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Pre-study: Ground improvement for marginally stable slopes

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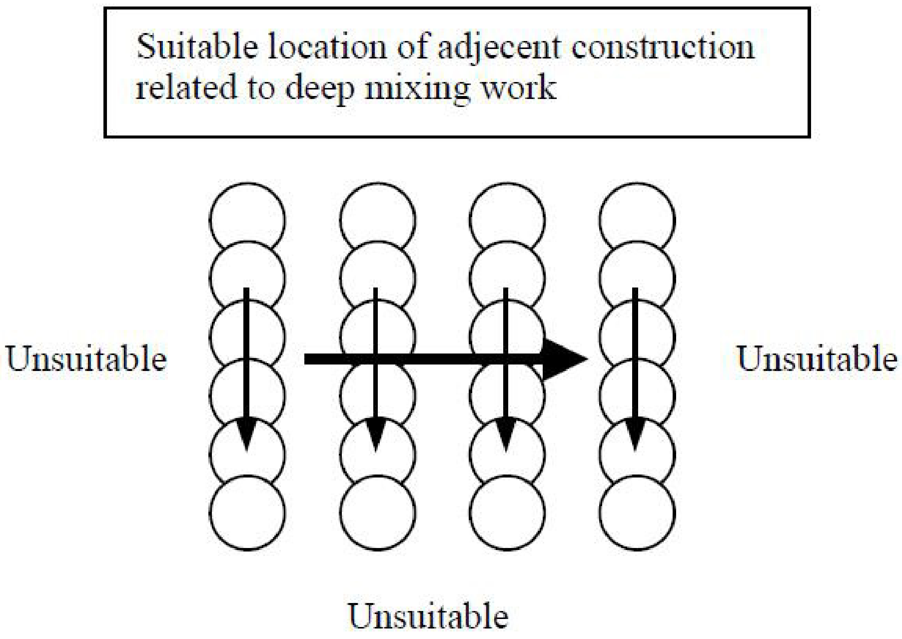

R A P P O R T

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Pre-study: Ground improvement for marginally stable slopes

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ABSTRACT

The report aims to give a critical review on various ground improvement methods that involve in-situ mixing and/or injection of stabilising agents in the form of powder or slurry into soft clays.

The project was initiated by Statens vegvesen, given the problems in Norway associated with slopes of marginal stability.

The report will focus on installation methods that are applicable for ground improvement in soft sensitive clays, with the aim of identifying installation methods that minimise pore pressure built-up during installation as well as deformations.

The methods considered include both dry and wet deep soil mixing and various other potential methods, including electro-osmotic injection of stabilising agents into the soft soil. Additionally, an evaluation of the achieved effect on strength parameters resulting from the use of wet slurry versus dry mixing is conducted.

Key words: ground improvement, installation, pore pressure, sensitive clay, slope stability

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Gothenburg, Sweden, November 2014

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Pre-study:

Ground improvement for marginally stable slopes

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ABSTRACT

The report aims to give a critical review on various ground improvement methods that involve in-situ mixing and/or injection of stabilising agents in the form of powder or slurry into soft clays. The project was initiated by Norwegian Public Roads Administration (NPRA), given the problems in Norway associated with slopes of marginal stability. This project is also a part of the Natural hazards – infrastructure for floods and slides (NIFS) project initiated by the Norwegian National Rail Administration (JBV), the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Public Roads Administration (NPRA).The report will focus on installation methods that are applicable for ground improvement in soft sensitive clays, with the aim of identifying installation methods that minimise pore pressure build-up during installation as well as deformations. The methods considered include both dry and wet deep soil mixing and various other potential methods, including electro-osmotic injection of stabilising agents into the soft soil. Additionally, an evaluation of the achieved effect on strength parameters resulting from the use of wet slurry versus dry mixing is conducted.

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Contents

1 Introduction

1.1 Motivation

The project was initiated by Norwegian Public Roads Administration (NPRA) in Norway, motivated by the problems in Norway associated with slopes with marginal stability. Slopes with marginal stability are slopes that in their natural state are just about stable, i.e. have a factor of safety (FOS) close to one, assessed typically with the limit equilibrium method in terms of total stress analyses. Currently, the most common ground improvement technique on soft sensitive clays in Scandinavia is dry soil mixing. Even though the method has largely been successful, there have been some failures in conjunction with cut slopes (some unpublished cases in Finland in early 90s involving cut slopes for bridge underpasses) as well as unexpected deformations (e.g. Viberg et al. 1998, Johansson 1998, Hallingberg 2005), most recently in the project BanaVäg i Väst in Sweden (Ekström 2014). These unsatisfactory performances have been largely attributed to installation effects, such as soil heave, changes in soil structure and excess pore pressures. Clearly, when considering stabilising marginally stable slopes, installation effects need to be taken into account. The key research questions, therefore, are: a) if the installation methods can be better understood and how can they be taken into account, and b) if there are methods, other than dry deep mixing, that could be utilised to stabilize marginally stable slopes in soft sensitive clays. Wet mixing, hybrid dry/wet mixing as well as various other potential methods, including electro-osmotic injection of stabilising agents into the soft soil will be considered.

1.2 Aims and objectives

The report aims to give a critical review on various ground improvement methods that involve in-situ mixing and/or injection of stabilising agents in the form of powder or slurry in the soft soil, as a basis for future research. The report will focus on installation methods that are applicable for ground improvement in soft sensitive clays, with the aim of identifying installation methods that minimise pore pressure built-up and soil deformations during installation. The methods considered include both dry and wet deep soil mixing and various other potential methods, including electro-osmotic injection of stabilising agents into the soft soil. Furthermore, an evaluation of the achieved effect on strength parameters resulting from the use of slurry versus dry mixing is conducted.

The objectives are the following:

- Perform a literature study on wet and dry mixing and other possible ground improvement methods that result in mixing or injecting stabilising agent into the soft clay to improve its stability and stiffness, with focus on installation effects and the effect of these on stability and deformations.
- Contact experts on wet and dry mixing both internationally and nationally in order to get their views on the limitations and possible improvements of existing methods, to complement the literature study.
- Based on above, identify possible techniques, improvements and research lines for further studies.

1.3 Limitations

The pre-study is based on literature research and expert interviews, and does not involve any experimental testing and/or analytical/numerical analyses. Furthermore, high pressure methods such as jet grouting, as well as other ground improvement methods, such as vibro replacement columns, ground freezing and vertical drains (when used alone) have not been considered.

2 Assessment of marginally stable slopes

The assessment of slope stability in Norway is usually conducted, similarly to the rest of Scandinavia, using Limit Equilibrium analysis and total stress. By definition a slope that is marginally stable has a factor of safety (FOS) close to one in its natural state. The values for the undrained shear strength used in the analyses are determined from either field vane tests or cone penetration tests, supported by laboratory testing. The reason for opting for total stress analyses is partly due to tradition, but also due to simplicity, given the difficulties in estimation of the long-term pore pressures, as necessary for analysing slope stability based on effective stress analyses. Especially the excess pore pressures that develop due to yielding of soil and on-going creep deformations are difficult to predict.

Based on slope stability analyses with the limit equilibrium method (LEM) using total stress, many of the natural slopes in Scandinavia appear to be only marginally stable. When considering the natural formation and geological history of natural slopes, one would expect that only natural slopes that have been very recently formed by e.g. erosion, would be marginally stable. However, many of the natural slopes have had a considerately long period to age, resulting in increased stability. Indeed the fact that many of the marginally stable slopes do not exhibit any measurable ongoing deformations is perhaps an indication of real stability. Furthermore, if many of the natural slopes in Scandinavia really are only marginally stable, one would expect very frequent incidents of slope failures. Based on LEM analyses using total stresses, most of the railway embankments in the South-Western part of Finland are marginally stable, and yet no major failures have occurred (Mansikkamäki 2014). This is the reason why Finnish Transportation Agency invested recently in a major research project that involved bringing an instrumented railway embankment to failure. The failure load far exceeded the failure load based on LEM analyses using total stresses (Mansikkamäki 2014) and formed a basis for exploring alternative methods of analyses.

In traditional LEM analyses with total stresses the key input parameter is the undrained shear strength of the soil. The undrained shear strength is, however, not a soil constant, as it is dependent on the stress history and stress state, as well as the stress path to failure. The latter in turn depends on the type of loading, hydraulic conductivity of the soil as well as the stiffness of the soil. Consequently, the mobilised undrained shear strength at failure is different at different parts of the failure surface (Bjerrum 1973). The so-called NGI-ADP method by Grimstad et al. (2002) attempts to account for the variation of mobilised strength on the failure surface, but is still a total stress method.

Natural soft clays are often anisotropic, and this influences both the stiffness and mobilised strength. In the case of cut slopes with marginal stability on soft soils, the effect of anisotropy has actually a positive effect on the predicted horizontal deformations, as demonstrated by Dawd et al. (2014). Sensitive soft soils exhibit, in addition to anisotropy, some apparent strain softening even in the normally consolidated range. This is partly due to the gradual destructuring of the apparent bonding between particles during shearing, as well as issues with strain localization in experimental testing (see e.g. Thakur et al. 2006, Gylland et al. 2013). The higher the sensitivity, the more significant the apparent strain softening is. The shear strength of sensitive soft clays is also highly rate-dependent, and the higher the strain rate, the higher the perceived undrained shear strength. These effects can only be accounted for with advanced soil models, such as the recently developed Creep-SCLAY1S model (Karstunen et al. 2013, Sivasithamparam et. al 2013, Sivasithamparam et. al *under review*).

