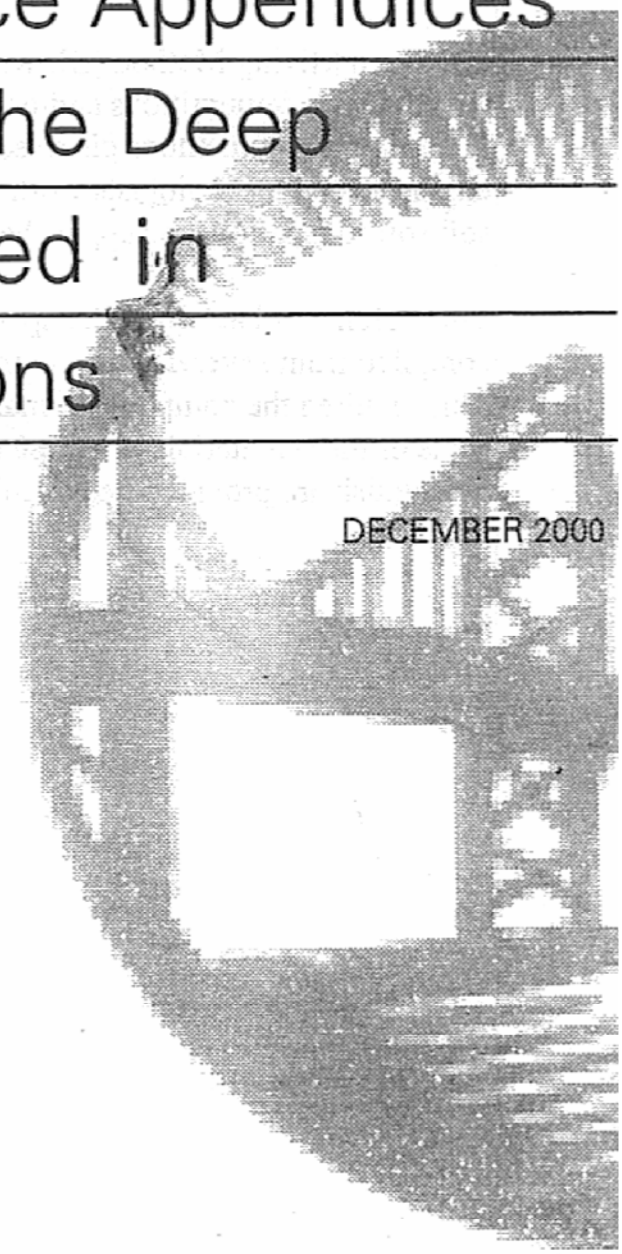
Supplemental Reference Appendices for An Introduction to the Deep Mixing Methods as Used in Geotechnical Applications



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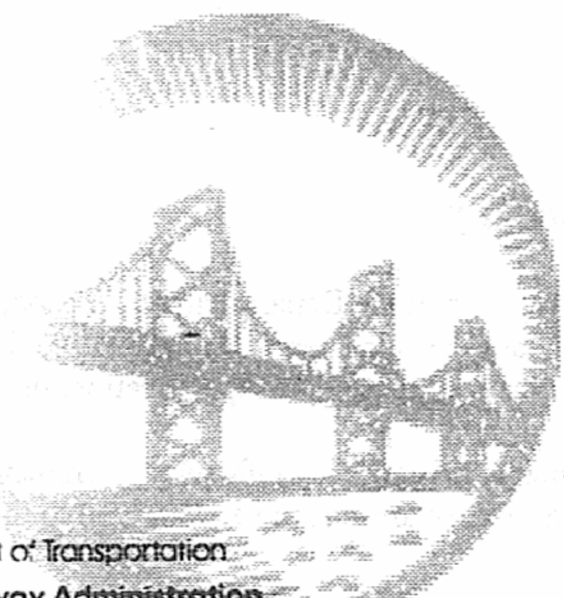

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Federal Highway Administration

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FOREWORD

The Deep Mixing Method (DMM) is an in situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. This report deals mainly with an expansion of the deep mixing methods discussed in Volume I of the series. The report should be of interest to engineers and technologists working in the fields of deep soil excavation and improvement of soft soil foundations to support heavy loads.

This volume of background, supporting information to FHWA report (FHWA-RD-99-138) was compiled from several sources. In many cases, original documents were no longer available. This required the compilers to make copies of copies, further reducing clarity and legibility of some of these materials. In these cases, the text and/or graphics that are difficult to read or distinguish are provided because they may still have marginal value to some readers.

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Director, Office of Infrastructure
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16. Abstract
The Deep Mixing Method (DMM) is an in situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. This report first traces the historical development of the various proprietary DMM methods and provides a structured summary of applications. It also compares the applicability of DMM with other competitive forms of ground treatment and improvement. The bulk of the report constitutes a description of the individual methods, focusing on the equipment, the procedures, and the properties of the treated soil. The report continues by describing the nature of the market in North America, Japan, and Scandinavia, while observations are also made on the various potential barriers to further growth in the United States. This report incorporates some factual data from an earlier Federal Highway Administration (FHWA) draft report (1996), but follows a different structure and philosophy.

This volume is the second in a series. The other volumes in the series are:

FHWA-RD-99-138 Volume I. An Introduction to the Deep Mixing Methods as Used in Geotechnical Applications
FHWA-RD-99-167 Volume III: The Verification and Properties of Treated Ground

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APPENDIX 1. DETAILS OF EACH DEEP MIXING METHOD

(Numbers in parentheses correspond to the method numbers in Table 3 and Figure 46 of Volume I)

DEEP SOIL MIXING – DSM (1)

1. INTRODUCTION

This system was developed by Geo-Con, Inc. while using SMW Seiko, Inc. equipment for the Jackson Lake Dam Project in 1987-1988 and the first application was in 1987 at Bay City, MI. It is therefore not surprising that it is a Wet Rotary Shaft (WRS) variant that uses from one to six augers (typically one or four) of an individual diameter of 0.6 to 1.0 m, (0.9 m is standard) to a maximum depth of 45 m (27 m is typical). The shafts are spaced so that their individual paddles overlap vertically and in plan, thus providing good panel (or column) continuity and efficient mixing. A wall of at least 0.61-m thickness is provided when 0.9-m-diameter augers are used, and each penetration by the four-auger arrangement provides a panel 2.74 m long.

2. GENERAL PROCESS

The shafts are rotated into the soil while grout, or other fluids, are injected. Air is not typically used to help "breakup" the soil, and neither is water favored. The Geo-Con principle is to get as much grout over the augers as possible, and this means significant grout injection during penetration and withdrawal. Adjacent shafts rotate in opposite directions and are spaced at 0.69-m centers. By combining auger flights and mixing blades along each shaft, the soil is lifted and blended with the grout as efficiently as possible while reducing torque requirements. Lateral continuity of the columns within and between each panel is also promoted by repenetration of the inside "primary panel" holes (Figures 1 through 3). Upon reaching target depth, further grout is injected, the shaft rotation direction is reversed, and the system is withdrawn. Usually the lowermost 3 m of each stroke is double-mixed to further promote homogeneity.

3. EQUIPMENT

<u>Base</u> Typically, a 135- to 160-tonne crawler crane is used, which carries a set of specially designed leads, which may also be"structurally integrated" into the crane body itself.

<u>Shafts</u> Between one and six shafts (four is the most common arrangement) are cable-suspended by a common beam (Figure 4), which also carries the individual hydraulic or rotary heads powered by a Caterpillar diesel engine. The heads have 67,000 N-m of torque and thus require a 450-kW power pack mounted on the rear of the crawler. Joint bands are used to separate and stabilize the shafts. These shafts are 250 to 300 mm in diameter, with a 50- to 75-mm center injection hole. At the end of each shaft is a single, steeply angled flight that makes one-half revolution in a distance roughly equal to the auger diameter.

Grout Plant — Comprises a lightning mixer (3.8-m^3 capacity), holding tank, and one positive displacement pump (e.g., Moyno L-10) for each shaft. Cement silos and screw feeds are also included.

Control — The rate of injection per shaft is computer-controlled, based on a selected target volume and shaft penetration rate (Figure 5).

Production — Instantaneous production rates are approximately 0.6 to 1.0 m/min during penetration and 2 m/min during withdrawal. These penetration rates depend on soil conditions (Figure 6). Walker (1994) reported industrial production rates (for treatment to 6.5 m depth) of up to 650 m^3/shift. Nicholson et al. (1997) report wall productions of 100 to 150 m^2/shift.

4. MIX CHARACTERISTICS

Grout. Varies between jobs depending on soil conditions and performance requirements. Generally, cement or cement-bentonite mixes are used, with substitutions or additives as appropriate. Cement factors range from 120 to 400 kg/m^3, with water/cement ratios of 1.2 to 1.75 (typically as high as 1.75 during penetration, but around 1.25 during withdrawal). Grout volume factors range from 15 to 40%. Bentonite concentrations vary from 0 to 5%, depending on permeability and strength requirements.

Treated Soil. Typical 28-day unconfined compressive strength ranges are:

Organics	0.4 – 1 MPa
Soft Clays	0.5 – 1.4 MPa
Med/Hard Clays	0.7 – 2.1 MPa
Silts	1.0 – 2.5 MPa
Silty Sands	2.1 – 3.5 MPa
Clean Sands	2.8 – 11.0 MPa

An additional 50% increase in compressive strength can be achieved at 56 days, with a slower increase to 160 days. Walker (1994) reported a 100% increase from 4 to 28 days.

Hydraulic conductivities of material treated with cement-bentonite grouts can be as low as 1 x 10^{-10}m/s, but typically they are in the range of 10^{-7} to 10^{-9} m/s. (The cost of achieving 10^{-10}m/s is about 1½ times that of obtaining 10^{-8} m/s.) E-values (modulus of elasticity) are assumed to be 500 to 1350 times unconfined compressive strength (UCS). Regarding spoils compaction, this may be a 60:40 soil to grout ratio (figures for 50% grout volume ratio). Spoils typically harden in 8 to 12 hours.

The results of a laboratory test using the Master Builders PT-1158 clay dispersant are shown on Table 1. It is highly significant that using the dispersant, twice the volume of clay could be treated with only 60% of the cement factor to provide twice the 28-day strength (Gause, 1998).

5. PATENTED/PROTECTED FEATURES

Geo-Con appears to have no patents on the equipment or the processes. However, there is a patent pending on the VERT™ Wall Concept – an application of the Deep Soil Mixing (DSM) and Shallow Soil Mixing (SSM) techniques.

6. PARTICULAR ADVANTAGES

DSM is a typical WRS technique that shares all the inherent advantages and disadvantages of that group of Deep Mixing Method (DMM) technologies. However, in relative terms, DSM provides good mixing efficiency and lateral continuity and exploits readily adjustable mix designs and injection rates. Pricing is very competitive, with typical costs (excluding any reinforcing steel) being as follows:

Method	Mobilization/ Demobilization ($k)	Installation	Grout Materials
DSM	150 to 175	$30 to 60/m^2$	$10 to 20/m^2$
SSM	50 to 150	$20 to 30/m^3$	$30 to 50/m^3$
Hydra-Mech℠	50 to 100	$15 to 40/m^3$	$30 to 60/m^3$
CF Jet Grouting	25 to 75	$100 to 200/m^3$	$140 to 200/m^3$

7. OPERATING COMPANY

Geo-Con is based in the United States, with offices in CA, FL, NJ, PA, and TX. Geo-Con operates within the United States, and has performed limited international work.

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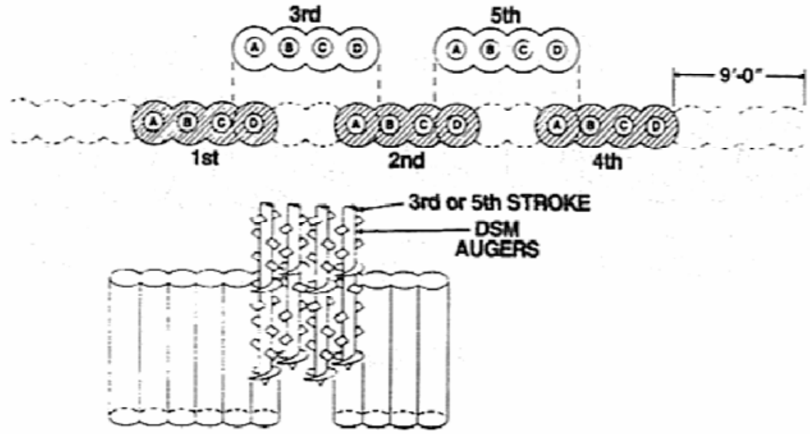

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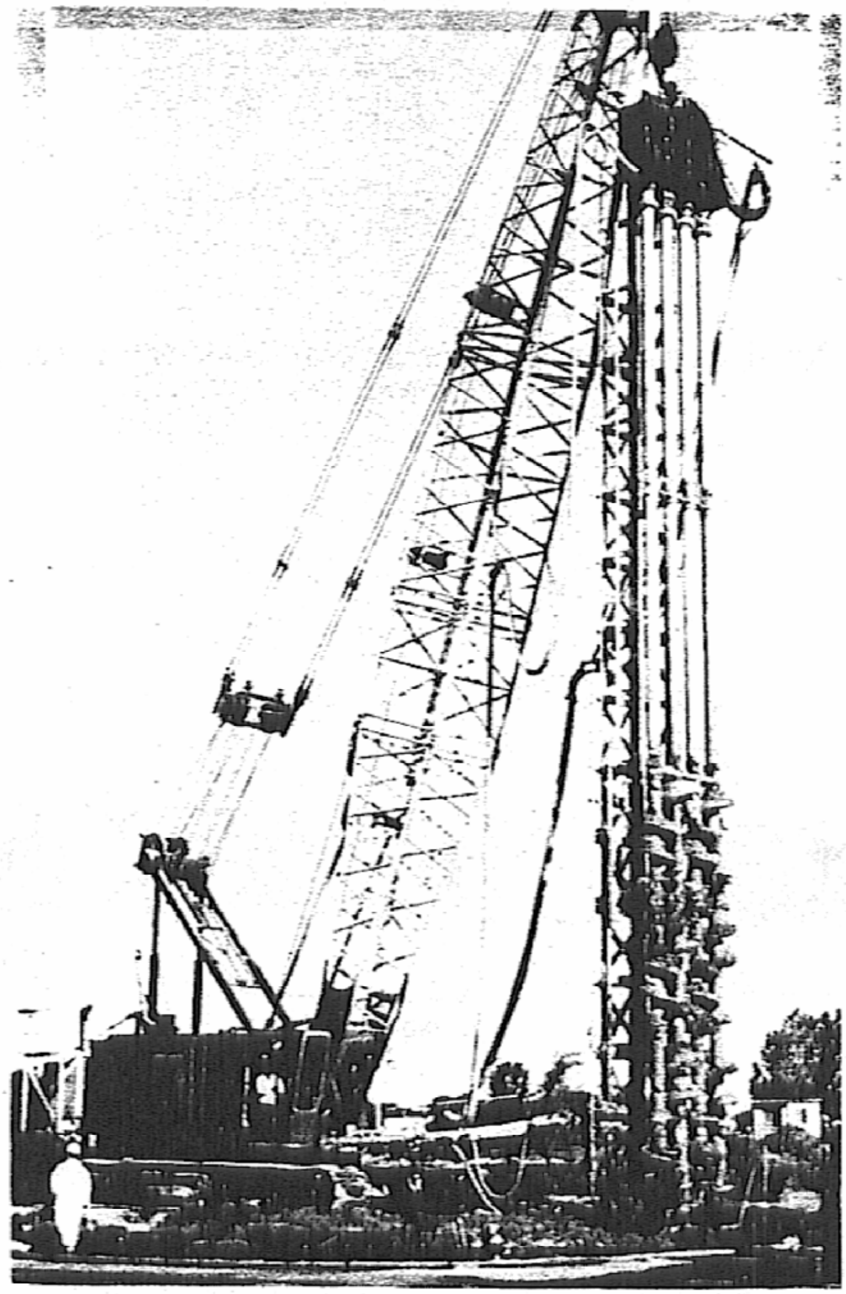

(b)

Figure 1. DSM geotechnical improvement processes: (a) column installation sequence and (b) DSM equipment (Geo-Con, Inc., 1998).

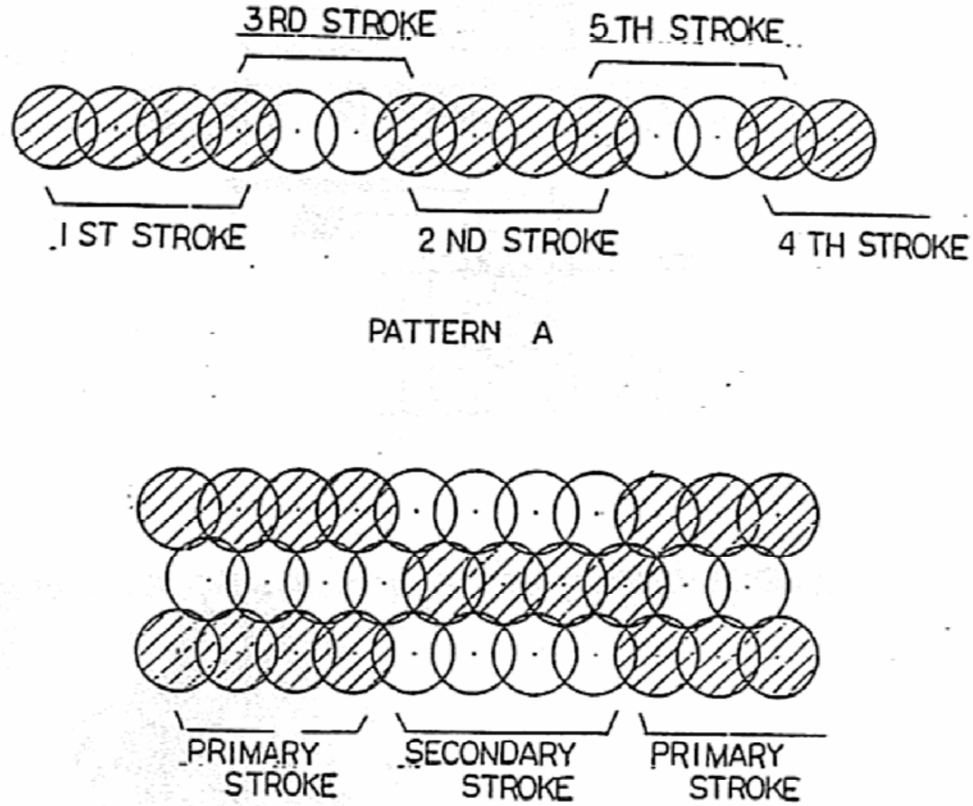

Figure 2. Multiple-shaft auger mixing patterns (Nicholson and Jasperse, 1998).

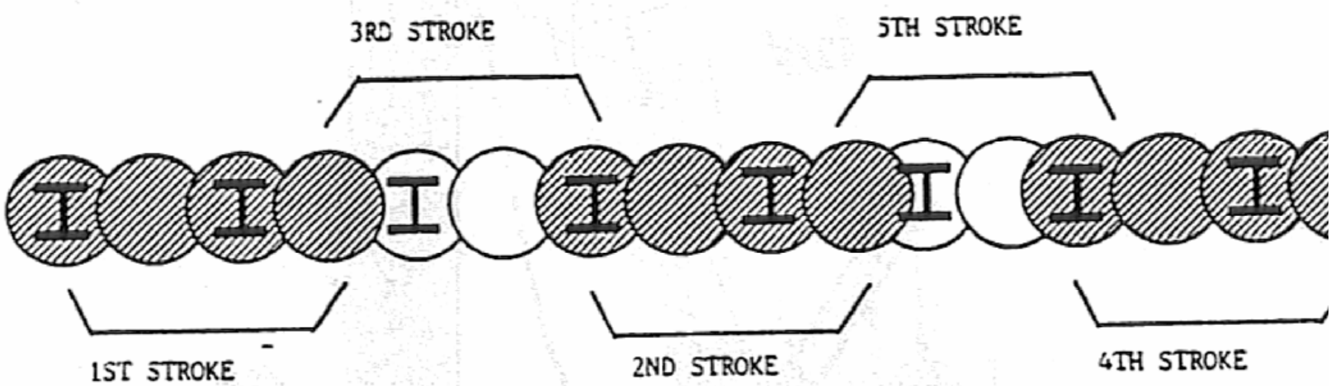

Figure 3. DSM with steel beams (Nicholson and Jasperse, 1998).

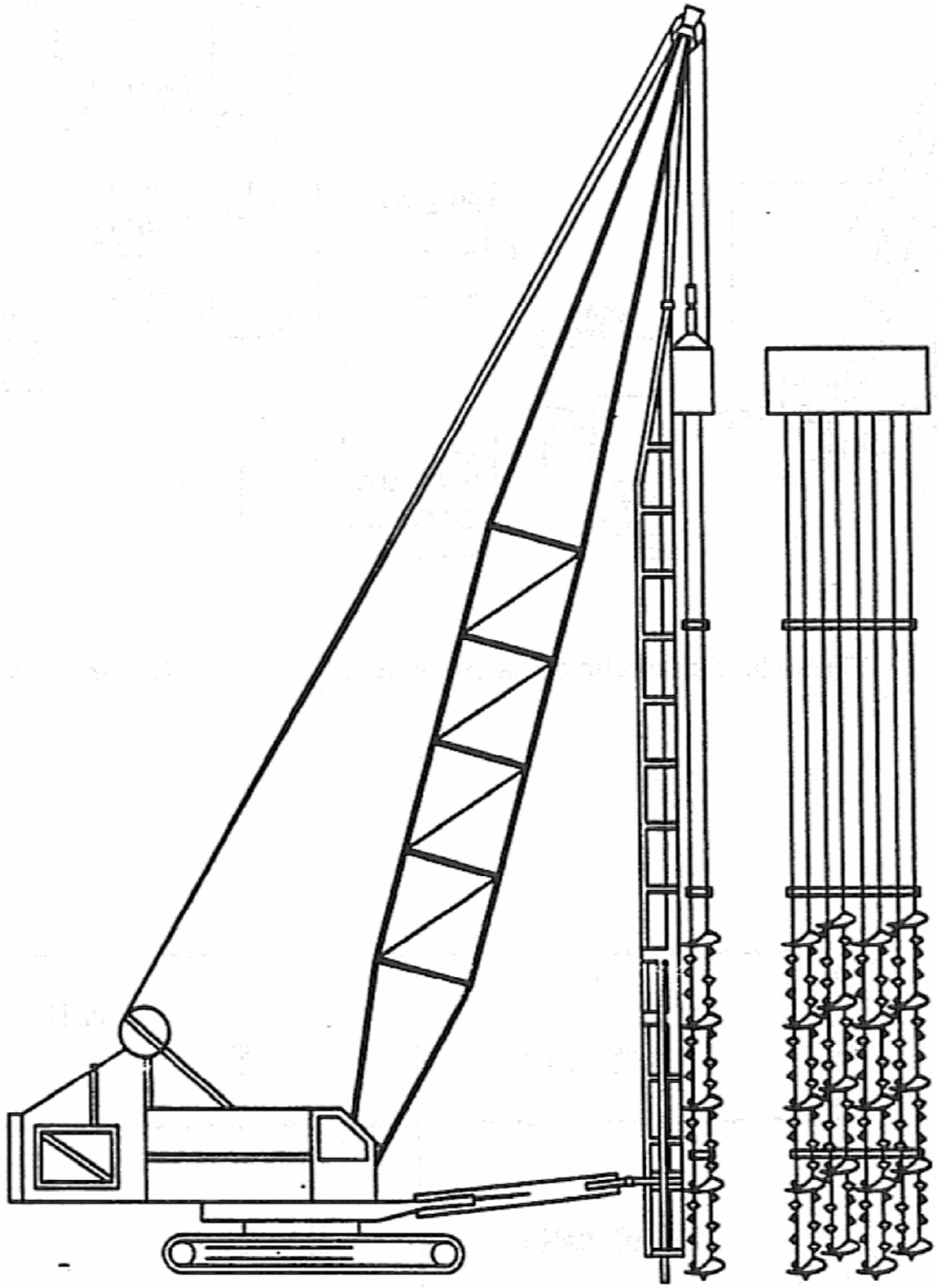

Figure 4. Schematic of shaft arrangement (Bahner and Naguib, 1998).

