Lime Columns—A New Type of Vertical Drains

Colonnes de Chaux—Un Nouveau Type de Drains Verticaux

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SYNOPSIS By mixing unslaked lime with clay in situ, it is possible to form cylindrical columns in the clay which have a high permeability compared with surrounding untreated soil. Test data indicate that unslaked lime increases the permeability of a clay 100 to 1000 times or more. Such lime columns will therefore function as vertical drains in the soil. The lime columns act also as reinforcement of the soil and increase the shear strength and reduce the total and differential settlements.

Lime columns have been tested as vertical drains in Sweden and in Finland and compared with other types of drains. In this article consolidation data from 18 load tests have been summarized and compared with calculated values using results from laboratory tests. The different drain types have been compared with respect to efficiency and it was found that one lime column with a diameter of 50 cm is equivalent with about three 15 cm diameter sand drains or two to three 10 cm wide paper-plastic drain strips (Geodrain).

INTRODUCTION

Sand drains in combination with preloading are extensively used to stabilize deep deposits of soft cohesive soils. The settlements are thereby reduced while the shear strength and the bearing capacity of the soil are increased (Johnson, 1970). Due to the disturbance of the soil during the installation of the sand drains the drainage effect can be reduced substantially and the advantages with vertical drains be more or less lost even though precautions have been taken during the installation of the drains to reduce the disturbance (Casagrande and Poulos, 1969). Other types of vertical drains have been developed which are either thin or have a small diameter to decrease the disturbance caused by the installation, e.g. the Cardboard Drain (Kjellman, 1948), the Sand-wick Drain (Dastidar et al, 1969) and the Geodrain (Hansbo and Torstensson, 1977).

A new method has recently been developed in Sweden with which it is possible to install drains - lime columns - in situ with very little disturbance of the surrounding soil, in spite of the large diameter of the drains. Lime columns, which have a diameter of 0.5 m and, so far, a maximum length of 10 m, also act as reinforcement in the soil in the same way as compacted sand drains (Tanimoto, 1973) or stone columns (Hughes and Withers, 1974). These columns are capable to carry relatively high loads and can be used to support light structures.

Another application of lime columns is around pile-supported structures, where the columns can reduce the negative skin friction caused by a surrounding fill or by a lowering of the ground water table. The lime columns will also reduce the lateral displacement of the piles due to creep of the surrounding soil. Lime columns may also be used instead of sheet piles as lateral support in deep cuts (Broms and Boman, 1975).

DESCRIPTION OF METHOD

The lime columns are manufactured in situ with a tool shaped as a giant "eggbeater". This tool is screwed down into the soil to the depth which corresponds to the required length of the drains. At the desired depth the rotation is reversed and unslaked lime is forced into the soil with compressed air through openings placed just above the blades of the mixing tool. The amount of lime corresponds normally to about 5 to 8 percent of the dry weight of the soil. The retrieval rate when the tool is pulled out of the hole is about 1/10 of the initial feed rate when the tool first is screwed into the soil. The rate is reduced, when suitable, in order to mix the lime thoroughly with the soil.

This is important due to the low diffusion rate of the calcium ions in most cohesive soils. The soil is compacted during the retrieval since the blades are inclined (twisted). The mast and the rotary table are usually mounted on a standard front wheel-loader, Volvo BM 641, as shown in Fig. 1. Also track-mounted loaders may be used when the bearing capacity of the soil is low.

A container is attached to the loader to store the unslaked lime. The volume of the container (2.5 m^3) is sufficient for more than four hour's work. The drilling unit is operated by one man, and the time required to manufacture a 10 m long column is about 10 minutes. The rotation rate is about 60 rpm. The capacity of the machine is 50 m/hour or about 300 m/8 hours (30 to 40 columns). The cost is at present less than Sw.Cr. 20 per meter ($ 1.50/ft). The lime columns have been found to be compatitive with sand drains due to the large surface area of the lime columns. The number of columns which are required to reach a certain degree of consolidation is thus low.