3 Deep mixing method

3.1 Introduction to deep mixing method

Deep mixing is a ground improvement method, in which stabilising agents are mixed with in situ soil using special blades. The stabilising agents typically contain cement and/or lime with added gypsum, fly ash or other substances, depending on the soil properties, the chemical composition of the pore water and the required properties for the stabilised soil. The interest in using inexpensive industrial by-products, such as fly ash is increasing based largely on economic reasons, but these may have detrimental effect in strength development if used in high dosages (Indraratna et al. 1995). Descriptions of deep mixing can be found in several specialist textbooks, including Bergado et al. (1994), Kirsch & Bell (2012), Kitazume & Terashi (2013), and keynote papers (e.g. Topolnicki 2003, Kitazume 2005, Larsson 2005). Hence only some key features of the method will be discussed in the following.

The most common use of deep mixing method is to form columns or blocks for foundation support. On-land applications comprise of road and railway embankments, buildings, industrial halls, bridge abutments, retaining walls and underground facilities (Topolnicki 2012). Novel applications involve the use of deep mixed columns for reducing vibrations of high speed railways (Holm et al. 2002) and under wind turbine foundations (Topolnicki & Soltys (2012) according to Topolnicki 2012). Deep mixing is also applied to stabilise landslides and critical slopes, using column arrangement in the form of panels, grids, lattices and blocks which intersect a potential failure surface. Good results in stabilisation of landslides have been achieved for example in New Zealand (O'Sullivan et al, 2009). If the stability of a slope without any ground improvement is low, i.e. FOS < 1.2, the stabilisation needs to be done by using panels, grids, lattices or blocks, i.e. the use of individual columns is not sufficient.

Deep mixing is primarily carried out using two different methods: dry mixing where the binder is introduced by air pressure and wet mixing where the binder is injected in a slurry form. Some successful trials have also been made using a hybrid mixing method, where dry mixing has been assisted with water jets (Eriksson et al. 2005, Eriksson 2014) resulting in wider applicability and more homogeneous columns than achievable with traditional dry mixing. In Scandinavia, because of the high in situ water content of sensitive soft soils, dry mixing has been the norm, and in this process the stabilising agents are fed in powder form with the help of compressed air. In contrast, in Japan and Poland, wet mixing is extensively used, using single or multiple mixing blades. The methods have been large standardised, and in addition to national guidelines, for applications in Europe there is a European design guide (EuroSoilStab 2002) and European standard for Execution of Special Works - Deep Mixing (EN: 14679: 2005).

The process of deep mixing involves three principal phases (Larsson 2005):

1) Penetration of the mixing tool to the required depth, which involves remoulding and disaggregation of soil structure. According to Japanese practice, stabilising agents are introduced already at this stage, if wet mixing is used.
2) Dispersion process, which includes incorporation and spreading of the binder, wetting of the solid particles (in the case of dry mixing), breakdown of agglomerates by kneading action and the distribution, which is the process by which the disaggregated agglomerates are (hopefully) randomly scattered through the mixture. As already mentioned, in wet mixing the stabilising agents are often introduced already during the penetration, i.e. Phase 1.

3) Molecular diffusion, which continues after the execution, involves the migration of calcium ions into the unstabilised soil, or within the stabilised soil, from parts with high concentration of ions to parts with low concentration. The binder will also migrate into any shrinkage cracks in the surrounding soil, as well as any vertical fractures and shear cracks created by the mixing process. The process of molecular diffusion is most likely the reason why the columns sometimes exhibit some self-healing tendencies.

With regards of dry deep mixing, Tables 3.1 and 3.2 from EN: 14679:2005 are comparing the Nordic and Japanese dry mixing techniques. From installation point of view, one of the key issues is the injection pressure. With dry mixing method the pressures normally vary between 200 and 800 kPa (see Table 3.1 from EN: 14679:2005) and typically a pressure of at least 300-500 kPa is simply needed simply to keep the powder flowing (Eriksson 2014) and creating a cavity for the powder for mixing with the soil. By default, for the latter, the pressure needs to be higher than the horizontal total stress in the soil. Furthermore, the pressure needs to be sufficient to create channels up to the ground for the evacuation of the air. A too high pressure may cause pneumatic fracturing outside the column periphery, and the relatively high air pressures, about 200 to 800 kPa as common in Sweden (Eriksson 2014), are notionally high enough to fracture the soil. At great depths, if too low pressures are used there is a risk that the cavity will be too small due to high in situ pressures (Kitazume 2005), resulting in poorly formed columns.

Table 3.1. Comparison of the Nordic and Japanese mixing techniques (EN: 14679:2005, AC_1 below refers to corrections made to the standard in 2010).

Equipment	Details	Nordic technique	Japanese technique
Mixing machine	Number of mixing shafts	1	1 to 2
	Diameter of mixing tool	0,4 m to 1,0 m	0,8 m to 1,3 m
	Maximum depth of treatment	25 m	33 m
	Position of binder outlet	The upper pair of mixing blades	Bottom of shaft and/or mixing blades (single or multiple)
	Injection pressure	AC1 Variable 200 kPa to 800 kPa AC1	Maximum 300 kPa
Batching plant	Supplying capacity	50 kg/min to 300 kg/min	50 kg/min to 200 kg/min.

Table 3.2 Typical execution values of the Nordic and Japanese dry mixing techniques (EN: 14679:2005).

Mixing machine	Nordic technique	Japanese technique
Penetration speed of mixing shaft	2,0 m/min to 6,0 m/min	1,0 m/min to 2,0 m/min
Retrieval speed of mixing shaft	1,5 m/min to 6,0 m/min	0,7 m/min to 0,9 m/min
Rotation speed of mixing blades	100 revolutions/min to 200 revolutions/min	24 revolutions/min to 64 revolutions/min
Blade rotation number[1)]	150 per m to 500 per m	≥ 274 per m
Amount of binder injected	100 kg/m^3 to 250 kg/m^3	100 kg/m^3 to 300 kg/m^3
Retrieval (penetration) rate	10 mm/rev to 30 mm/rev.	10 mm/rev to 35 mm/rev.
Injection phase	Typically during retrieval	Penetration and/or retrieval

Based on Table 3.2, in the Nordic method the powder is introduced only during retrieval, whilst in Japan it is introduced sometimes both during penetration and retrieval. This is because of the rather fast reaction of the powder type of stabilising agents that are typically used in Scandinavian applications, in contrast to cement mixes used in Japan. In Scandinavia industrial ready-made lime-cement mixes are mostly used, whilst in Japan various cement mixes are common. Because in Japan typically dual shaft machines are used, the penetration/withdrawal speed and rotation speed are lower in Japan than Scandinavia (Kitazume & Terashi 2013), but yet resulting in higher blade rotation number (see Table 3.2 from EN: 14679:2005). The blade rotation number is defined as the number of mixing blades passing during 1 m of single shaft movement through the soil (Topolnicki 2012). The higher the blade rotation number, the better the stabilisation effect and the lower the coefficient of variation (Larsson & Nilsson 2005), as shown in Figure 3.1.

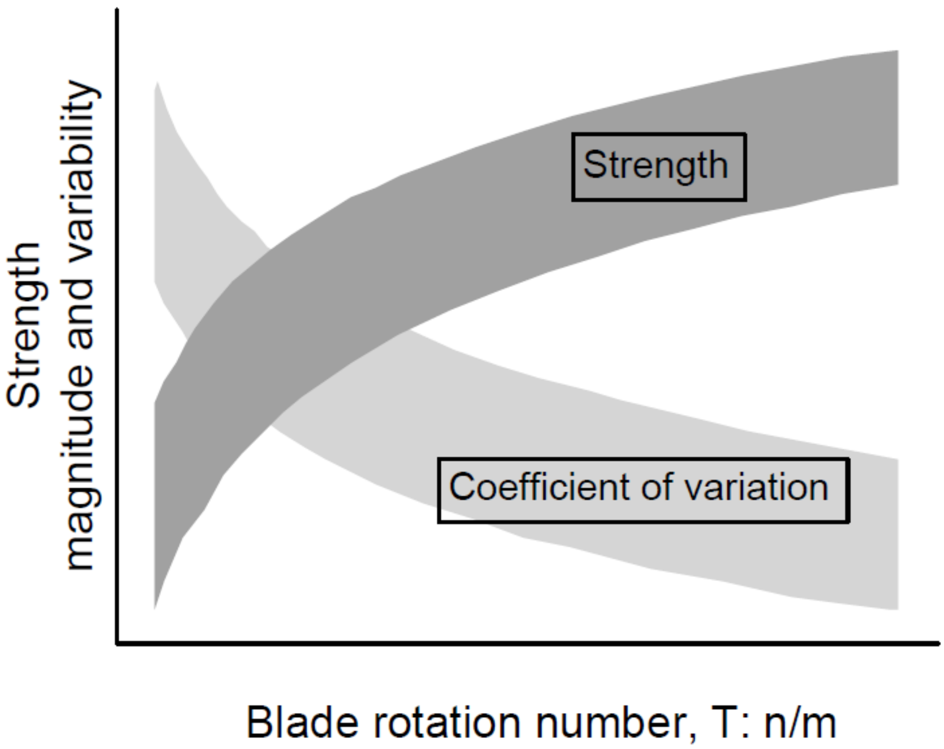

Figure 3.1. Effect of blade rotation number on the strength and variability of the stabilised soil (Larsson 2005).

