Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

Arbetsrapport 27
2003-04

A complementary field study on the uniformity of lime-cement columns – Field tests at Strängnäs

Stefan Larsson
Marcus Dahlström
Bengt Nilsson

Svensk Djupstabilisering

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Swedish Deep Stabilization Research Centre

The Swedish Deep Stabilization Research Centre coordinates research and development activities in deep stabilization of soft soils with lime-cement columns. A joint research programme based on the needs stated by the authorities and the industry is being conducted during the period 1996 – 2004. Members of the Centre include authorities, lime and cement manufacturers, contractors, consultants, research institutes and universities.

The work of the Swedish Deep Stabilization Research Centre is financed by its members and by research grants.

The Swedish Deep Stabilization Research Centre is located at the Swedish Geotechnical Institute and has a Steering Committee with representatives choosen from among its members.

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Linköping 2003

Förord SD

Svensk Djupstabilisering (SD) baserar verksamheten på sin FoU-plan som bl a innehåller ett antal stora FoU-projekt. För att öka underlaget för dessa forskningsprojekt satsar SD på kompletterande mätningar/ analyser i lämpliga förstärkningsprojekt. Redovisningen av dessa mätningar /analyser granskas ej av SD utan redovisade resultat och framförda åsikter är författarens. Redovisningarna är arbetsrapporter inom SD.

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I föreliggande SD arbetsrapport redovisas resultat av en kompletterande studie till SD:s forskning inom området vidareutveckling av inblandningstekniken. Studien omfattar fältförsök och statistisk analys av hållfasthetens variation över pelartvärsnittet och längs pelaren.

Linköping i juli 2003

Göran Holm
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Arbetsrapport

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Förord

Denna rapport redovisar resultat från ett andra fältförsök inom projektet ”Vidareutvecklad blandningsteknik” som är en del av Svensk Djupstabilisering. Fältförsöken avser studier av inverkande faktorer i installationsprocessen vid djupstabilisering med kalkcementpelare.

Arbetet har genomförts av LCM (LC Method AB, tidigare LC-Markteknik AB) i samband med förstärkningsarbeten för vägprojekt E20, förbifart Strängnäs, trafikplats Lunda. Omfattningen av testpelarna och installationsordning är framtagen av författarna. Pelarinstallationen är utförd av Leif Sämsgård och Bengt Nilsson. Maskinen har beteckning M 814. Fältprovningen är utförd av Marcus Dahlström och Stefan Larsson. Pelarna installerades onsdag och torsdag, vecka 44, år 2002. Testningen utfördes måndag-torsdag vecka 45. Den statistiska utvärderingen är utförd av Stefan Larsson.

Inom projektet har också en parallell studie utförts i syfte att testa hållfasthetsfördelningen över pelarlängden. Denna studie har utförts som ett examensarbete för civilingenjörsexamen för Mari Kuokkanen och Per Hedman på avdelningen för Jord- och bergmekanik på Kungliga Tekniska Högskolan i Stockholm. Denna studie redovisas separat, Hedman & Kuokkanen (2003).

Projektet är en del av Svensk Djupstabilisering som också är huvudsaklig finansiär tillsammans med LCM och Tyréns AB. Författarna vill tacka Per-Evert Bengtsson, Helena Eriksson, Göran Holm och Helen Åhnberg för deras värdefulla kommentarer på manuskriptet.

Stefan Larsson	Marcus Dahlström	Bengt Nilsson
Tyréns AB	LCM	LCM

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Sammanfattning

Inledning

Rapporten redovisar resultat från ett andra fältförsök inom projektet ”Vidareutvecklad blandningsteknik” som en del av forskning och utveckling inom det branschgemensamma forskningsprogrammet Svensk Djupstabilisering. En enkel testmetod och ett omfattande fältförsök presenterades och diskuterades i SD Arbetsrapport 23, Larsson et al. (2002a). Fältförsöket utfördes i Håby och omfattade en studie av ett antal faktorer i installationsprocessen. Resultaten från detta fältförsök var dock något osäkra eftersom jordens egenskaper varierade över provytan. Det beslutades därför att upprepa försöken i ett fältförsök i samband med förstärkningsarbetena vid vägprojektet E20, förbifart Strängnäs, trafikplats Lunda.

Metod och försöksupplägg

Rapporten presenterar resultat från ett andra fältförsök där en enkel metodik användes för studie av inverkande faktorer i blandningsprocessen på hållfasthetsfördelningen över pelartvärsnitt. Huvudsyftet med testmetodiken är att i en och samma studie kunna analysera ett antal inverkande faktorer. Metodiken kan i korthet beskrivas på följande sätt:

1. Testpelare installeras med de kombinationer av de faktorer i blandningsprocessen som avses studeras. För varje kombination installeras två eller tre pelare.
2. Samtliga testpelare schaktas fram till ett lämpligt djup och tvärsnitten testas med ett stort antal penetrometerförsök som kompletteras med okulära besiktningar.
3. Resultaten från penetrometerförsöken utvärderas statistiskt med flerfaktoranalyser.

De statistiska analyserna utfördes med avseende på stabiliseringseffekten, som definieras som hållfastheten över pelartvärsnittet dividerat med hållfastheten i omgivande ostabiliserad jord, samt variationskoefficienten med avseende på penetrometerförsöken. Metodens begränsningar diskuterades i Larsson et al. (2002a). Följande faktorer varierades vid fältförsöken och analyserades senare i statistiska flervariabelanalyser:

1. Stigningen på blandningsverktyget som valts till 15 och 30 mm/varv.
2. Rotationshastigheten som valts till 80 och 160 mm/varv.
3. Antalet blad på blandningsverktyget. För detta syfte har verktyget ”Pinnborr” studerats genom att variera antalet blad till 2 och 6 blad. I en kompletterande analys varierades antal blad till 2, 6, 8 och 12 blad.
4. Tanktrycket som valts till 3,5 och 5,0 bar.
5. Munstyckets diameter som valts till 22 och 37 mm.

Dessutom utfördes ett antal mycket begränsade jämförelser med:

- Standardverktyget.
- Verktyg utan blad.
- Ett modifierat verktyg där utblåsningshålet är placerat alldeles bakom ett av de två bladen.

Försöken utfördes på pelare med diametern 0,6 m. Bindemedelssammansättningen var kalk/cement 50/50 % och bindemedelsmängden 25 kg per meter pelare motsvarande 88 kg/m^3. Totalt testades 80 pelare på två närliggande nivåer (1,9 respektive 2,3 m under markytan) med ca 3200 penetrometerförsök i två försöksomgångar.

Resultat

Baserat på förstärkningseffekten och variationskoefficienten har inverkande faktorer studerats med statistiska flervariabelanalyser. Följande slutsatser kan dras av försöken i Strängnäs.

- Antalet blad på blandningsverktyget och stigningen har en signifikant inverkan på stabiliseringseffekten och variationskoefficienten. De två faktorerna kan sannolikt länkas samman till den kombinerade faktorn ”Blade rotation number” som är det totala antalet blad som passerar en meter pelare. Resultaten från fältförsöken i Håby och Strängnäs indikerar att stabiliseringseffekten och variationskoefficienten beror av logaritmen på ”Blade rotation number”, Fig. S1.
- Varken rotationshastigheten, tanktrycket eller munstyckets storlek har någon signifikant inverkan på stabiliseringseffekten eller variationskoefficienten.
- Den okulära besiktningen överensstämde väl med resultaten från penetrometerförsöken. Mängden synligt oblandat bindemedel avspeglade spridningen väl då variationskoefficienten är relativt stor, > 0,20.
- Resultaten visar att pelarnas hållfasthetsegenskaper med avseende på penetrometerförsöken kan skilja även fast de installerats lika. Detta visar att fåtalsprovning kan ge missvisande resultat.

Den föreslagna metoden har visat sig användbar för studie av inverkande faktorer i blandningsprocessen. Det är värdefullt att fortsätta med studier av inverkan av jordens egenskaper, bindemedelstyper, blandningsarbete och olika typer av blandningsverktyg.