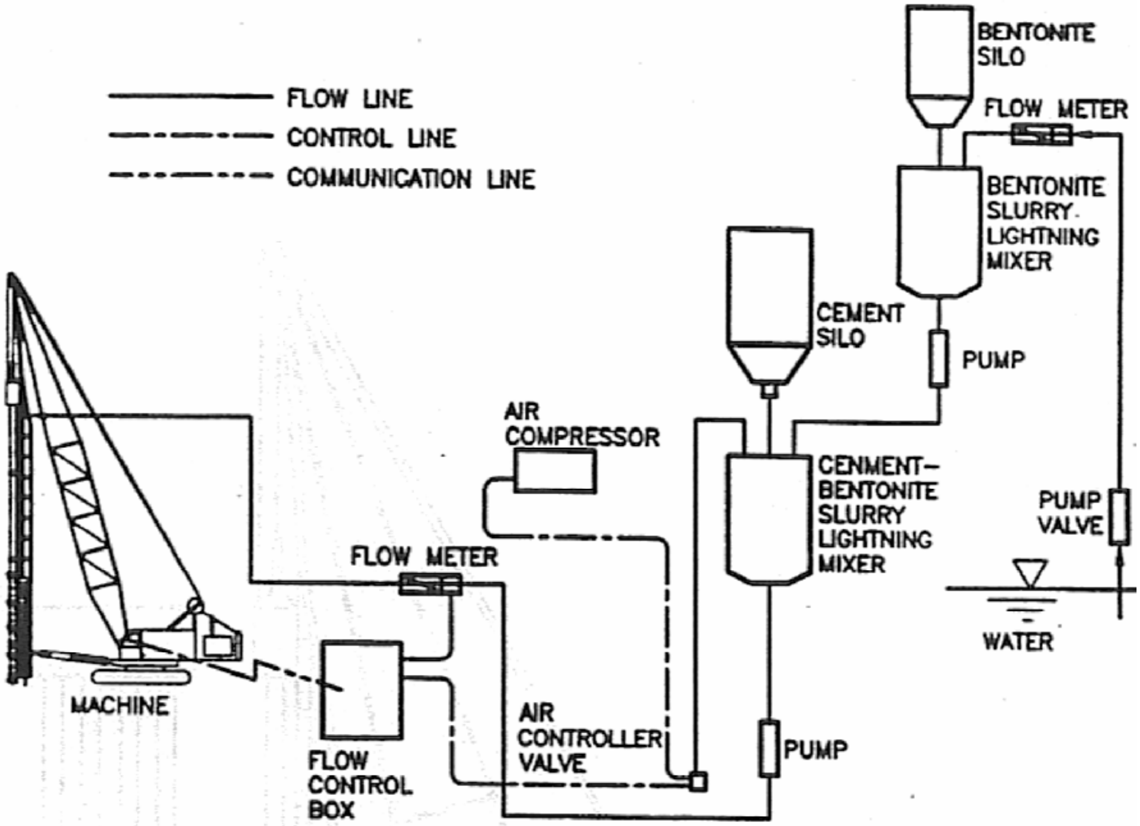

Figure 5. Schematic of batch plant (Bahner and Naguib, 1998).

	FT/MIN
LOOSE SAND	3 - 5
DENSE SAND	2 - 3
CLAY	2 - 3

1 ft = 0.305 m

Figure 6. Typical penetration rates for DSM (Jasperse, 1989).

Table 1. Laboratory test results on Master Builders, Inc.'s PT-1158 (Gause, 1998).

	Untreated	Treated
Boston Blue Clay, pcy (kg/m^3)	1220 (750)	2500 (1480)
Cement, pcy (kg/m^3)	630 (370)	360 (210)
Water, pcy (kg/m^3)	940 (560)	360 (210)
PT-1158 % by weight of soil	0	9.5%
Consistency	Fluid	Fluid
UCS, psi (MPa)	180 (2.2)	350 (2.4)

SOIL MIXED WALL (SMW, RSW, and Others) (2)

1. INTRODUCTION

This method is classified as WRS and is conducted by a number of Japanese contractors belonging to the Soil Mixed Wall (SMW) Association. The method began development by Seiko Kogyo, Inc. in 1972, evolving from the now-defunct single-auger Mix in Place (MIP) technique, which they licensed from Intrusion Prepakt (Cleveland, OH) for work in Japan. The first commercial application was in Japan in 1976. The concept is to use multiple augers to create vertical continuous membranes of treated soil for hydraulic cut-off and/or support of excavation. This was the first "contemporary" DMM system to be used in the United States (1986), and it spawned several similar techniques (e.g., DSM, Raito Soil-Cement Wall (Attachment 1) in both the United States and Japan).

2. GENERAL PROCESS

The details of installation vary from company to company and between and within individual projects. For example, water alone or bentonite slurry may be used during penetration, with the grout only being injected during withdrawal. Alternatively, water or a very high water content grout may be injected through the outer augers and compressed air injected through the central augers during penetration to help break up and loosen the soil. In order to improve the quality of mixing, especially in stiff cohesive soils, the augers are "oscillated" over the lower one-third of the panel depth while grout is being injected. The method does employ a large amount of fluid injection, and thus generates a correspondingly large amount of spoils. Generically, more efficient mixing occurs when grout is injected during penetration.

Walls are formed in the fashion shown in Figure 7, with the inside holes of each group of three being repenetrated and remixed to promote material mixing and lateral continuity. The system employs from two to five augers (up to six in Japan), although three are standard. Individual augers are 550 to 1500 mm in diameter, although a typical size is 850 to 900 mm (Figure 8). Inter-axis spacing is typically 460 to 600 mm. A maximum depth of treatment of 60 m is claimed, although few applications exceed 30 m.

Rotation rates are 15 to 20 rpm during penetration (slightly higher during withdrawal), somewhat lower than that of other DMM methods. Rotation direction alternates for adjacent augers, which overlap in plan (Figures 8 and 9) – both features promoting better mixing.

According to the opinion of Taki (1997), the SMW method is not regarded as a true DMM technique in Japan, inferring that it is more of a soil removal and grout replacement method. He also notes, correctly, that no papers were presented on this method at the 1996 Tokyo Conference on Deep Mixing.

3. EQUIPMENT (Figures 7, 8, and 9, and Attachment 1)

Base — Comprises a custom-built crawler crane with fixed vertical leads. The leads are supported at three points to maintain rigidity for alignment purposes. The base itself may weigh up to 275 tonnes. Verticality of the leads (displayed in real time in the control cabin) can be nominally accurate to within 1 in 500, and column verticality is usually reliable to 1 in 100, especially at shallower depths. The base also carries the generator for the electric drive head.

Shafts — The multiple shafts are mounted on the leads and are powered by one high-torque motor and gear box system, which travels up and down the leads. This head is one of the key technical features of the system, and the gear box has the capacity to redistribute torque to the shaft(s) requiring the most energy at any given time. Two bands are used to separate and stabilize the shafts. The various overlapping segments of discontinuous flight augers and mixing paddles are positioned along each shaft in order to reduce the torque demand that otherwise results from a continuous-auger system. These auger segments are designed to provide a degree of vertical movement of the soil while minimizing direct removal to the surface. Flights and paddles at different elevations in each shaft promote mixing efficiency. The design of the auger flights and paddles varies with soil type, with three basic variants existing (for cohesives, sands, and gravels).

For the current Fort Point Channel Project in Boston, MA, a special machine has been devised (M250), using a 350-tonne Manitowoc crawler crane and three shafts with 1500-mm-diameter paddles. Each stroke treats an area approximately 1500 mm wide x 3700 mm long to a maximum target depth of 36 m. In a series of attempts to improve productivity and enhance mixing quality (in the clay), no fewer than 22 different stroke sequences (including complete repenetration) have been used Due to the large diameter and depth, and the stiff nature of the soil, it has been necessary to reduce torque demands by removing the discontinuous flight auger sections, leaving just six paddles spaced about 400 to 500 mm apart vertically in the lower part of each shaft. This makes this particular modified method somewhat of a hybrid between WRS and Wet Rotary End (WRE).

Grout Plant — Consists of a computer-controlled module containing mixer, holding tanks, positive displacement pumps, and batching scale. It is capable of accomodating multiple components delivered in bulk. The pumps deliver grout to each shaft individually to enhance accurate control of the slurry flow.

Control — The automatic batching system measures water and cement (and other materials) by weight. These parameters are preset.

Production — Production is dependent on the site conditions, depth treated, and local labor capabilities. Reported production rates vary from 100 to 200 m^3 of treated soil per day. For wall construction, this amounts to approximately 50 to 200 m^2 of wall per 8-hour shift.

Instantaneous production rates are shown below. For scheduling purposes, 10 minutes set-up time would be added to the calculated time for column mixing.

Penetration Rate – between 0.5 and 1.5 m per minute
Withdrawal Rate – generally 1.5 to 2 m per minute

4. MIX CHARACTERISTICS

Grout. The mix design is customized based on job requirements and soil conditions. Generally, cement-bentonite, bentonite-cement-flyash (75:25), or clay slurries are used with typical mixes containing up to 5% bentonite by weight of cement, and typical water/cement ratios of 1.5 (sandy) to 2.5 (cohesives). At Fort Point Channel, Boston, 25% replacement of cement by pfa is used to reduce cost, although pfa is not used for the water-based work for environmental reasons. In addition, additives may be used to control bleed, make the mix more workable, and so on. The amount pumped is a function of soil type and the strength requirements of the wall. Cement factors ranging from 250 to 750 kg of cement have been used per cubic meter of soil, although 250 to 350 kg/m^3 is a typical range.

Data from case histories include:

- Lake Cushman Dam, WA. Cut-off wall for dam. The first 20 m consisted of glacial outwash. The lower 17 m was glacial till. The cement factor was 220 kg/m^3, and the mix comprised 7% bentonite (BWOC) and a water/cement ratio = 1.3. Soilcrete strengths of up to 1.28 MPa were obtained.

- Central Artery Project, CO7A1, Boston, MA. SMW used for excavation support. Constructed in fill, marine, glaciomarine and glaciolacustrine deposits. The fill consisted of random fill from cohesive to granular material with urban debris such as wood and concrete. Marine deposit is known locally as "Boston Blue Clay," which included lenses of sand and silt. The glaciomarine consisted of silt, clay, gravel, and cobbles and was broken into an upper and lower unit. Several mixes were designed for the project. The cement factor ranged from 200 to 450 kg/m^3 of treated ground. Figure 10 shows the cement dosage along the alignment as well as the strength of various sections along the alignment. The water/cement ratio varied, but in general was 1.25, but as low as 1.0. The required strength for the project was 0.62 MPa.

- EBMUD Wet Weather Storage Basin. The ground treated consisted of Bay Mud, a plastic, fat clay. The grout mix used (per m^3 of treated soil) contained 286 kg cement, 5.2 kg bentonite, and 750 kg water. The target strength was 0.48 MPa. Actual strengths ranged from 0.48 to 1.03 MPa. Graphs of strength versus depth and permeability versus depth are shown in Figure 11.

- Ikoma Tunnel Project. The ground treated consisted of sand and gravel with a 3-m layer of 60- to 100-cm-diameter boulders. The mix used (per m^3 of treated soil) contained 450 kg cement, 20 kg bentonite, and 670 kg of water. Strengths of this soil-cement mix averaged 2.45 MPa.

Treated Soil. Saito et al. (1980) report that the relationship between unconfined compressive strength (UCS) and shear strength (direct shear) is

$$\tau_o = 0.53 + 0.37q_u - 0.0014\, q_u^2 \ (q_u \leq 6 \text{ MPa})$$

where, τ_o = 28-day shear strength (direct shear, no normal stress); and
q_u = 28-day UCS (kg/cm^2).

The q_u to τ_o ratio is about 2 when q_u is < 1 MPa and reduces gradually as q_u increases. Tensile strengths measured by splitting tests were lower than for direct uniaxial tests: for UCS less than 6 MPa, the splitting tensile strength (lab) = 8 to 14% UCS. Field data show similar results (CDM Association, 1994).

Figures 12a and 12b show typical relationships between cement factor and unconfined compressive strength. In general, for wet sampled material, for silt and clay, the strength ranges from roughly 0.34 MPa to 1.24 MPa, although the expectations in the Fort Point Channel Project are in excess of 2.2 MPa for treatment in clay (minimum density = 1.9 tonnes/m^3). For gravels, the strength ranges between 1.38 MPa and 4.13 MPa, and for sand, the strength ranges from 1.24 MPa to 4.13 MPa. These values are for wet sampled material. Core samples (Figure 12b) interestingly show a twofold increase in strength over wet sampled material. Although strength is related to cement content, the increase in cohesive soils is less than in cohesionless soils.

Hydraulic conductivity of soil-cement/bentonite mixes varies from 1×10^{-7} m/s to as low as 1×10^{-10} m/s in exceptional conditions. The lower hydraulic conductivity mixes are generally bentonite or clay soil mixed without cement. Average hydraulic conductivities for cement soil mixes are on the order of 1×10^{-8} to 1×10^{-9} m/s.

Figure 13 shows unconfined compressive strength and modulus of elasticity values for various soil-cement mixes. The graph shows generally that the modulus of elasticity (E) of the soil-cement mix generally ranges from 350 to 1350 times the unconfined compressive strength of the soil-cement mix, although later work (below) has indicated a lower ratio range. For cohesives with less than 10 to 15% sand, the E_{50} to q_u ratio is 400 to 600. Poisson's ratio is about 0.5 (undrained), and 0.3 to 0.45 under other conditions (CDM Association, 1994).

The amount of slurry pumped into the ground is a function of ground type and soil-cement strength requirements. The volume of slurry injected (with respect to the volume of native soil) ranges from 50% in sand to more than 100% in very stiff soils. These volumes are also indicative of the spoil volumes generated by this method (50 to 70%). The spoil is easily disposed of if it is left to set for a day or longer. The mixed soil is intended to be relatively homogeneous for design purposes, although lumps of unmixed clay are common, especially in stiff soils. There may be 30 to 50% cement loss in spoil (sand and clay).

A report by O'Rourke et al. (1997) further summarizes data recorded from the CO7A1 Project in Boston. Major findings include:

- The results of UCS testing as obtained from 75- and 150-mm-diameter field samples were very similar (average 3.83 MPa at 56 days; variability obscures strength gain with time).

- Apparent Cement Factor (ACF) was defined as $= \frac{\text{total weight of cement used}}{\text{volume of soil mixed}}$

  Then for ACF = 2.5 to 3.5 kN/m^3, UCS varies from 2 to 9 MPa (but with no strong correlation).

- The average total unit weight of 14.7 ±1.3 kN/m^3 was about 20% less than the total weight of the virgin marine clay (Figures 14 and 15 show limited correlation to strength).

- Laboratory tests were conducted on the relationship between strength and water content (strongly dependent).

  For CF = 2 to 2.5 kN/m^3 (w/c = 1.5); UCS = 1 to 2.2 MPa
  For CF = 3 to 4 kN/m^3 (w/c = 0.8 to 1.0); UCS = 1.5 to 3.3 MPa
  (Figures 16, 17, and 18; and Table 2)

  Such data were much less variable than field data due to variability in field mixes; variability in field preparation, curing, and handling; and combination of mix and field sample control.

- Lab tests showed secant modulus at 0.5 q_u is equal to 50 to 150 times q_u (Figure 19). Takenaka (1995) suggests E = 350 to 1,000 q_u (Figure 20), although the accuracy of these data has been subject to considerable debate. Values range typically from 60 to 120 MPa.

- Drained triaxial compression tests (Takenaka, 1995) suggest that the Poisson's ratio is 0.05 to 0.15 (axial strain < 5%).

- Takenaka (1995) also found from direct tension tests that tensile strength = 10 to 20% UCS.

5. PATENTED/PROTECTED FEATURES

Seiko is quoted as saying there are no patents on their system. However, it may be that certain of the mechanical elements (e.g., head design) are protected.

6. PARTICULAR ADVANTAGES

The SMW system can produce vertical continuous membranes when installed correctly in appropriate ground conditions. Industrial production can be high, and noise and vibration levels are low. However, the method does generate significant spoil volumes that may not be homogeneous and may take a long time (or added cement) to set. Also, due to auger configuration and rpm, in situ mixing quality may be poor in certain soils.

7. OPERATING COMPANIES

SMW Seiko, Inc. has offices in Hayward, CA and Boston, MA and is a subsidiary of Seiko Kogyo of Japan. Most, if not all, of the work east of the Mississippi is conducted in a joint venture with Nicholson Construction Co. (Bridgeville, PA), while Kajima (a major Japanese contractor with a U.S. base) frequently provides financial/bonding assistance.

It is understood that there is an SMW Association in Japan. The technique is popular in Japan, the United States and in various Southeast Asian countries.

A very similar-looking method (RSW: Raito Soil-Cement Wall) is offered by Raito, Inc. of Burlingame, CA, a subsidiary of its Japanese parent. No details are available, but the promotional photograph (Attachment 1) shows a triple-auger system without mixing paddles.

8. REFERENCES

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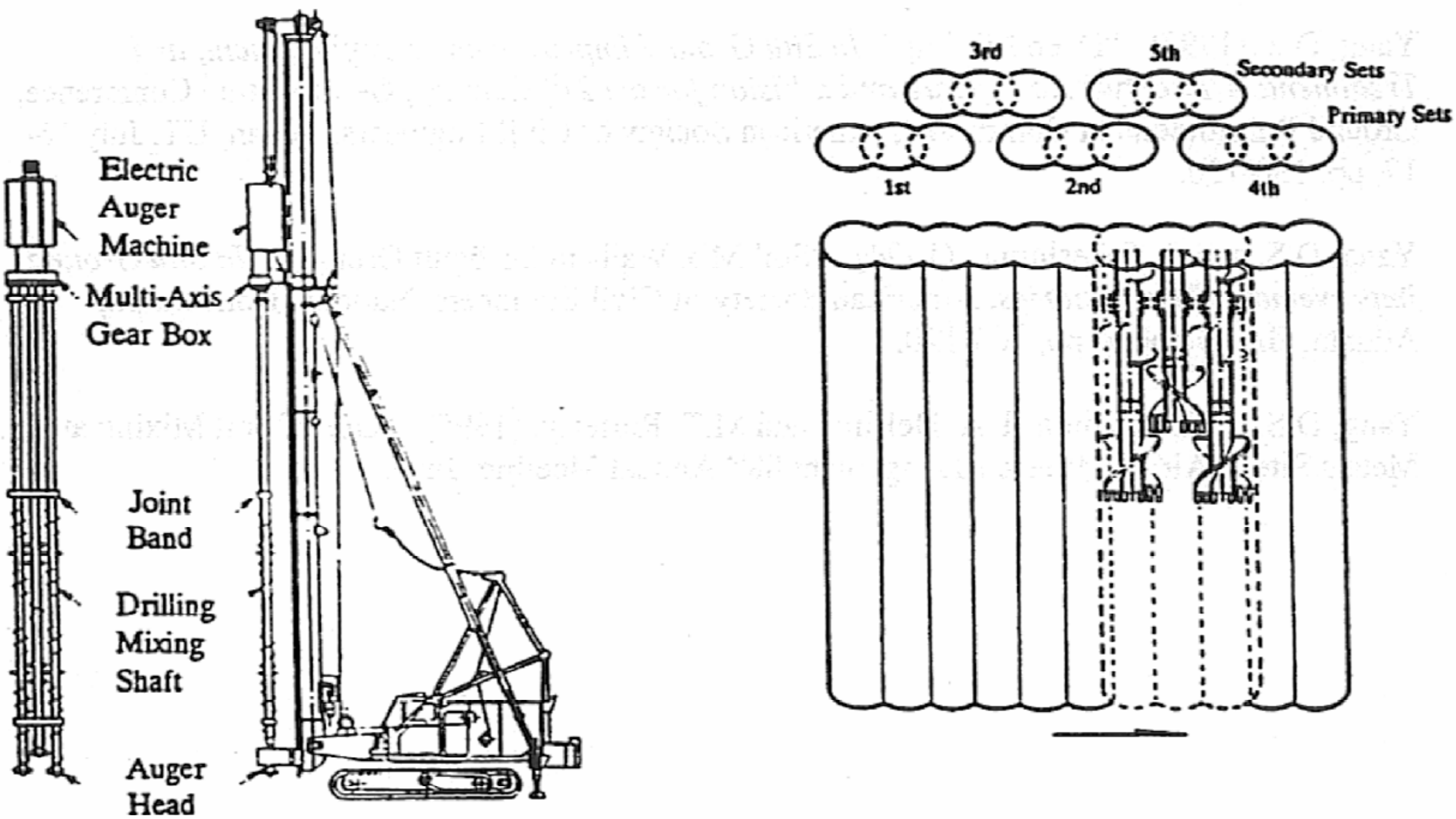
Yang, D.S. and S. Takeshima. (1994). "Soil Mix Walls in Difficult Ground." *In Situ Ground Improvement Case Histories*, American Society of Civil Engineers, National Convention, Atlanta, GA, October, pp, 106-120.

Yang, D.S., S. Takeshima, T.A. Delfino, and M.T. Rafferty. (1995). "Use of Soil Mixing at a Metals Site." Air and Waste Management 88th Annual Meeting, June.

CF		w/c	q_u	
(kN/m^3)	(pcy)		(kN/m^2)	(psi)
1.0	172	1.25	500 - 1200	75 - 175
2.0	344	1.25	1000 - 1900	145 - 275
2.5	430	1.25	1250 - 2250	180 - 325
3.0	515	0.80 - 1.00	1500 - 2600	215 - 375
4.0	687	0.80 - 1.00	2000 - 3300	290 - 475

Table 2. Estimated unconfined compressive strengths for cured moisture contents of approximately 40% (O'Rourke et al., 1997).



Soil-cement Mixed wall Machine

Soil-cement Mixed Wall Installation Procedure

Figure 7. General diagram of the base machine, leads, gearbox, and augers for SMW (Taki and Yang, 1991).

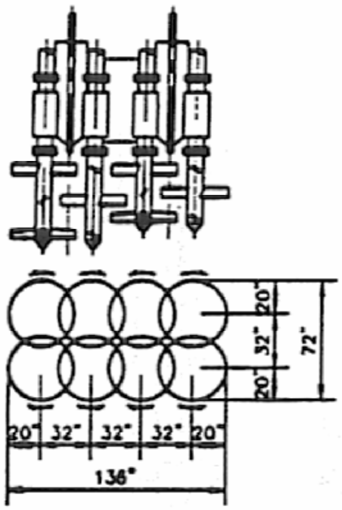
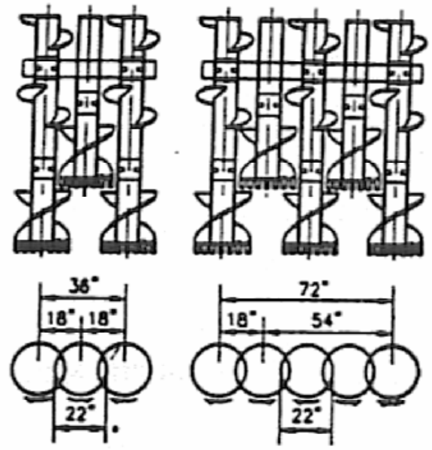
Title	**CDM** **Cement Deep Mixing**	**SMW** **Soil Mix Wall**
Sketches of Representative Mixing Mechanism	 ø = 39" to 63" available 1 ft = 0.305 m	 ø = 22" to 40" available 1 ft = 0.305 m
Descriptions	Rotation of multiple axis shafts create relative movement and shear in soil for soil-reagent mixing.	Uses multiple auger, paddle shafts rotating in alternating directions to mix in situ soil with cement grout or other reagents to form continuous soil-cement walls.
Number of Mixing Shafts	2, 4, 6, 8 shafts	1, 2, 3, and 5 shafts
Major Reagents	Cement or lime slurry	Cement-bentonite slurry, bentonite slurry, clay slurry, or other stabilizing reagent slurries.
Applicable Surface Soils	Very soft silt and clay or very loose sandy soils usually undersea	Soft to hard silt and clay, loose to very dense sand, gravel, and cobble soils. Cobble and boulder soil and bedrock with predrilling.
Major Applications	Large scale soil stabilization of sea floor for offshore or waterfront development.	Continuous walls for excavation support and groundwater control; Column blocks, lattice, or areal patterns for stabilization.
Remarks	Developed by Port and Harbor Research Institute	Developed by Seiko Kogyo, Co. Ltd.

Figure 8. General arrangement of three- and five-auger SMW systems in comparison to CDM mixing tools (after Taki and Yang, 1991).

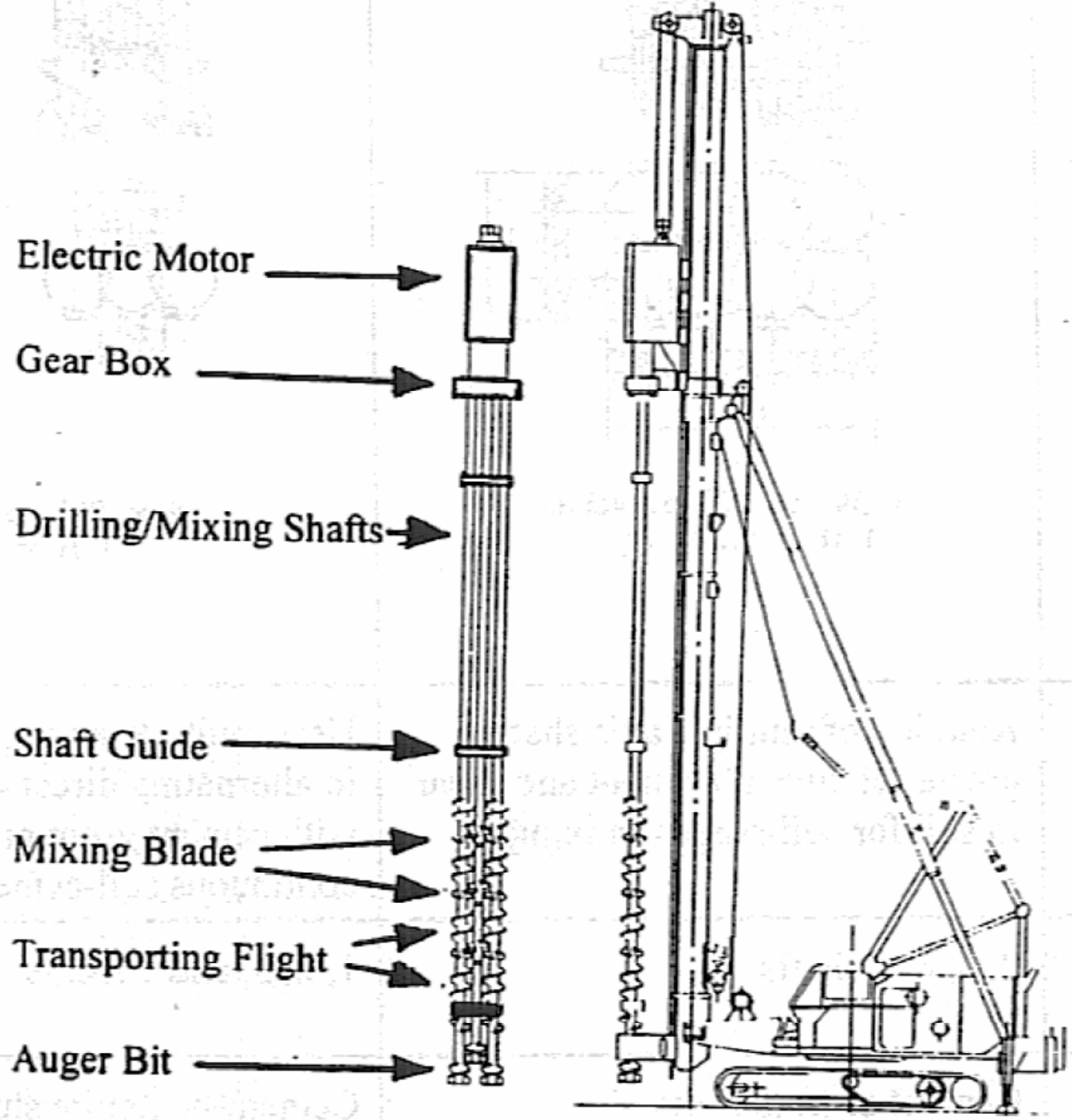


Figure 9. Illustrating overlap of augers and mixing paddles (Taki and Bell, 1997).