The amount and type of powder used in deep mixing are highly variable, dependent of the soil type and target strength of the columns. More details about the mixing processes associated with Nordic dry mixing can be found in Larsson (2003). The factors that may influence the process and its results can be summarised as follows (Larsson 2005):

a) Rheology of the soil, the binder and the amount of binder;
b) In situ stress conditions in the soil during column installation;
c) Pressure used, and in case of dry mixing also the amount of air used;
d) Geometry of the mixing tool;
e) Mixing energy: the retrieval rate and rotation speed of the mixing tool;
f) The apparent preconsolidation stress, compaction energy, temperature, the availability of water and seepage flow, which all affect the molecular diffusion.

Of the factors above, the effect of soil rheology on the mixing process is poorly understood, and the same applies to the influence of factors such as the rotation speed, air pressure, the amount of air and compaction (Larsson 2005). What comes to the geometry of the mixing tool, commercial secrecy with regards to the details of the mixing tools has prevented any scientifically sound comparative studies. However, by modifying the design of the mixing tool, by changing the orientation of the nozzle so that the stabilising powders are blown inwards rather than outwards (Takeida & Hioki 2005) and injecting only during the retrieval, subsurface ground displacement were reduced by 1/3 to 1/2 as compared to the conventional blade (Takeida & Hioki 2005).

With regards of wet soil mixing, Tables 3.3 and 3.4 from EN: 14679:2005 are comparing European and Japanese wet mixing techniques, considering both on land and marine (i.e. offshore) installation. Generally the installation pressures for wet mixing tend to be higher than for dry mixing, and the amount of binder needed to achieve the same strength as in dry deep mixing is higher in the wet method, given additional water is introduced to the soil to be stabilised. Penetration injection is typically used for on-land applications of wet method, because the slurry helps to lubricate the mixing tool and assists in breaking up the soil into smaller pieces. Normally 80%-100% of the total slurry volume is used in this stage. This is also beneficial to the homogeneity and strength of the columns because the natural soil is mixed twice with the binder (Topolnicki 2012). From the outset, the injection pressures in Table 3.3 appear to be high, and much lower pressures (50 to 150kPa) have been used in practice for installing cement columns in sensitive Ariake clay (Shen et al. 2003a).

Table 3.3. Comparison of European and Japanese wet mixing techniques (EN: 14679:2005)

Equipment	Details	On land, Europe	On land, Japan	Marine, Japan
Mixing machine	Number of mixing rods	1 to 3	1 to 4	2 to 8
	Diameter of mixing tool	0,4 m to 0,9 m	1,0 m to 1,6 m	1,0 m to 1,6 m
	Maximum depth of treatment	25 m	48 m	70 m below sea level
	Position of binder outlet	Rod	Rod and blade	Rod and blade
	Injection pressure	500 kPa to 1 000 kPa	300 kPa to 600 kPa	300 kPa to 800 kPa
Batching plant	Amount of slurry storage	3 m^3 to 6 m^3	3 m^3	3 m^3 to 20 m^3
	Supplying capacity	0,08 m^3/min to 0,25 m^3/min	0,25 m^3/min to 1 m^3/min	0,5 m^3/min to 2 m^3/min
Binder storage tank	Maximum capacity		30 t	50 t to 1 600 t

Table 3.4. Typical execution values of European and Japanese wet mixing techniques (EN: 14679:2005)

Mixing machine	On land, Europe	On land, Japan	Marine, Japan
Penetration speed of mixing shaft	0,5 m/min to 1,5 m/min	1,0 m/min	1,0 m/min
Retrieval speed of mixing shaft	3,0 m/min to 5,0 m/min	0,7 m/min to 1,0 m/min	1,0 m/min
Rotation speed of mixing blades	25 rev/min to 50 rev/min	20 rev/min to 40 rev/min	20 rev/min to 60 rev/min
Blade rotation number	mostly continuous flight auger	350 per meter	350 per meter
Amount of binder injected	80 kg/m^3 to 450 kg/m^3	70 kg/m^3 to 300 kg/m^3	70 kg/m^3 to 300 kg/m^3
Injection phase	Penetration and/or retrieval	Penetration and/or retrieval	Penetration and/or retrieval

Traditionally, the amount of binders are listed as the amount of dry powder per m^3 of the soil, but more recently, there has been an increasing trend to use water/cement ratio (Horpibulsk at al. 2011), analogously to concrete where Abrams' law is broadly applied. Hence, for dry mixing, clay-water/cement ratio w_c/C can be adopted, for wet mixing, the sum of clay water and added water need to be used. Horpibulsk at al. (2011) demonstrate that in laboratory conditions very repeatable stress-strain response can be achieved for a particular clay at a given w_c/C ratio tested after a specific curing time. In Finland 3D electrical resistivity model is combined with point specific measurements and sampling to adjust the amounts of binder on temporal basis based on water content in the soil (Korkiala-Tanttu 2008).

The lime used in dry mixing is typically unslaked quicklime (CaO) which absorbs moisture in the natural soil to become hydrated (slaked) lime ($CaO + H_2O = Ca(OH)_2$). The hydration reaction is rapid and generates a large amount of heat. During the process, quicklime almost doubles in volume and the water content of the soft soil is reduced (Kitazume 2005). With the existence of sufficient pore water, hydrated lime dissolves into water and increases the calcium and hydroxyl ion content. The calcium ions exchange with the cations on the surface of the clay minerals, and furthermore, under high pH conditions the silica and aluminium in the clay minerals dissolve into the pore water and react with calcium to form tough water-insoluble gels of calcium-silicate and/or calcium-aluminate. The latter reaction, the so-called pozzolanic reaction, proceeds as long as the pH condition is maintained and there is excess calcium in the system (Kitazume 2005). The pozzolanic reaction products are behind most of the strength increase in lime-stabilised soils, as they cement the particles together. Because of the immediate reduction of water content, lime is often used in stabilisation of sensitive clays (Locat et al. 1990). According to Bergado et al. (1994), Miura et al. (1986) found out that the improvement by mixing quicklime is more effective for clays located nearshore than onshore locations for soft Ariake clays, suggesting that the salt content of the clay might have a positive influence. Ariizumi (1977) according to Bergado et al. (1994), suggested that the addition of NaCl may act as a catalyser, and the ions Cl^-, Na^+ and Mg^{+2} may accelerate the pozzolanic reactions. As yet, there does not appear to be systematic studies on the role of salts in stabilisation of sensitive clays, even though the beneficial effects on adding salts to sensitive clays is well known (see e.g. Rosenqvist 1953).

The cement-type of binders used in deep mixing include typically Portland cement alone, in combination with lime, blast furnace slag or fly ash, see Table 3.5. When cement is mixed with a wet soil, it reacts with water in the soil, and instantly a hydration process commences in which a hard cement paste is formed of calcium-silicate-hydrate gel. The CSH-get is formed on the cement particles and increases in size filling the void between the particles (Dahlström 2012), see Fig. 3.2 (Janz & Johansson 2002). Gypsum is often added to the cement to moderate the reactions, in order to delay the setting. A common feature with all of the materials listed in Table 3.5 is that their reaction rate depends, at large degree, on the surface area of the materials exposed to the water (Janz & Johansson 2002).

The so-called hybrid methods of deep mixing include the CDM-LODIC method, which is a Japanese method developed for minimising lateral displacement during construction by removing a soil volume equal to the volume of the injected cement slurry (Kamimura et. al. 2005). In Scandinavia, so-called MDM (Modified Dry Method) has been tested. MDM is another hybrid method, which incorporates the advantages and disadvantages from wet and dry mixing into one single rig (Eriksson et al. 2005). In this method, the binder is fed pneumatically, but at the same time water is added through a separate port of the mixing tool. The addition of water facilitates penetration to stiff soils, it fluidises low plastic clays as well as ensures the complete hydration of the added binder (Gunther et. al 2004, according to Eriksson et al. 2005). Compared to dry mixing, MDM has the following advantages: ease of penetration into stiff to firm soils, immediate activation and hydration of large quantities of the binder, fluidization and disaggregation of plastic soils, higher homogeneity and ability to stabilise dry soils, such as dry crust (Eriksson et al. 2005).

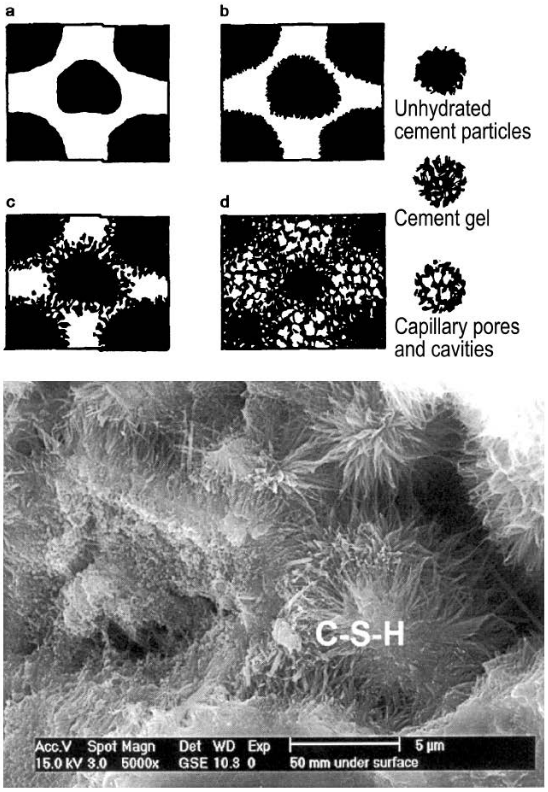

Fig. 2.1
Structure of cement paste:
a) Immediately after mixing
b) After a few minutes
c) Upon setting
d) After some months
(Fagerlund 1994)

Fig. 2.2
ESEM photograph of cement gel containing CSH crystals.
Photo: Finger Institute, Weimar University.