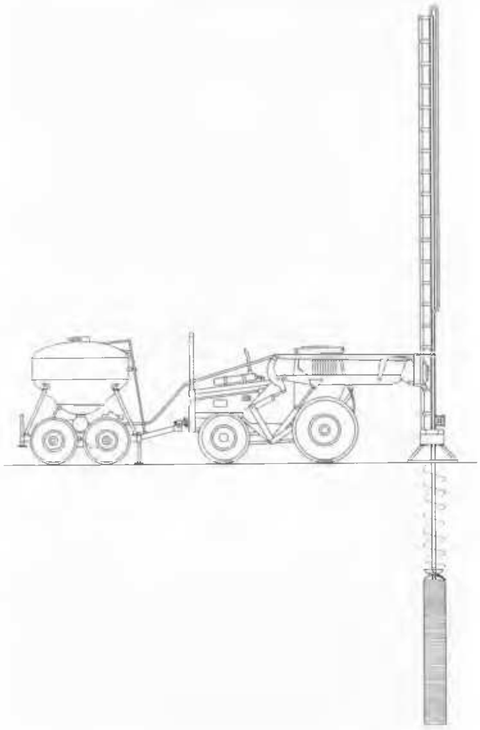

Fig. 1 Drilling unit. The mast is folded during transportation

ACTION OF LIME IN SOILS

Principally, four different chemical reactions take place when unslaked lime is mixed with moist soil (Arman and Munfakh, 1970). These reactions are:

. Hydration

. Ion exchange and flocculation

. Cementation (Pozzolanic reaction)

. Carbonation

The hydration reduces the water content and raises the temperature of the soil. Thereby the shear strength is increased. The ion exchange starts immediately after the mixing of the lime with the soil. When the clay flocculates, water stable aggregates are formed which have a low compressibility and high permeability compared with the surrounding soil. The shear strength of the lime-stabilized soil increases gradually with time due to pozzolanic reaction in the soil and can be as high as 1 MPa after one year. The bearing capacity of a 0.5 m diameter lime column varies normally between 50 kN to 500 kN depending on the soil type and the amount of lime added. The risk of carbonation is rather low within the soil, and is further reduced due to the compaction of the "egg-beater".

SWEDISH TEST SITE

The efficiency of lime columns as drains have been investigated at Skå-Edeby located 25 km west of Stockholm. This test site (Fig. 2 and Table I) has been used by the Swedish Geotechnical Institute since 1957 as its test field to investigate the behaviour of 15 cm diameter displacement type sand drains (Hansbo, 1960; Holtz and Broms, 1972).

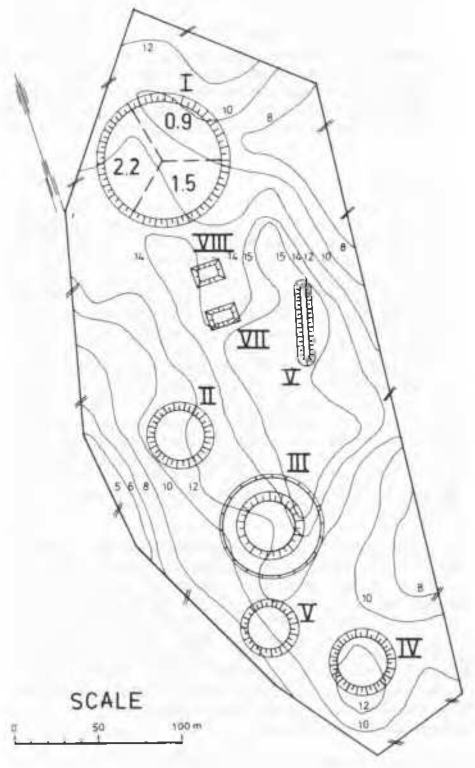

Fig. 2 The test field at Skå-Edeby. Numbers at contour lines refer to the depth of the clay layer in metre

TABLE I. Test areas at Skå-Edeby, Sweden (See Fig.2)

Area No.	Drain spacing c/c (m)	Load $\Delta\sigma$ kPa	Loading date	Compression index C_c	Coefficient of consolidation c_v $\times 10^{-8}$ m^2/s
I	0.9	27	1957-06-19	1.8	0.7
	1.5	27	1957-06-19	1.9	0.5
	2.2	27	1957-06-19	1.5	0.5
II	1.5	27	1957-06-20	1.5	0.6
III	1.5	39	1957-06-28	1.4	0.5
IV	-	27	1957-07-07	1.4	0.5
V	-	27	1961-04-25	-	0.8
VI	0.9	27	1972-09-19	1.6	0.5
VII	1.4	10	1973-05-21	1.6	0.7
VIII	-	10	1973-05-21	1.6	0.7

Areas I to III: Sand drains (ϕ0.15 m)
Area VI : Geodrains
Area VII : Lime columns (ϕ0.50 m)

The soil consists from the surface of a slightly organic mottled post-glacial clay down to about 5 m depth, and of a glacial varved clay to firm bottom, 10 to 15 m below the ground surface, as shown in Fig. 3. The clay is weathered at the surface and forms a 1 m thick dry crust. The clay content is about 80 percent.