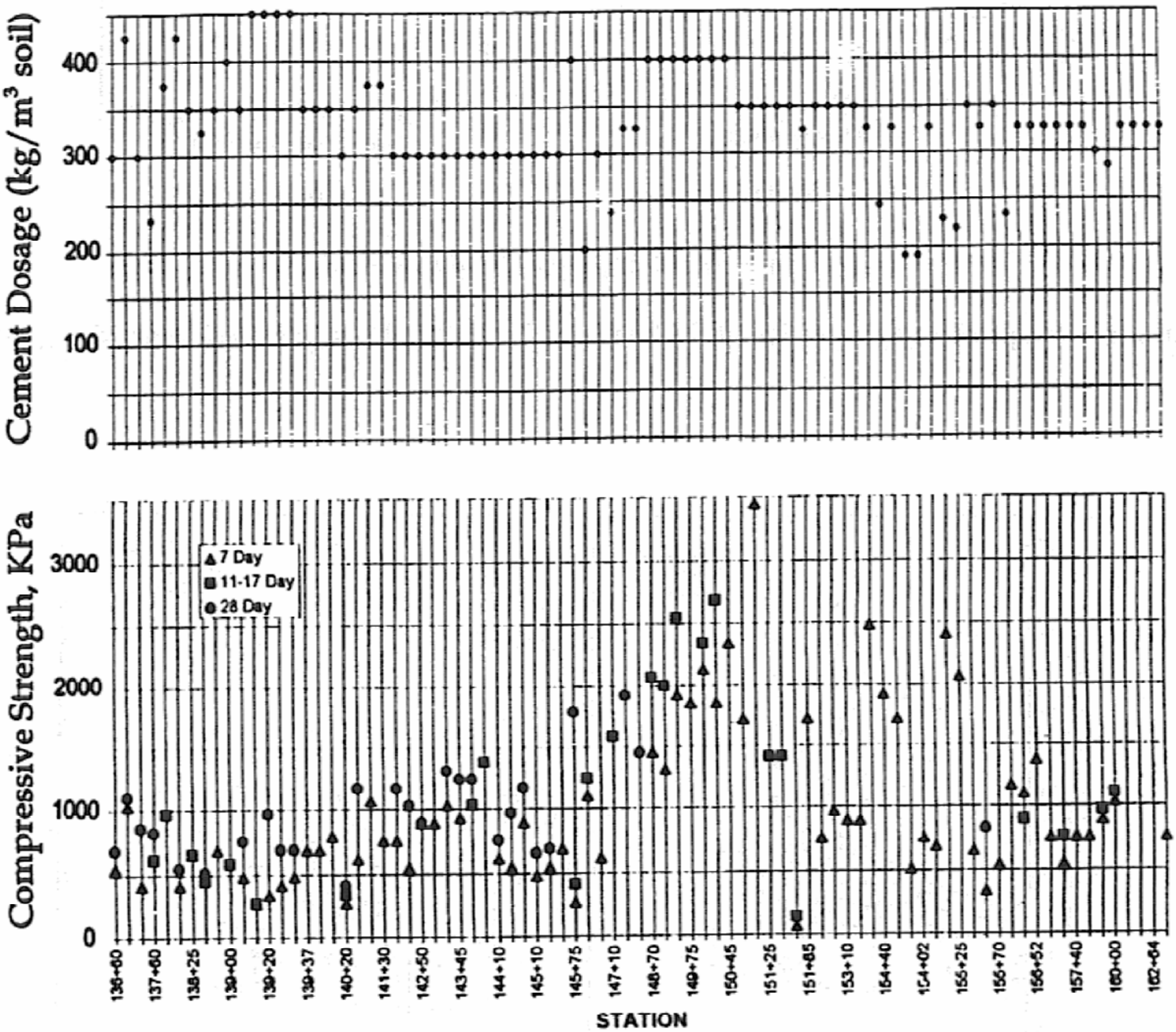
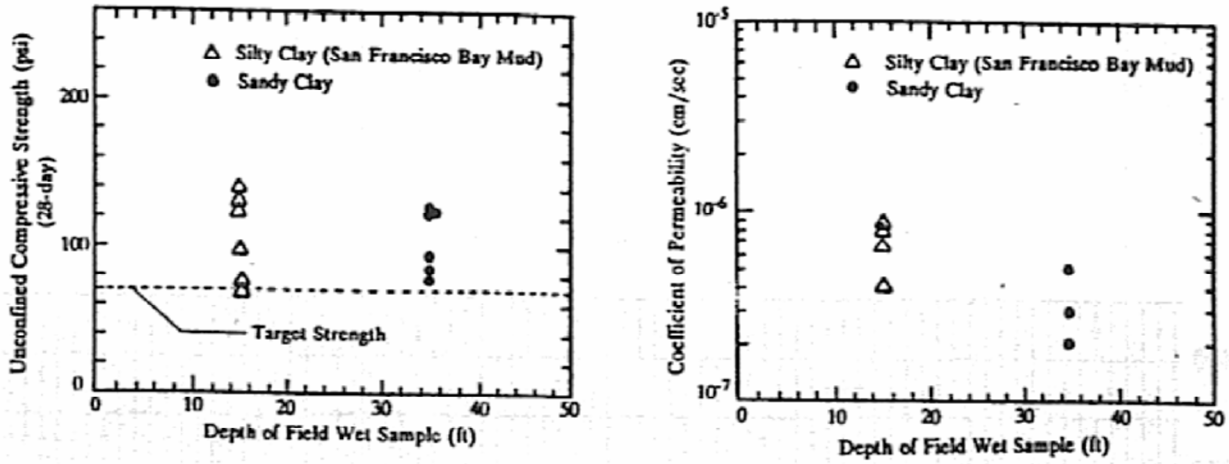


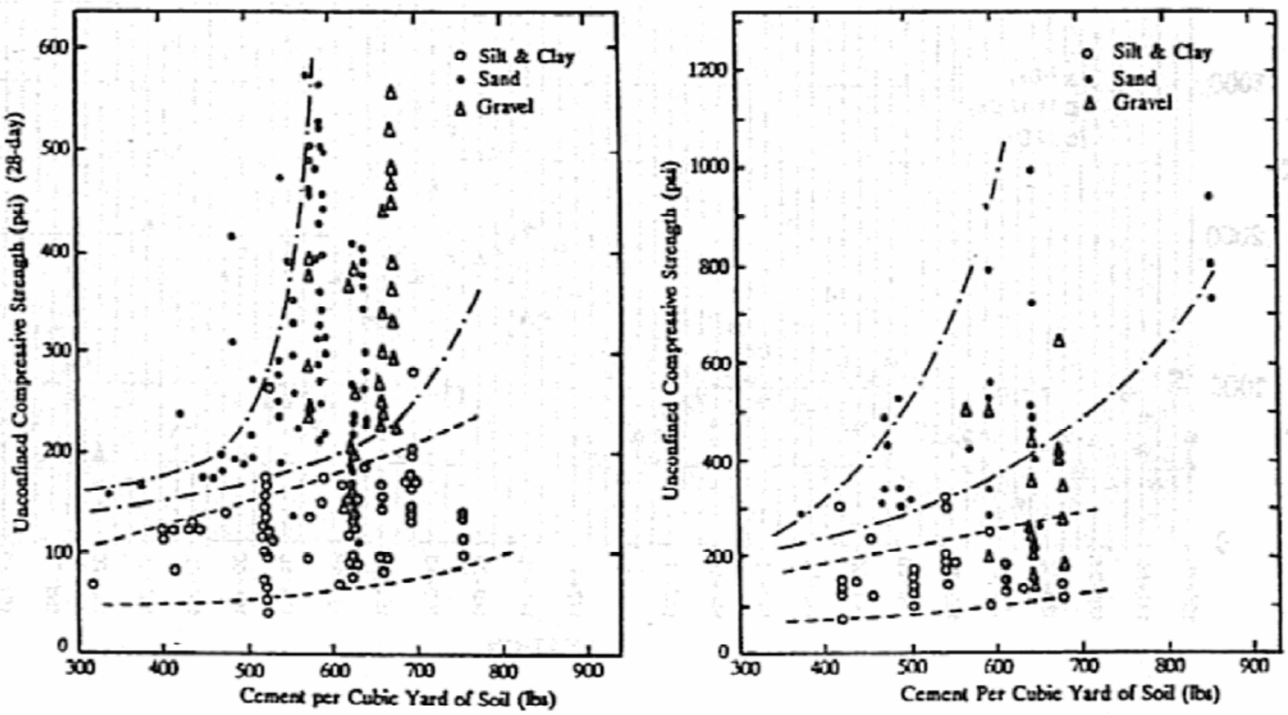
Figure 10. Cement dosage and strength of various sections along the alignment of the SMW on the Central Artery Project (Yang and Takeshima, 1994).



a. **Strength** b. **Permeability**

1 ft = 0.305 m, 1 psi = 6.895 kN/m^2

Figure 11. Engineering properties of Soil-cement for EBMUD Project (Taki and Yang, 1991).



a. **Field Wet Samples** b. **Core Samples**

1 pcy = 0.00582 kN/m^3, 1 psi = 6.895 kN/m^2

Note: Taki (1997) notes that the above data feature cement-bentonite (5%) grouts. Other DMM types, especially those with single shaft, may produce strengths 2 to 3 times higher.

Figure 12. Strength of soil-cement in SMW (Taki and Yang, 1991).

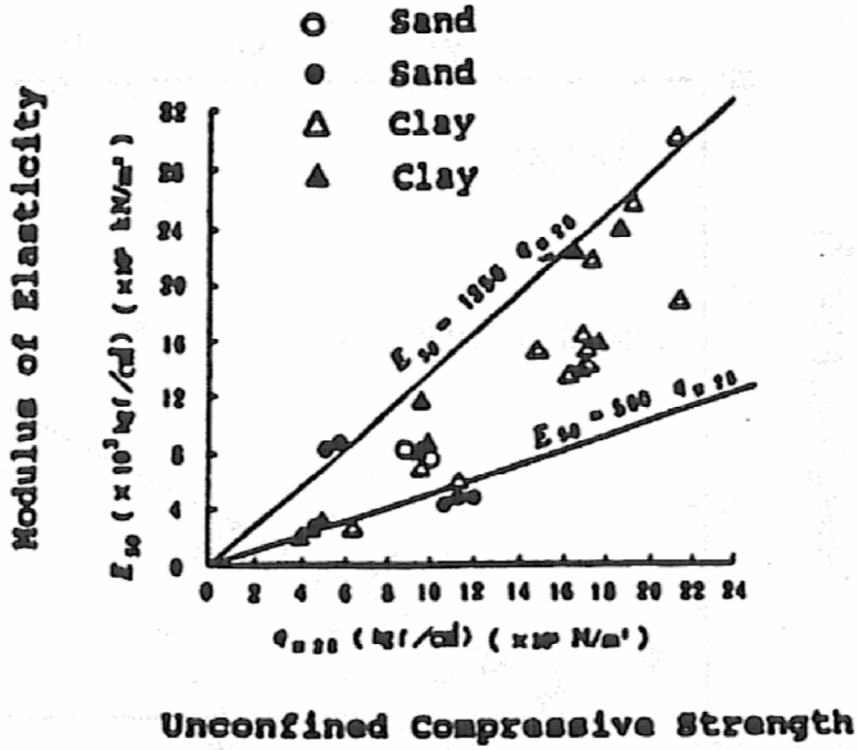


Figure 13. Relationship between modulus of elasticity and unconfined compressive strength in SMW (Taki and Yang, 1991).

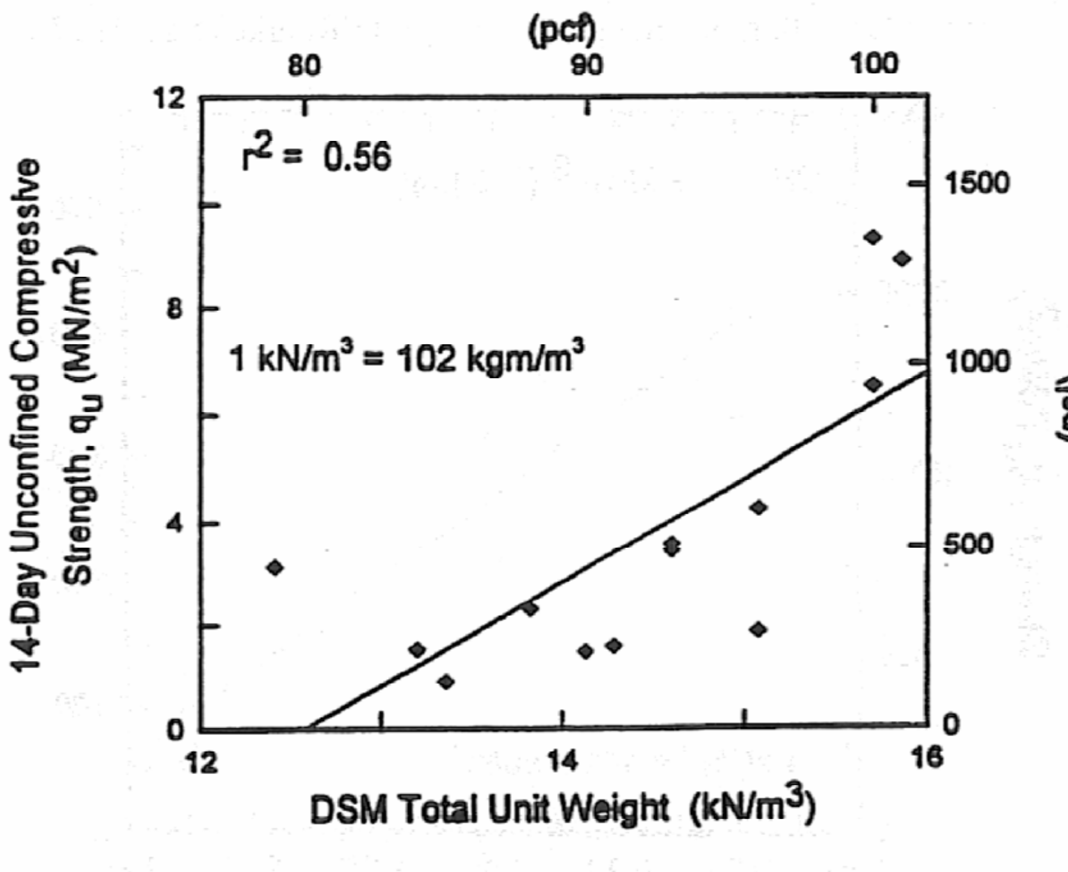


Figure 14. Unconfined compressive strength as a function of total unit weight for data involving different installation procedures (w/c = 1.0 to 1.25) (O'Rourke et al., 1997).

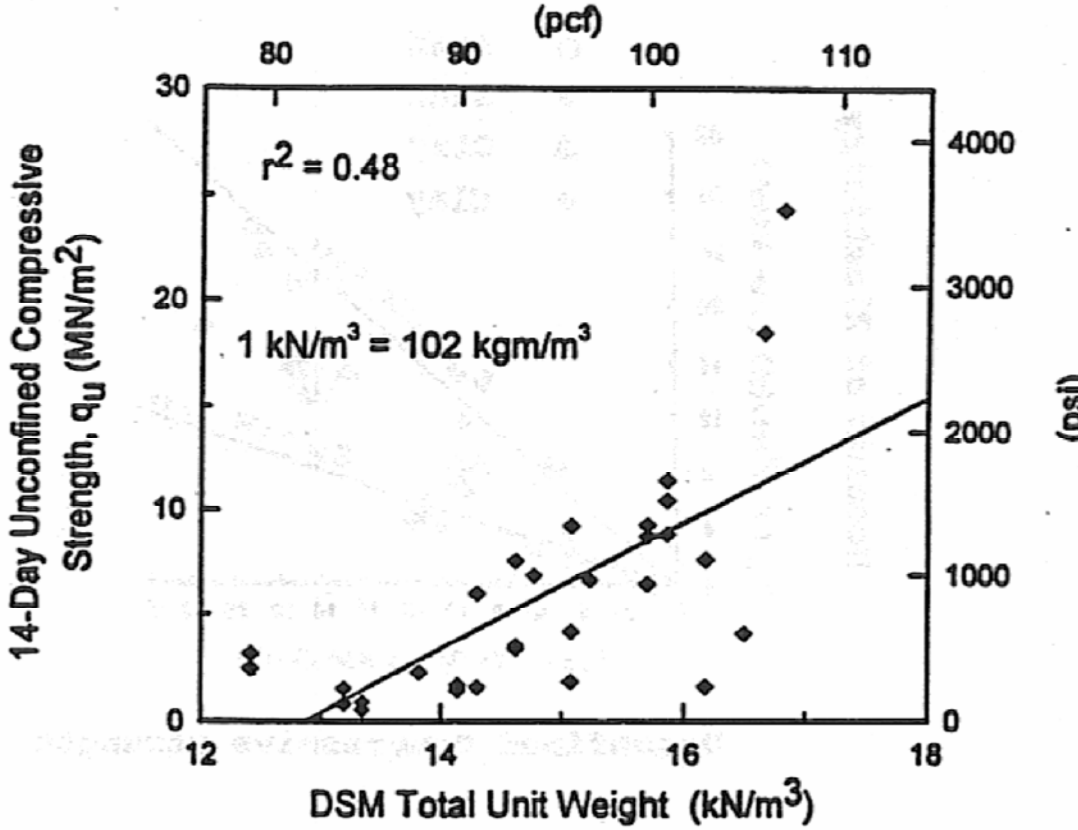


Figure 15. Unconfined compressive strength as a function of total unit weight for screened data set (w/c = 1.0: grout on upstroke only) (O'Rourke et al., 1997).

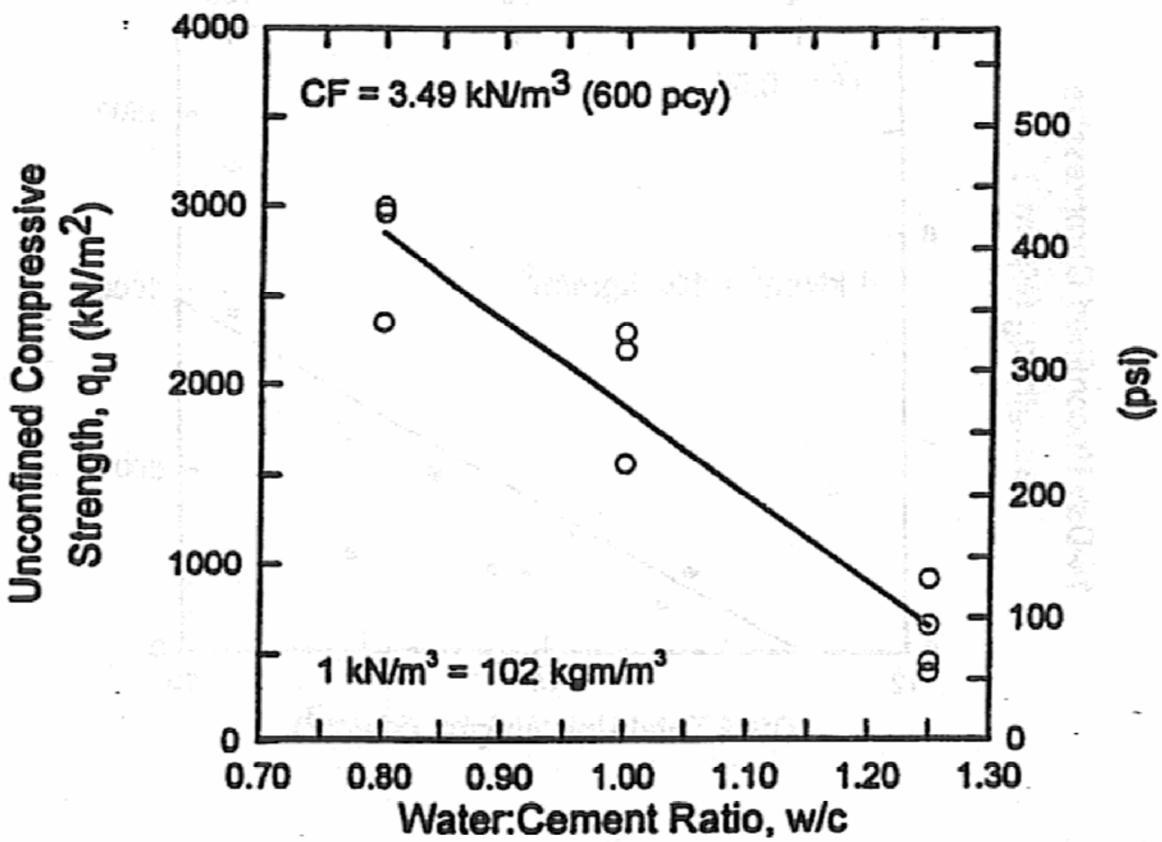


Figure 16. Unconfined compressive strength versus water:cement ratio for CF = 3.49 kN/m³ (O'Rourke et al., 1997).

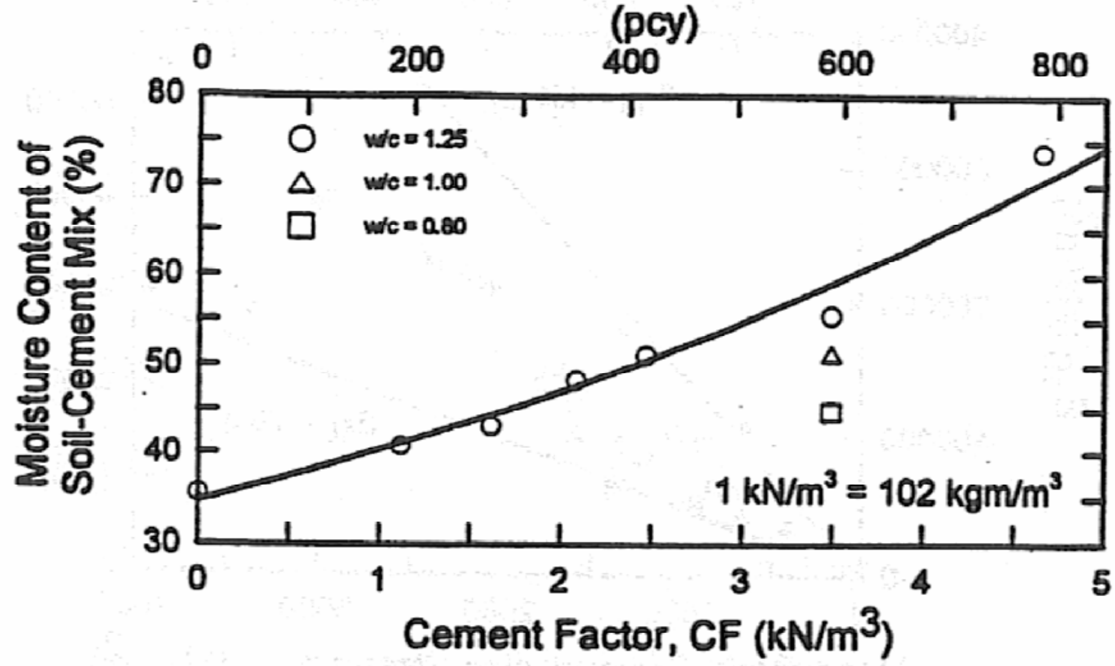


Figure 17. As-mixed moisture content versus cement factor (O'Rourke et al., 1997).

