observations of any problems and deviations when making the columns. The objective is that column work could be monitored in real time, continuously transferring actual data to the database.

10 Final summary

The study developed the skills and capabilities to create a more economical, ecologically efficient and functional deep stabilisation method. By refining three-dimensional site investigation data into a strength estimate for column stabilisation and forwarding this information to machine automation, the quantity of binding agent can be optimised on a column-specific basis in the depth direction. The coarse estimations suggest that the optimisation can decrease the use of binder agent from 10…30 %, which means savings from 5…20 % depending on the site characteristics. The objective is to create columns that are homogenous in strength in the depth direction. Together with the more precise positioning of columns allowed by machine automation, this will improve the quality and functionality of the end product and reduce the risk arising from the non-homogeneity of the structure. This will improve the management of settlement, for example.

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