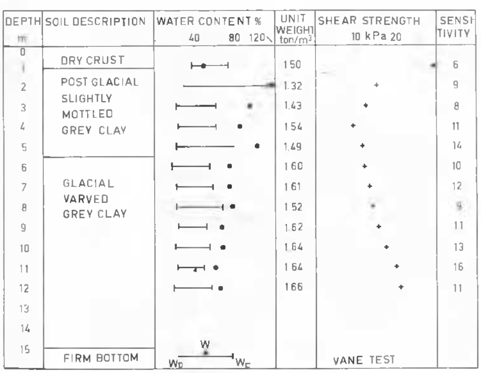

Fig. 3 Soil conditions at Test Area VII, Skå Edeby

To test lime columns, two rectangular areas, 8mx15 m^2, were loaded by 0.6 m thick sand fills. The applied load was 10 kPa which corresponds to the weight of a small family house. About 6 m long columns were installed below one of the areas (No. VII). Area No. VIII was not stabilized (reference area). The spacing was 1.4 m which corresponds to 10 percent of the soil enclosed by the columns. The settlements were measured with rods which were attached to soil screws located at different levels below the ground surface. The consolidation of the upper 6 m of the soil is shown in Fig. 4 for the two areas (No. VII and No. VIII).

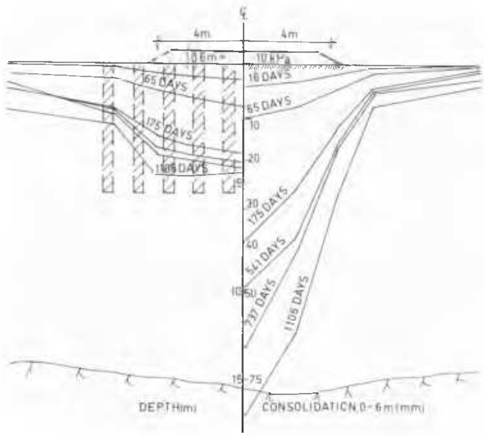

Fig. 4 Settlement profiles of Test Areas Nos VII and VIII, Skå-Edeby

In Fig. 5 the measured time-consolidation relationships have been plotted for the two areas for the same soil layers. Also the fitted curves according to Eq.(1) are shown with values from Table III.

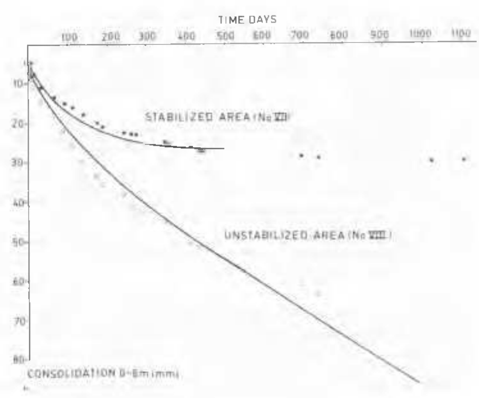

Fig. 5 Settlement-time relationship of Test Areas Nos Nos VII and VIII, Skå-Edeby

FINNISH TEST SITE

Lime columns as well as other drain types have also been investigated in Finland. The purpose of the tests was to investigate possible foundation methods for the East-Suburb Centre in Helsinki (Tammerinne and Rathmayer, 1974). The tests have been carried out by the Technical Research Center of Finland on behalf of the City of Helsinki.

The test areas, Table II, are located along a proposed road. Each test area is about 20 m long. The areas were loaded incrementally by gravel fills. The maximum height of the fills and the bottom width were 3.3 m and 18 m, respectively.