Figure 3.1. Evolution of the structure of cement paste and ESEM image of cement gel (Janz & Johansson 2002).

Table 3.5. Reactions and reaction timescales of different binders (Janz & Johansson 2002)

Binder	Reaction	Coreagents	Time scale
Cement	Hydraulic	Water	Days
Lime	Puzzolanic[1]	Water + puzzolanic soil or puzzolanic additive	Months
Granulated blast furnace slag	Latent hydraulic	Water + $Ca(OH)_2$ from e.g. cement or lime	Weeks
Fly ash[2] and silica fume	Puzzolanic	Water + $Ca(OH)_2$ from e.g. cement or lime	Months

1) An initial hydraulic reaction forms $Ca(OH)_2$, which then participates in a pozzolanic reaction. The strength gain is due to the products of the secondary pozzolanic reaction.

2) Fly ash from power and heating plants fuelled with pulverized coal.

The choice between the dry and wet process of soil mixing has mainly been done based on local practice, tradition and equipment available. According to Topolnicki (2012), Terashi (2003) has underlined that from the point of view of engineering properties, for soils stabilised with the same type of binder in powder and slurry form, there is no substantial difference between both mixing processes. This observation has been demonstrated by numerous investigations conducted on laboratory mixed soils, but is difficult to repeat in field conditions (Topolnicki 2012). When a sufficient, but not too high, amount of cement in powder or slurry form is mixed thoroughly to the soft soil higher compressive strength is expected for the dry than the wet process. Generally for very soft soil with high water content, reasonable strength gain is easier to achieve using dry binder (Topolnicki 2012). Laboratory studies by Larsson & Kosche (2005) suggest that there is no major difference in cement columns manufactured with dry method compared to the wet method, however, the installation method did not introduce air and hence results might not be applicable to field conditions. However, most notably, the peptizer (lignosulphate) used to facilitate mixing in laboratory had a significant unfavourable influence on the undisturbed undrained shear strength, causing at high contents total strength loss, liquefying the kaolin clay used (Larsson & Kosche 2005). Compared to the wet mixing, which may result to high volume of spoil, up to 50% to 60% of the treated volume in some cases (O'Rouke & McGinn 2004, according to Larsson 2005), the dry mixing has also the advantage of no or low spoils. Clearly, there are advantages of incorporating the binder into the soil while the mixing tool is penetrating into the soil, but with unslaked lime this is not possible due to the fast hydration process.

Due to the amount of air used in dry mixing, typically 8-10 m^3 per min (Eriksson et al. 2005), dry mixed columns tend to be more heterogeneous than wet or hybrid (MDM) mixed columns. In the field, the introduction of air is causing problems such as strength and stiffness variations (Topolnicki 2012). Aalto (2001) performed a series of laboratory model tests involving air pressure feed of stabilising powder to form deep mixed columns. His research demonstrated that the amount of air influences considerably the uniformity and the strength of the stabilised columns. According to EN:14679: 2005 "In dry mixing the air pressure shall be kept as low as possible to avoid problems of air entrainment and ground movements". One of the detrimental side effects of dry mixing is formation of crater-formed holes in the surface (Larsson 2005), typically in the dry crust, which need to be filled and compacted with granular fill. The latter can be avoided by using the hybrid method MDM (Eriksson et al. 2005), which has the advantage of being able to produce competent columns also in the dry crust layer, as well as in layers of variable stiffnesses and water contents. The benefit of the wet method and the hybrid MDM is the ability to penetrate through hard layers, as well as better column homogeneity than achieved with the dry method.

3.2 Installation effects associated with deep mixing method

Most of the research on deep mixing has not looked at the installation effects, and indeed the analyses and design methods that are commonly adapted tend to assume that in particular the soil between the columns stays intact. Given deep mixed columns are constructed by penetrating into the soils and mixing in situ soft soil with chemical admixtures using rotating blades, the installation disturbs the soil, and furthermore, induces property changes in the surrounding clay (Shen et al. 2003a).

The installation effects, therefore, include:

1) <u>Heave due to to the penetration of the mixing tool and injection of stabilising agents.</u> The actual penetration of the mixing tool and the injection of additional materials in terms of stabilising agents, water (wet/hybrid mixing) and air (dry mixing) will induce volume changes in the soil, which in the short term (undrained conditions) manifest as excess pore pressures (see Point 4 below) and heave. In Bana Väg i Väst project, on some locations the heave due to installation has been of the order of tens of centimetres (Ekström 2014), which are unlikely to be purely elastic. This raises the question how this might influence the apparent modulus of the soil for any subsequent loading. According to Fang & Yin (2007), cracks in the columns (see Point 3 below) seem to have a lot of influence on the negative pore water pressures in unloading stages, which would be typical in cases when the columns are used for creating cut slopes. In conjunction with a slope stabilisation works Viberg et al. (1999) report horizontal movement around 300mm. Larsson (2005)

reports on Japanese measurements that indicate that the lateral movements may be very large when the measuring point lies under the stabilisation.

2) Disturbance of the surrounding soil during mixing (Shen et al. 2003a). The first force is caused by an expanding action due by the injection pressure of the stabilising agents. The second force is a shearing force resulting from the rotation of the blades. These dual effects can generate excess water pressures and disturb the surrounding clay, so that a plastic zone is formed around the column. The extent of the disturbance depends on the sensitivity of the clay, injection pressure and the configuration of the blades (Shen et al. 2003a).
3) Soil fracturing around column (Shen et al. 2003a). The soil fracturing around the column can happen during installation of the columns, caused by the rotation of the blades and the injection pressure. To some extent, the formation of radial fractures around the blades is analogous to soil fracturing in laboratory shear vane tests (Shen et. al 2005), illustrated in Figure 3.3, corresponding to the situation after the vane wings were rotated for 360°. In sensitive clays, according to Gylland et al. (2013), the fracturing outside the zone affected by the blade of the vane is not as extensive as shown in Fig. 3.3. However, in deep mixing we also have the injection pressure and the soil strength influencing this process. According to Shen et al. (2003a), the fracturing region may extend to 2-4 times the column diameter. Additionally, vertical cracking occurs in the close region around the column. In the case of dry mixing, vertical fractures are beneficial, as they allow the air to escape from the system. For vertical fracturing, tensile failure mechanism approach (Andersen et al. 1994) can be used to estimate the stress conditions required trigger vertical fractures (see Shen et al. 2003b), whilst for radial cracking, the mechanism is likely to be a combination of tensile and shear failure mechanism (Shen et al. 2003b).
4) Thixotropy (Shen et al. 2003a). Clay soils are thixotropic materials due to their microstructure (Mitchell 1960). In thixotropic materials the structures progressively break down on shearing and slowly rebuild at rest with time (Barnes 1997). It is estimated that sensitivities of clays up to 8 or so may be possible due to thixotropy (Skempton & Northey 1952). For Ariake clay (Shen et al. 2005), thixotropic recovery of strength was much quicker at high salt content 10.3g/l, as shown in Fig. 3.4.
5) Pore pressure equilisation and resulting deformations (Shen et al. 2003a). Installation of the columns can induce high excess pore pressures, and the dissipation of these pore pressures results in consolidation and increase in effective stress. The latter may result in strength increase in the surrounding soil, but in sensitive soils that might not always be the case (see e.g. Castro & Karstunen 2010). According to Shen et al. (2003a), this process is similar to that associated with driving piles or installation of sand compaction piles or stone columns. According to Perzon (2014) and Johansson (1998), the installation pore pressures in typical Swedish soil conditions normally vary between 20 and 30 kPa, and will in most cases decrease rapidly, within 24 hours. Viberg et al. (1998) state that surprisingly high pore pressures (and horizontal movements) can be measured during installation without causing failure. According (Perzon 2014), after a time period of 2-3 hours, the increase in shear strength in the columns will compensate for the reduction of shear strength (due to the excess pore pressures) in the soft clay layers. Liu et al. (2005) found recovery of the soil strength to take about 28 days. When working in natural slopes with low factors of safety (FOS around 1), the increase in pore pressure may be a concern, and extensive controlling measures are needed. Other adapted measures include a defined installation order, and to work in favourable period with low natural ground water pressure (Perzon 2014). Deep drainage can also be combined with deep mixing (Viberg et al. 1998) to reduce pore pressures. In order to reduce the lateral ground movements, the installation should be performed in rows away from the adjacent constructions, as illustrated in Figure 3.5 (Larsson 2005). According to Larsson (2005), Kakihara et al. (1996) compared in parallel dry mixing and wet mixing and concluded that the lateral

movement were larger with wet method than dry method. Topolnicki (2014) proposes using vertical drains to prevent unwanted excess pore pressure build-up, but of course some soil disturbance and pore pressure build up may occur during the penetration of the mandrel into the soil to install the drains. However, this approach was successfully used in China (Liu et al. 2005), reducing the excess pore pressures during column installation by almost 50%. It is often assumed that the permeability of the columns is higher than that of unstabilised clay. Based on model tests, Fang & Yin (2007), suggest that the consolidation is largely accelerated due to the presence of column resulting in a lower excess pore pressure in the soil during subsequent loading, rather than the column having higher permeability than the in situ clay. Therefore, it is the effect of increased stiffness that gives an apparent increase in the coefficient of consolidation, rather than increased permeability. Microstructural studies by Taguchi et al. (2009) confirm that stabilisation lead to reduced pore sizes, which also suggests reduced permeability.