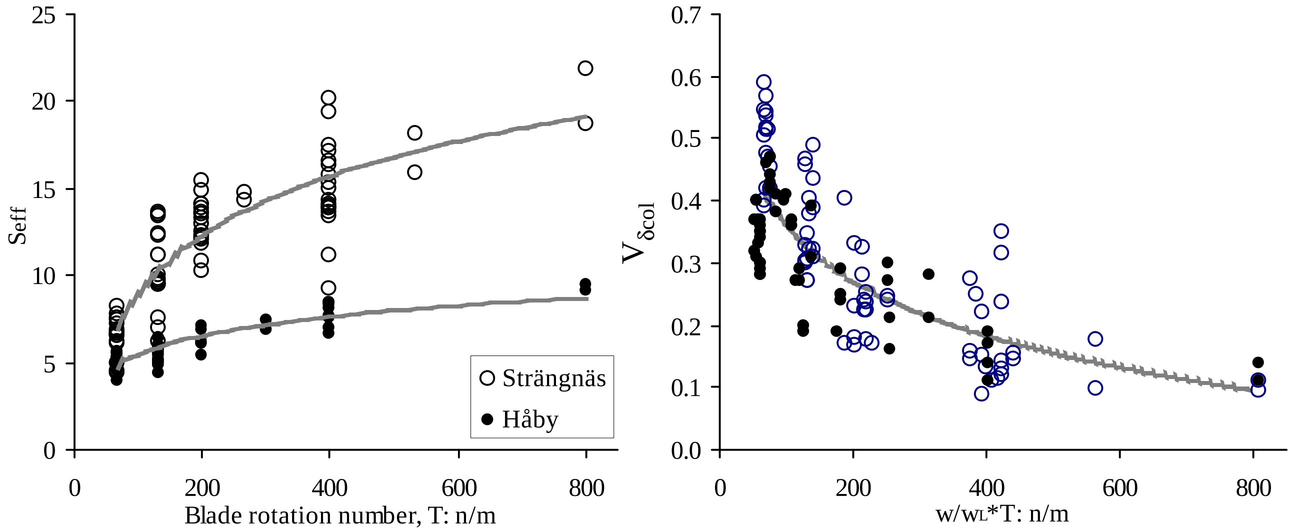


Fig. S1. **a) Stabiliseringseffekten S_{eff} , som funktion av Blade rotation number T ; och**

b) variationskoefficienten $V_{d\,col}$, som funktion av kvoten mellan vattenkvoten och flytgränsen multiplicerad med Blade rotation number, $w/w_L \cdot T$.

Introduction

The work presented in this report covers findings of a research project which is a part of the work of the Swedish Deep Stabilization Research Centre (SD) concerning development of the installation process for lime-cement columns by deep mixing. The process which is considered is dry deep mixing, where compressed air is used as the medium for the transport of dry binder from the tank to the soil. An essential factor in the success of this ground improvement technique is to ensure that the binder is uniformly dispersed throughout the stabilised soil. The initial stage of the work, presented and discussed by Larsson *et al.* (2002a, 2002b), include a summary of the literature on factors influencing the mixing process, a simple field method for the study of several influential factors in the mixing process of lime-cement columns. The test method facilitates the development of mixing processes in the field, and the method was employed in a field study at Håby, Sweden. The influence of several parameters in the installation process were investigated by statistical multifactor analyses. The study included the influence of the number of blades on the mixing tool, the retrieval rate, the rotation speed, the diameter of the binder outlet and the binder air tank pressure. The aim was not to promote any specific combination of installation parameters, but to illustrate the influence of various factors. It was concluded that the upper pair of mixing blades, in connection with the binder outlet hole, has a significant and determining influence on the binder dispersion and that the retrieval rate and the number of blades influence the mixing process significantly. However, since the strength of the unstabilised soft soil varied within the test site, which has a considerable influence on the mean value and the coefficient of variation of the strength in the columns evaluated from hand-operated penetrometer tests, the findings were somewhat uncertain. It was therefore not possible to detect any influences of combinations of factors.

This report presents results from a complementary field test carried out at Strängnäs, Sweden. The purpose is to verify the findings from the previous tests and to further investigate the mixing process in a different soil. With a few exceptions, the experimental design procedure was similar with the test at Håby. Hand-operated penetrometer tests on excavated column sections were used for testing the strength characteristics, one week after the column installation. The effects of the number of blades on the mixing tool, the retrieval rate, the rotational speed, the outlet hole diameter and the binder air tank pressure were evaluated using a statistical design approach and analysis of variances

The test site

The selected site is located at Strängnäs on Road E20, 80 km west of Stockholm. A specific area of the site was allocated to the tests, where the soil consisted of a 6 to 8 m soft clay. The soil profile and properties are shown in Fig. 1. The soil can be divided into four representative layers, namely the crust with grey-brown clay, gyttja bearing clay, varved grey clay, and silty clay. The size of the test site was 25 x 50 m^2. The soil properties at the test levels, 1.9 and 2.3 m of depth, were evaluated from fall-cone tests on undisturbed samples, and by a hand-operated penetrometer. Table 1 shows the results from the laboratory tests on

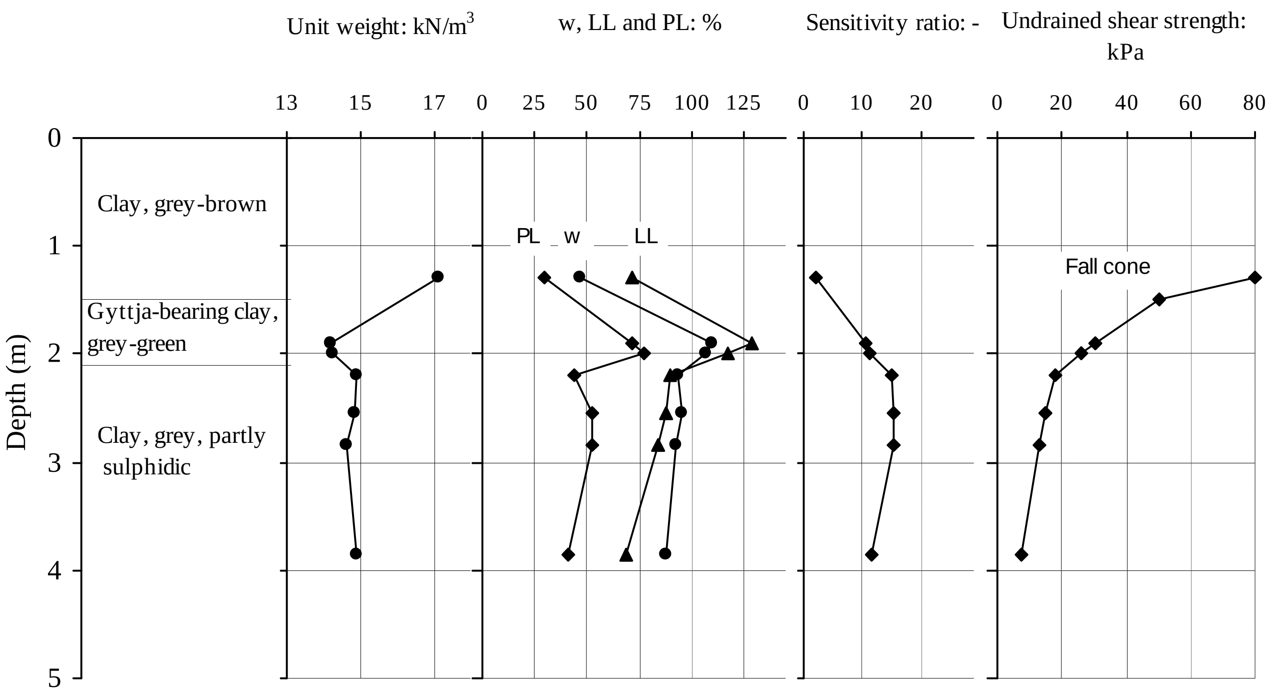


Fig. 1. Soil profile and soil properties at the test site. The samples are taken at the columns marked EX 1 to EX 6, according to Fig. 2.

Table 1. Soil properties at the test site (1.9 – 2.3m depth).

No [1)]	Soil	Unit weight, γ_t: kN/m^3	Water content, w: %	LL, w_L: %	PL, w_P: %	Sensi-tivity, S_t	Undrained shear strength, c_u: kPa	Com.
1.9	Clay, grey	15.5	85.3	82.6	34.1	13	16	roth threads
1.24	Clay, grey, partly sulphidic	15.1	81.5	76.4	31.7	12	13	
1.29	Gyttja bearing clay, grey	15.4	84.9	84.9	33.5	12	19	sand particles
1.44	Clay, grey, partly sulphidic	15.9	74.1	72.4	32.8	12	16	
2.23	Clay, grey, partly sulphidic	14.9	111.4	105.6	48.6	12	14	roth threads
2.30	Gyttja bearing clay, grey	14.9	99.3	94.3	44.1	15	17	
2.10	Gyttja bearing clay, grey-brown	14.4	99.0	102.5	39.9	13	24	
3.8	Gyttja bearing clay, grey-brown	14.5	122.7	118.4	61.9	12	16	
3.22	Gyttja bearing clay, grey-brown	14.2	112.4	117.2	70.0	11	20	
4.7	Gyttja bearing clay, grey-brown	14.2	110.5	121.7	76.9	11	26	
4.15	Gyttja bearing clay, grey-brown	14.3	119.3	128.6	82.3	10	20	
4.24	Gyttja bearing clay, grey-brown	14.2	135.7	144.4	76.8	11	21	

[1)] The number corresponds to the column row and number, according to Fig. 2.

undisturbed soil samples and Fig. 2 shows a plan over the test site and the location of the samples. Five penetrometer tests were performed in the unstabilised soft soil close to every second column on the two test levels.