TABLE II. The different tests at the Finnish test site

Area No.	Drain type	Drain spacing	Load (kPa)	Loading date
1	Undrained (reference area)	-	27 48	1974-12-15 1975-06-30
2	Geodrains (installed with mandrel)	1.6	27 48	1974-12-15 1975-06-30
3	Geodrains (without mandrel)	1.6	27 48	1974-12-15 1975-06-30
4	Geodrains (with mandrel)	0.8	27 48	1974-12-15 1975-06-30
5	Geodrains (with mandrel)	1.6	- (a)	1975-01-20
6	Lime columns (length 6 m)	1.4	24 47 62	1975-01-11 1975-06-25 1975-09-18
7	Lime columns (length 8 m)	1.4	24 47 62	1975-01-11 1975-06-25 1975-09-18
8	Compacted sand drains ϕ400 mm	2.0	46 (b) 37	1975-08-22 1975-08-24
9	Sand drains ϕ400 mm	1.6	46 (b) 37	1975-08-22 1975-08-24
10	Sand drains ϕ150 mm	1.1	46 37	1975-08-22 1975-08-24

(a) Vacuum loaded.
(b) "Russian drains" (part of a technical exchange program)

The test site is underlain by a young 7 to 9 m thick layer of postglacial clay which rests on silt and sand layers. Firm bottom is located at about 13 m depth. The ground surface of the clay layer is desiccated and forms a 1 m thick dry crust but the clay is very homogeneous (Fig.6) except for a thin silt layer at about 3 m depth. The compression index (C_c) of the clay is about 1.3 and the coefficient of consolidation c_v is about 1.5 x 10^{-8} m^2/s.

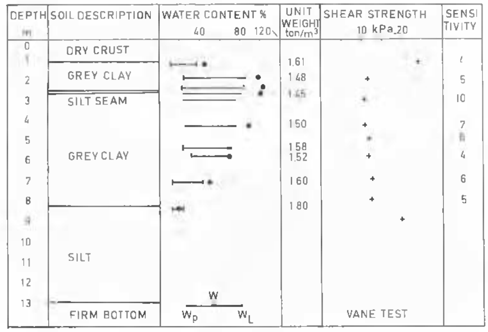

Fig. 6 Soil conditions at the Finnish test site

The installation of the drains were completed just before the test areas were loaded. The load on the areas where sand drains were used had to be reduced due to the low bearing capacity of the soil. Settlements were measured with rods attached to plates placed on the original ground surface below the fills. The time-settlement relationships for the unstabilized areas (No. 1) and the two areas stabilized with lime columns (Nos 6 and 7) are plotted in Fig. 7, as well as the time-load relationships. Fitted curves according to Eq.(1) are also shown in Fig. 7 using the data in Table III.

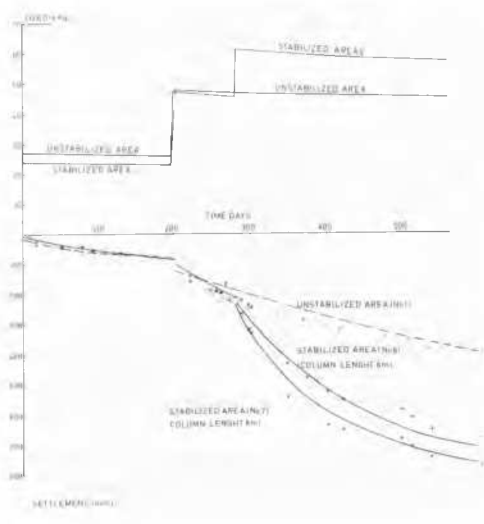

Fig. 7 Load-time and settlement-time relationships of Test Areas Nos 1, 6 and 7

EVALUATION

The measured time-settlement relationships have been compared with the equation:

$$\frac{\delta - \delta_o}{\delta_p} = 1 - \exp(-K\,t) \qquad (1)$$

where δ = the measured total settlement

δ_o = the initial settlement (fitted)

δ_p = the primary settlement due to consolidation (fitted)

$\exp(x) = e^x$

K = drainage factor (fitted)

t = time

According to Barron (1948) the consolidation equation in the case of symmetrical radial flow can be written as:

$$U = 1 - \exp\left(-\frac{8\,c_{vh}\,t}{D^2 \cdot f(n,s,k_n/k_s)}\right) \qquad (2)$$