6) <u>Cementation effects due to diffusion of cations</u> (Shen et al. 2003a). Immediately after installation of columns, ions in the columns start to diffuse to the surrounding soil due to the differences of ion concentrations. In case of fractures, these may be filled with stabilising agents, providing yet another location for cations diffusion. Overall, chemical reactions take place in the surrounding clay, which speeds up the strength regain in the surrounding soil (Shen et al. 2003b). According to Larsson & his co-workers (Larsson & Kosche 2005, Larsson et al. 2009), this diffusion process is very complex, as it is partly driven by the concentration gradient of the diffused ions, partly by the water pressure gradient, partly by the electrical gradient (Mitchell 1991) and partly by the temperature gradient. In cement columns, diffusion might not play major role once the columns have hardened (Shen et al. 2003a), but in lime columns, in the so-called transition zone, the process can go on for several months (Larsson et al. 2009).
7) <u>Heating (Shen et al. 2005)</u>. Hydration and pozzolanic reactions generate heat which raises the temperature in the columns and the surrounding clay. According to Shen et al. (2005), Enami et al. (1987) measured maximum temperature in the soil-cement columns of about 40°C and the temperatures increased until 10 to 30 days after installation. The high temperature can lead to drying, which results in reduction in the water content in the columns and the surrounding soil. Consolidation at high temperatures can also speed up the ageing effect of marine clay. This mechanism is likely to be more significant in dry mixing than in wet mixing.

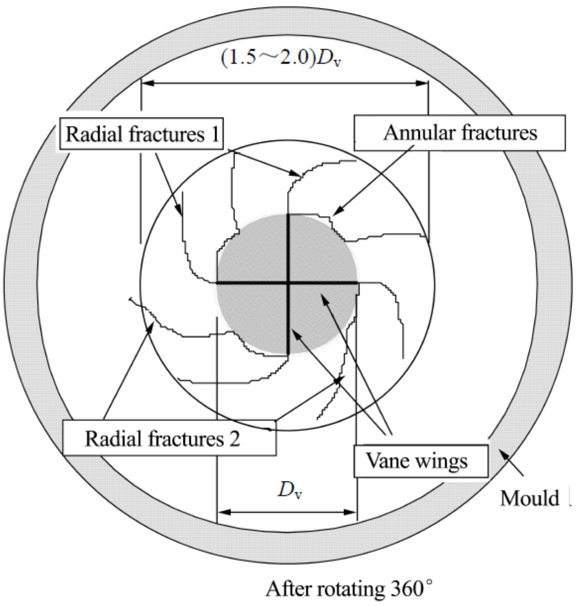

Figure 3.3. Soil fracturing in laboratory vane shear test (Shen et al. 2005).

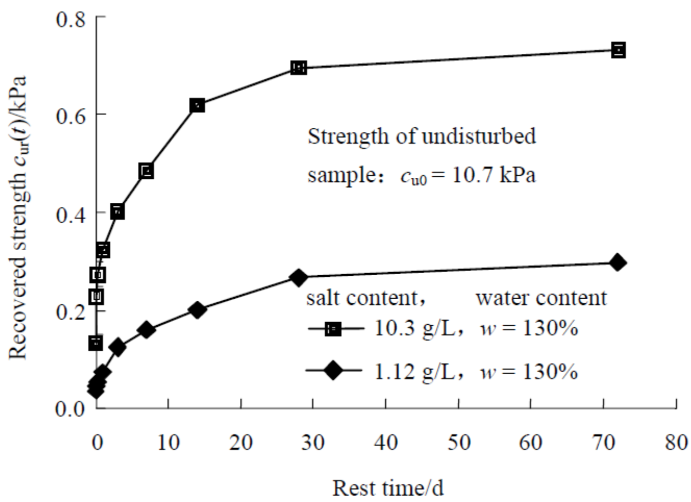

Figure 3.4. Thixotropic recovery of Ariake clay after remoulding with different salt concentrations (Shen et al. 2005).

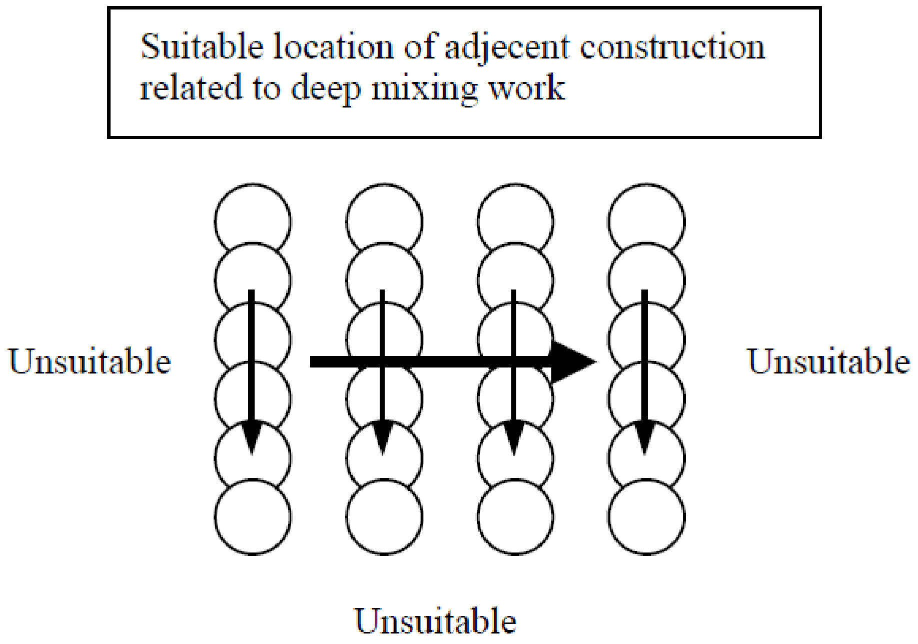

Figure 3.5. Recommended sequence of installation in relation to adjacent construction (Larsson 2005).

3.3 Strength development in deep mixed columns

Inherent to both dry and wet mixing is the difficulty in predicting the attainable average field strength and the rate of strength development (Terashi 1997, 2005). According to Terashi (2005), the strength development is dependent on many factors, and when this is combined with our knowledge until now, these can be summarised in Table 3.6. The difficulty is that in laboratory mould tests, there is no way of simulating III and IV, except for the amount of binder and curing time (Terashi 2005).

The choice of the stabilising agent, however, is important. The pozzolanic reactions in lime treatment on clayey soils are slow, lasting for years, whilst the formation of cement hydration products is relatively rapid. According to Topolnicki (2012), Terashi (2003) has underlined that from the point of view of engineering properties of soils stabilised with the same type of binder in powder and slurry form, there is no substantial difference between both mixing processes. This observation has been demonstrated by numerous investigations conducted on laboratory mixed soils, but is difficult to repeat in field conditions (Topolnicki 2012). When a sufficient but not too high amount of cement in powder or slurry form is mixed thoroughly to the soft soil higher compressive strength is expected for the dry than the wet process. Laboratory studies by Larsson & Kosche (2005) suggest that there is no major difference in cement columns manufactured with dry methods compared to the wet method, however, the installation method did not introduce air and hence results might not be applicable to field conditions. From the point of view of functionality of the columns and/or stabilised soil in the actual engineering application, the uniformity of the columns is important, in particular when stabilising marginally stable slopes. Due to variability, typically full sized columns fail at 70% of the average unconfined compressive strength of the core samples (Terashi 2005). Most of the installation effects, discussed in the previous section, cannot be reproduced in laboratory conditions.

From geomechanical point of view, it is unfortunate that laboratory testing of stabilised clays has largely relied on unconfined compression tests, which is a crude index test. In situ, the curing occurs in anisotropic stress conditions at temperatures that are less than standard laboratory temperatures (most laboratories still test soils at 20°C). Balasubramaniam et al. (2005) demonstrate via series of triaxial and oedometer tests that the stress-strain response of lime-cement treated soft Bangkok clay after 2-month curing time resembles the behaviour of heavily overconsolidated clay, with low compressibility before yield and very little pore pressure development under undrained shearing. On the "wet" side of critical state, the behaviour is rather similar to soft sensitive clays, with increasing brittleness associated with increasing amount of stabilising agents. For cements stabilised samples there appears to be a unique slope of normal compression line (regardless of water content), which is apparently a function of the percentage amount of cement, as shown in Fig. 3.5 (Lorenzo & Bergado 2004). This is suggesting that too much stabilising agent has been added, and hence not all cement has had the opportunity to hydrate. The peak failure strength on the "dry" side of critical state coincides with the tension cut off criterion, and there is notable strength degradation from the peak conditions to critical state, with a critical state friction angle close to that of natural clay. Given the very high initial void ratios of the stabilised samples of Lorenzo & Bergado (2004) and the sample preparation and curing methods used, deriving conclusions from these test results to be applied to in situ stabilised clays would be rather unwise.