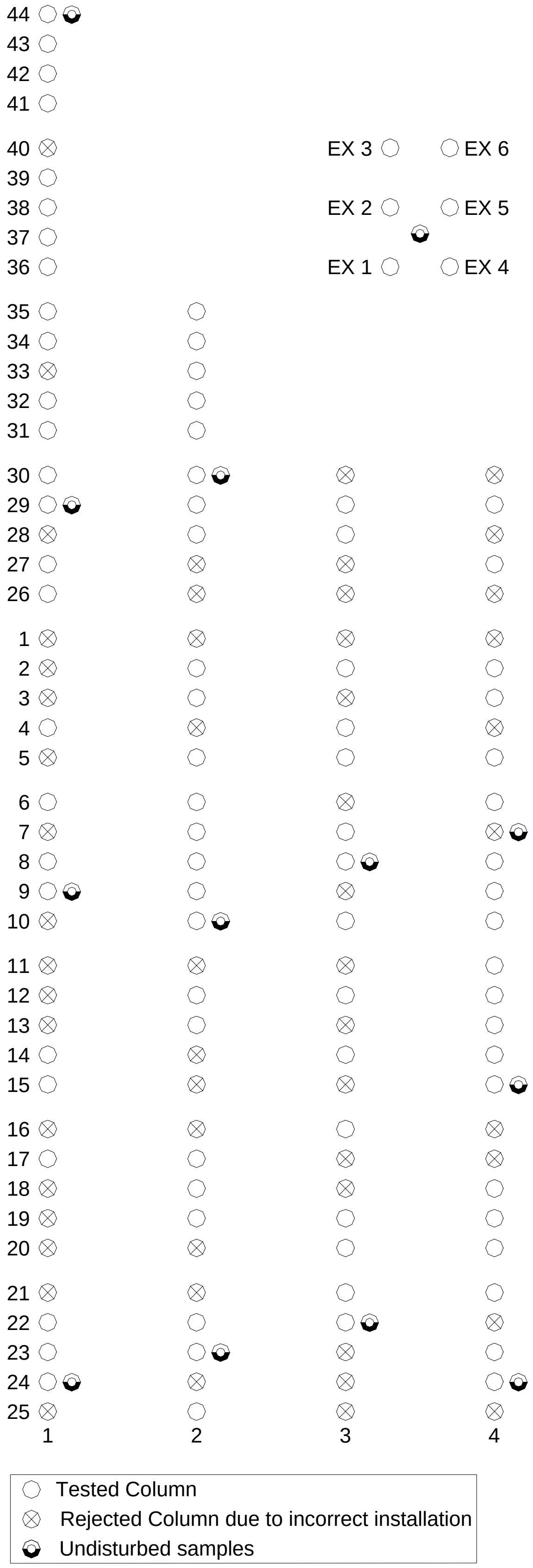


Fig. 2. Test site and the test columns.

Experimental programme

Testing procedure

Details of the testing methodology were previously presented and discussed in Larsson *et al.* (2002a, 2002b). The methodology is briefly described below.

The test columns were excavated down to 1.9 and 2.3 m deep open test pits, as shown in Fig. 3a. Each column section was tested directly after the excavation. The tests were performed by a large number of hand-operated penetrometer tests, 6 to 7 days after installation of the columns. The hand-operated penetrometer was provided with a spring-loaded cylinder, 12 mm in diameter, and was pushed approximately 30 mm into the soil. The cylindrical-shaped head has a sliding ring, which moves over a calibrated scale as load is applied.

The penetrometer tests were carried out at two adjacent levels (1.9 m and 2.3 m respectively), in order to compensate for local variations in the axial direction. The test results have been evaluated with respect to the strength and the coefficient of variation, which have been taken as a measure of the mixing quality. The penetrometer tests were reported in terms of the spring deformation directly rather than via an assumed correlation with undrained shear strength since the failure mechanisms in stabilised soil are unlikely to be the same as those in the unstabilised surrounding soft soil. The results have been expressed in terms of the stabilisation effect, S_{eff}, in this study defined by

$$S_{eff} = \frac{\bar{d}_{col}}{\bar{d}_{soil}} \tag{1}$$

where $\bar{d}_{col}$ and $\bar{d}_{soil}$ are the average spring deformation in the column and in the surrounding soil respectively. $\bar{d}_{col}$ and $\bar{d}_{soil}$ are evaluated from 20 and 5 penetrometer tests respectively, on the two test levels. All data has been presented for comparatively purposes and should therefore only be used as an index for strength properties.

The coefficient of variation $V_{d\,col}$, as a measure of the mixing quality, is calculated as

$$V_{d\,col} = \frac{s_{d\,col}}{\bar{d}_{col}} \tag{2}$$

where $s_{d\,col}$ is the standard deviation calculated as

$$s_{d\,col} = \sqrt{\frac{\sum_{i=1}^{n} (d_{i,col} - \bar{d}_{col})^2}{n-1}} \tag{3}$$

where $d_{i,col}$ is the spring deformation from each test and n is the number of tests over a column cross-section.

(a) **(b)**

Fig. 3. (a) Excavation of test pit; and (b) the column machine used in Strängnäs.

In order to make random testing possible, four templates of plywood were used, the templates, 0.6 m in diameter, were divided into 104 equal sized areas, from which 20 were randomly selected for testing. Before testing a column section, one of the four templates was chosen out of random. A total of 40 tests were performed for each column.

The penetrometer tests were complemented by visual examination for each cross section. The visual examination contained photographs and recorded subjective judgments.

Statistical design approach

Multifactor experiments were used in order to try to distinguishing influencing factors in the mixing process. The use of multifactor experiments is a popular and useful tool in the study of the effect of different factors in complex chemical- and physical processes, and increasingly used in geotechnical engineering. Multifactor experiments provide an applicable tool for the understanding of complex processes since all input factors can be investigated simultaneously. If the experiment comprehends a number of factors, the tests are often performed with each factor at only two levels, *2^n factorial experiments*. The main reasons for using 2^n factorial experiments are to reduce the number of tests. However, since each factor is measured at only at two levels, it is impossible to determine if the influence caused by variations in a factor vary linearly, or e.g. exponentially. For that reason, 2^n factorial experiments are mostly used for screening test, in order to recognise the most affecting factors. The tests should then be followed by experiments where only a few factors are varied at several levels.

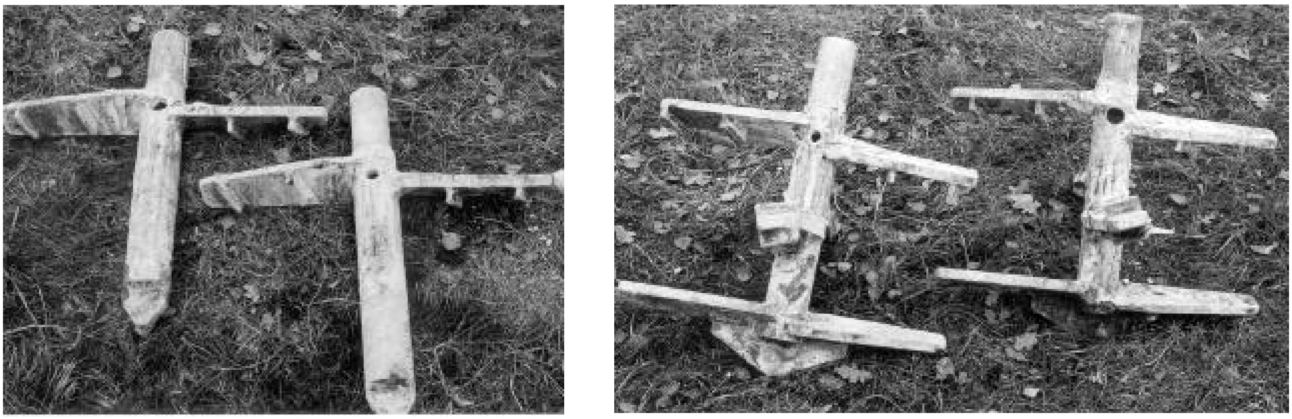
Table 2. Experimental design for statistical test 1 (2^n- factorial experiment).