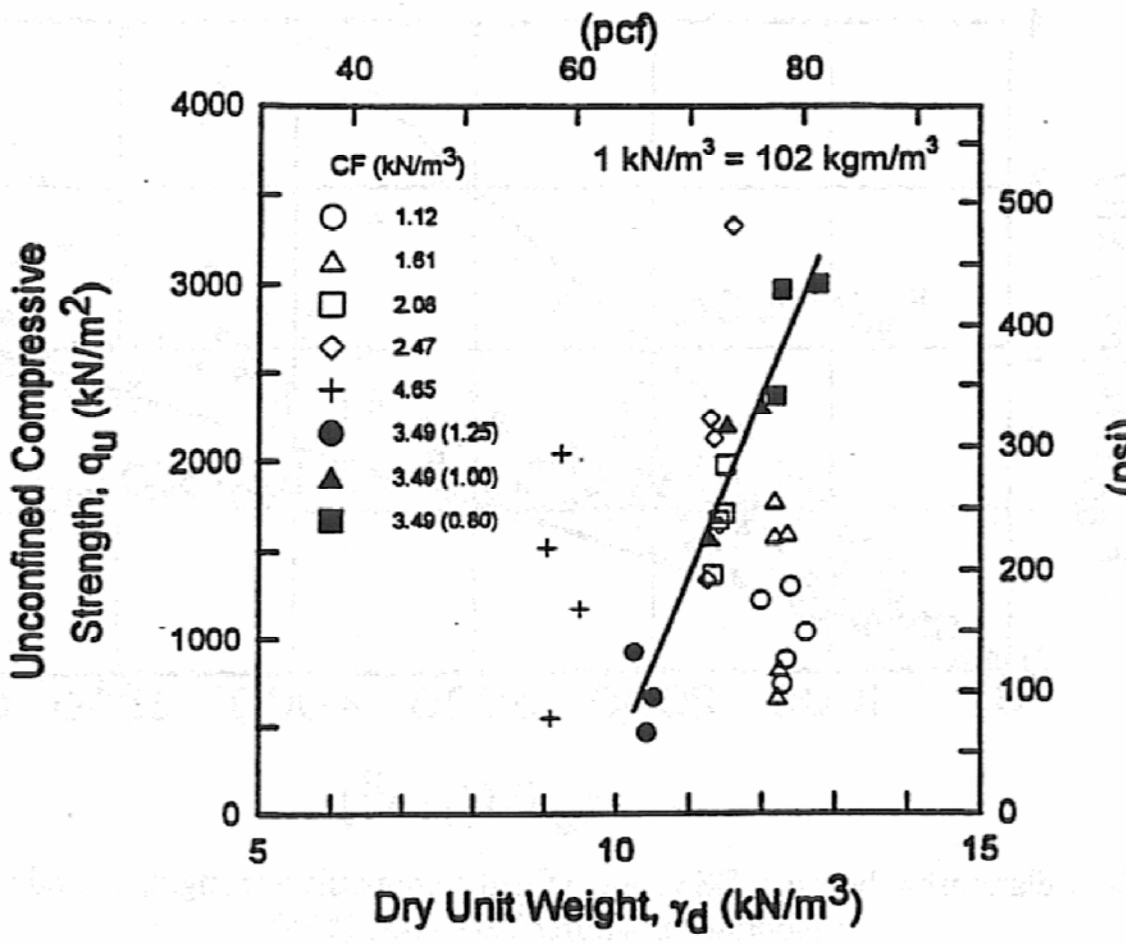


Figure 18. Unconfined compressive strength versus dry unit weight (O'Rourke et al., 1997).

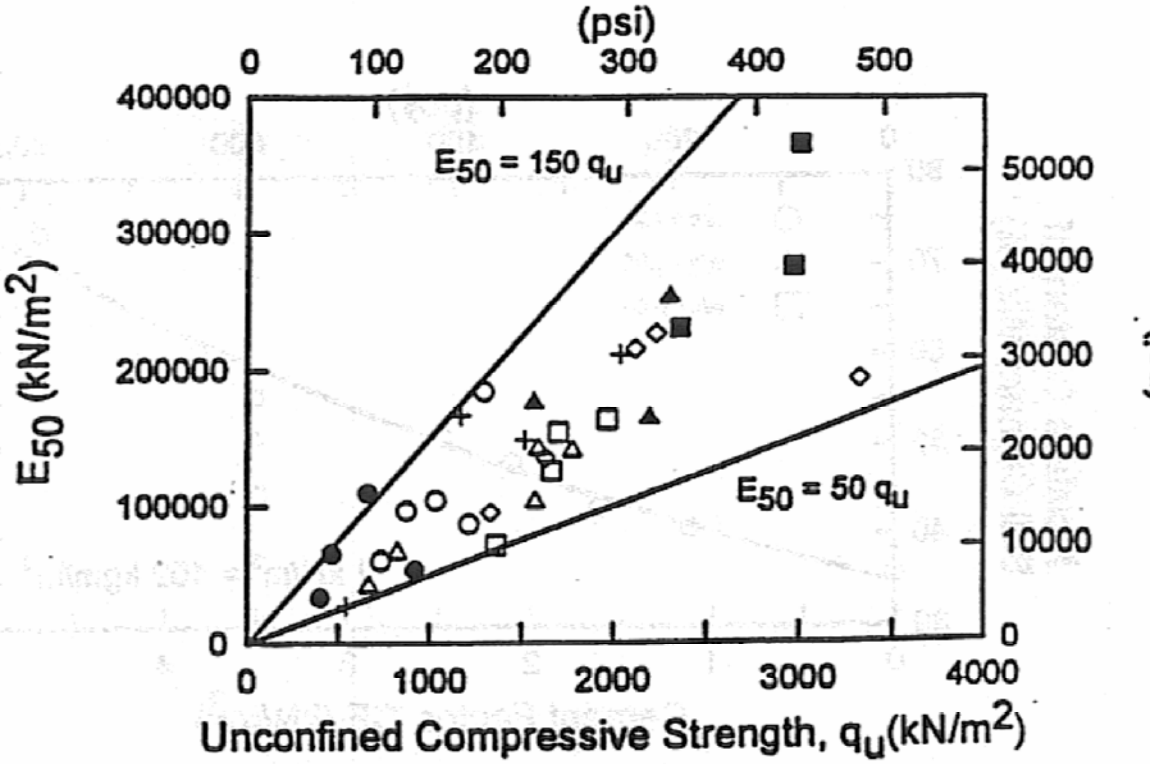


Figure 19. E_{50} versus q_u laboratory-prepared and cured soil-cement tested by Geotesting Express (O'Rourke et al., 1997).

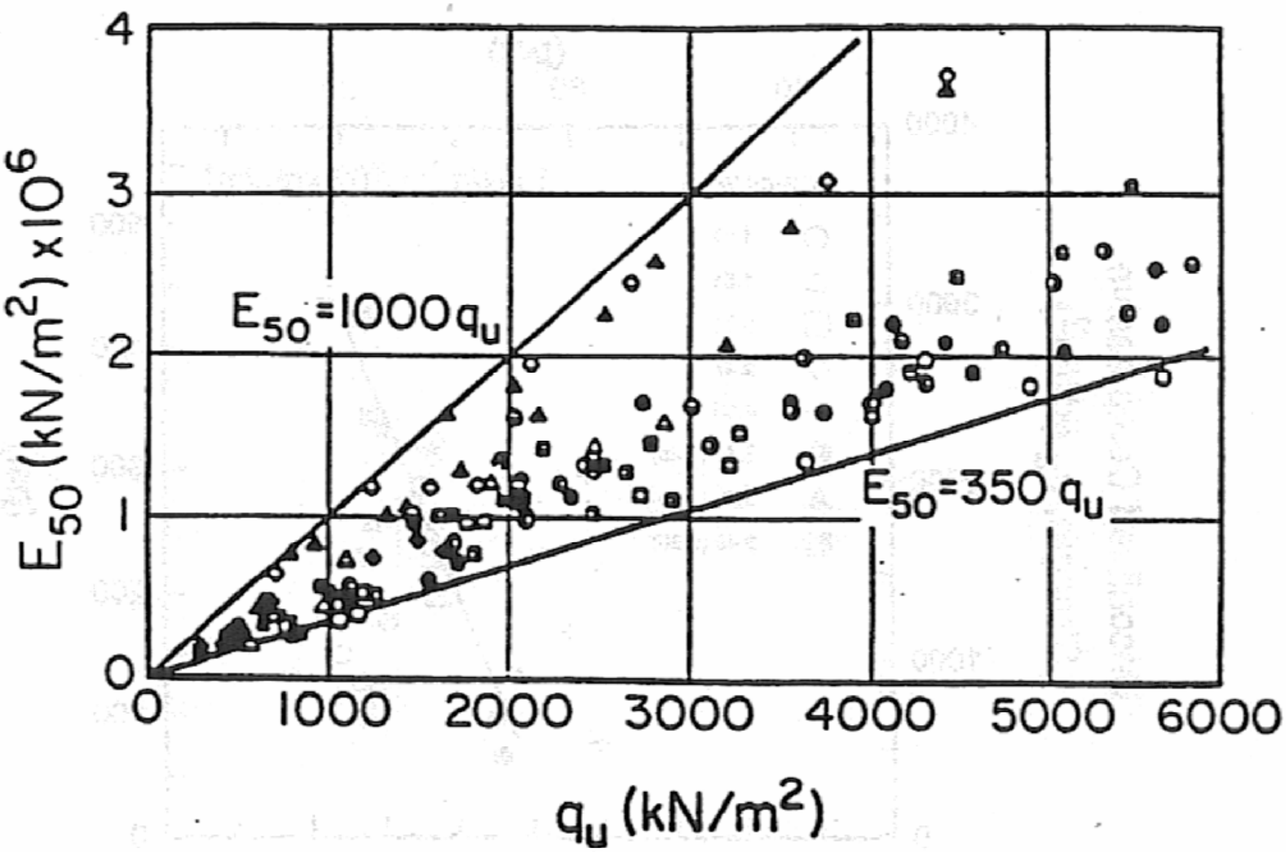
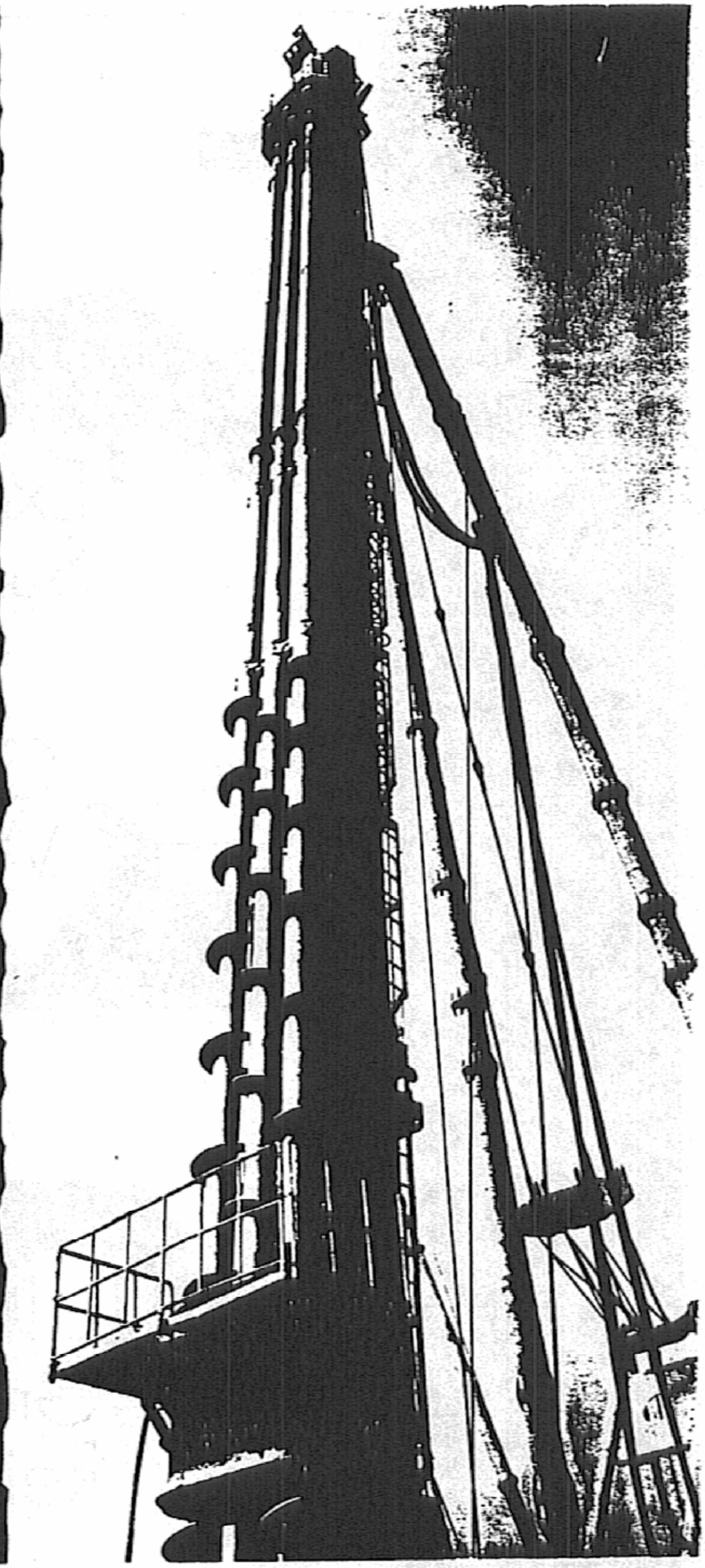


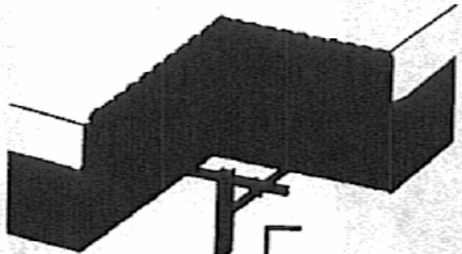
Figure 20. Relationship between DSM unconfined compressive strength, q_u, and static linear modulus, E_{50} (after Takenaka, 1995).

Attachment 1. RSW brochure.

RAITO OIL-CEMENT ALL

RSW method mixes in situ soils with cement grout using multi-shaft auger to produce subsurface soil-cement walls for excavation support, groundwater control, or ground reinforcement.

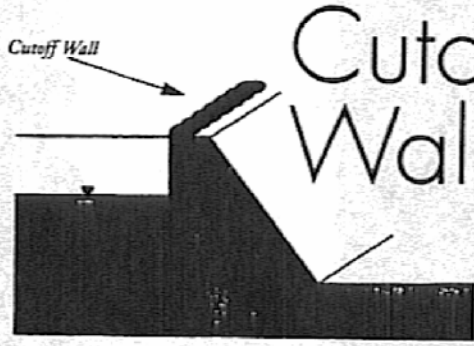




Steel H-piles or other reinforcing members are installed inside the soil-cement columns to resist the lateral forces.

Excavation Support Wall

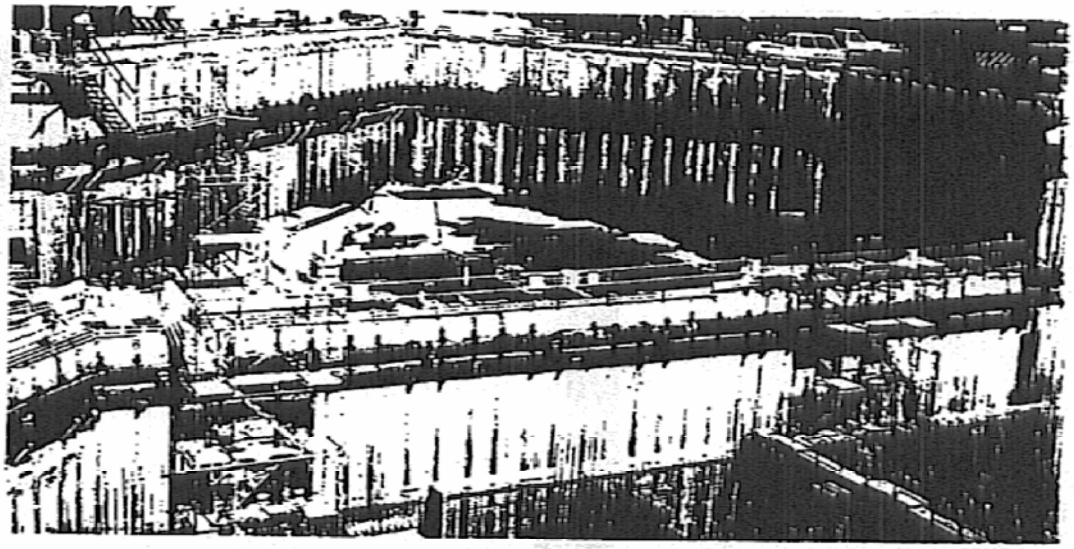
Cutoff Wall



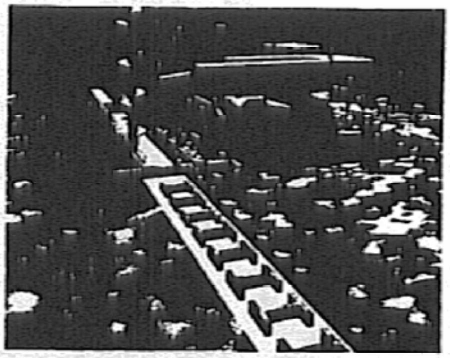
RSW method installs soil-cement wall, soil-bentonite wall, soil-clay-bentonite wall for use as barrier walls to contain groundwater or underground pollutants.

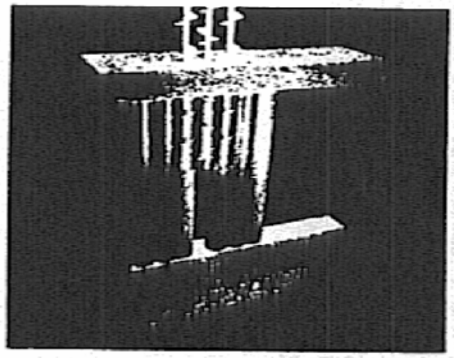
RSW method also installs soil-cement wall, panel, grid, or block for ground stabilization or liquefaction prevention.

Ground Reinforcement

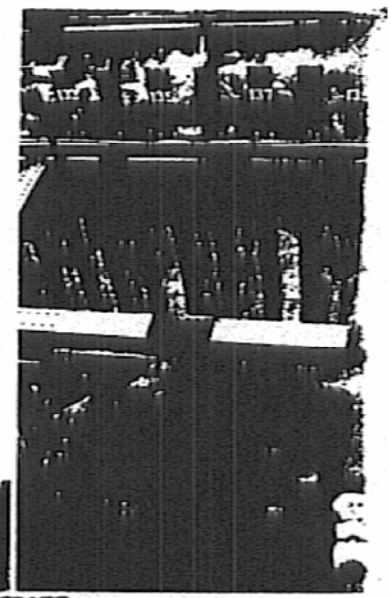


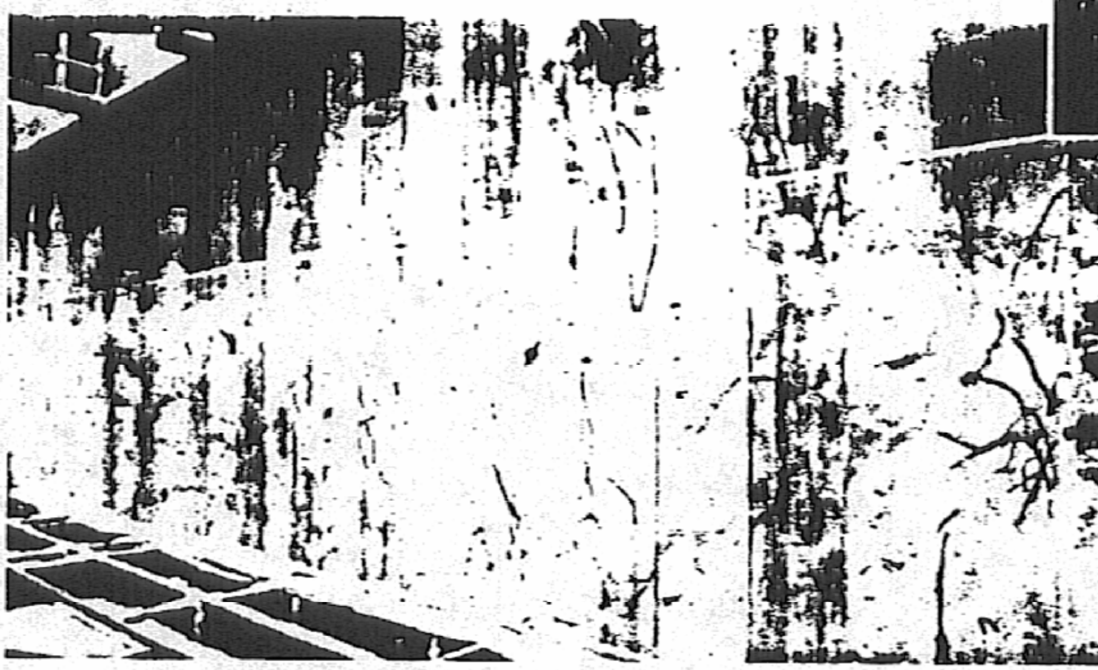
RSW Wall for Excavation Support and Groundwater Control





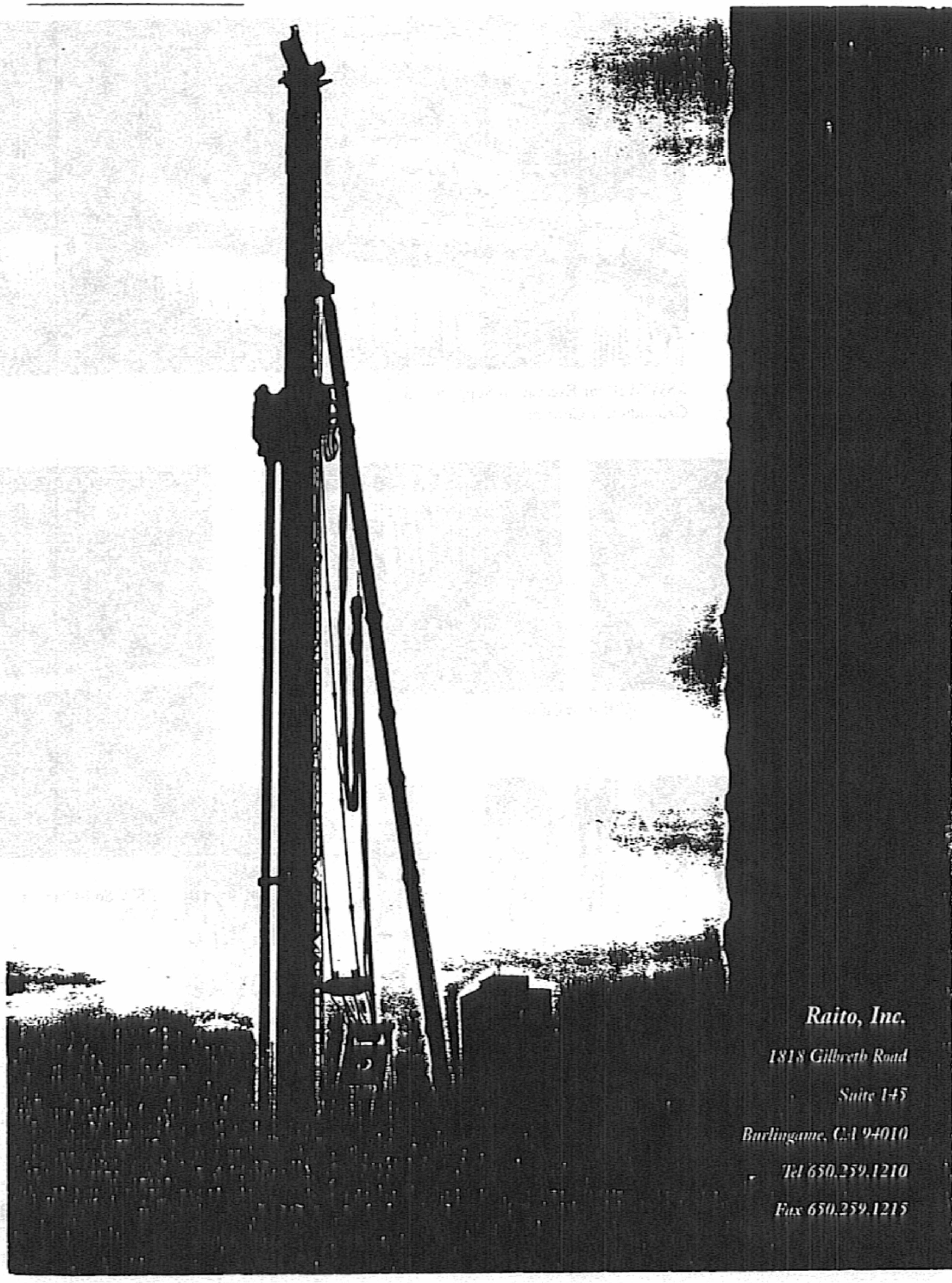
Wall Installation





RSW Soil-Cement Walls

Raito


Raito, Inc.
1818 Gilbreth Road
Suite 145
Burlingame, CA 94010
Tel 650.259.1210
Fax 650.259.1215

MULTIMIX (3)

1. INTRODUCTION

This technique is classified as WRS and represents a joint development between Rodio and Trevi in the late 1980s/early 1990s. Although the relatively scarce published data refer to a three-auger method, it is understood that more recently, a one-auger system has been developed. The special goals of the method were to create overlapping soil-cement columns with minimum soil removal or unmixed zones between and within columns. It can be used for temporary and permanent structures, including hydraulic cutoffs and structural elements (steel elements can be vibrated into place). Field testing has proven its suitability in cohesionless soils of low to medium density and in cohesive soils of low to moderate strength. The former are the particular technical and economic targets.

2. GENERAL PROCESS

The cable-suspended system is advanced at about 0.5 m/min to promote good mixing. A maximum practical depth is 23 m. Grout is injected on the way down at a constant rate via the tip of the augers. Rotation direction and auger direction alternate on adjacent augers. A pre-stroke with water can be used to loosen clays. In this case, grout is injected via the outer shafts only in the second penetration. The auger flights loosen the soil and lift it to the mixing paddles, which blend it with the grout. As the shafts advance, the soil and grout are remixed by additional paddles mounted above. The total vertical extent of shaft mixing is about 8 to 10 m. The augers are then reversed, with continued injection (apparently mainly through the external augers) of grout at about the same rpm. In especially resistant or heterogeneous ground, water (plus or minus appropriate additives) is used in a predrilling phase. Continuous diaphragms are formed in the same sequence as DSM or SMW.