where U = degree of consolidation

c_{vh} = coefficient of consolidation with horizontal flow

D = equivalent diameter of influence zone around a drain

TABLE III. Comparison between calculated and measured drainage rates

Test sites					Calculated values (from laboratory tests)			Test results (from field tests)			
Test site	Test No.	Drain type	Drain spacing c/c (m)	Load $\Delta\sigma$ (kPa)	Initial settlement δ_o (mm)	Primary settlement δ_p (mm)	Drainage factor K (1/day)	Number of observations	Initial settlement δ_o (mm)	Primary settlement δ_p (mm)	Drainage factor K (1/day)
Sweden	I	Sand drains ϕ 0.15 m	0.9	27	40	1200	5×10^{-3}	21	30	1140	5.8×10^{3}
			1.5	27	40	1300	2	21	20	980	2.1
			2.2	27	40	1000	1	21	20	1020	1.2
	II	-"-	1.5	27	40	1100	2	20	15	990	4.0
	III	-"-	1.5	39	60	1200	2	17	50	1250	2.5
	IV	Undrained	-	27	40	1000	0.2	19	35	800	0.4
	VI	Geodrains without mandrel	0.9	27	40	900	3	17	40	630	5.9
	VII	Lime columns	1.4	10	5	25(a,b)	4	14	5	22	8.5
	VIII	Undrained	-	10	10	250(a)	1	23	6	240	0.3
Finland	1	Undrained	-	27	30	450	0.4	6	20	470	0.7
		-"-	-	48	-	690	0.4	17	150	610	0.7
	2	Geodrains with mandrel	1.6	27	30	450	2	6	20	350	2.5
			1.6	48	-	690	2	17	180	650	2.6
	3	Geodrains without mandr.	1.6	27	30	450	2	5	20	350	2.5
			1.6	48	-	690	2	19	200	500	3.5
	4	Geodrains with mandrel	0.8	27	30	450	10	6	-	-	-
			0.8	48	-	690	10	18	300	500	6.2
	6	Lime columns (length 6 m)	1.4	24	15	80(b)	7	5	10	90	6.6
			1.4	47	-	450(b)	7	7	70	370	6.5
			1.4	62	-	650(b)	7	12	230	540	10
	7	Lime columns (length 8 m)	1.4	24	15	80(b)	8	5	10	90	6.7
			1.4	47	-	430(b)	8	7	80	320	6.9
			1.4	62	-	600(b)	8	12	190	520	9
	8	Sand drains compacted ϕ 0.4 m	2.0	37	-	-	2	12	50	610	2.5
	9	Sand drains ϕ 0.4 m	1.6	37	-	580	4	12	50	750	3.5
	10	Sand drains ϕ 0.15 m	1.1	37	-	580	5	12	45	750	3.3

Test Nos. I to VI triangular pattern of the drains, the rest square pattern.

a) For the top 6 m (see Fig. 3). Below 6 m the expected settlement is 100 mm.

b) Values reduced because part of the load is carried by the lime columns.

$$f(n, s, k_n/k_s = \frac{n^2}{n^2 - s^2} \cdot lu(\frac{n}{s}) - \frac{3}{4} + \frac{s^2}{4n^2} +$$

$$+ \frac{k_n}{k_s} \cdot \frac{n^2 - s^2}{n^2} \quad \ln(s)$$

$n = \frac{D}{d}$ (d = equivalent drain diameter)

$s = \frac{d_s}{d}$ (d_s = diameter of the smeared zone)

k_h = permeability for horizontal flow

k_s = permeability of the smeared zone

With no smear and isotropic conditions, the permeability is the same in all directions, Eq.(2) can be rewritten as:

$$U = 1 - \exp\left(- \frac{8\, c_v \cdot t}{D^2 \cdot f(n)}\right) \qquad (3)$$

where $f(n) = \frac{n^2 - 1}{n^2} \cdot \ln(n) - \frac{3}{4} + \frac{1}{4\, n^2}$

According to Richart (1957) Eq.(3) and Eq.(2) may give the same consolidation process, if in Eq.(3) instead of the drain diameter (d) a fictive effective drain diameter (d_e) is introduced. This effective drain diameter may also include effects of loss of permeability along a drain and, to some extent, horizontal drainage layers, and other factors which will have an influence on the consolidation process.

With $U = (\delta - \delta_o)/\delta_p$ Eqs (1) and (3) can be compared. The drainage factor (K) will in this case be

$$K = \frac{8\, c_v}{D^2 . f(n)} \qquad (4)$$

In Table III the estimated settlements and the estimated drainage factor from Eq.(4) have been compared with the fitted values from Eq.(1).

CONCLUSIONS

The drainage factor (K) is a direct measure of the time required to reach a certain degree of consolidation according to the expression:

$$t = - \frac{1}{K} \ln (1 - U) \qquad (5)$$

where t is time in days.

Eq.(5) and the values of the fitted drainage factors from Table III in combination with the different drain spacings indicate that the drainage effect of one lime columns is equivalent to that of two to three 10 cm wide drain strips (Geodrain), or three 15 cm diameter sand drains. The drainage effect of two lime columns was approximately equal to that of three 40 cm diameter sand drains.

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