Test	Factor	Low level	High level
Test 1	Number of blades	2	6
	Retrieval rate (mm/rev)	15	30
	Rotational speed (rpm)	80	160
	Outlet hole (mm)	22	37
	Tank pressure (kPa)	350	550

Table 3. Experimental design for statistical test 2 (two factorial experiment).

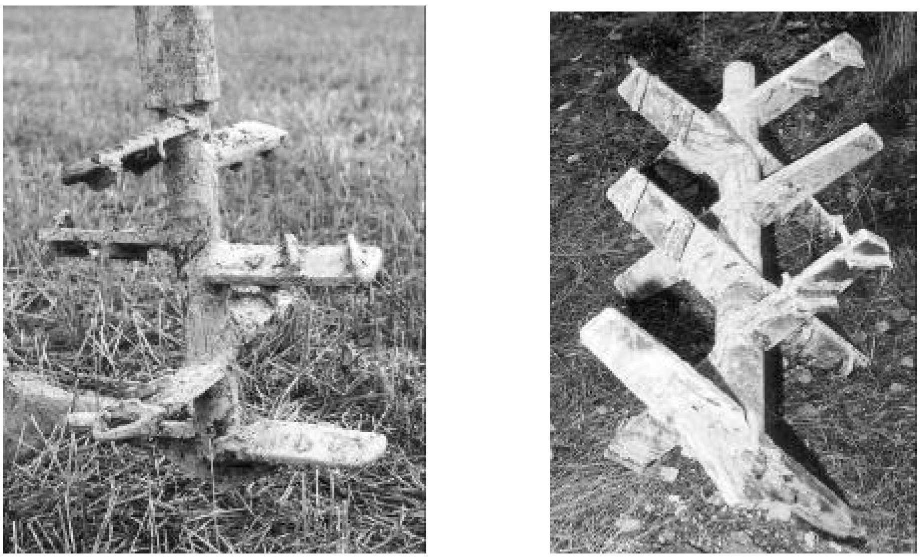
Factor				
Number of blades	2	6	8	12
Retrieval rate (mm/rev)	15	30		

Com; Rotational speed = 160 rpm; Outlet hole = 37 mm; Tank pressure = 550 kPa



(a) (b)

Fig. 4. The mixing tools used in Test 1: (a) mixing tools with two blades and (b) mixing tools with 6 blades.



(a) (b)

Fig. 5. (a) The Pinnborr provided by; (a) 8 blades; and (b) 12 blades.

The statistical analysis used is an analysis of variances, ANOVA, that segregates different sources of variation in the results. The procedure described by Johnson (1994) has been used for the analysis of variances based on two- and 2^n-factorial experiments and tests for the significance of the factorial effects, using the 5 % level of significance. The statistics in ANOVA is the F-test of difference of group means, testing if the means of the groups formed by values of the independent factor, or combinations of values for multiple independent factors, are different enough not to have occurred by chance. A null hypothesis condition was used to accept or reject the differences between the group means. If the group means do not differ significantly then it is inferred that the independent factor did not have an effect on the dependent parameter. If the F-test shows that overall the independent factor is related to the dependent parameter, then the multiple comparison tests of significance are used to explore just which value groups of the independent considered factor have the most to do with the relationship.

Five factors according to Table 2, connected to the installation process, were investigated in Test 1. This test included 2560 penetrometer tests in 64 columns. Other factors were kept constant as far as possible. The quantity of binder was 88 kg/m^3 which corresponds to 25 kg/m, for the 0.6 m column, with the proportion 50 % quicklime (CL90-O) and 50 % cement (white cement, CEM II/A-LL). The tolerance for the binder content was set to ±10 %, this is the common practice in Sweden. The length of the columns are about 5 m. White cement was used to facilitate the visual examination. Table 4 shows the installation data for each column and Fig. 2 shows the location at the test site. The column machine used for the column installation can be seen in Fig. 3b.

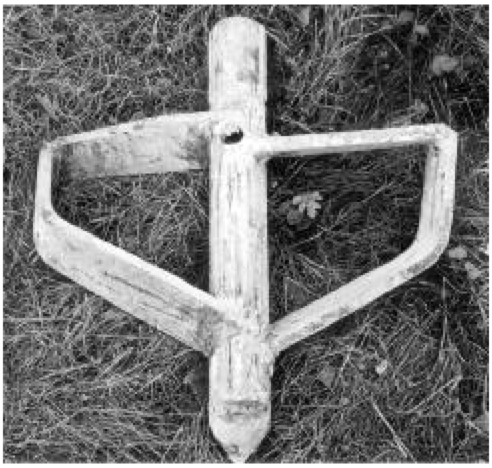
In order to study the influence of the number of blades in a wider interval, 16 columns were installed, with mixing tools provided by 2, 6, 8, and 12 blades respectively. A number of these mixing tools are shown in Figs. 4–5. The statistical test, Test 2, was performed as a two-factor experiment according to Table 3. All columns included in Test 2 were installed with a rotation speed of 160 rpm, an air pressure in the binder storage tank of 550 kPa, and an outlet hole diameter of 37 mm. Table 5 shows the installation data for the columns.

Additional comparisons

A number of additional limited comparisons were performed in addition to the factors investigated in Test 1 and 2. No statistical tests were performed due to the limitation and fractional characteristics of the tests.

1. A simple comparison by the Swedish “Standard tool” (SGF, 2000) was performed (Fig 6a). Only the retrieval rate was varied and the comparison included therefore four columns.
2. As a simple comparison, a mixing tool was tested with the outlet hole placed just behind the blade, as shown in Fig. 6b. Only the binder air tank pressure was varied, 350 and 500 kPa respectively. The purpose for testing this mixing tool was to study the influence of the location of the outlet hole in relation to the mixing blades. It was assumed that the placing of the outlet hole, just behind one of the blades, would influence the spreading of the binder. However, it is uncertain whether the result is that the binder is more evenly spread or if the binder ends up around the column periphery.
3. Four columns were installed by a mixing tool without blades in order to investigate the binder distribution caused by the air pressure. Only the binder air tank pressure was varied, 350 and 500 kPa respectively. The purpose of this limited comparison was to verify the findings at Håby where a large number of columns were installed without any mixing tool, and where it was observed that pneumatic fracturing, as a mixing mechanism, had a minor influence on the binder dispersion.

Table 6 shows the installation data for the columns.



(a)

(b)

Fig. 6. (a) The Swedish Standard mixing tool; and (b) the Pinnborr with 2 blades and the binder outlet hole placed behind one of the blades.

Results

General

The results from the hand-operated penetrometer tests are presented in Tables 4–6. The results presented are the mean values evaluated from the performed tests at the two test levels, 1.9m and 2.3 m respectively. The results of the two statistical tests are presented in Tables 7–8. No statistical tests were performed for the additional comparisons since the number of columns tested was inadequate. The results from these penetrometer tests are therefore presented and commented under the discussion section.

Table 4. Installation data and results from the penetrometer tests in columns included in Test 1.

Column Repetition 1	2	Blades: n	Retr rate: mm/rev	Rot speed: rev/min	Outl hole: mm	Tank pressure: kPa	Rep.1 S_{eff}	$V_{d\,col}$	Rep.2 S_{eff}	$V_{d\,col}$
1:4	1:6	2	15	80	37	350	10.0	0.27	13.5	0.31
1:8	1:9	6	15	80	37	350	14.1	0.09	15.0	0.15
1:14	1:15	2	15	160	22	350	9.8	0.27	9.6	0.35
1:17	2:5	6	15	80	22	350	13.8	0.11	15.7	0.11
1:22	1:23	2	15	80	37	550	12.4	0.30	12.3	0.30
1:24	2:10	6	15	80	37	550	13.9	0.25	17.1	0.14
1:26	1:27	6	30	160	37	550	12.1	0.33	12.5	0.17
1:29	1:30	2	30	160	22	550	6.7	0.55	6.8	0.59
1:31	1:32	6	30	160	22	550	13.7	0.17	10.8	0.40
1:36	1:37	2	30	160	37	350	4.3	0.51	6.5	0.40
1:38	1:39	6	30	160	37	350	11.8	0.18	15.5	0.23
1:41	1:42	2	30	160	22	350	6.5	0.52	4.9	0.51
1:43	1:44	6	30	160	22	350	12.1	0.28	10.3	0.32
2:2	2:3	2	15	80	22	350	13.5	0.32	9.4	0.40
2:6	2:7	6	15	80	22	550	9.2	0.35	16.3	0.13
2:8	2:9	2	15	80	22	550	7.6	0.31	7.0	0.49
2:12	2:13	6	15	160	37	350	13.6	0.12	13.4	0.31
2:17	2:18	2	15	160	37	350	9.7	0.33	9.4	0.47
2:22	2:23	6	15	160	22	350	17.4	0.27	16.6	0.15
2:25	3:2	6	15	160	22	550	19.4	0.16	11.1	0.24
3:14	3:16	2	15	160	22	550	14.2	0.37	11.1	0.32
3:19	3:20	2	15	160	37	550	9.4	0.39	6.2	0.43
3:21	3:22	6	15	160	37	550	20.1	0.13	14.3	0.22
4:2	4:3	6	30	80	37	350	14.9	0.24	12.3	0.22
4:5	4:6	2	30	80	37	350	4.5	0.51	7.5	0.42
4:8	4:9	2	30	80	22	350	6.1	0.47	7.2	0.45
4:10	4:11	6	30	80	22	350	13.3	0.17	13.5	0.25
4:12	4:13	6	30	80	22	550	12.9	0.22	14.1	0.18
4:14	4:15	2	30	80	22	550	6.9	0.48	6.6	0.54
4:18	4:19	6	30	80	37	550	14.1	0.24	13.9	0.22
4:20	4:21	2	30	80	37	550	8.2	0.39	7.4	0.57
4:23	4:24	2	30	160	37	550	7.8	0.54	6.2	0.42

Table 5. Installation data and results from the penetrometer tests in columns included in Test 2.