3. EQUIPMENT (Figure 21)

Base	Suitable specialized carrier, e.g., Soilmec EC or Linkbelt LS 38/318 (33-m mast, 25-m stroke, 80-kN hoist, and pull-down).
Shafts	The head has three independent 60-kN-m hydraulic rotary motors (running off a 400-hp power pack at 8 to 25 rpm), which can accommodate a range of interauger spacings (450 to 600 mm) and auger diameters (550 to 800 mm) (Figure 22). Different auger types are used in different soil conditions.
Grout Plant	Mixer supplying 5 to 15 m^3/h (50 hp); compressor providing 15 m^3/min at 12 bar; "Feeding plant" consisting of 3 hydraulic piston pumps (115 mm by 130 mm), delivering 150 to 350 L/min at up to 40 bar (40 hp).

Control	Parameters are automatically recorded (for construction control and as-built records). These are principally the hydraulic circuit pressure, rpm, depth, cumulative volume of fluid, rate, and pressure of grout injection.
Production	Penetration rates can vary from 0.35 to 1.1 m/min and withdrawal can vary from 0.48 to 2 m/min.

4. MIX CHARACTERISTICS

Grout. Especially in cohesive soils, low water/cement ratio grouts are used (0.6 to 1.0). Bentonite can be used (but not in cohesives), and fluidifier/retarders are used under certain circumstances, e.g., where penetration rates are low. The cement factor depends on the soil and the results required, but is typically 200 to 250 kg/m^3 of soil. Generally, low effluent volume is sought (10 to 20%). Volume ratio reflects penetration rate and varies from 15 to 40%.

Treated Soil. In general (as a result of the Casalmaicco and Pietrafinna tests, respectively), strengths of 0.5 to 5 MPa in granular soils, and 0.2 to 1 MPa in cohesives can be achieved, although locally, strengths of up to 10 to 20 MPa can be attained in certain very resistant soils. Permeabilities less than 10^{-7} m/s are claimed.

Pagliacci and Pagotto (1994) reported on field tests conducted in Thailand, in saturated marine and fluvial soils (loose sands and soft low-plasticity clays) between 5 to 16 m deep. N-values ranged from 1 to 3; undrained shear strengths (clays) were 15 to 35 kPa and the sands had a relative density of 20%. The deposits were slightly organic, with a water content greater or equal to the liquid limit. A target UCS of 0.6 to 1 MPa was set, and the E-value was in excess of 200 MPa. Trevi selected a cement factor of 250 kg/m^3 of soil.

Preliminary lab tests were conducted on very soft plastic clays using four different grouts with different sand contents, using a 250-kg/m^3 cement factor (Table 3). They recognized that, in practice, the real proportion of materials in situ is governed by the amount and composition of the spoil. This is difficult to be determined theoretically and so there are two hypotheses (Figure 23):

First:	Volume of spoil = volume of grout.	Spoils consist of soil/grout.
Second:	Volume of spoil = volume of grout.	Spoils consist only of soil.

Data on mixed soil samples are provided in Table 4, Table 5, and Figure 24 (hypotheses 1 and 2).

It was concluded that hypothesis 2 was more logical and more desirable. Field testing provided the results found in Figure 25 and led to the following conclusions.

1. To avoid spoil with a high percentage of cement, the natural water content must be increased well in excess of the liquid limit.

2. The use of sand improved strength despite increased mechanical wear and tear on the equipment.

3. Redrilling without adding any fluid greatly improved the quality of mixing.

As a consequence, in the 68,000 m of production columns completed in 7 months:

- Columns were double-drilled. The first pass involved drilling with water, if necessary, and mixing occurring during uplift at 1 m/min. The second pass involved redrilling without any additional fluid injection.

- Grout water/cement ratio = 0.6, sand:cement = 0.5, and cement factor = 250 kg/m^3 soil.

- Columns were 1m in diameter, 7 to 15.5 m long.

Coring provided UCS = 1.5 to 2.5 MPa at 28 days. Plate load tests were also conducted. From another source (Rodio Brochure, 1992), the following parameters were recorded:

	Casalmaiocco (sands and gravels)	**Cesena (silts and clays)**
Penetration		
Rate	0.35-1.1 m/min	0.2-0.4
Rotation	12-30 rpm	25
Total grout factor	200-400 L/m^3 (150-300 L/m)	150-300 L/m^3 (140–420 L/m)
Equivalent cement factor	80-450 kg/m^3 (70-370 kg/m)	130-400 kg/m^3 (100-300 kg/m)
Withdrawal		
Rate	0.48-2.0 m/min	0.4-3.0 m/mm
Rotation	12-20 rpm	14-28 rpm
Water/cement ratio	0.6-0.7	0.6-0.7
Water/cement-bentonite ratios	w/c = 0.5; b/w = 0.09	w/c = 0.5; b/w = 0.09
28-day UCS	0.5-5.0 MPa	0.2-1.0 MPa
Permeability	10^{-7}-10^{-8} m/s	10^{-7}-10^{-8} m/s

5. PATENTED/PROTECTED FEATURES

The process is patented by Trevi.

6. PARTICULAR ADVANTAGES

Method claims better mixing efficiency and less spoil generation than other WRS methods.

7. OPERATING COMPANIES

Both Trevi and Rodio are Italian-based, with U.S. offices (Boston and Bridgeville, PA, respectively). The system has seen some use in Italy and in Thailand, but none in the United States to date.

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Rodio, Inc. (1990). Technical Information.

Table 3. Main characteristics of cement grout/mortars (Pagliacci and Pagotto, 1994).

MORTAR TYPE	S/C	C/W	FLOW-CONE VISCOSITY	U.C.S. 28 DAYS
(-)	(-)	(-)	(sec)	(MPa)
A	2.0	1.18	25	12.20
B	1.0	1.52	19	20.50
C	0.5	1.66	20	22.50
D	0.0	1.80	12	24.30

Table 4. Main characteristics of soil-cement mortar samples (Pagliacci and Pagotto, 1994).

MORTAR TYPE	CEMENT PER C.M. OF SOIL	C/W	SAND PERCENTAGE
(-)	(kN/m3)	(-)	(%)
HYPOTHESIS n° 1			
A	1.68	0.295	36.6
B	1.86	0.313	22.4
C	1.95	0.318	12.6
D	2.04	0.323	0.0
HYPOTHESIS n° 2			
A	2.50	0.465	52.9
B	2.50	0.430	30.6
C	2.50	0.413	16.8
D	2.50	0.396	0.0

Table 5. Unconfined compressive strength values for different mortar type, mix hypothesis, and curing time (Pagliacci and Pagotto, 1994).

MORTAR TYPE	HYPOTHESIS n° 1		HYPOTHESIS n° 2	
	U.C.S. 7 DAYS	U.C.S. 28 DAYS	U.C.S. 7 DAYS	U.C.S. 28 DAYS
(-)	(MPa)	(MPa)	(MPa)	(MPa)
A	0.23	0.60	0.65	1.45
B	0.22	0.54	0.42	1.20
C	0.22	0.49	0.34	0.99
D	0.24	0.60	0.37	0.86

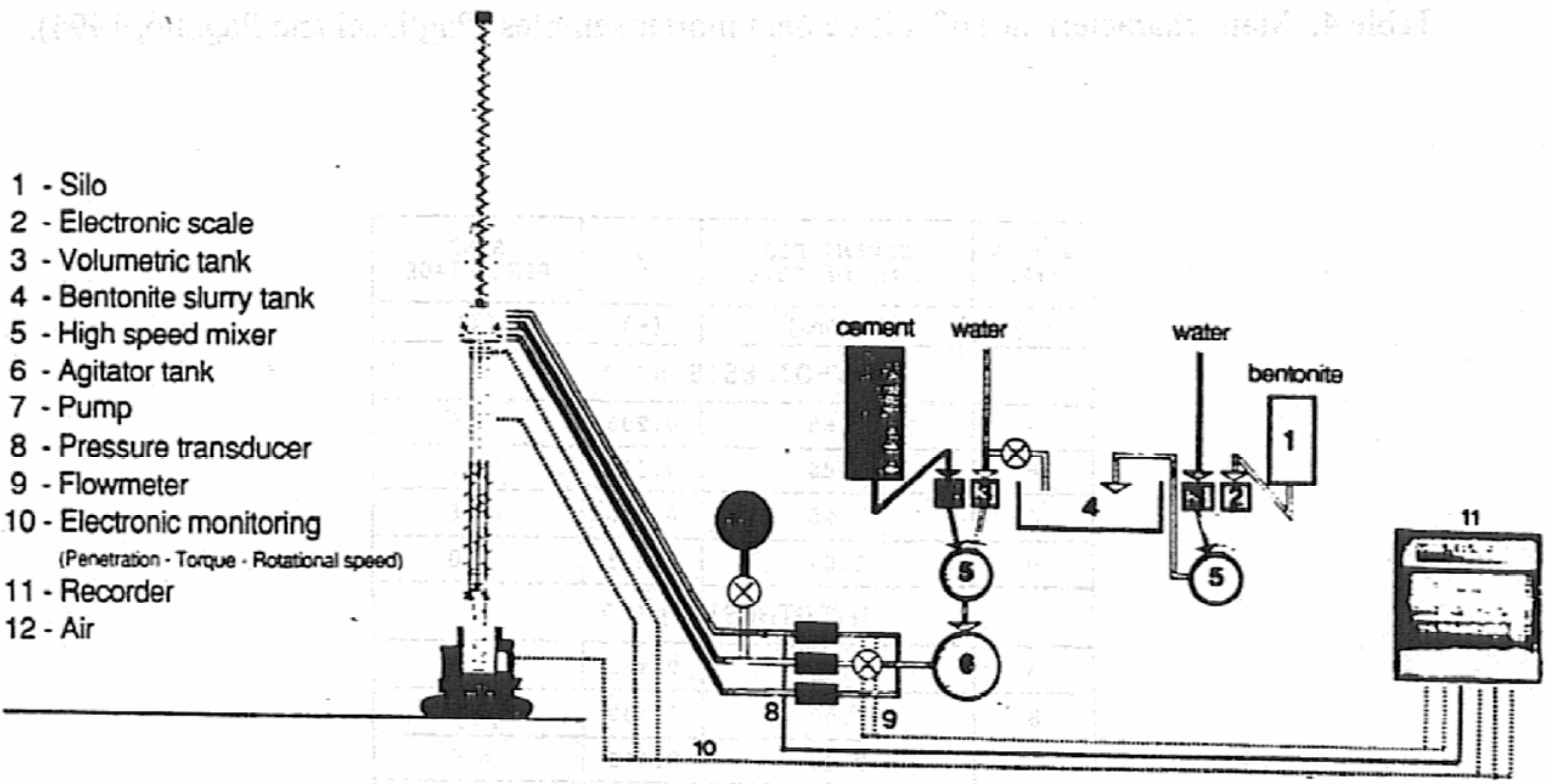

Figure 21. Schematic of equipment and grout plant (Rodio, Inc., 1990).

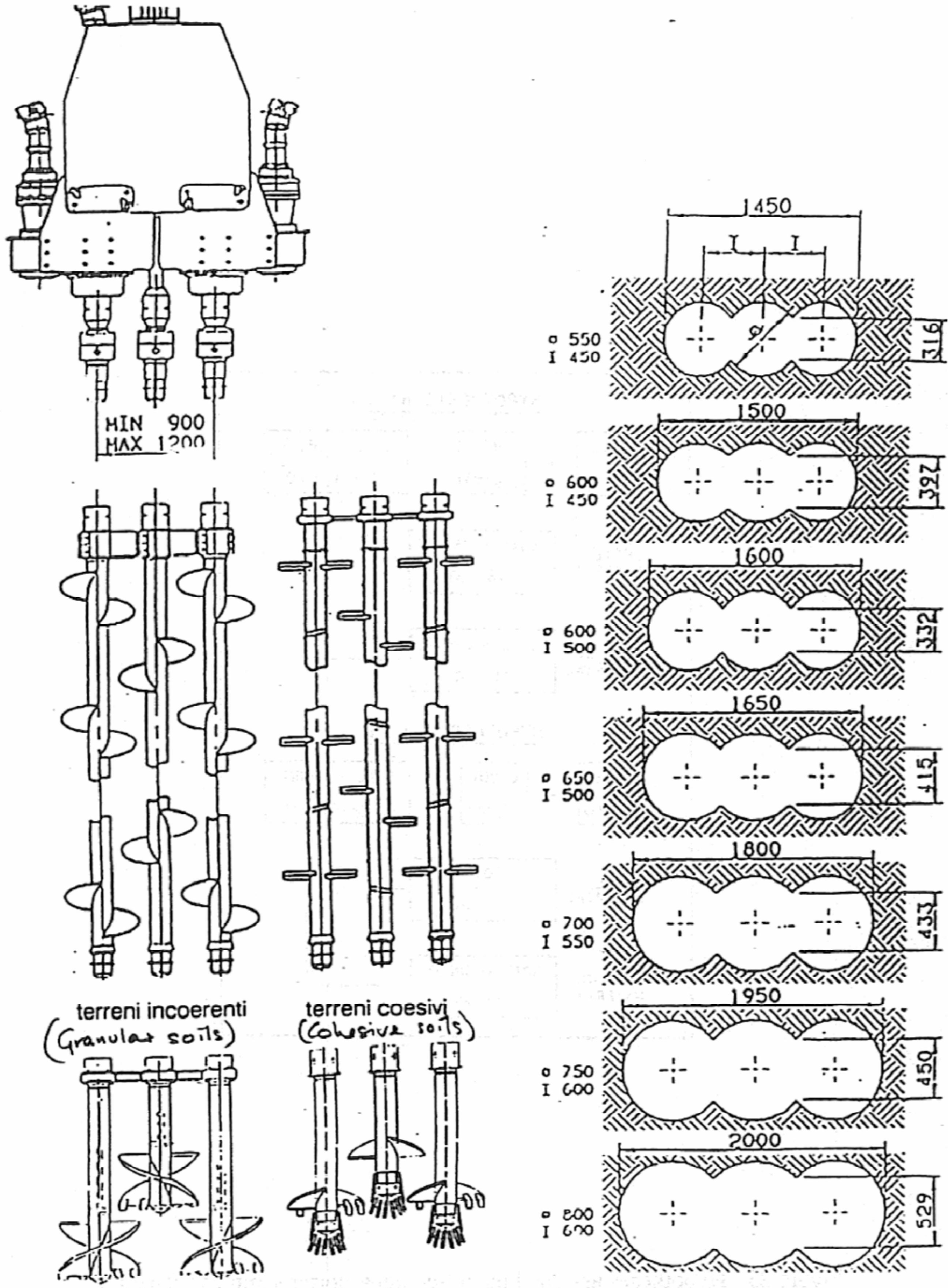

Figure 22. Schematic of two augers used in the Multimix process and a diagram of obtainable shapes (Rodio, Inc., 1990).

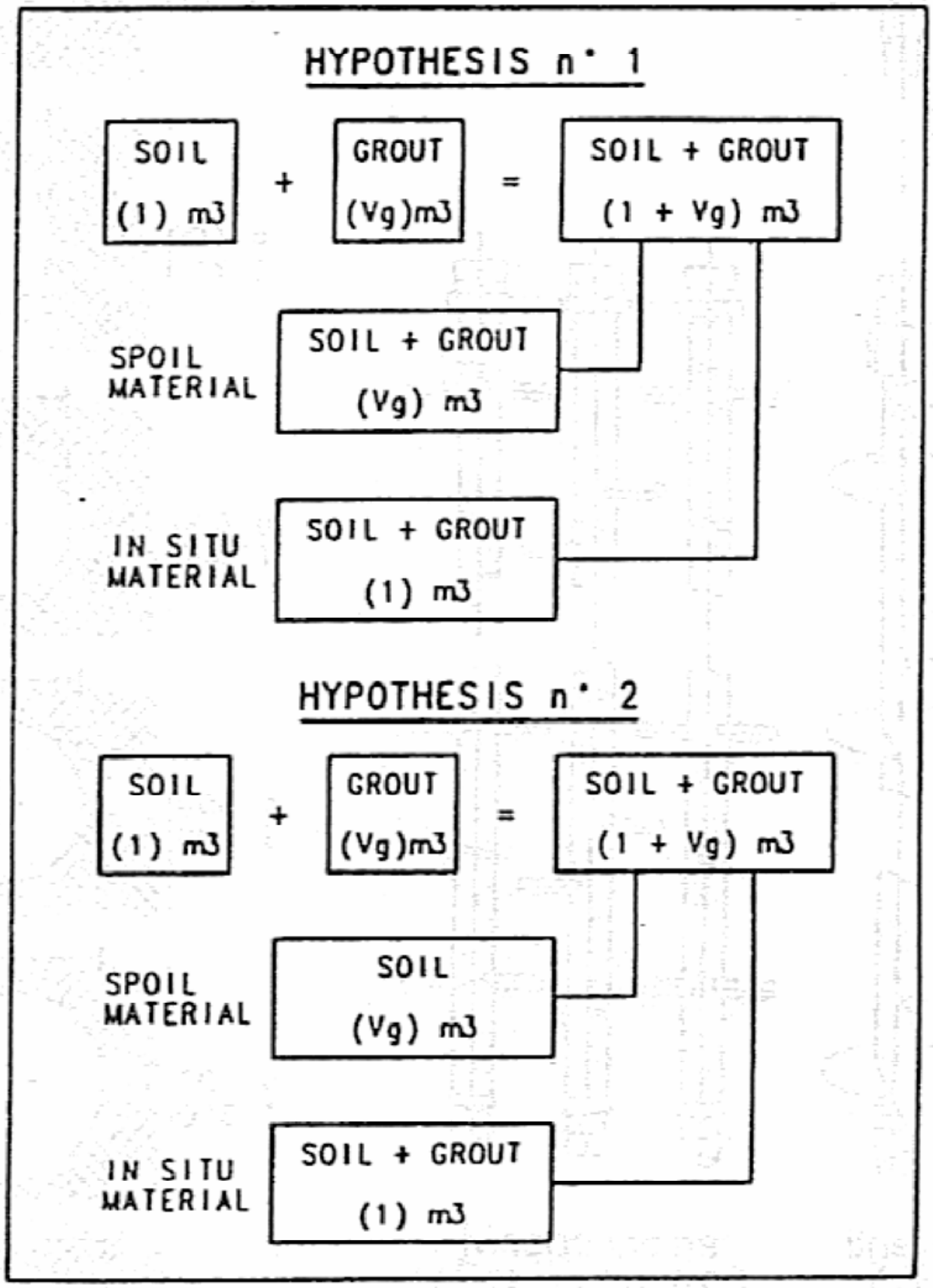

Figure 23. Hypotheses assumed in soil-cement mortar samples preparation (Pagliacci and Pagotto, 1994).

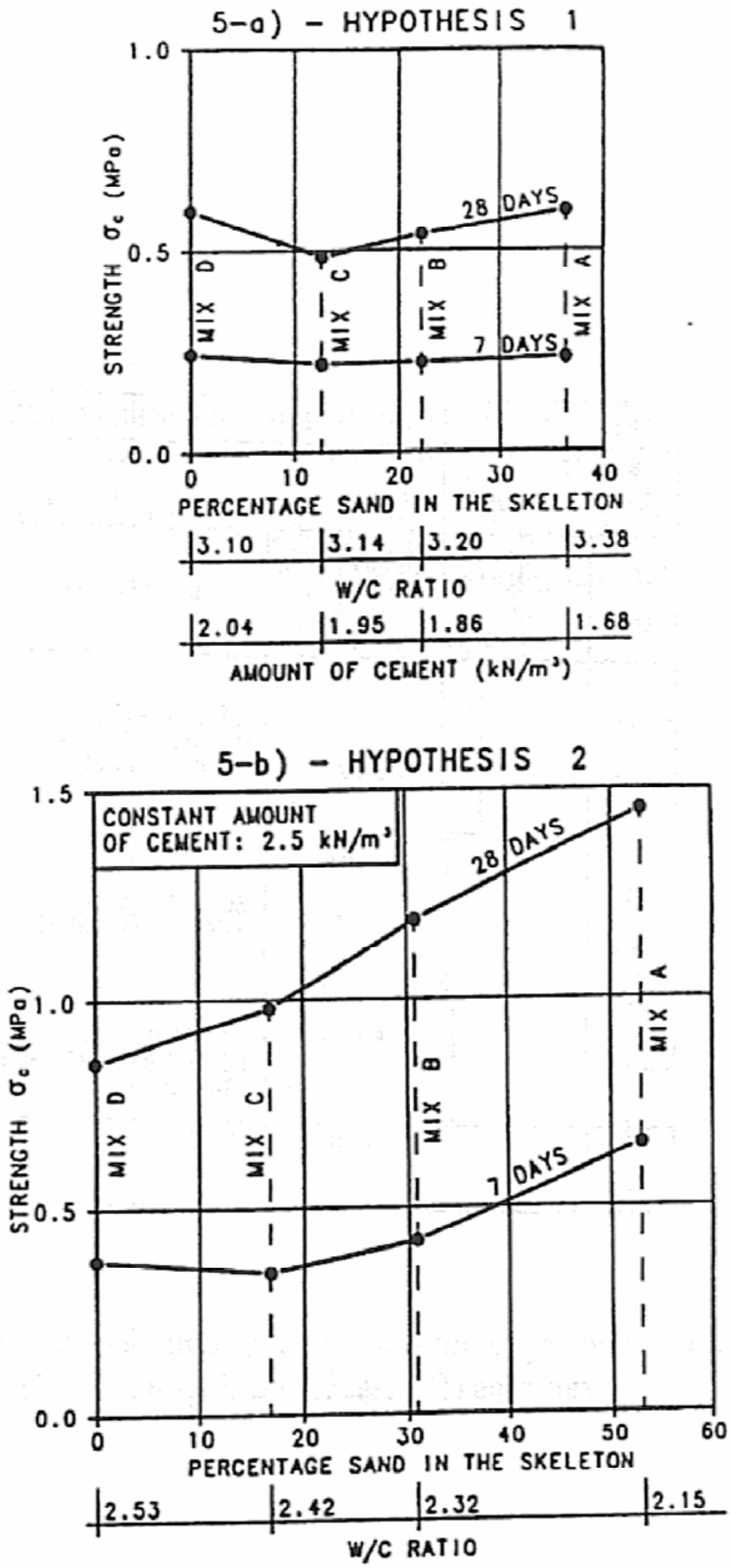

Figure 24. Unconfined compressive test results on soil-cement mortar samples (Pagliacci and Pagotto, 1994).

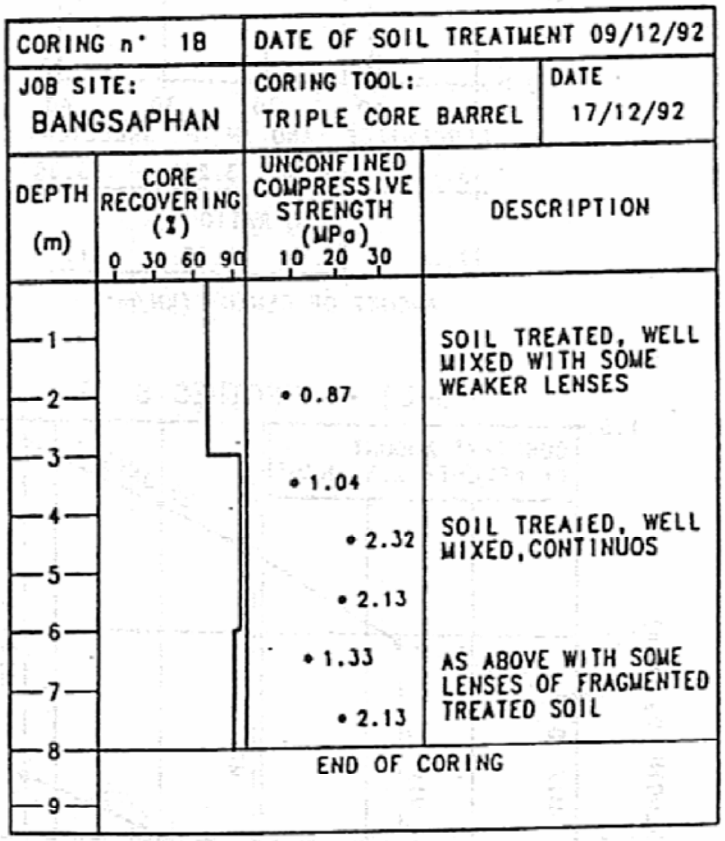

Figure 25. Results from coring of an improved column and laboratory testing on recovered samples (Pagliacci and Pagotto, 1994).

1. INTRODUCTION

This Bachy system is mainly used in a WRS version, although a dry variant Dry Rotary Shaft (DRS) has also been developed for soils of very high water content. Colmix was developed in France in the mid-1980s in response to a competition set by the French National Railways (SNCF) and the Laboratoire Centrale des Ponts et Chausées (LCPC). This competition invited bids to design and implement a "process to construct stabilized and compacted soil columns to improve the stability of railway embankments." Colmix duly won the "Prix de l'Innovation" in 1987 from the Fédération Nationale des Travaux Publics (FNTP), having been first used on a railway embankment at Vierzon, France in 1986. Two major points of differentiation with the Scandinavian Lime-Cement Column method (Method #23) are claimed:

- "The degree and fineness of the homogeneity of the soil-binder mix," and
- "The possibility to recompact in place the final soil-binder mix."

2. GENERAL PROCESS

Colmix creates columns, blocks, or panels of treated soil using multiple, overlapping counter-rotating continuous flight augers. The counter-rotation also discourages deviation, as noted in the French patent. The augers break up, lift, and mix the soil with a lime and/or cement slurry as they penetrate. The direction of rotation is reversed during withdrawal to further mix and compact the treated mass. (In particularly stiff soils, the soil is retreated several times.) Schematics of the two- and four-auger systems are shown in Figures 26 and 27, respectively. Column sizes tend to be 10 to 20% larger than the auger diameter, due to the compaction energy.