3.4 Numerical modelling of deep mixed columns/stabilised soil

In most cases, the installation of deep mixed columns results in a complex 3D structure, which is often modelled as a 2D homogenised rigid-perfectly plastic material for stability analyses and as a 1D composite material for settlement analyses (EuroSoilStab 2002). During 1995-2006 an extensive research programme was conducted by the Swedish Deep Stabilization Research Centre (Holm, 2006). Part of the programme was the construction and monitoring of four test embankments of lime/cement stabilised soil in the Göta River valley (Baker et al, 2005, Alén et al, 2005b). As an outcome of this project, Alén et al. (2005a, 2006) proposed a new design method for settlement predictions based upon the idea that the mixed columns and the soil can be considered as a composite material, with the top of the columns yielding. The method is included in the Swedish technical guideline for construction of road and railway embankments (Trafikverket, 2011).

Table 3.6 Factors affecting the strength increase in deep mixing.

I Characteristics of binder	
1	Type of binder
2	Quality of binder (chemical composition, surface area)
3	Mixing water (for wet mixing) and secondary additives
II Characteristics of the soil and initial conditions	
1	Physical, chemical and mineralogical properties of the soil
2	Organic content
3	pH of the pore water
4	In situ water content
5	In situ stresses and apparent preconsolidation pressure
III Mixing conditions	
1	Degree of mixing
2	Timing of mixing/remixing
3	Quantity of binder
4	Quantity of air (in dry mixing)

IV Curing conditions	
1	Temperature
2	Curing time
3	Humidity
4	Wetting/drying cycles
5	Freezing and thawing cycles

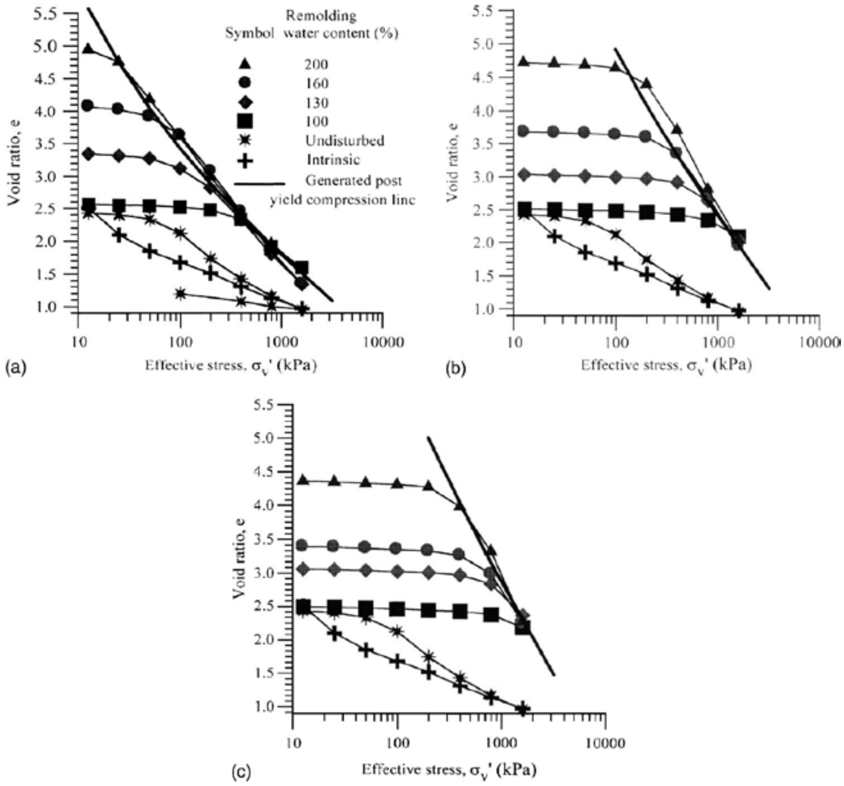

Figure 3.6. One-dimensional compression curves at: (a) 5%, (b) 10%, and (c) 15% cement contents (Lorenzo & Bergado 2004).

Similarly to the design method by Alén et al. (2005a), the basic idea of so-called volume averaging technique (VAT) is to model the soil-column system as a homogenous material, instead of modelling columns and soil individually. By doing so, the geometric discretisation of the problem can be simplified considerably, as illustrated for an embankment example in Figure 3.7. The two constituents, soil and column, can be modelled by two individual non-linear constitutive models, representative of the material response of the constituents.

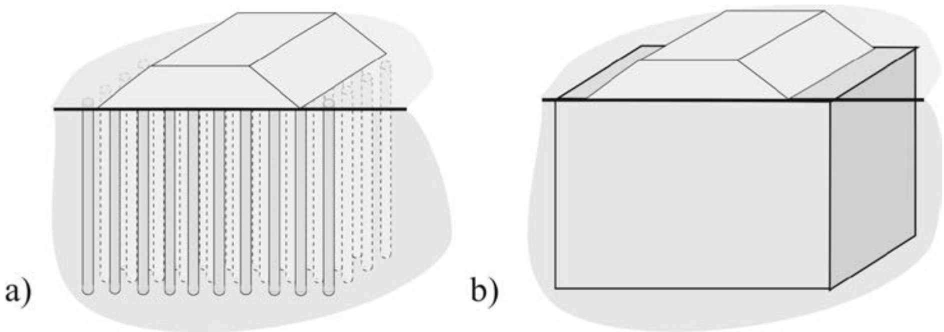

Figure 3.7. Volume averaging for embankment on deep mixed columns.

Numerical modelling approaches for column improved ground have been proposed by several authors, including Schweiger and Pande (1986). However, in the latter, the equilibrium conditions for the shear stresses between soil and column were not satisfied. Lee and Pande (1998) developed the method further. They derived an equivalent elastic material stiffness matrix from the individual stiffness matrices of the two constituents and their respective volume fractions, as illustrated in Figure 3.8, by applying certain static and kinematic constraints. Any constitutive model can be used to describe the individual constituents. The values of the parameters of the individual model can be derived by testing the materials individually using standard elementary laboratory tests. Once the material behaviour for the averaged material is described by the volume averaging technique, it can be applied to boundary value problems subject to arbitrary loading conditions. Karstunen (1999) identified the potential of the method for deep mixed columns.

A major drawback in the method by Lee and Pande (1998) was the violation of the elementary constitutive relations for occurring plasticity. This issue was overcome by Vogler (2008), who introduced a novel sub-iterations scheme following the ideas of Sloan et al. (2001). Furthermore, Vogler (2008) improved the way the constituents were modelled, to account for the highly non-linear material response. Vogler & Karstunen (2007, 2008) used VAT for modelling deep mixed columns with two advanced constitutive models for soft soil and deep mixed column: the SCLAY1S model (Wheeler et al. 2003, Karstunen et al. 2005) to represent the sensitive soft soil and the MNhard model (Benz 2007) to represent the deep mixed columns. The column parameters were derived based on exhumed columns published by Aalto (2003). Becker & Karstunen (2013, 2014) provided extensive verification for the method by comparing 2D VAT simulations with 3D simulations, considering representative centre to centre spacings and stiffness ratios. Given the recent developments in advanced creep modelling of soft natural clays (e.g. Karstunen et al. 2013, Sivasithamparam et al. 2013, Sivasithamparam et al. *under review*), incorporating long terms creep affects in the soil modelling has become possible. Venda Oliveira et al. (2009) suggest that is it not only the creep of the soil that needs to be considered, but also the creep of the stabilised column material. However, given the evidence of unexplained heave and large unexpected deformations in some Swedish applications (Ekström 2014), it is also necessary to gather high quality data on the effect of soil disturbance and unloading on the subsequent long term foundation response. A further restriction of the VAT method in its current form is that due to the assumed static and kinematic conditions for the soil and columns, it cannot be applied for natural slopes without some major modifications. However, this only requires some critical thinking, combined with simple mathematics.

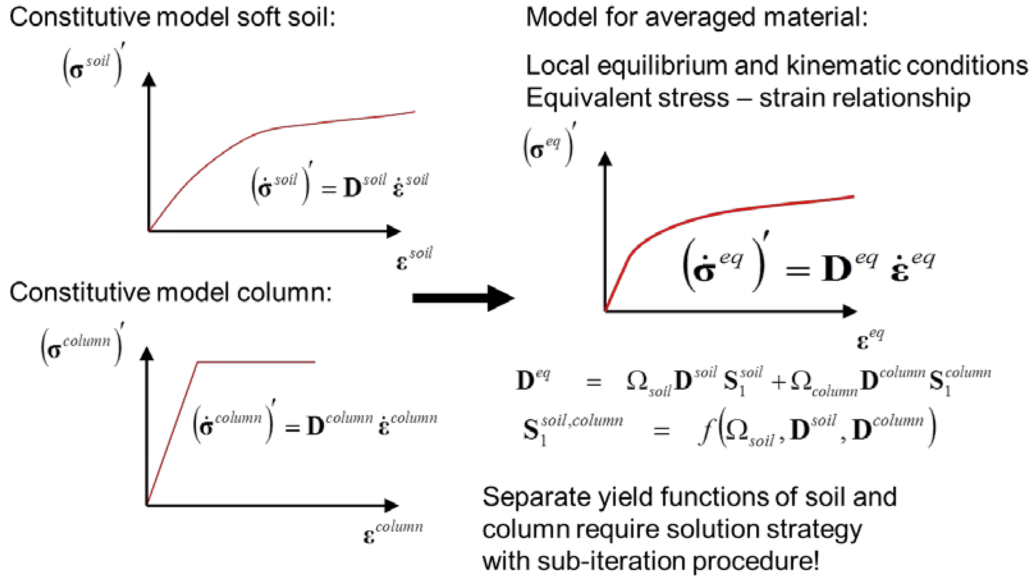

Figure 3.8. Mathematical principle of volume averaging.