Column rep 1	rep 2	Tool	Blades: n	Retr rate: mm/rev	Rot speed: rev/min	Outl hole: mm	Blade rot. number: n/m	Rep.1 S_{eff}	$V_{d\,col}$	Rep.2 S_{eff}	$V_{d\,col}$
1:26	1:27	Pinnb	6	30	160	37	200	12.1	0.33	12.5	0.17
1:34	1:35	Pinnb	8	30	160	37	267	14.3	0.24	14.7	0.25
2:28	2:29	Pinnb	12	30	160	37	400	14.0	0.14	15.3	0.16
3:4	3:5	Pinnb	8	15	160	37	533	15.9	0.18	18.1	0.10
3:7	3:8	Pinnb	12	15	160	37	800	21.9	0.09	18.7	0.11
3:19	3:20	Pinnb	2	15	160	37	133	9.4	0.39	6.2	0.43
3:21	3:22	Pinnb	6	15	160	37	400	20.1	0.13	14.3	0.22
4:23	4:24	Pinnb	2	30	160	37	67	7.8	0.54	6.2	0.42

Table 6. Installation data and results from the penetrometer tests in columns installed by the Swedish standard tool, the special 2-blade Pinnborr, and the mixing tool without blades.

Col rep 1	rep 2	Tool	Blades: n	Retr rate: mm/rev	Rot speed: rev/min	Outl hole: mm	Tank pressure: kPa	Rep.1 S_{eff}	$V_{d\,col}$	Rep.2 S_{eff}	$V_{d\,col}$
2:30	2:31	Std	4	30	160	37	550	8.6	0.44	10.9	0.38
3:10	3:12	Std	4	15	160	37	550	18.5	0.19	13.5	0.36
3:28	3:29	Spec	2	30	160	37	550	4.1	0.49	7.0	0.43
4:27	4:29	Spec	2	30	160	37	350	8.7	0.48	6.8	0.51
2:32	2:33	-	0	30	160	37	350	-	-	-	-
2:34	2:35	-	0	30	160	37	550	-	-	-	-

The results from the two ANOVA tests, analysis of variances, are presented in Table 7 – 8. The analyses show an estimate of the main effect of the factors (independent variables) and the interaction effects. Results presented by bold figures are significant for the 5 % level. A main effect is the direct effect of a factor (independent variable) on the measured parameter (dependent variable). An interaction effect is the joint effect of two or more factors on the measured parameter. It is important to emphasize the fact that the proposed test methodology does not show whether or not, the studied factors have a definite influence on the mixing process. The test methodology show if the factors and their combinations have a significant influence with reference to the present test method.

Test 1

Test 1, included 64 columns installed by mixing tools provided by two and six blades, respectively. Table 7 shows the results from the statistical analyses with respect to the spring deformation $\bar{d}_{col}$, the stabilisation effect S_{eff} and the coefficient of variation $V_{d\,col}$, based on the 2560 penetrometer tests in the 64 columns.

Table 7. Analysis of variance, 2^5 factorial experiment, Test 1.

Source of variation	$\bar{d}_{col}$ F	S_{eff} F	$V_{d\,col}$ F
Replication	< 1	< 1	< 1
Main effects:			
A. Number of blades	**121**	**116**	**123**
B. Retrieval rate	**8.3**	**32**	**27**
C. Rotational speed	**8.9**	< 1	2.9
D. Outlet hole	< 1	< 1	1.2
E. Tank pressure	< 1	< 1	1.8
Two-factor interactions:			
AB	**6.1**	2.7	**4.8**
AC	1.6	< 1	< 1
AD	1.1	< 1	< 1
AE	0.5	< 1	< 1
BC	**8.6**	1.4	< 1
BD	< 1	< 1	< 1
BE	< 1	< 1	< 1
CD	< 1	2.4	< 1
CE	< 1	< 1	< 1
DE	1.4	1.0	< 1
Three-factor interaction			
ABC	2.5	1.8	< 1
ABD	< 1	< 1	< 1
ABE	< 1	< 1	< 1
ACD	2.6	1.1	1.4
ACE	2.4	< 1	< 1
ADE	< 1	< 1	< 1
BCD	< 1	3.6	**4.7**
BCE	1.4	< 1	1.0
BDE	< 1	1.0	< 1
CDE	0.7	1.7	< 1
Four-factor interaction			
ABCD	1.1	< 1	< 1
ABCE	< 1	< 1	< 1
ABDE	< 1	2.3	< 1
ACDE	< 1	1.6	< 1
BCDE	1.8	< 1	< 1
Five-factor interaction			
ABCDE	< 1	2.6	< 1

Comment: $F_{0.05}$=4.17 and $F_{0.01}$=7.56 for 1 and 31 degrees of freedom.

The analysis with respect to spring deformation $\bar{d}_{col}$, shows that the number of blades on the mixing tool, the retrieval rate and the rotation speed have a significant influence. There are additional number of combinations of factors with significant influence. However, the significant influence of the rotational speed is most likely a consequence of the number of columns installed by 80 rpm where the shear strength of the unstabilised soil was about 26 kPa. As shown in Table 1, the undrained shear strength in the unstabilised soft soil varied from 13 to 26 kPa over the test site (1.9 m to 2.3 m depth). The analysis with respect to the stabilisation effect S_{eff} , showed that only the number of blades on the mixing tool, and the retrieval rate had a significant influence. Similar results are shown by the analysis with respect to the coefficient of variation $V_{d\,col}$. As expected, the effect of the number of blades is stronger than the effect of the retrieval rate. The analysis with respect to the coefficient of variation $V_{d\,col}$ also showed that the combination of number of blades and the retrieval rate has a significant influence. These results were expected since the number of blades was varied by a factor of 3 and the retrieval rate was varied by a factor of 2. However, the analysis with respect to the stabilisation effect S_{eff} , did not show a significant effect of the combination of these two factors. The diameter of the outlet hole and the binder tank pressure showed no significant influences on the stabilisation effect S_{eff} , or the coefficient of variation V_{col} . However, the analysis only show that the rotational speed, the diameter of the outlet hole and the binder tank pressure do not have significant effect in the relatively narrow varied intervals.

Test 2

In order to study the influence of the number of blades in a wider interval, the columns in Test 2 were installed with mixing tools provided by 2, 6, 8, and 12 blades. Table 8 shows the result from the two factorial experiment, including 16 test columns. Also this test shows that the number of blades and the retrieval rate have a significant influence on the stabilisation effect S_{eff} and the coefficient of variation $V_{d\,col}$.

Table 8. Analysis of variance, two factorial experiment, Test 2.

Source of variation	*Degrees of freedom*		$\bar{d}_{col}$	S_{eff}	$V_{d\,col}$
		$F_{0.05}$	F	F	F
Replication	1	5.59	1.5	1.5	< 1
Main effects:					
A. Number of blades	3	4.35	**18**	**21**	**21**
B. Retrieval rate	1	5.59	**13**	**13**	**5.8**
Two-factor interactions:					
AB	3	4.35	1.5	1.3	< 1

Discussion

General

The results from the field tests in context of the findings from the field test at Håby presented by Larsson *et al.* (2002a, 2002b), are discussed in the following sections. It should be noted that the discussion only refers to the conditions existing during the tests. The findings are only valid for the parameters, intervals and combinations tested.