The initial developments featured two- and three-auger machines, but the four-auger machine was developed for an environmental project in Ardeer, Scotland (1994 to 1995) and six and eight augers are noted in the Australian patent of 1995. Most recently, only even-numbered augers are being used, the axes of which are centered at the vertices of a regular n-sided polygon (Figure 28).

3. EQUIPMENT

<u>Base</u> A variety of carriers can be used depending on field conditions and requirements. Cranes, excavators, and drilling rigs have been used.

<u>Shafts</u> A fixed lead, typically 10 m long, carries the geared, multi-spindle motor (0.15 to 1.5 m-tonnes), which turns the spaced augers (Figure 29). The augers have opposite pitches and rotate in opposite directions. The grout is injected via one or several outlets at the auger tip. A servo-control system maintains a constant thrust or a constant penetration/withdrawal speed. Figures 30 and 31 are extracts from

the U.S. Patent, and Figure 32 illustrates typical auger configurations and dimensions. Larger sections to depths of 20 m can be created using purpose-built, continuous flight auger (cfa) piling rigs (5 to 15 m-tonne).

<u>Grout Plant</u> The grout plant features a colloidal mixer, a large holding tank, and double-acting piston pumps for each auger (Figure 33). Materials are supplied in bags or bulk (in silos with screw feeds).

<u>Control</u> Drilling parameters are recorded automatically to permit synchronization of the binder injection with the rate of penetration. The appropriate rate of injection is achieved by a Lutz system using a flowmeter on the outlet of the holding tank linked by cable to a computer on the rig. This allows the driller to preset the required volume of grout and ensures even flow distribution to each auger. Full parametric printout is provided for each column (Figure 34).

Homogeneity, integrity, and quality are further verified by:

- Sonic velocity measurement in three directions.
- Uniformity of response to phenolphthalein (cement content).
- Wet mix sampling.
- Excavation and exposure/extraction.
- Laboratory testing.
- Coring (although, in practice, difficult).

<u>Production</u> Penetration is typically at 0.8 m/min and withdrawal is at 1.0 m/min. At the Ardeer project, Bachy constructed 2,407 columns, each 5 m deep, in 20 weeks, for a total treated length of 12,035 m (601 m/week, or 460 m^3/week). At peak production, one column per 15 min was produced, with a maximum of 44 columns per day.

4. MIX CHARACTERISTICS

<u>Grout</u>. Depending on the desired properties of the treated soil, various "binder" mixtures containing cement, lime, and flyash (pfa) are used in proportions ranging up to 32% by weight of dry soil. The higher percentage of binder is generally used in environmental applications. Lower percentages of binder are generally incorporated into the soils when used for structural stabilization. Those percentages range from 5 to 8% lime and 10 to 15% cement by weight of dry soil. The water:solids ratio is usually 1:1. Bachy reports that dry powder (quicklime) or cement can be used in soils with a high water content, and that they have developed a series of slurries intended to absorb heavy metals, and allow the sorption of organics. Fluid grouts typically have a density of around 1.50, a Marsh viscosity of 40 to 50 seconds, and less than 5% bleed. For most embankment/foundation purposes, and assuming a cement factor of 200 kg/m^3, the process requires the volume ratio to be about 30 to 50%. Due to the efficiency of the mixing and the low water/cement ratios, spoil volumes are moderate (lower than with SMW, for example).

Treated Soil. In clays, unconfined compressive strengths range from 3 to 6 MPa at 28 days using the above-referenced cement and volume factors. E-values (around 300 MPa) range from 50 to 100 times UCS, while the shear strength is typically equivalent to 33% UCS. Data from sandy soil show higher strengths. Permeabilities at Ardeer were as low as 6×10^{-8} m/s. At an earlier site in Vierzon, France, Harnan and Iagolnitzer (1992) reported a water content for soil of 24% for a grout composed of 400 kg/m^3 cement, 320 kg/m^3 slaked lime, and 724 kg/m^3 water. For a 0.08-m^2 section, the grout usage was 39 to 40 L/lin. m of column. The column therefore contained approximately 10% cement and 8% lime by dry soil weight. Later projects (A64 Motorway) used 8% slaked lime and 32% CPJ45 cement by weight of dry soil (clay-treated strengths were 2 to 3 MPa at 7 days and 3 to 6 MPa at 28 days).

5. PATENTED/PROTECTED FEATURES.

The Colmix system was patented in the United States in 1987, patent number 4,662,792. The patent abstract reads:

> "The invention relates to civil engineering works. In particular, it relates to a device suitable for forming a primary column of stabilized and compacted soil, which comprises at least two parallel shafts driving in opposite directions, two parallel augers with opposite pitch, each auger being provided at the opposite end to the drive shaft with a loosening drillhead and the distance between the axes of the augers being less than the diameter of an auger, the shafts and the shanks of the augers comprising a bore connected to a source of material to be added, and at least one orifice which communicates with the said bore being provided on the shank of each auger so as to discharge the material to be added and allow it to be mixed with the loosened soil. Applicable in particular for the compaction of railroad territory."

It is also patented in France and several other countries, including Australia (1995).

6. PARTICULAR ADVANTAGES

Bachy claims low spoil, and minimal vibration and noise. The system is logistically very flexible and adaptable, and can be moved and set up readily. It can be used in close proximity to existing structures.

7. OPERATING COMPANY

The Colmix System is owned by Bachy of France. They operate throughout the world. Recently (March 1997), Bachy merged with Soletanche, the other major French geotechnical specialist.

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Barker, P., M. Wyllie, and A. Esnault. (1996). "Investigation, Planning, and Execution of the Remediation of Ardeer Landfill, Scotland." International Symposium on Major Recent Case Histories, Paper 19, Paris, February, 18 pp.

Harnan, C.N. and Y.U. Iagolnitzer. (1992). "COLMIX: The Process and Its Applications." *Grouting in the Ground.* Institution of Civil Engineers, Thomas Telford, London, pp. 511-525.

Patent No. 10133/95. (1995). Memoire Descriptif a L'Appui D'Une Demande de Brevet D'Invention en Australie. Sondages Injections Forages (SIF) Entreprise Bachy. For "Improved Device for the In-Situ Production of Columns of Stabilized and Compacted Soil," January 11.

U.S. Patent 4,662,792. (1987). Method and Device for the In-Situ Formation of Columns of Stabilized and Compacted Soil. Inventor: Jean-Claude Gessay, Assignee: Sondages Injections Forages (SIF), Enterprise Bachy, May 5.

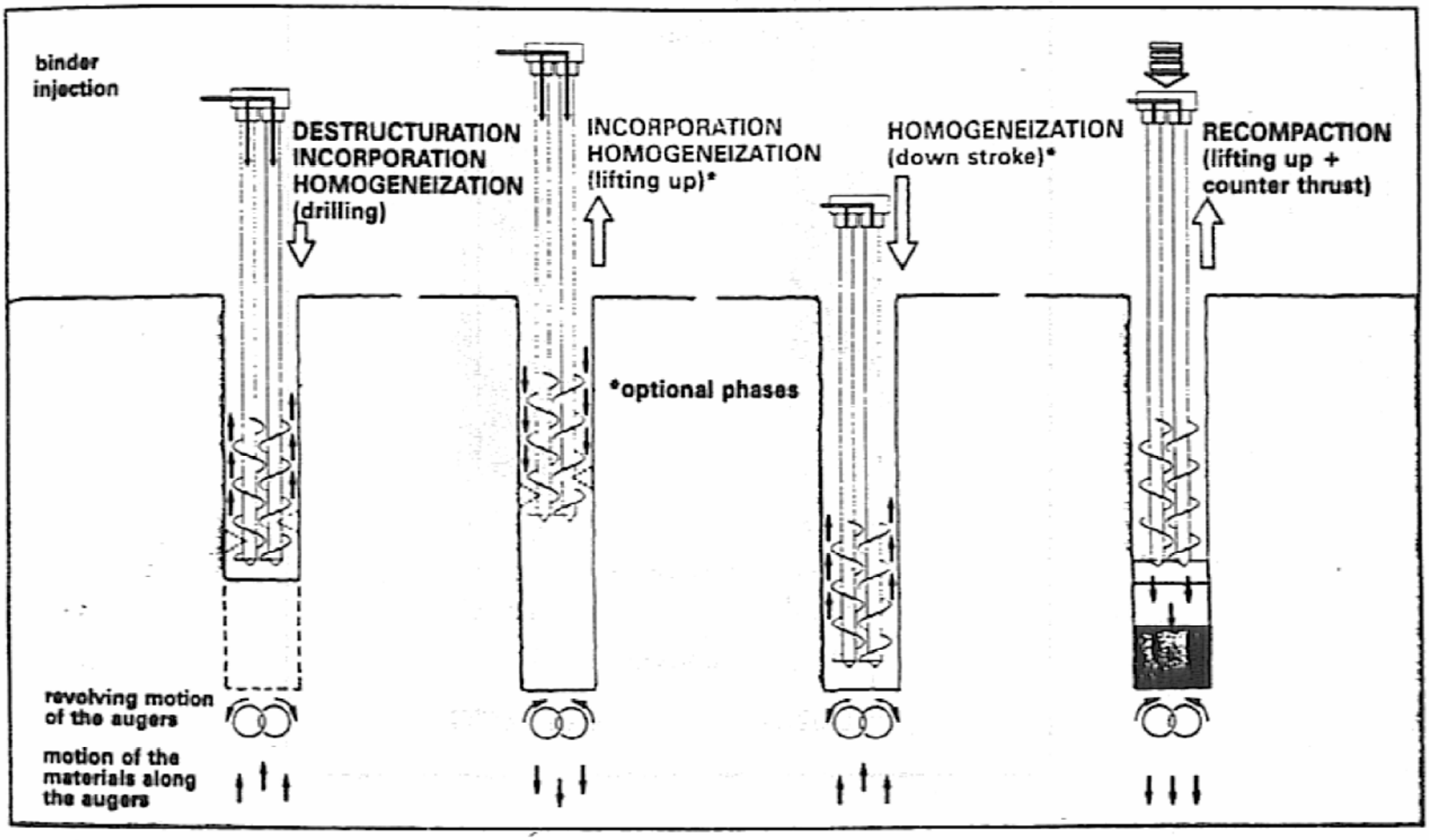

Figure 26. Implementation principle (Bachy, 1996).

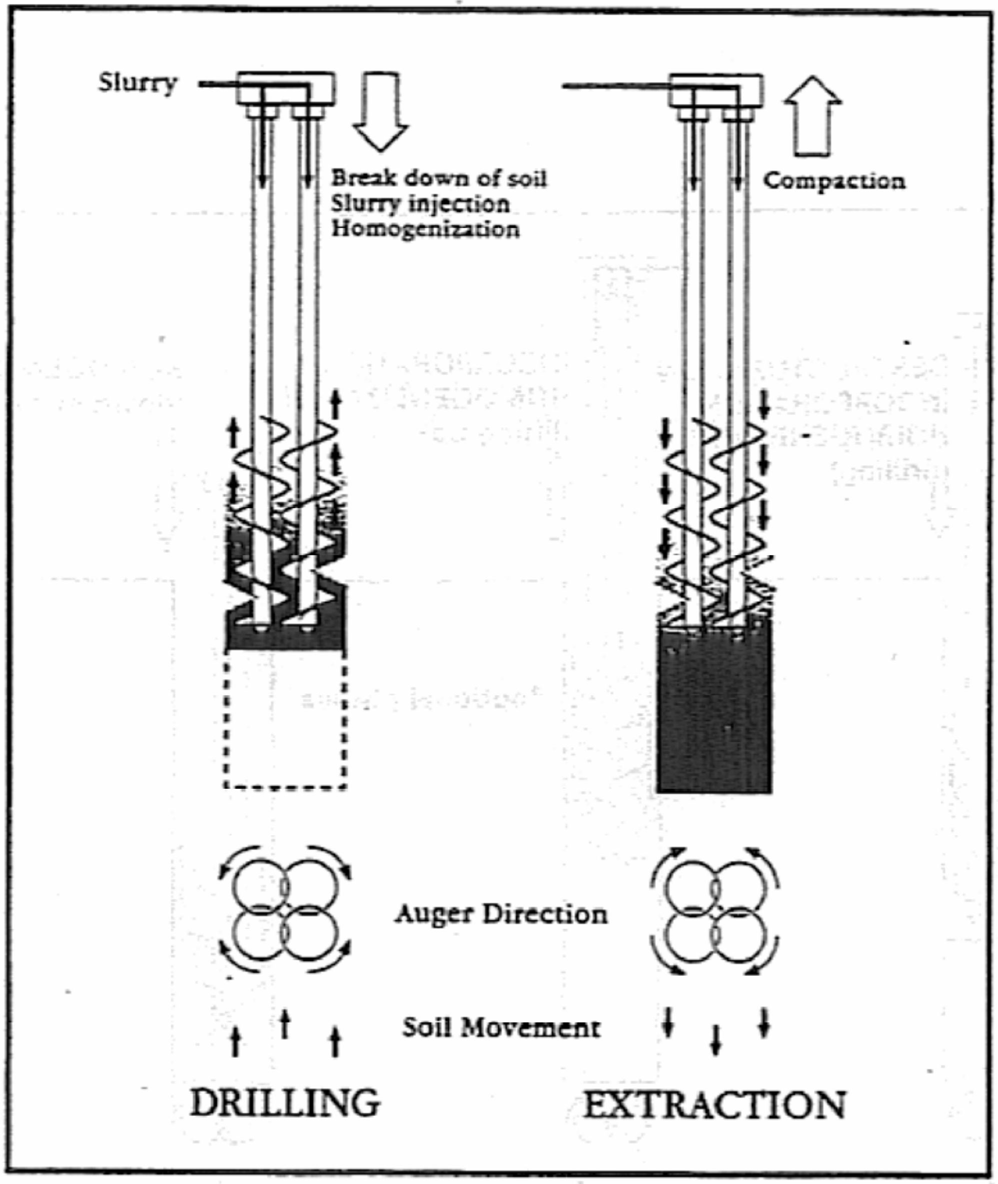

Figure 27. Colmix process (Bachy, 1996).

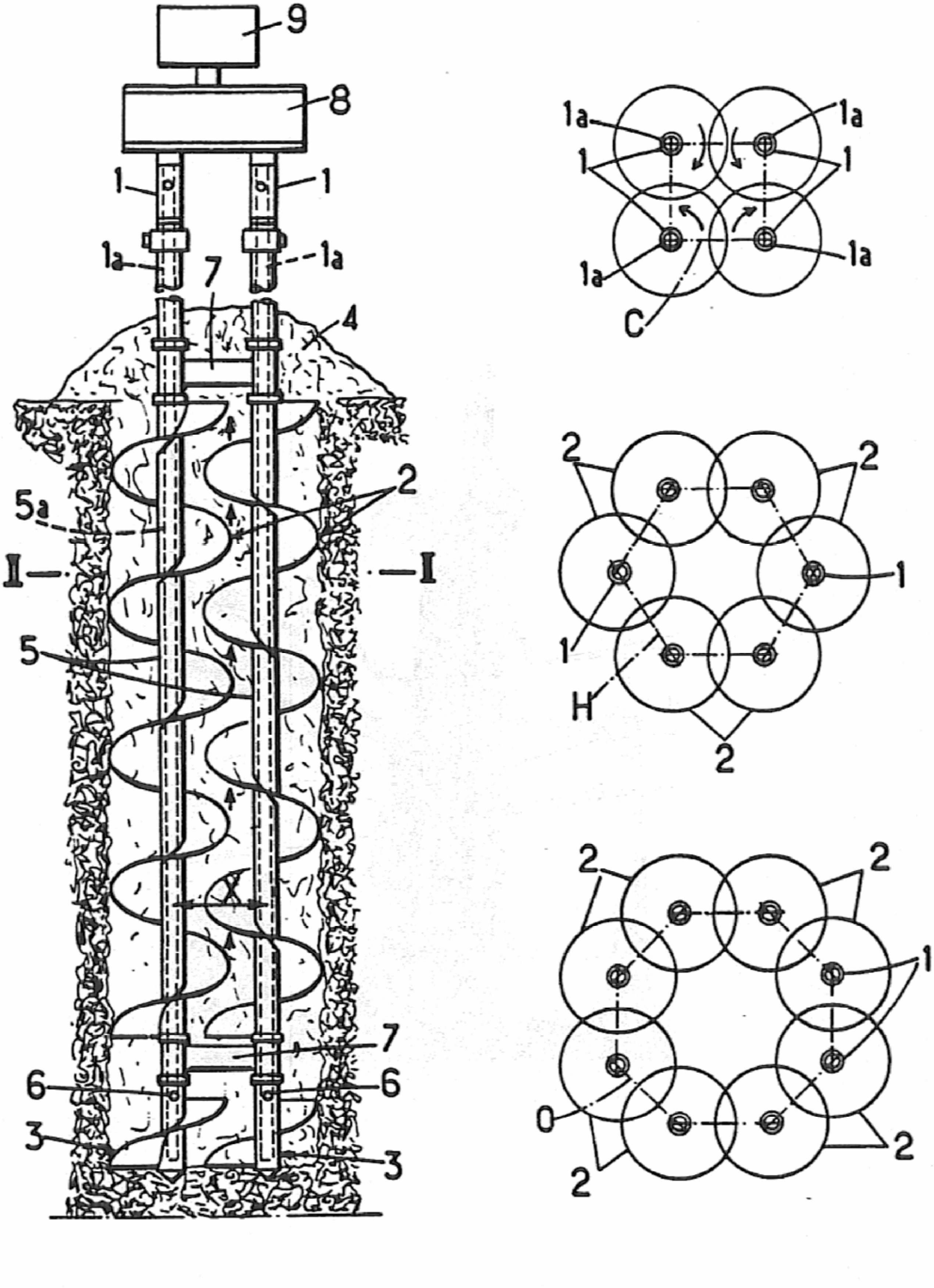

Figure 28. Auger configurations - Australian Patent (1995).

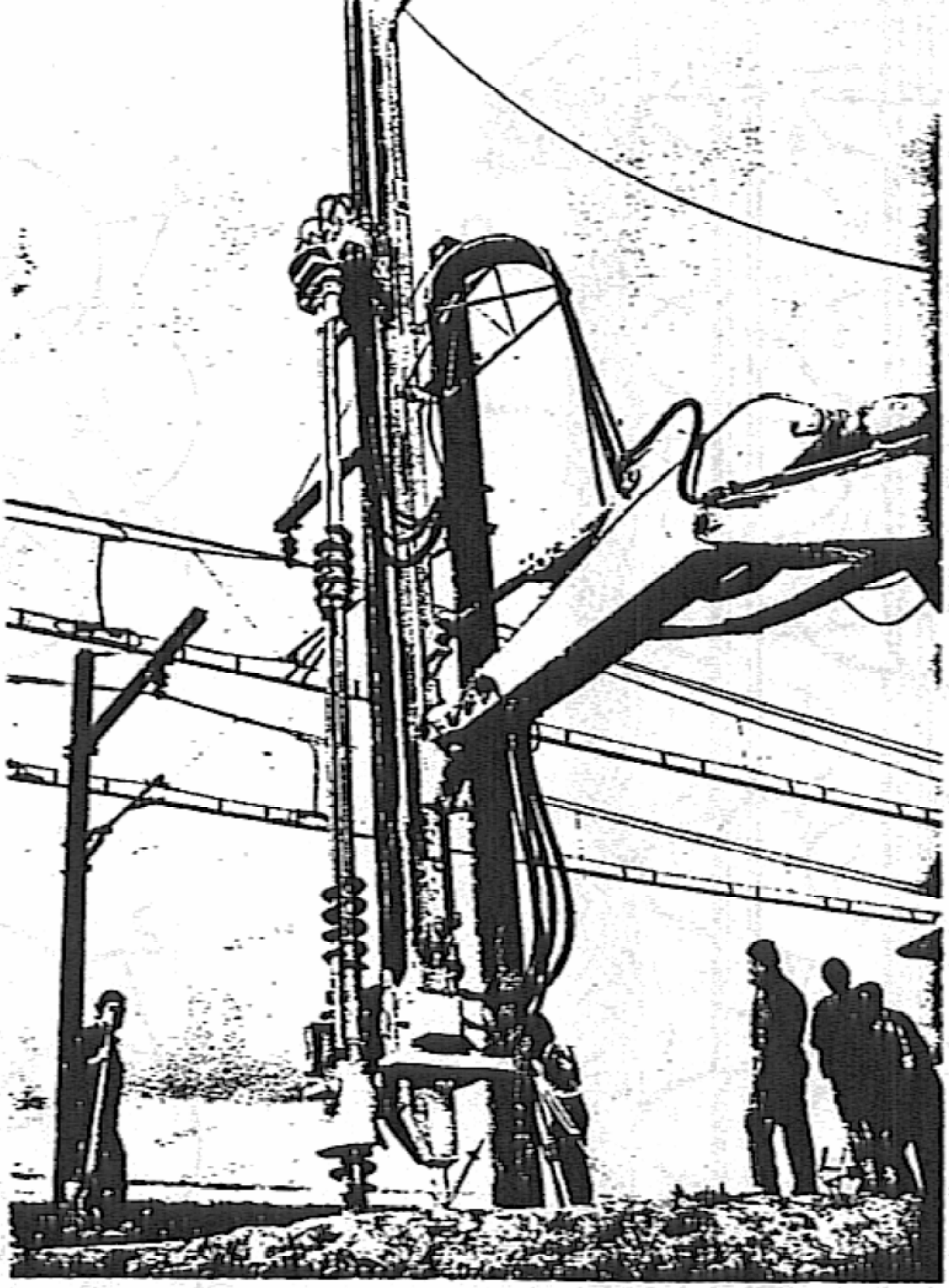

Figure 29. Fixed lead and mixing tool (Bachy, 1996).

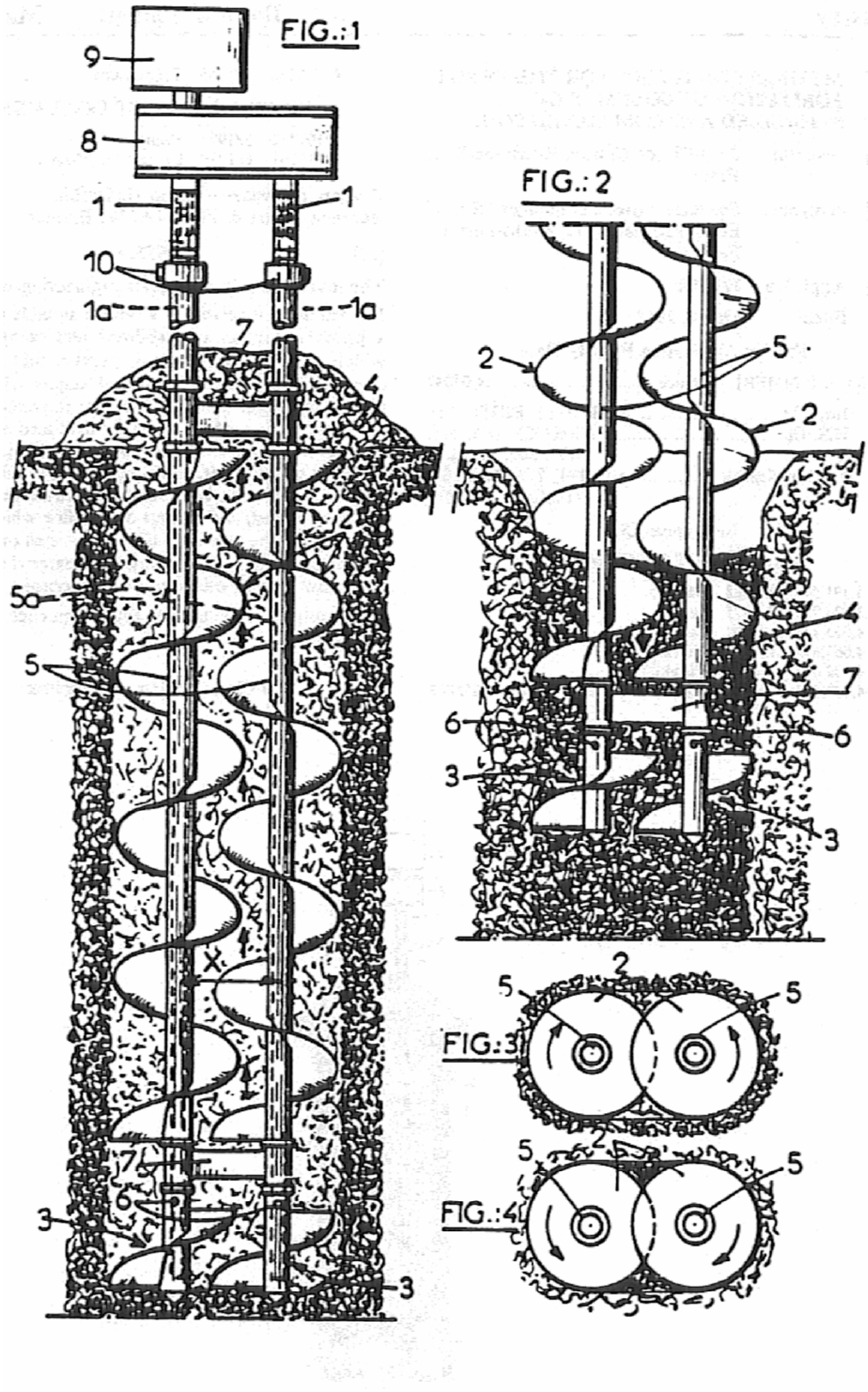

Figure 30. Auger configurations – U.S. patent (1987).