Similarly to most published numerical analyses related to deep mixing, in applications of volume averaging technique until now, no installation effects have been taken into account. This would be possible by accounting for the installation effects via state parameters and imposed pore pressures. As discussed in Section 3.2, installation effects are significant, and in the case of marginally stable slopes these cannot be ignored. Installation effects due to pile driving in sensitive clay was studied by Bozozuk et al. (1977) and Roy at al. (1981, 1982). Following on from this work, in Sweden, the installation effects due piling (see e.g. Edstam 2011) are typically modelled using the approach by Sagaseta & Whittle (2001), inspired by the paper on Sagaseta (1997) on volume loss in tunnelling. However, there are significant differences between the installation of driven displacement piles and deep mixed columns. The shearing action during penetration of the blade is mainly soil disturbance due to remoulding of the clay, with no major volume change. Presumably, the soil within the blade reach will be completely remoulded, but in particular in sensitive clays, the plasticized zone outside the area of the blades is unlikely to be very large. The situation changes when the injection starts, and the volume of the column is created by jetting the stabilising agent combined with rather violent mixing. The effect, according to Shen et al. (2003b), can be described as a combination of cavity expansion and shear. Castro & Karstunen (2010) and Castro et al. (2014) modelled stone column installation via cavity expansion, studying the effects of the installation on medium sensitive clay (Castro & Karstunen 2010), and the effects of that soil disturbance on subsequent loading. Similar approach can be used to study the installation effects of deep mixed columns. Additionally to the coupled hydraulic and mechanical effects, the temperature effects, resulting from the chemical reactions would need to be taken into account.

4 Alternative methods for stabilising soft clays

4.1 Introduction

Traditionally, ground improvement methods with minimal disturbance are soil injection methods, e.g. chemical injections (Chu et al. 2009) with sodium silicate or epoxy resins (e.g. Gallagher & Mitchell 2002, Anagnostopoulos 2005) or bio-cementation (Van Paassen et al. 2010a, 2010b, DeJong et al. 2011). In all processes the material is permeated in the pores at low pressure and in the case of bio-cementation (sometimes called microbially induced calcite precipitation) first bacteria, and subsequently urease, is injected in the soil to trigger the ureolysis. Unfortunately, these methods are generally not applicable in fine-grained materials, such as soft clays, because the size of the injected chemicals or the size of the bacteria in the groundwater is typically larger than the average pore size of soft clays. Another problem associated with the bio-cementation methods is the difficulty to control the cementation process and not to cement the soil directly adjacent to the injection well. The latter is not an issue for chemical injections with resins where the reaction time can be carefully controlled, though typically more injection wells are required when compared to bio-cementation. Additionally, the original bio-cementation methods produce urea as a waste product, which is very costly to dispense of in the current strict environmental regulations. Most recently biological methods have been developed that use the bacteria existing in-situ, which only need additional injections to feed them. The latter processes are difficult to control and the first results still have to be reported in the scientific press. However, potentially no additional waste products are generated.

Injection of salt (or ionic solutions) has a measurable positive effect on the mechanical properties of clays (Mitchell & Soga 2005) including quick clay (e.g. Helle et al. 2013). Unfortunately, the natural time scale of the flow and diffusion processes in these soils is very large. A well-known technique to outperform the natural time scales in geotechnical and environmental engineering is to apply an additional electrical gradient. The merits of the combinations of these techniques will be further elaborated in the next section.

4.2 Stabilisation via electro-osmotic injections

Application of an electrical charge on a fine-grained medium such as a natural clay, typically reduces the size of the diffuse double layer surrounding the clay platelets, hence increasing the apparent permeability of the material, as well as that an electro-osmotic flow (electrophoresis) is triggered where the flow of charged particles (from the electrical field) is dragging other charged material along. Electro-osmosis as a pure consolidation technique (e.g. Bjerrum et al. 1967, Casagrande 1983, Burnotte et al. 2004) is often perceived highly impractical and energy consuming. The latter may still apply, but with the difference that the process can be started and stopped dependant on the availability of inexpensive energy, and new polymer electrode materials (Hamir et al. 2001) have been successfully tested (Fourie & Jones 2010). So, surplus energy outside peak times can be potentially used as intermittent electrical regimes improve the efficiency (Micic et al. 2001).

Most importantly, the method can be extended for the controlled injection of ionic solutions using electro-phoresis. This enhancement of the traditional method of electro-osmotic soil improvement not only speeds up the rate of consolidation, but also improves the intrinsic soil properties beyond the improvement gained from solely consolidation (Ou et al 2009). As a result this method combines the benefits of chemical injections with the speed up gains of electrokinetically enhancing the flow regime in impermeable soils. In the proposed application the in and out flux of water should be properly controlled in order to minimise the magnitude of any additional soil deformations.

However, to date, only very limited, but positive, experience on this unique method has been gathered, and all of this has been performed outside Europe (Acar et al. 1997, Thevanayagam & Rishindran 1998, Alshawabkeh & Sheahan 2003, Jones et al. 2011). The reverse process, however, i.e. removal of materials from contaminated soils is a well-studied topic in the discipline of soil remediation (Segall & Bruell 1992, Acar & Alshawabkeh 1993, Shapiro & Probstein 1993, Page & Page 2002, Virkutyte et al. 2002). Transport of ions into and out of a clay is not only feasible, the conductivity of the clay platelets positively influences the effectiveness of the method.

Although the process of electro-osmosis in speeding up the consolidation and the flow processes is investigated using multiphysics modelling, i.e. coupling the electrical equations with the traditional consolidation equations (Esrig 1968, Wan & Mitchell 1976, Lewis 1972, Feldkamp & Belhomme 1990, Yuan et al. 2012), or by means of the multiphysical approach on the grain level (Lemaire et al. 2007), the mechanical response of the treated soil is only evaluated by studying the obtained gains in strength and compressive stiffness (e.g. Bjerrum et al. 1967, Morris et al. 1985, Fourie et al. 2007). Until now no explicit formulation of the effects of ground improvement by electro-osmosis or ionic injections in the subsoil are accounted for in constitutive models for soft soils. This mainly results from lack of experimental data on the micro-scale and boundary value level. Yet, from the point of view of analyses for design, such a model is important. Hence, a remaining issue is that the effect of the method on the fundamental soil behaviour of stabilised clay, as captured by systematically probing the response in controlled laboratory experiments or measuring the change on micro level is not known. There is total absence of a proper constitutive model for the stabilised soils, yet this is needed to be able to use this promising method in a predictive manner in engineering practice.

5 Discussion and recommendations

5.1 Discussion

The report presents a critical review on various ground improvement methods that involve in-situ mixing and/or injection of stabilising agents in the form of powder or slurry in soft sensitive clays. Norwegian Public Roads Administration (NPRA) initiated the project as a result of issues with slopes that are marginally stable. A special focus was on installation effects, attempting to identify methods that allow controlling or minimising excess pore pressure build-up and deformations. The methods considered included dry and wet deep soil mixing, as well as electro-osmotic injection of stabilising agents into the soft soil.

Deep mixing is a common ground improvement method, used extensively, e.g. in Scandinavia and Japan. When looking at the possibilities for the use of deep mixing method for stabilising marginally stable slopes, this pre-study clearly demonstrates that the problem is not trivial and that the research done so far does not provide clear solutions. Even though the installation effects are conceptually reasonably well understood, these effects are largely ignored in analyses and design. However, when dealing with stabilising marginally stable slopes, it is not possible to ignore these. Installation of deep mixed elements in soft soils induces excess pore pressures, heave and lateral deformations, and to analyse these with any accuracy, 2D and 3D effective stress based model are required. In execution, the current practice installation effects are dealt with by adopting a work scheme based on sequential execution of deep mixing, and moving the equipment around the site in a pattern to allow pore pressure dissipation without stopping the work. In cases when this is perceived too risky, alternative methods are chosen, since the installation effects of deep mixing are not easily quantified, and there is an uncertainty in the work progress in or near a marginally stable slope.

From stability point of view, the key question is: what is the real margin available for additional pore pressure increase within the slope resulting from installation. To answer this question, we firstly need to analyse the stability of the slope without any ground improvement, using the best geological and hydrogeological knowledge available, with state-of-the art soil models, which account for the governing features of soft clay behaviour, such as anisotropy, structure and rate effects. Recent research (Dawd et al. 2014) demonstrates that for marginally stable cut slopes, changes in anisotropy resulting from the formation of the cut are actually contributing to increased stability and a reduction of deformations. A remaining issue, which none of the model developers have adequately addressed, is how to represent the initial anisotropy in subsoil with inclined soil strata, such as natural slopes. One option would be to exploit the tensorial nature of the initial fabric. This can be confirmed by numerically simulating the geological processes related to the formation of the deposit.