Test 1 and 2

From the two statistical tests, based on a hypothesis test by analysis of variances and the traditional significance level of 5 %, it can be concluded that the retrieval rate and the number of blades have a significant influence on the stabilisation effect S_{eff} and the coefficient of variation $V_{d\,col}$. The two parameters, retrieval rate and number of blades, can most likely be combined by the coupled factor “Blade rotation number”, provided that the blades have similar geometry. The Blade rotation number T, is expressed as (modified after Nakamura *et al.*, 1982)

$$T = \sum M \times \frac{1}{s} \tag{3}$$

where ΣM is and the number of blades on the mixing tool and s is the retrieval rate. The Blade rotation number is the total number of mixing blades passing during 1 m of shaft movement.

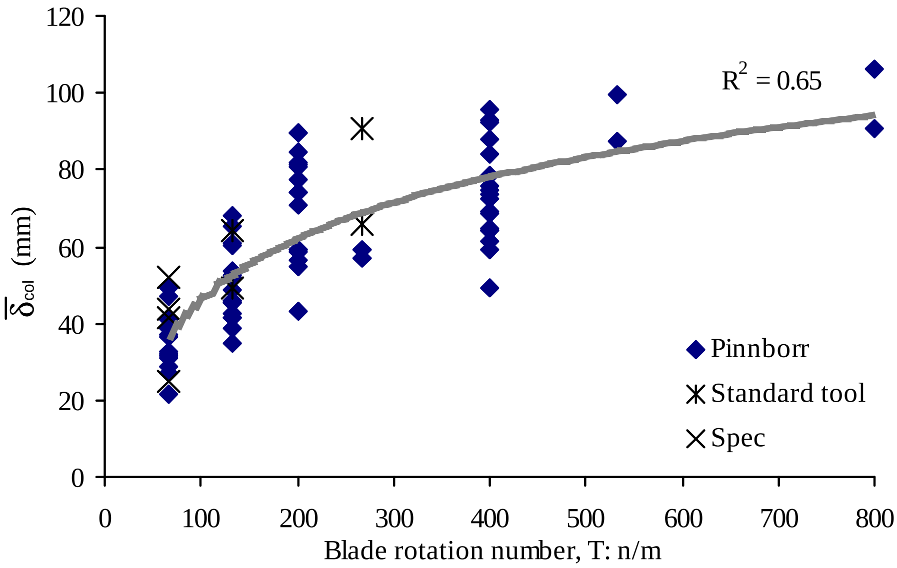


Fig. 7. The spring deformation $\bar{d}_{col}$ as a function of the Blade rotation number T.

Figs. 7 – 9 show the results from 3200 penetrometer tests in 80 columns. Each point represents 40 penetrometer tests. Fig. 7 shows the spring deformation as a function of the Blade rotation number. The scatter in the results is considerable, which can partly be due to the varying soil properties but also to the fact that the test procedure has a number of sources of errors, as discussed by Larsson *et al.* (2002a, 2002b). Furthermore, the binder content throughout the columns is not uniform. Fig. 8 shows the same results, but the stabilisation effect according to Equation 1, as a function of the Blade rotation number. The correlation is good over the present interval and the relation is approximately logarithmic. Fig. 9 shows the coefficient of variation $V_{d\,col}$ as a function of the Blade rotation number. The scatter is high but the correlation is good over the tested interval and the relation is approximately logarithmic. An approximately logarithmic or a power law relation between the column strength and the mixing work has previously been reported by e.g. Muro *et al.* (1987a, 1987b), Larsson *et al.* (1999) and Nishida *et al.* (1996). However, it is not possible to predict the strength magnitude based only upon the mixing work since the strength in stabilised soil highly depends on the composition and the conditions during the curing period.

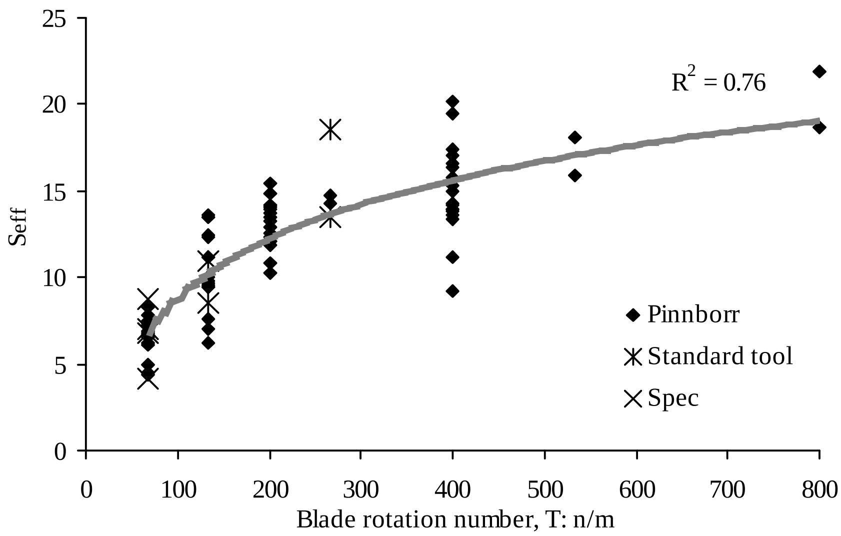


Fig. 8. The stabilisation effect S_{eff}, as a function of the Blade rotation number T.

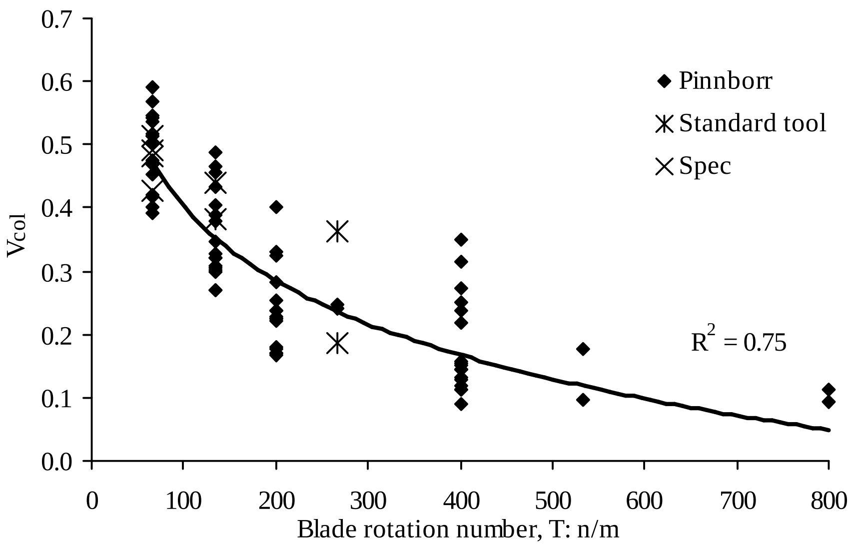


Fig. 9. The coefficient of variation $V_{d\,col}$, as a function of the Blade rotation number T.

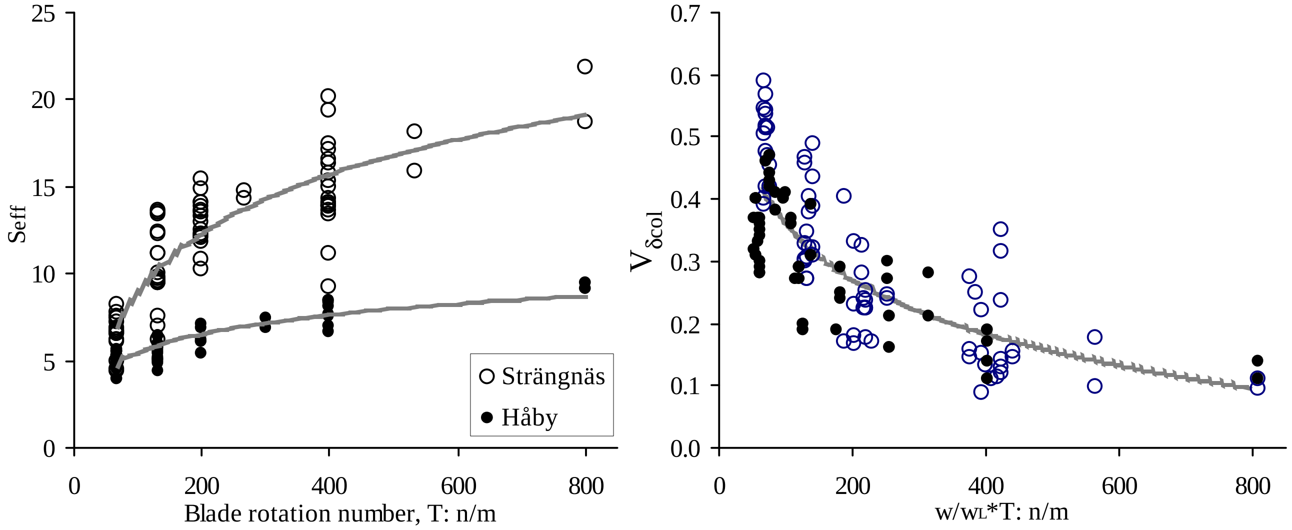


Fig. 10. **a) The stabilisation effect S_{eff}, as a function of the Blade rotation number T; and b) the coefficient of variation $V_{d\,col}$, as a function of the quotient between the water content and the liquid limit multiplied by the Blade rotation number $w/w_l \cdot T$.**