United States Patent [19]
Gessay

[11] **Patent Number:** **4,662,792**
[45] **Date of Patent:** **May 5, 1987**

[54] **METHOD AND DEVICE FOR THE IN-SITU FORMATION OF COLUMNS OF STABILIZED AND COMPACTED SOIL**

[75] Inventor: **Jean-Claude Gessay**, Roissy-en-Brie, France

[73] Assignee: **Sondages Injections Forages "S.I.F." Enterprise Bachy**, Levallois-Perret, France

[21] Appl. No.: **729,798**

[22] Filed: **May 2, 1985**

[30] **Foreign Application Priority Data**

May 7, 1984 [FR] France 84 07047

[51] **Int. Cl.⁴** **E02D 3/12; E02D 5/46**
[52] **U.S. Cl.** **405/233; 405/241; 405/269; 405/271**
[58] **Field of Search** **405/241, 263, 266, 267, 405/269, 271, 233**

[56] **References Cited**

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2010361	6/1979	United Kingdom .

Primary Examiner—David H. Corbin
Attorney, Agent, or Firm—A. W. Breiner

[57] **ABSTRACT**

The invention relates to civil engineering works.

In particular, it relates to a device suitable for forming a primary column of stabilized and compacted soil, which comprises at least two parallel shafts driving in opposite directions, two parallel augers with opposite pitch, each auger being provided at the opposite end to the drive shaft with a loosening drillhead and the distance between the axes of the augers being less than the diameter of an auger, the shafts and the shanks of the augers comprising a bore connected to a source of material to be added, and at least one orifice which communicates with the said bore being provided on the shank of each auger so as to discharge the material to be added and allow it to be mixed with the loosened soil.

Applicable in particular for the compaction of railroad territory.

6 Claims, 4 Drawing Figures

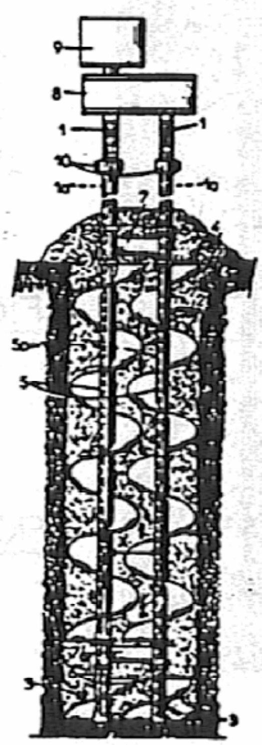

Figure 31. Excerpt from U.S. Patent (1987).

Auger	W mm	L mm	Section m²	Perimeter m
Twin	230	410	0.08	1.08
	290	500	0.13	1.33
	360	625	0.20	1.66
	420	740	0.27	1.96
	500	875	0.38	2.32
Triple	360	890	0.29	2.19
	420	1060	0.41	2.60
	500	1250	0.57	3.07
Quadruple	500	875	0.69	3.27
	850	1490	2.00	5.56

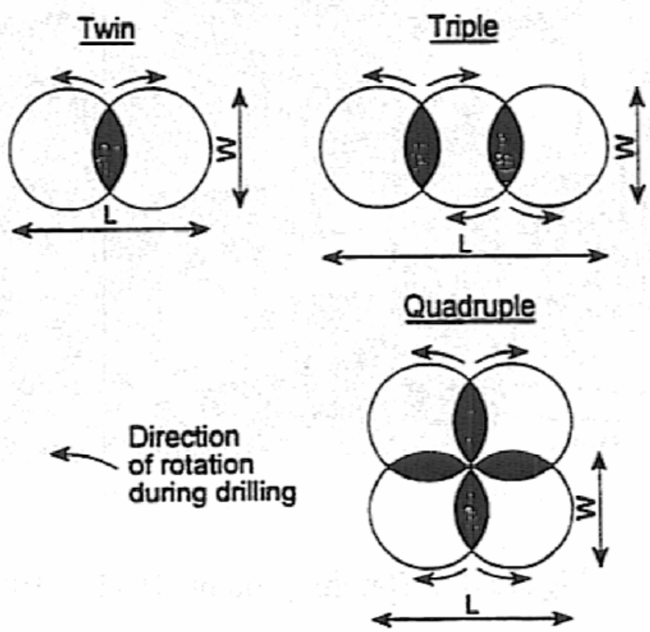

Figure 32. Various auger configurations and dimensions of the Colmix system (Bachy literature, 1996).

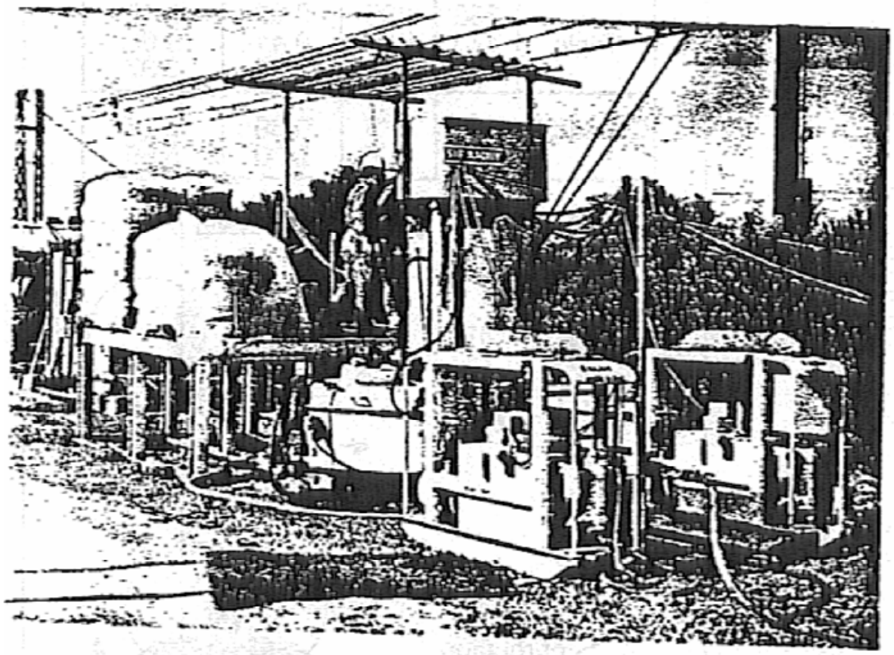

Figure 33. Batching plant (Bachy, 1996).

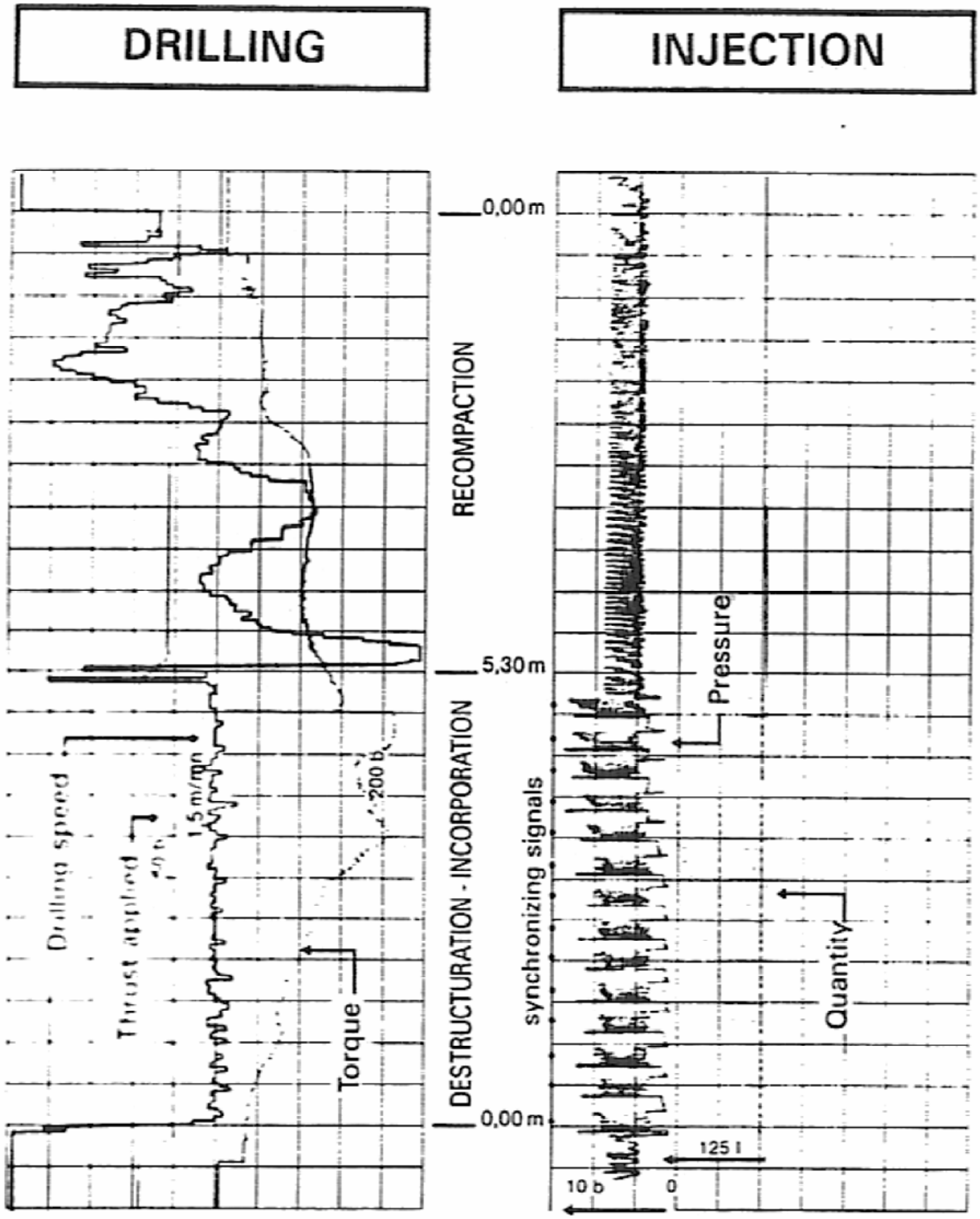

Figure 34. Records of drilling and injection parameters (Bachy, 1996).

SOIL REMOVAL TECHNIQUE – SRT (5)

1. INTRODUCTION

The Soil Removal Technique (SRT) is classified as WRS. The process was developed to alleviate horizontal deformation of the soil potentially caused by conventional CDM methods and hence displacement of adjacent underground structures. This new method was developed to minimize such horizontal soil displacement by removing soil during the penetration phase, thus countering the effects of volume increase during cement injection. The development of this system is in the operational prototype stage.

2. GENERAL PROCESS

The upper continuous flight augers remove the soil during penetration. Cement slurry is injected while the augers are being withdrawn.

3. EQUIPMENT

<u>Base</u> The equipment is similar to CDM double-auger set-ups, except for the shaft configuration (Figure 35).

<u>Shafts</u> This system consists of a dual-shaft assembly mounted on a set of fixed leads. Continuous flight augers are located at the top of the shaft, underlain by a series of three horizontal mixing vanes, and an auger with cutting teeth at the base of the shaft. Grout is injected through upper nozzles located between the continuous flight augers and the mixing blades, and lower nozzles located within the excavation auger. This produces columns of 1 to 1.2 m in diameter, to a claimed maximum depth of 40 m. Mixing paddles or blades are located directly above the excavation blade.

<u>Grout Plant</u> Assumed to be equivalent to current CDM equipment.

<u>Control</u> Assumed to be equivalent to current CDM equipment.

<u>Production</u> Assumed to be equivalent to current CDM equipment.

4. MIX CHARACTERISTICS

<u>Grout</u>. Cement grout of unreported composition was used with no reported cement or volume factor. Assumed to be similar to CDM.

<u>Treated Soil</u>. Target strength of 0.5 MPa in soft silt was achieved. Lateral displacements were reduced to 9 mm, which was 11 to 33% of conventional CDM displacements in this example.

Cores showed that the strength of the treated soil was only 70% of the conventional CDM due to the effects of soil removal at the particular water/cement ratio selected.

5. PATENTED/PROTECTED FEATURES.

There are no patents on this system identified in the reference cited below, but some may exist.

6. PARTICULAR ADVANTAGES

The method reduces horizontal displacement/stresses imposed during mixing, and also obviates the need for pre-augering.

7. OPERATING COMPANY

The equipment was developed by Shimizu Corp. of Japan, and the system has been tested in Japan.

8. REFERENCE

Hirai, T., J. Ise, T. Kusakari, M. Gotou, and Y. Hibi. (1996). "Development and Application of the Deep Mixing Soil Stabilization Method to Control Displacement of Adjacent Ground." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 485-490.

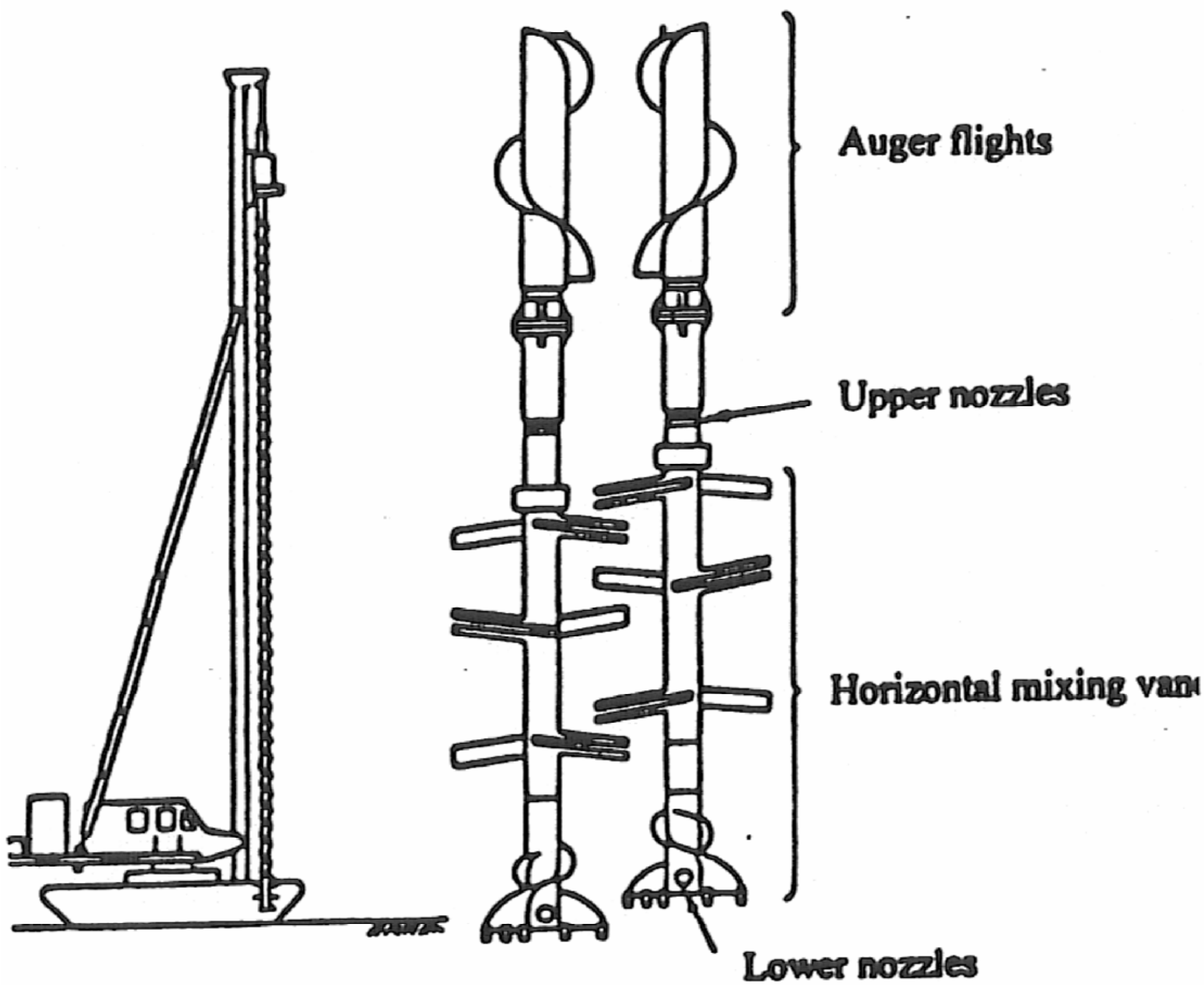

Figure 35. Shaft configuration for Soil Removal Technique (Hirai et al., 1996).

CEMENT DEEP MIXING – CDM (6)
(Also incorporating FGC-CDM)

1. INTRODUCTION

The CDM Association was formed in 1977 and encompasses a large number of very similar WRE variations, different only in certain details of the equipment used. CDM was originally used for massive marine projects in order to stabilize soft cohesive soils and fills, but it is now also used on land-based projects for ground treatment, improvement, and retention. CDM is the contemporary group name for a series of earlier and current methods developed by different contractors, such as DCM, CMC, DCCM, RDM (Raito, Inc.), DECOM (Toa Corp.), Demic, POCM (Penta Ocean Chemical Mixing), and so on.

Currently, a new offshoot, FGC-CDM, is being developed in which flyash and gypsum are used (together with cement) in the grout to provide low-strength treated soil, while still encouraging sufficient fluid injection to facilitate efficient penetration and mixing.

CDM was developed in Japan under the "instruction" of the Port & Harbor Research Institute of the Ministry of Transportation, "and other customers" (CDM, 1994). A general CDM brochure is provided as Attachment 2, and a brochure on RDM is included as Attachment 3.

The technique is offered in the United States by Raito., Inc, in California, who won the first U.S. application in early 1999.

2. GENERAL PROCESS

The machine carries from two (typical on DCM) to eight overlapping shafts (most common) for marine work, each of a diameter of 1 to 1.6 m. Up to 12 shafts on one carrier have been used. For land work, each machine has one or two shafts (e.g., RDM), each typically 0.7 to 1.0 m in diameter. Each shaft has four to six mixing blades. The maximum depth capacity is 70 m below sea level (marine) or 40 m (land).

The shafts are simultaneously advanced at rotational speeds of 20 to 30 rpm, usually accompanied by some grout injection at a rate of 0.5 to 2.0 m/min (1 m/min average). At target depth, a final 2 to 8 min of in situ mixing occurs, followed by withdrawal at up to 60 rpm at 1 to 2 m/min and the injection of the balance of the grout via the upper injection port. The paddles on adjacent shafts overlap in plan and are staggered in height to promote efficient mixing.

For FGC-CDM, "slight equipment modifications" (Terashi, 1997) are required (unspecified).

3. EQUIPMENT (Figures 36, 37, 38, and 39)

Base — For marine work, this is typically a large, barge-mounted tower or derrick. For land work, details are provided in Figure 37 for the typical double-shaft rig.

Shafts — Details of typical treated soil volumes (in one pass) are shown in Figure 38, while typical shaft geometries are illustrated in Figure 39 (with SMW shafts for contrast.)

Grout Plant — Details are provided in Figures 36 and 38.

Control — A very high emphasis is placed on the automated control and recording of the various drilling and injection parameters, as illustrated in Figure 40 and in Attachment 2. The use of the Execution Management Unit is claimed to offer real-time understanding of actual field conditions, reliable execution, and excellent quality control and assurance.

Production — Instantaneous production is illustrated in Figure 44, reflecting the information provided in Section 2 above, and is summarized below:

tl	Time for surveying, positioning mixing blades	10 to 15 minutes
vl	Penetration speed of mixer in unimproved part	0.5-2.0 m/min – depending on soil stiffness
v2	Penetration speed of mixer in improved part	0.5-2.0 m/min – depending on soil stiffness
t2	Time for improving the tip	2.0 minutes
v3	Withdrawal speed of mixer in improved part	0.5-1.5 m/min – depending on soil stiffness
v4	Withdrawal speed of mixer in unimproved part	0.5-1.5 m/min – depending on soil stiffness

Industrial output for marine works is about 1,000 m^3 of ground treatment per shift. For landwork, the output is 10 to 20% of this figure.

4. MIX CHARACTERISTICS

Injected Materials. The process typically uses Portland or blast furnace cement, with fresh water or seawater. Cementitious materials are added at a rate of about 140 to 300 kg (dry) per cubic meter of soil to be treated. The water/cement ratio varies from 0.6 to 1.3 (typically 1.0). By volume, slurry ranges from 150 to 300 L/m^3 of soil to be treated. Accelerating additives can be used, as can dispersants and stabilizers. Other binders include bentonite, gypsum, and flyash, as for example, in CDM-FGC.

Treated Soil. The reaction of the grout and the soil (presumably also the case with the dry methods) is a two-phase chemical reaction (Figure 42):

- Hydration of cement and water forming "an ettringite of capillary crystals."
- With time, the hydration production generates a pozzolanic reaction with the clay minerals in the soil.

It was concluded by Asano et al. (1996) that there is a direct relationship between the water/cement ratio in soilcrete and its unconfined compressive strength, regardless of the composition of the grout or its age (Figure 43). They experimented with FGC-CDM, where flyash and gypsum were substituted for cement to give low-strength soilcrete (< 0.5 MPa) while maintaining high grout volume factors (250 to 400 L/m^3) to ensure lubrication and good mixing (Figure 44). Low strengths were also made possible by using lime substitution (0.5 to 1.5 MPa) for cement (e.g., C:L = 4:6, slurry content 200 L/m^3). Otherwise, for normal CDM, strengths for 200- to 300-L/m^3 grout are 2 to 4 MPa. The ratio of 60- to 28-day strength is about 1.4 to 1.5, and the ratio of 28- to 7-day strength is about 1.5. The cement factor also controls the strength of the treated soil, as shown in laboratory tests (Figure 45). Field and laboratory variations in strength with soil type, w/c ratio, cement factor, and procedure for CDM used at Yantai (Min, 1996) are shown in Figure 46. Further data on the influence of the cement factor and grout composition on strength are shown in Figure 47, and for the influence on soil type and depth are shown in Figure 48. Terashi (1997) reports that for lime-treated marine clay in a Japanese project, the ratio between 15-year and 60-day field strengths was almost 3 to 1.

In general, there is also evidence that laboratory sample strengths are somewhat higher for equivalent conditions than for field sample strengths. The ratio of UCS to shear strength is about 2 when UCS< 1 MPa, but is reduced as the UCS increases.

Tensile strength is 8 to 20% UCS. (Typically, 15% is used for design purposes.)

The ratio of UCS to E-value (E_{50}) for laboratory samples is shown in Figure 49 [1:350 to 1,000], and for field samples in Figure 50 [1:150 to 500]. Okumura (1996) states that the ratio increases "exponentially" depending on the UCS. In cohesive soils with sand contents less than 10 to 15%, the ratio is 400 to 600.

Deterioration of soilcrete under exposure to marine conditions increases with the log of time.

Permeability of treated soil is usually in the range of 10^{-8} to 10^{-9} m/s; it is lower if bentonite is used, or if the clay is treated, or if more cement is added (Figure 51).

Special field tests have been conducted widely by the Japanese Government and the CDM Association. These are summarized in the proceedings of the Tokyo conference (1996).

5. PROTECTED OR PATENTED FEATURES.

The use of this method is controlled by the CDM Association in Japan, although in recent years, the Chinese have also developed "native" CDM.

6. PARTICULAR ADVANTAGES

- Excellent for treating large volumes of soft soil.
- Excellent research and development history and data (e.g., relationship of mix design and treated soil strength).
- Powerful association and members.
- Long history of successful application.
- Low noise, vibration, and contamination potential.
- Centralized control system.
- Low to moderate spoils.

7. OPERATING COMPANIES – GEOGRAPHIC REGION

The process was developed by the Port and Harbor Research Institute of the Ministry of Transportation of the Japanese Government from research which began in 1967. The CDM Association was established in Japan in 1977 and has 48 member companies – contractors, manufacturers, and suppliers. Only members of the CDM Association are permitted to participate, although China has independently followed Japanese developments since 1993. By far, the greatest volume of work is still conducted in Japan, and no case histories appear to have been produced on work outside of Japan or China. One example to date has been executed in the United States. Through March 1991, the total volume of soil treated was 18.1 million m^3 (Figure 52), most of which would seem to have been for marine projects (Figure 53). The mainspring behind FGC-CDM is the Electric Power Development Company.