With the help of advanced soil models, it is possible to quantify and model installation effects, using e.g. cavity expansion analogy, as was done for stone column installation in sensitive soils by Castro & Karstunen (2010) and Castro et al. (2014). The recent advances in modelling soft sensitive clays as rate-dependent materials (Karstunen et al. 2013, Sivasithamparam et al. 2013, 2014) enable to account for rate dependency of soil disturbance resulting from installation. For deep mixing, additionally to the cavity expansion, the shearing due to the cutting action would need to be accounted for. Thermal effects potentially influence the process on top of the hydro-mechanical response, till date these are not explicitly accounted for in a numerical analysis. For a given slope, assessed to be marginally stable with current methods used in practice (e.g. LEM using total stress analyses), numerical studies can be used to assess the permissible increase in pore water pressures. These analyses can then be extended to account for the installation effects of the columns, either directly or indirectly (by imposing known amount of degradation, based on unit cell analyses of installation) in order to study the mechanism of failure, as function of the distribution of the excess pore pressures due to soil degradation.

In order to adequately perform the numerical studies above, for the long-term effects in particular, it is also necessary to accurately model the mechanical response of the column material. Unfortunately, the stress-strain behaviour of stabilised soil has not been systematically investigated. Incomplete experimental evidence so far, suggests critical state type of models, with damage (or destructuration) included. Systematic experimental studies that include curing the samples at a properly scaled temperature and stress level need to be conducted, and in case the stabilising agents are mixed into the soil in slurry form, the effect of ionic strength of the slurry should be investigated.

With regards to the choice of stabilisation method, both wet and dry methods have their respective advantages and disadvantages. Even though dry mixing has clear advantages over the wet mixing in very "wet" soft soils, there are only limited possibilities for reducing installation pressures. A combination with vertical drains should be investigated, as based on experience in China the excess pore pressures from installation can potentially be halved. Feasibility studies using advanced numerical analyses, using state-of-the art soil models, should be made first, before embarking on costly field studies. Especially, any additional disturbance resulting from the installation of vertical drains requires attention. From practical point of view, in order to avoid issues with poor columns or even holes in the dry crust and/or surface layers, which are vital in the stability of natural slopes, the hybrid method of dry mixing, so-called modified dry mixing (MDM) that also involves water jets when needed, looks more promising than traditional dry mixing. The benefit of this hybrid method is that it also improves the homogeneity of the columns; another vital aspect in slope stability.

With regards to the wet method, the homogeneity of the columns is clearly an advantage, and provided the type and amount of the stabilising agents is appropriately selected (such as accounting for the free water present in the soil in situ), the strength development is expected to be similar to that of dry mixing. Given the wet method involves introducing additional water into a clay with high water content, the benefits of water with optimised ionic strength for the slurry when stabilising sensitive clays should also be investigated. In Japan, wet mixing has successfully ben applied in very "wet" clays, clays with in situ water contents between 100 and 120%. Wet mixing has the advantage over dry mixing that it is easier to control the installation pressures, given flow of the slurry is easier to control than flow of powder. However, a significant negative side effect is the amount of wet spoil that in the case of natural slopes might cause softening of the dry crust. The effects of any peptisers, used to control the stability and curing of the cement-based slurry, on the untreated surrounding natural clay need to be studied both in the laboratory, and in the field during the installation of trial columns, to ensure that there are no unexpected detrimental side effects.

Of the methods investigated as part of this pre-study, the method with the least disturbance and therefore possibly most effective for marginally stable slopes is electro-osmotic injection. With that technique, only some wells need to be installed and the size and location of the treated area can be carefully controlled. Without doubt the method will be more costly than deep mixing, but it has a great potential when applied in combination with deep mixing. For example, targeted zones, such as the most sensitive clay layers at the soil-rock interface or areas with artesian pore pressures, could be treated with electro-osmotic injections, prior to deep mixing. Given the method has not been applied in Scandinavian soil, studies at laboratory scale has been started at Chalmers (Marie Curie IEF Fellowship of Dr Jelke Dijkstra). Until now no explicit formulation of the effects of ground improvement by electro-osmosis or ionic injections in the subsoil are accounted for in constitutive models for soft soils. This mainly results from lack of experimental data on the micro-scale and boundary value level. Yet, from the point of view of analyses for design, such a model is important, and yet another topic for further research.

5.2 Recommendations for further research

Based on the above, this pre-study has identified a number of possible open questions, which could be addressed as part of PhD and/or post-doc projects, as follows:

1. **PhD/post-doc project on numerical modelling and stabilisation with deep mixing, of a real marginally stable slope identified in collaboration with Norwegian Public Roads Administration (NPRA).** Combined geotechnical and hydrogeological expertise is needed in the site characterisation, and special focus should be in the appropriate modelling of the initial situ state on both soil fabric and the sensitivity (bonding). Benchmark numerical studies of the installation effects can give valuable insights in rate-dependent soil degradation during installation that subsequently is fed into the numerical model of a stabilised slope for various scenarios. With regards to modelling long-term deformations, the use of a volume averaging technique would be attractive, as it enables modelling the combined effects of columns and the soil at field scale within 2D and 3D FE analyses, using appropriate constitutive model for both constituents. However, further research is needed to identify, if the static and kinematic assumptions can be appropriately modified for periodic ground improvement in a slope. Given the amount of experimental testing needed, for both natural and stabilised soil, a combined Chalmers-NTNU project would be the best option, involving PhD students/research staff to be appointed at both universities. Based on recent computational research, creep of the natural clay and the stabilised clay need to be accounted for.
2. **PhD project relating to electro-osmotic injection of stabilising agents.** This innovative research topic requires expertise on element level testing and micromechanical testing, as well as physical model testing. Synergies with ongoing (MC Fellowship funded by the EC) and future (Revealing the evolving microstructure in fine grained matter- funded by Vetenskapsrådet, Sweden 2015-2018) should be exploited, as well as the experimental facilities at MaxLab in Lund. Development of a constitutive model for e-o stabilised soil requires expertise in designing non-standard testing paths in order to test particular ideas of model hypotheses.
3. **Industry PhD project relating to R&D developments of deep mixing technique.** This is a systematic field study on the installation effects and best practice using a) Traditional dry mixing in conjunction with vertical drains or other means for rapid de-watering; b) Hybrid dry mixing, with and without drains and c) Wet mixing using different installation pressures, varying the ionic strength of the slurry. All sections would need to involve wall or grid type of column pattern, as applicable for slope applications. Given the extent of the testing programme, it would be best to create the test sections as part of a real infrastructure project on a level ground, so that the columns formed could later on be utilised. Extensive instrumentation is needed to have reliable measurements of the heave, excess pore pressures and later movements due to the installation of columns. For the sake of consistency, the same stabilising agents at the same water/cement ratio should be used for all columns, and the uniformity and quality of the columns would need to be tested via exhumation of individual test columns and in situ column testing. Samples of exhumed columns would need to be tested under consolidated undrained and drained conditions, and furthermore, column permeability tests should be done.

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Nr. 5 Kontrollstasjon: NVEs gjennomgang av elsertifikatordningen

Nr. 6 New version (v.1.1.1) of the seNorge snow model and snow maps for Norway. Tuomo Saloranta

Nr. 7 EBO Evaluering av modeller for klimajustering av energibruk

Nr. 8 Erfaringer fra ekstremværet Hilde, november 2013

Nr. 9 Erfaringer fra ekstremværet Ivar, desember 2013

Nr. 10 Kvartalsrapport for kraftmarknaden. 4. kvartal 2013. Ellen Skaansar (red.)

Nr. 11 Energibruksrapporten 2013

Nr. 12 Fjernvarmens rolle i energisystemet

Nr. 13 Naturfareprosjektet Dp. 5 Flom og vann på avveie. Karakterisering av flomregimer. Delprosjekt. 5.1.5

Nr. 14 Naturfareprosjektet Dp. 6 Kvikkleire. En omforent anbefaling for bruk av anisotropifaktorer i prosjektering i norske leirer

Nr. 15 Tilleggsrapport: Oppsummering av Energimyndighetens og NVEs gjennomgang av elsertifikatordningen

Nr. 16 Flomberegning for Nesttunvassdraget (056.3Z). Thomas Væringstad

Nr. 17 Årsrapport for tilsyn

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Nr. 19 Flom og jordskred i Nordland og Trøndelag desember 2013. Elin Langsholt, Erik Holmqvist, Delia Welle Kejo

Nr. 20 Vindkraft i produksjon i 2013

Nr. 21 FoU-prosjekt 81072 Pilotstudie: Snøskredfarekartlegging med ATES (Avalanche Terrain Exposure Scale) Klassifisering av snøskredterreng for trygg ferdsel

Nr. 22 Naturfareprosjektet: Delprosjekt 3.1. Hvordan beregne ekstremverdier for gitte gjentaksintervaller? Manual for å beregne returverdier av nedbør for ulike gjentaksintervaller (for ikke-statistikker)

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Nr. 36 Kvartalsrapport for kraftmarknaden 1. kvartal 2014. Gudmund Bartnes (red.)

Nr. 37 Preliminary regionalization and susceptibility analysis for landslide early warning purposes in Norway

Nr. 38 Driften av kraftsystemet 2013

Nr. 39 Naturfareprosjektet Dp. 6 Kvikkleire. Effekt av progressivbruddutvikling for utbygging i områder med kvikkleire: Sensitivitetsanalyse basert på data fra grunnundersøkelser på vegstrekningen Sund-Bradden i Rissa

Nr. 40 Naturfareprosjektet DP. 6 Kvikkleire. Effekt av progressiv bruddutvikling for utbygging i områder med kvikkleire: Sensitivitetsanalyse-1

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