Fig. 10 shows the results from the two field tests at Håby and Strängnäs. The magnitude of the stabilisation effect S_{eff} after one week differs from the two sites as can be seen in Fig. 10a. At Håby, an empirical relation was found where the coefficient of variation $V_{d\,col}$ depends on the quotient between the water content w and the liquid limit w_L. In the present study, the quotient between the water content and the liquid limit had no significant influence on the statistical analysis since the quotient varied in a narrow interval ($0.9 < w/w_L < 1.1$). Fig. 10b shows the coefficient of variation $V_{d\,col}$ as a function of the quotient between the water content and the liquid limit multiplied by the Blade rotation number, $w/w_L \cdot T$. Similar results are obtained from the two test sites with the exception of the low interval $T < 200\,n/m$, where the coefficient of variation is somewhat higher at the test site in Strängnäs. According to the figure, $w/w_L \cdot T \geq 400 n/m$ the result has a relatively low coefficient of variation $V_{d\,col}$.

Similar results of the strength variation, mostly presented by the coefficient of variation, have previously been reported by others. A sufficiently good column quality is normally achieved when the Blade rotation number exceeds 360 n/m, according to Mizuno *et al.* (1988). Based on model tests, Dong *et al.* (1996) recommend $T > 250\,n/m$, depending on the strength required. Hayashi & Nishikawa (1999) recommends $T = 400 - 500\,n/m$ for sufficiently good uniformity and enhance cost-effectiveness for stabilisation of peaty ground. However, a somewhat higher value on the coefficient of variation was reported.

Muro *et al.* (1987a, 1987b), and Nishida *et al.* (1996) have reported a power law relation and an approximately logarithmic relation respectively, between the mixing quality with respect to a mixing index and the mixing work. However, the mixing work, evaluated as mixing energy and mixing time, can not be transformed and compared with the Blade rotation number.

It is well known that the mixing work influence the mixing process. However, most studies, just like this presented study, present results of the influence of indirect measures of the mixing work, e.g. the Blade rotation number, the retrieval rate, mixing time or the lifting speed in combination with the rotational speed.

The mixing energy per cubic meter of stabilised soil (in terms of J/m^3) can probably be a combining key factor. However, the mixing energy is not well investigated and it has not been clearly tested and shown whether the mixing energy is a combining factor. In Sweden, the mixing energy is normally not measured or recorded. It is a tradition to focus on the retrieval rate as an indirect measure of the mixing work. If the mixing energy is a combining factor, the test series can be reduced and the focus can be transferred to parallel comparisons of several different mixing tools, which is the main objective of the proposed test method. In that case, comparisons with fundamentally different geometries can be performed, such as screws, kneaders, vertical paddles etc.

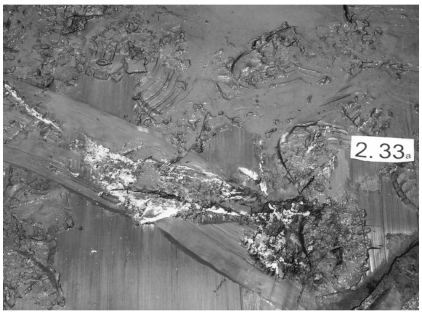
The results from the two extensive test series do not clarify whether the studied factors influence the mixing process, by means of strength distribution, since most of the studied factors were only varied in two relatively narrow levels. Furthermore, it is important to emphasize that all tests are performed at shallow depths where the confining pressure is low during column installation. However, the results shows that a number of factors do not considerably influence within the studied intervals and existing conditions. For practitioners, these results facilitate the discussions concerning the mixing process and causes for heterogeneities in manufactured columns since the number of influencing factors can be reduced. In order to increase the knowledge of the fundamental mechanisms occurring when binder and soft soil are mixed, the factors in the installation process must be further investigated in wider intervals and at greater depths.

Visual examination

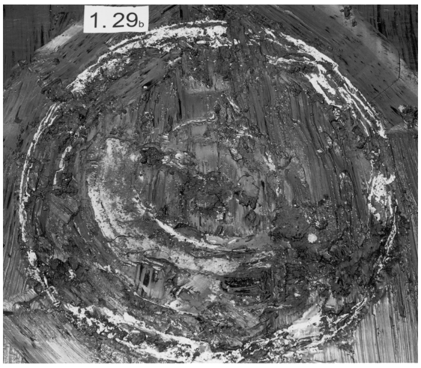
A visual examination can not be used for quality assessment since the visual impression is not necessarily equivalent to the binder distribution (Larsson, 2001). Visual judgements are associated with human senses, and are therefore highly individual and subjective. For example, it is difficult for the human sight and feeling to detect strength variations for high strength materiel. However, since visual examination is simple it is tempting to judge the column quality based on individual visual assessments.

In this study, the visual examinations were used to support the statistical analyses. Even if there are uncertainties with visual judgements, the visual binder dispersion and the subjective impression of the strength appeared to correspond to the results obtained from the hand-operated penetrometer. Fig 11 shows a selection of photographs on column sections manufactured by different Blade rotation number. A trend can be seen where the visible clumps and layers of unmixed binders decrease when the Blade rotation number increases. Furthermore, the coefficient of variation decreases when the columns become more uniform and obtain a colour similar to the surrounding soft soil. The majority of the columns installed by $T \geq 400 n/m$ are visually similar. It appears that there are no visual differences over the column section when the coefficient of variation is less than approximately 0.20. When the column strength becomes relatively uniform or high, the visual examination can not distinguish any differences.

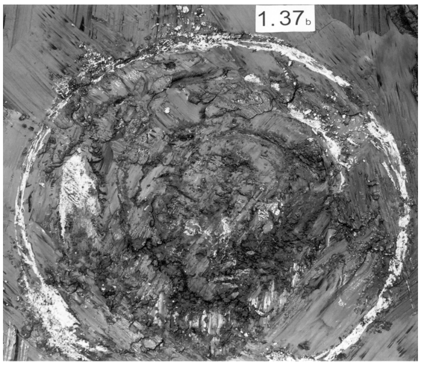
The visual examination also reflects the scatter in the results even when the columns are equivalently installed. In Fig. 11, four column sections installed by $T = 400 n/m$ are shown. A distinct difference in visual appearance can be observed and the coefficient of variation differs correspondingly. As shown in Fig. 8 and 9, there are two results that deviate from the trend (column 2.6 and column 3.2). These two columns have a low stabilisation effect S_{eff} and high coefficient of variation $V_{d\,col}$. The visual examination also showed that these two column sections differed from all other columns installed by $T = 400\ n/m$.
As shown in Fig. 11, there were sharp traces of unmixed binders in clumps and layers, and the character was grainy, whereas the others had a more even grey colour tone, similar to the unstabilised surrounding soft



Column 2.33 T= 0 n/m

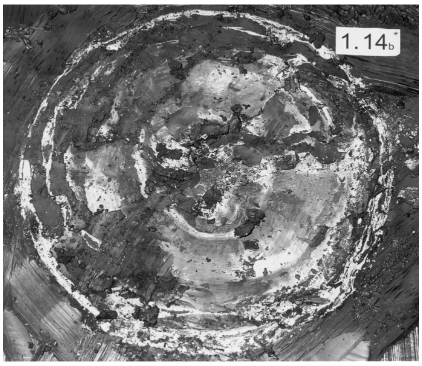


Column 1.29; T=67 n/m
S_{eff}=6.7 $V_{\delta col}$=0.55

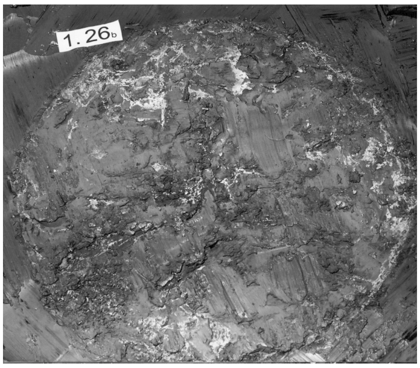


Column 1.37; T=67 n/m
S_{eff}=6.5 $V_{\delta col}$=0.40

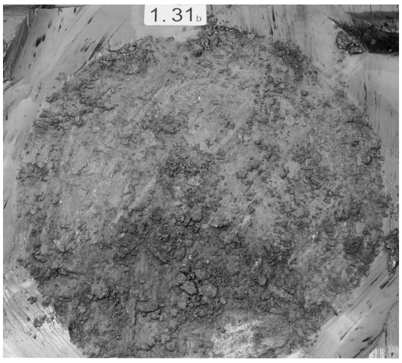
Column 2.18; T=133 n/m
S_{eff}=9.4 $V_{\delta col}$=0.47



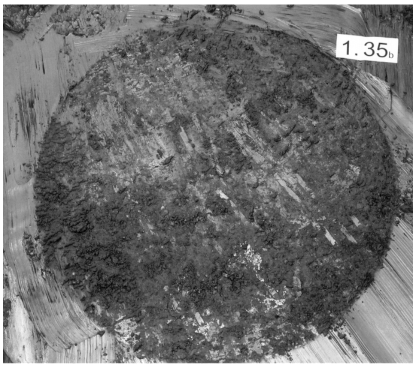
Column 1.14; T=133 n/m
S_{eff}=9.8 $V_{\delta col}$=0.27



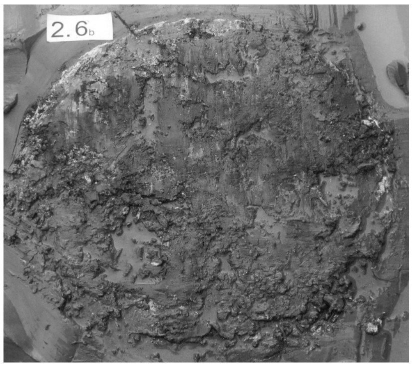
Column 1.26; T=200 n/m
S_{eff}=12.1 $V_{\delta col}$=0.33



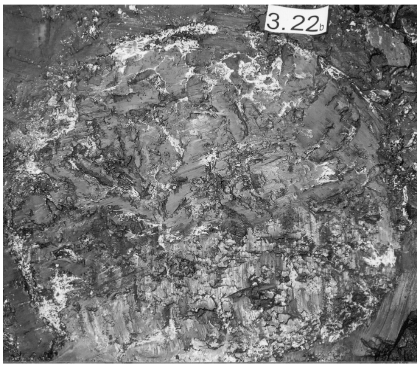
Column 1.31; T=200 n/m
S_{eff}=13.7 $V_{\delta col}$=0.17



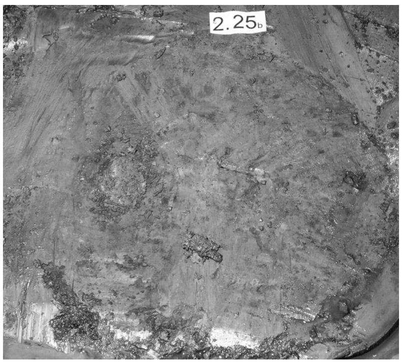
Column 1.35; T=267 n/m
S_{eff}=14.7 $V_{\delta col}$=0.25



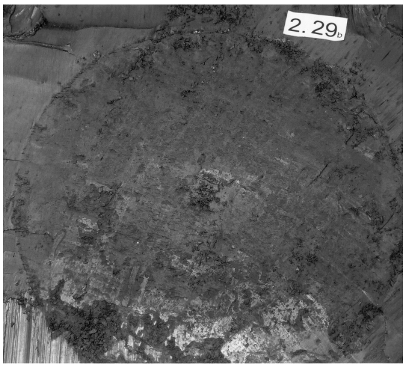
Column 2.6; T=400 n/m
S_{eff}=9.2 $V_{\delta col}$=0.35



Column 3.22; T=400 n/m
S_{eff}=14.3 $V_{\delta col}$=0.22



Column 2.25; T=400 n/m
S_{eff}=19.4 $V_{\delta col}$=0.16



Column 2.29; T=400 n/m
S_{eff}=15.3 $V_{\delta col}$=0.16

Fig. 11. Twelve examples of column sections where the Blade rotation number differs.

soil. There is no clear reason for this deviation but it shows that single columns can differ considerably even if the installation is performed with great care.

Additional comparisons

Mixing tool without blades

The four columns installed without mixing blades had different shapes as shown in Fig. 11. The air jet has expanded or cut a circular cavity, 0.1 – 0.2 m in diameter, which was filled by the binder. Pneumatic fracturing was observed in all four column sections. The extent of this fracturing was limited to one vertical channel going out from the centre of the column. The channels were about 10 to 50 mm wide and up to 500 mm long. The vertical channels were somewhat wider than the once observed at the Håby-tests. The reason is probably due to the lower shear strength in the soft soil at Strängnäs. However, pneumatic fracturing can not be considered as a significant mixing mechanism even though the shear strength is low.

The placing of the outlet hole

Four columns were installed by a mixing tool provided with two blades and the binder outlet hole was placed close to one of the blades. The stabilisation effect and the coefficient of variation did not differ from the other columns, as can be seen in Figs. 8 – 9. According to the visual examination a thin binder ring could be observed in the column periphery. The thin ring was somewhat thinner than the binder-rings in the column periphery observed in other columns installed by $T = 67 n / m$ (Fig. 11).

This limited comparison does not show whether or not the placing of the outlet hole has an effect on the binder dispersion over the column length. Further investigations are required, where larger-diameter columns and lengths, with higher *in-situ* stresses, need to be looked upon.

The Swedish Standard mixing tool

The Swedish Standard mixing tool was used for four of the columns. As shown in Figs. 8-9 there are no significant difference between the Swedish Standard mixing tool and the Pinnborr, provided that they are equipped with the same number of mixing blades. The results were as expected, but the comparison is based on a limited amount of tests. The visual examination did not show any significant difference.

Development of the test method

It should be investigated whether the test method can be used for columns with higher strengths-, and undrained shear strength approximately higher than 150 kPa. The reason for testing the columns short after installation is the uncertainty in the failure mechanism if the shear strength is high and the column material is brittle. If the test can be performed with a sufficiently high reliability, the columns can be tested when they reach their full strength. Given the strength magnitude and the variation, together with the critical failure mechanism and the scale of scrutiny, such tests can support probabilistic design. Statistical design approaches for deep mixing have been proposed by Honjo (1982) and Omine *et al.* (1998, 2001). However, probabilistic design has not yet been common practice for the design of deep mixing.

According to the Japanese design guide (CDIT 2002), the *in-situ* design strength can be derived from field test by incorporating the strength deviation. The average strength measured from *in-situ* stabilised soil is normally reduced with respect to the standard deviation. The resulting variance is, however, relatively large when it is determined by a penetrometer test with a small selected test volume. It should be investigated whether a variance reduction can be adopted with respect to present failure mechanisms and scale of scrutiny. The application of a proper variance reduction will have an affect on the design strength, as the variance has a large influence on the probability of failure. With knowledge of the present failure mechanism and a proper scale of scrutiny, the installation process can be designed to attain a sufficient mixing quality, with respect to the resulting property variance.

With an increased knowledge of the mixing quality as a function of the mixing work, the test method may be a useful tool for the cost-optimization of the mixing process. Reflections of cost-optimization analysis have previously been discussed by e.g. Nishida *et al.* (1996) and Hayashi & Nishikawa (1999).

In order to reduce the number of tests a fractional statistical experiment design can be adopted. Such a statistical design approach facilitates tests where a number of different mixing tools are compared, since the number of columns is reduced in the test.

Conclusions

The influence of the number of blades on a mixing tool, the retrieval rate, the rotational speed, the outlet hole diameter and the binder tank pressure on the strength over shallow excavated column sections were investigated. The stabilisation effect and the coefficient of variation with respect to the results from a hand-operated penetrometer were evaluated. The results should be interpreted in the context of the conditions at the two sites. Based upon the results presented in this report, the following conclusions can be drawn;

a) The number of blades and the retrieval rate are shown to exhibit significant influence on the stabilisation effect and coefficient of variation. The two factors can be linked to the coupled factor “Blade rotation number”, which is the total number of mixing blades passing during one meter of shaft movement. The study indicates that the stabilisation effect and the coefficient of variation is a function of the logarithm of the Blade rotation number.

b) Neither the rotational speed, the binder tank pressure nor the diameter of the binder outlet hole have any significant influence on the stabilisation effect or the coefficient of variation.

c) The visual examination appeared to be a complementary tool to the hand-operated penetrometer. The visible clumps and layers of unmixed binders reflected the coefficient of variation as a measure of the mixing quality.

d) The tests show that the column quality can differ even though they are installed in the same way. The strength is highly stochastic with large variations even if the installation is performed with great care. Single or few tests can therefore result in misleading conclusions.

The proposed method can also be used with other sets of binders and soils, in order to study influence factors such as mixing work and mixing tool geometry.

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