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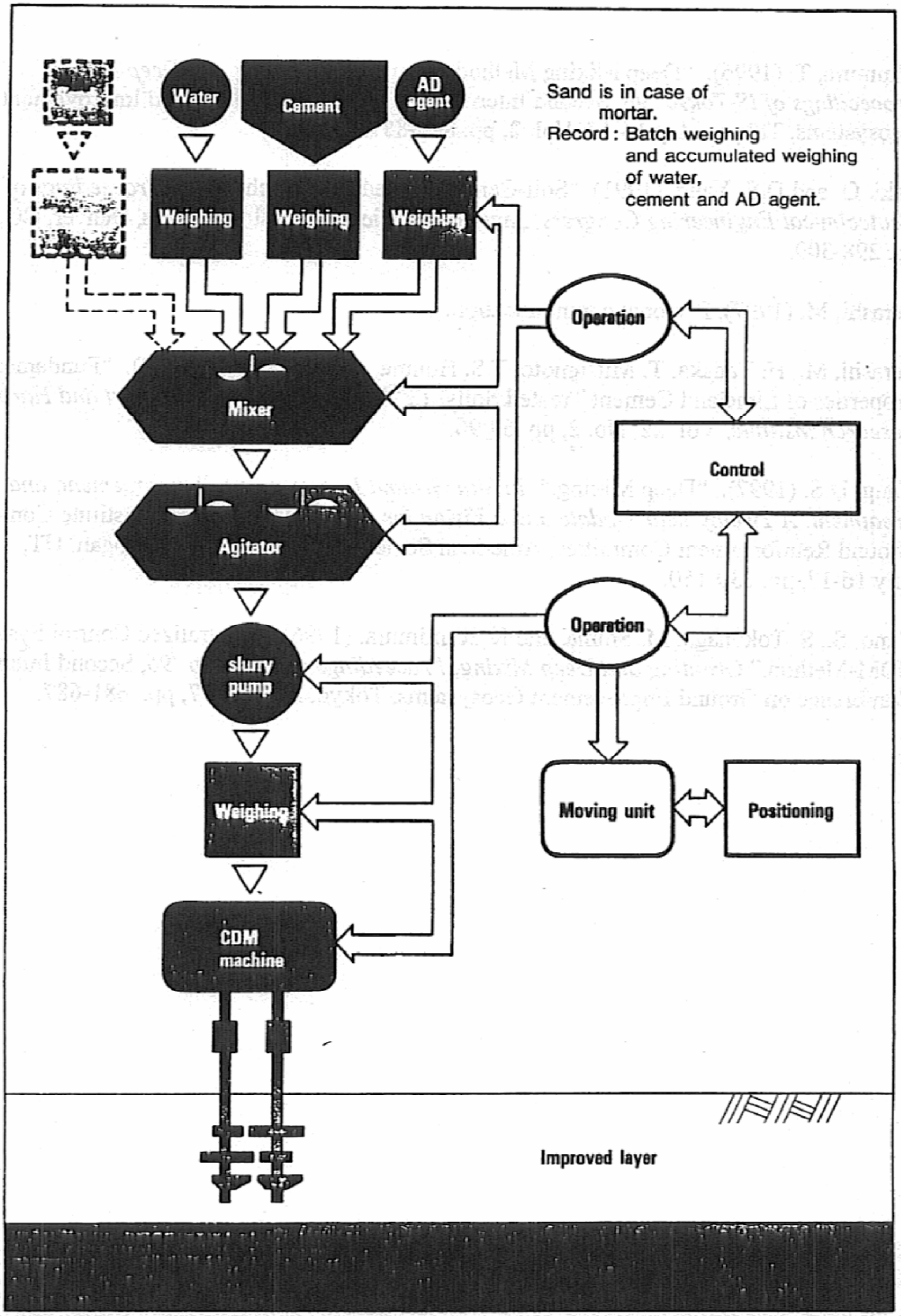
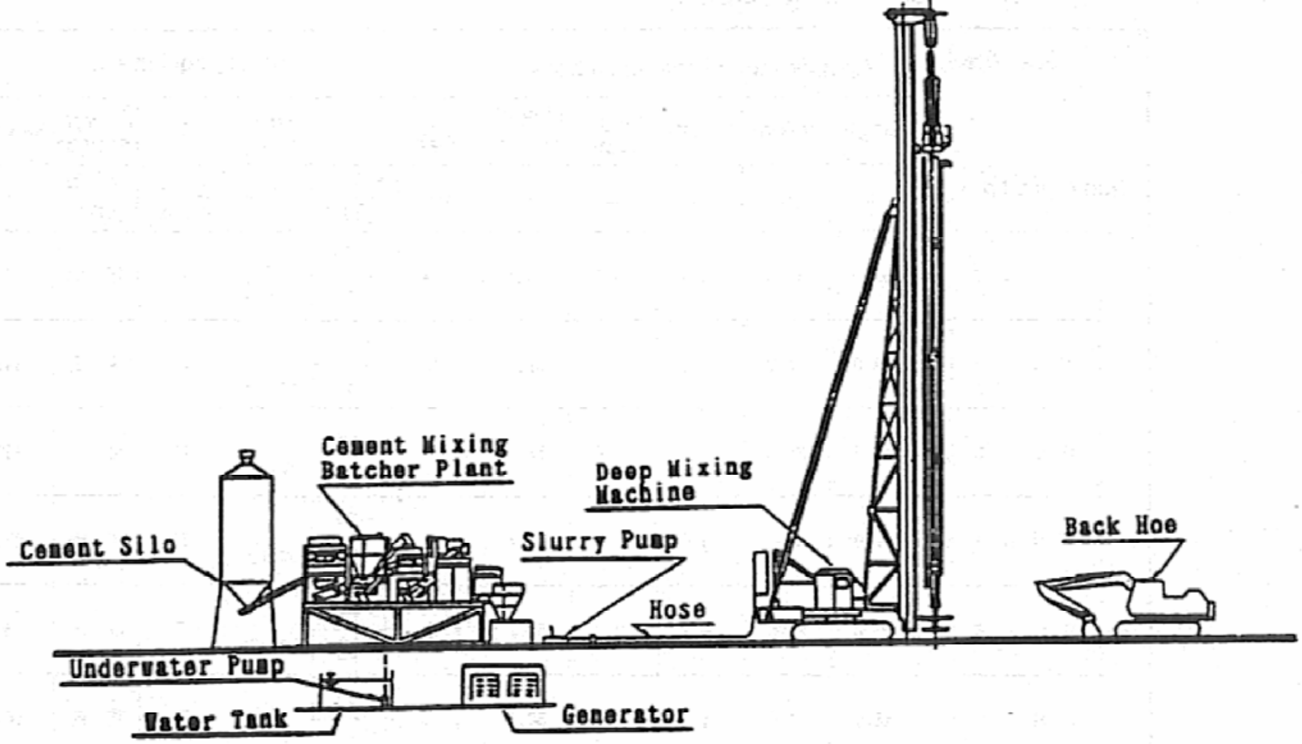
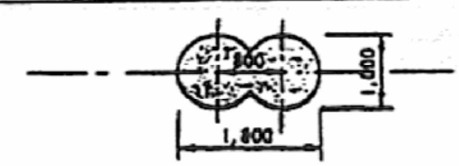


Figure 36. Procedures of the CDM Method (CDM Association, 1996).



Maximum Penetration Length / Machine	10m	20m	30m	40m
Deep Mixing Machine (Including the system control meters)	Crawler Crane: 25 to 27 tons Leader Length: 20m Processor Output: 45KW × 2	Crawler Crane: 35 to 37 tons Leader Length: 30m Processor Output: 55KW to 60KW × 2	Crawler Crane: 50 to 55 tons Leader Length: 40m Processor Output: 75KW to 90KW × 2	Crawler Crane: 50 to 55 tons (Special Crawler Device) Leader Length: 50m Processor Output: 75KW to 90KW × 2
Generated Power	250KVA	300KVA	400KAV	450KVA
Back Hoe	Crawler Type 0.8m^3	Crawler Type 0.8m^3	Crawler Type 0.8m^3	Crawler Type 0.8m^3
Cement Mixing Plant	10m^3/h	10~20m^3/h	30m^3/h	20m^3/h
Cement Silo	30t	30t	30t	30t
Water Tank	10m^3	10m^3	10m^3	10m^3
Underwater Pump	100mm × 2 units	100mm × 2 units	100mm × 2 units	100mm × 2 units
Grout Pump	200 liters/min. × 2 units	200 liters to 300 liters/min. × 2 units	300 liters/min. × 2 units	300 liters/min. × 2 units
Agitator Tank	2m^3	2~5m^3	5m^3	5m^3
Generator Power	100KVA	100~125KVA	125KVA	125KVA
Standard Improved Cross Section				

Notes: 1. The configuration of the machinery operated in conjunction with the cement mixing plant varies according to the amount of admixtures, length of the improvement, etc.
2. When soil quality and execution conditions make the use of the configurations presented in this table difficult, other configurations are considered.

Figure 37. Equipment configuration for the CDM method (Yano et al., 1996).

Cement Deep Mixing (CDM)

	Specification / Name of ship	Specification of ship main body: Length	Width	Depth	Water draft	Height tower	Mixing equipment: Impr area	1	Prod rate	2	Power source	Weight
		m	m	m	m	m	m²	水7 m 海8面下	m³/hr	C：3 F：4	電5動 油6圧	t
一船式	デコム7号	63.0	30.0	4.5	3.2	69.5	5.74	−70 50	e 90以上	C	電 動	410
	ポコム2号	48.0	28.0	4.1	3.0	61.0	5.75	−65 40	e 90以上	C	油 圧	341
	DCM3号	47.5	28.0	4.6	3.0	55.5	5.74	−65 40	e 90以上	C	油 圧	330
	デコム5号	60.0	27.0	4.0	2.7	67.4	6.91	−60	e 90以上	F	電 動	270
	DCM6号	56.0	26.0	4.2	2.2	52.2	4.42	−60 38	c 50~70	F	油 圧	160
	CMC8号	53.0	24.0	4.0	2.0	58.4	4.63	−43	c 50~70	F	電 動	105
	ポコム10号	52.0	22.8	4.0	2.8	60.5	3.81 (4.65)	−49 40	c 50~70	F	油 圧	178
	ポコム11号	50.0	24.0	3.6	2.0	56.0	3.81	−40 36	c 50~70	F	電 動	120
	ポコム8号	38.0	14.0	2.3	1.5	36.0	2.23	−30	b 30~50	F	電 動	58
	CMC3号	36.0	15.0	2.5	1.8	46.0	2.0	−35	a 30以下	F	電 動	21
	CMC5号	40.0	18.0	3.5	2.0	45.0	2.0	−35	a 30以下	F	電 動	21
	デコムS－3号	30.0	15.0	3.0	1.5	35.0	1.74	−26	a 30以下	F	油 圧	16
二船式	DCM5号	38.6	18.6	3.2	1.4	36.5	3.47	−40 25	b 30~50	F	油 圧	60
	デコムS－5号	26.0	10.5	2.2	1.2	30.0	1.5	−21.5	a 30以下	F	電 動	20

1. Depth of Improved Area
2. Location of mixing equipment
3. C: Center
4. F: Front
5. Hydraulic
6. Electric
7. Below water surface
8. Below sea floor

Figure 38. Geometries of columns produced in one pass and details of the grout (after CDM Association, 1994) (1 of 2 pages).

Torque	Horse power	Grout Plant: cement silo	Mixer-	Agitator	Grout pump	Remarks
kg·m	ps	t×基	m³×基	m³×基	l/min×台	
4,000	4,500	400×4	3.5×2	18×1	250×8	
4,100	5,020	250×4	3.5×1	9×1	150×12	
4,000	5,830	150×2	2.6×2	20×1	250×8	
7,000	3,600	300×4	3.5×1	9×1	250×8	
2,250	3,400	150×2	2.0×2	20×1	250×8	
4,890	2,400	150×2	1.5×2	6×2	420×4	
4,200	2,620	150×2	2.0×1	5×1	200×4 450×2	H.7.6には (　　)の仕様に 改造が完了予定
3,300	3,460	150×2	2.0×1	·5×1	200×4 450×2	H.7.2 完成予定
3,000	1,090	120×1	2.2×1	6×1	250×4	
1,440	1,150	50×1	1.5×1	4×1	600×2	
1,440	1,030	50×2	1.0×1	2×1	600×2	
1,350	300	50×1	0.85×1	2×1	120×2	
2,000	1,940	100×2	2.0×2	5×1	250×4	
2,550	700	30×1	2.9×1	2×1	300×2	

Configuration

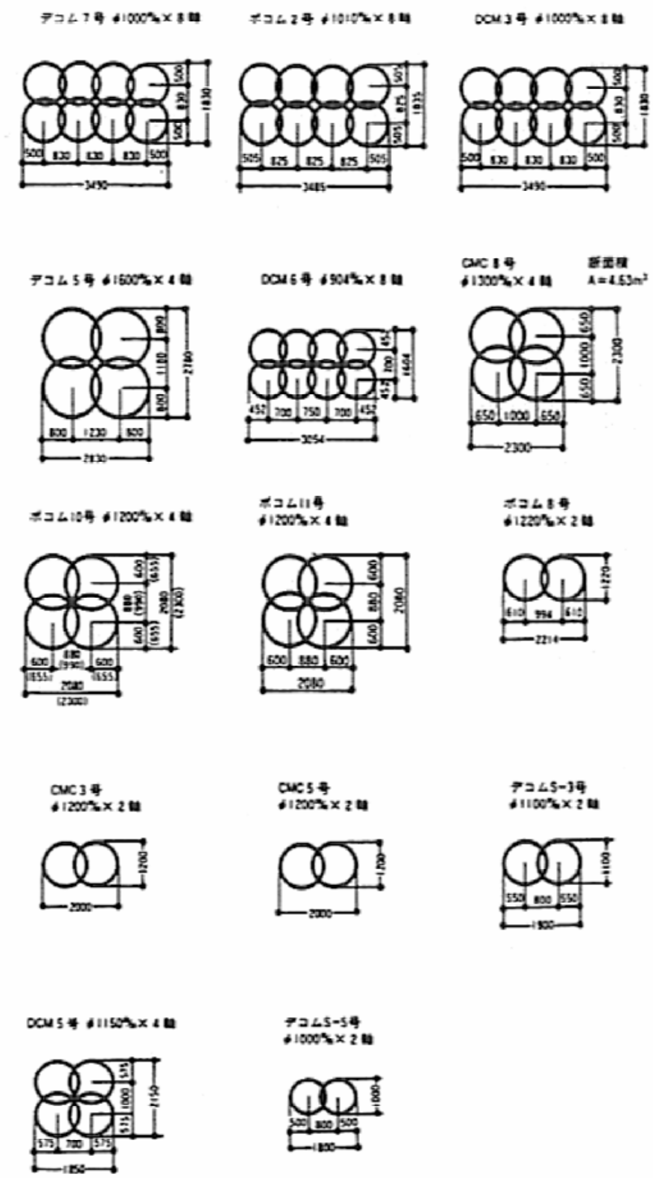


Figure 38. Geometries of columns produced in one pass and details of the grout (after CDM Association, 1994) (2 of 2 pages).

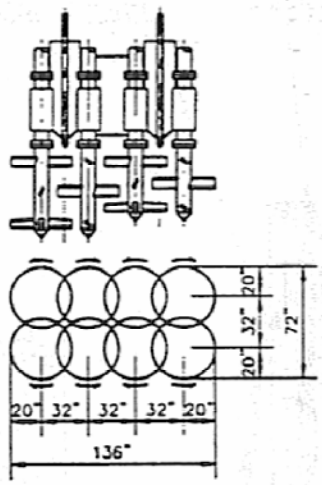
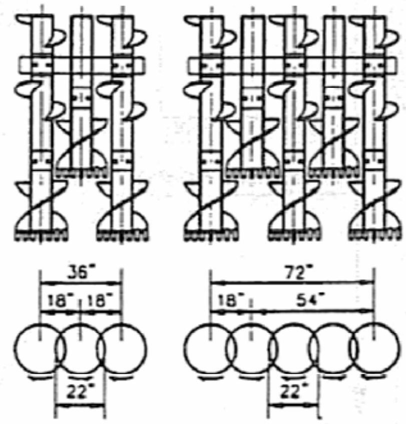
Title	CDM Cement Deep Mixing	SMW Soil Mix Wall
Sketches of Representative Mixing Mechanisms	 ø = 39" to 63" available 1 ft = 0.305 m	 ø = 22" to 40" available 1 ft = 0.305 m
Descriptions	Rotation of multiple axis shafts create relative movement and shear in soil for soil-reagent mixing.	Uses multiple auger, paddle shafts rotating in alternating directions to mix in situ soil with cement grout or other reagents to form continuous soil-cement walls.
Number of Mixing Shafts	2,4,6,8 shafts.	1, 2, 3, & 5 shafts.
Major Reagents	Cement grout, lime or other cementitious slurry.	Cement grout, bentonite slurry, clay slurry, or other stabilizing reagent slurries.
Applicable Subsurface Soils	Very soft silt and clay or very loose sandy soils usually undersea.	Soft to hard silt and clay, loose to very dense sand, gravel, an cobble soils. Cobble and boulder soil and bedrock with predrilling.
Major Applications	Large scale soil stabilization of sea floor for offshore or waterfront development.	Continuous walls for excavation support and groundwater control; Column blocks, lattice, or areal patterns for stabilization.
Remarks	Developed by Port and Harbor Research Institute.	Developed by Seiko Kogyo, Co. Ltd.

Figure 39. Comparison of the CDM and SMW systems (Taki and Yang, 1991).

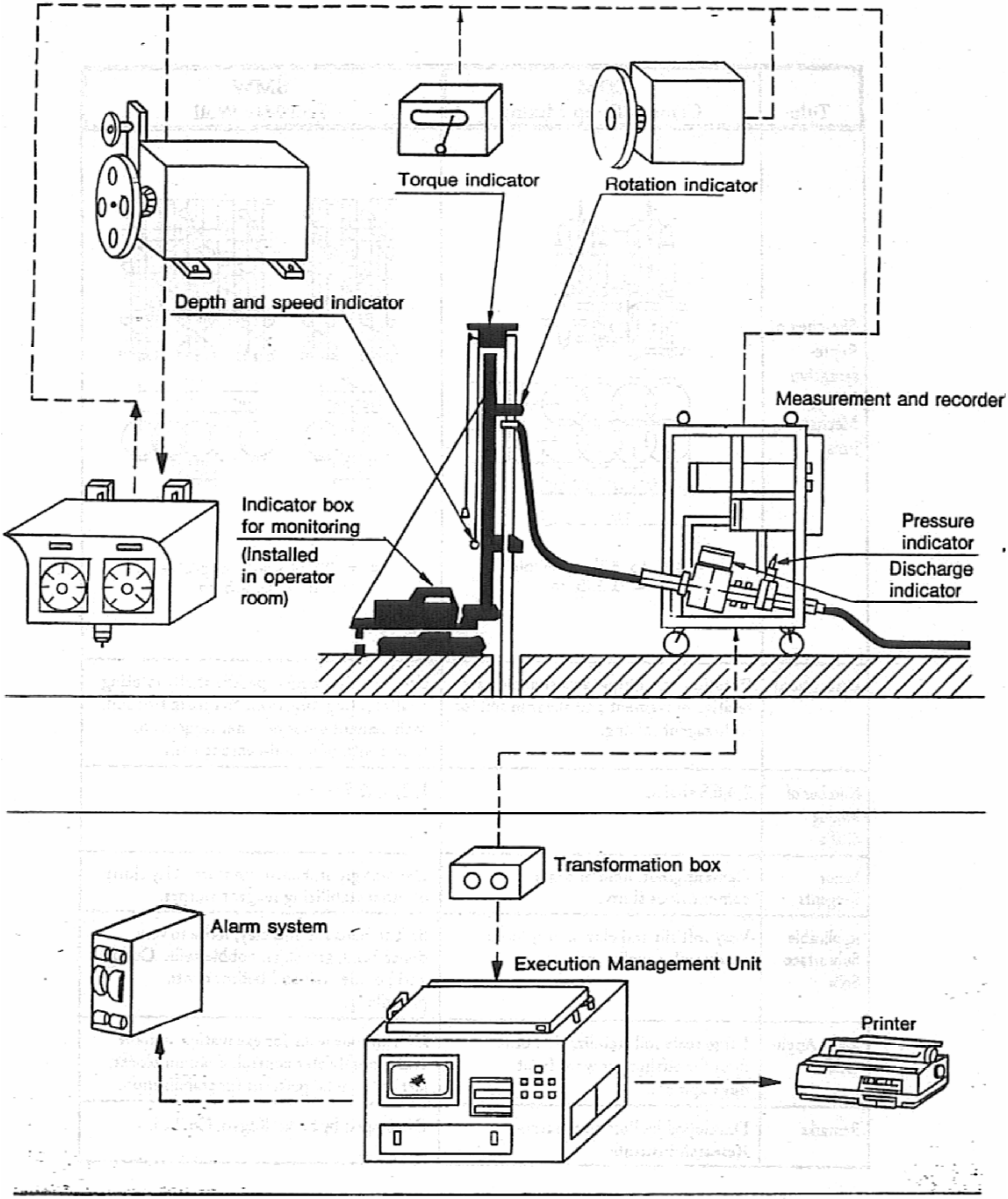


Figure 40. Computer control and management systems (Yano et al., 1996).

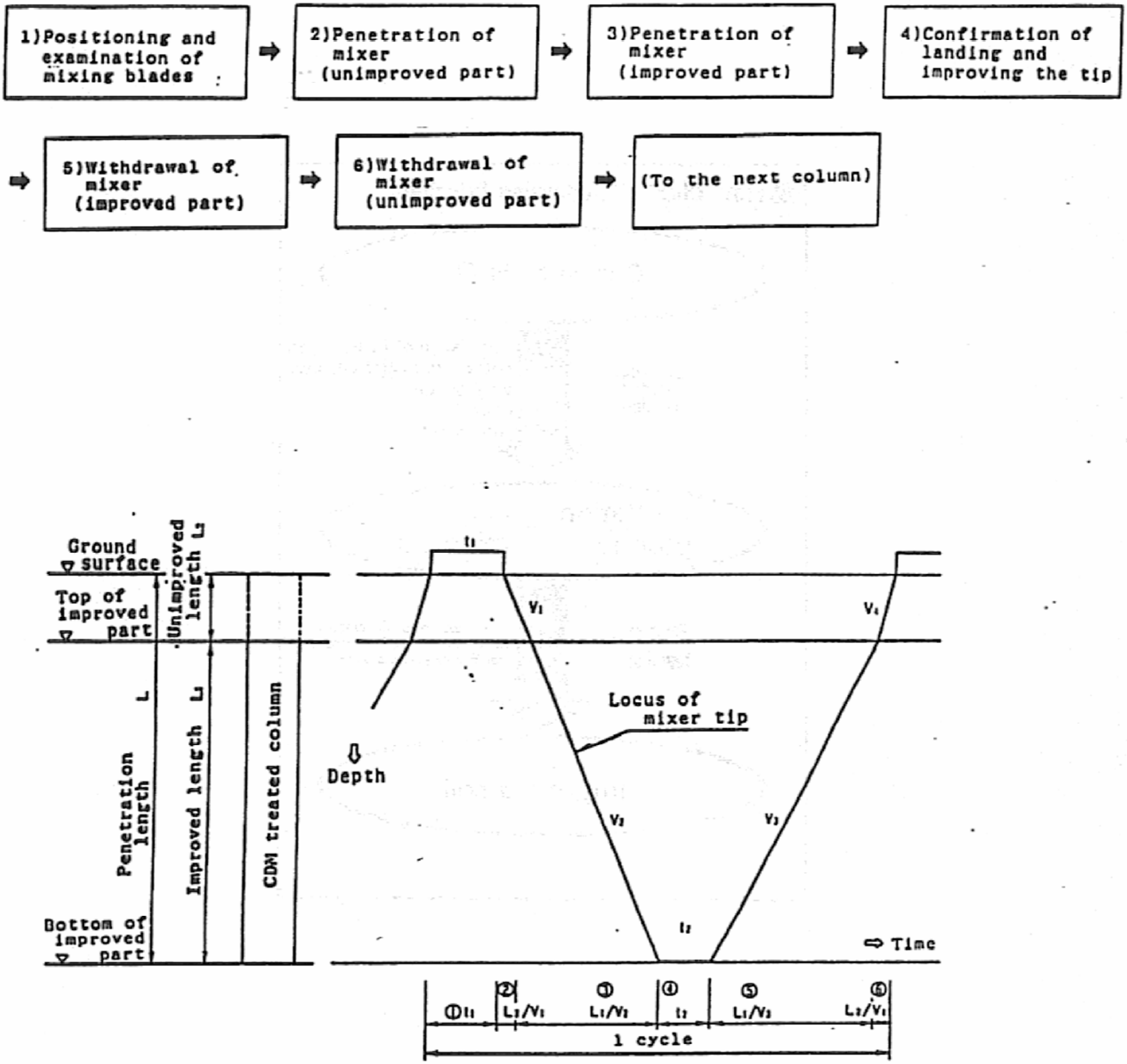


Figure 41. Instantaneous production (CDM Association, 1994).

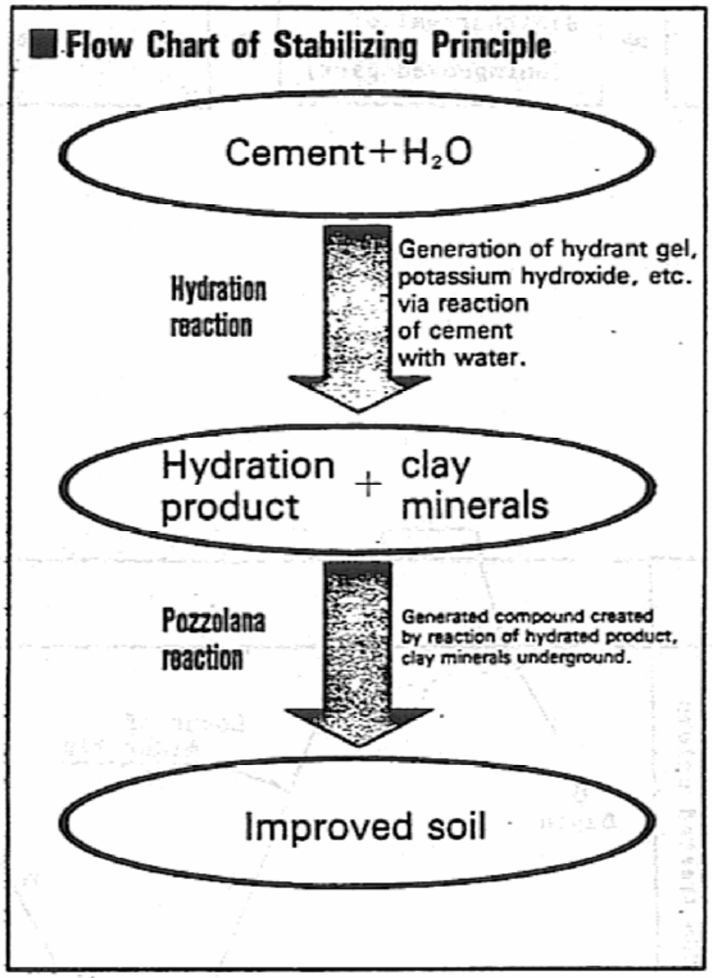


Figure 42. Reaction of the grout and the soil (CDM Association, 1994).

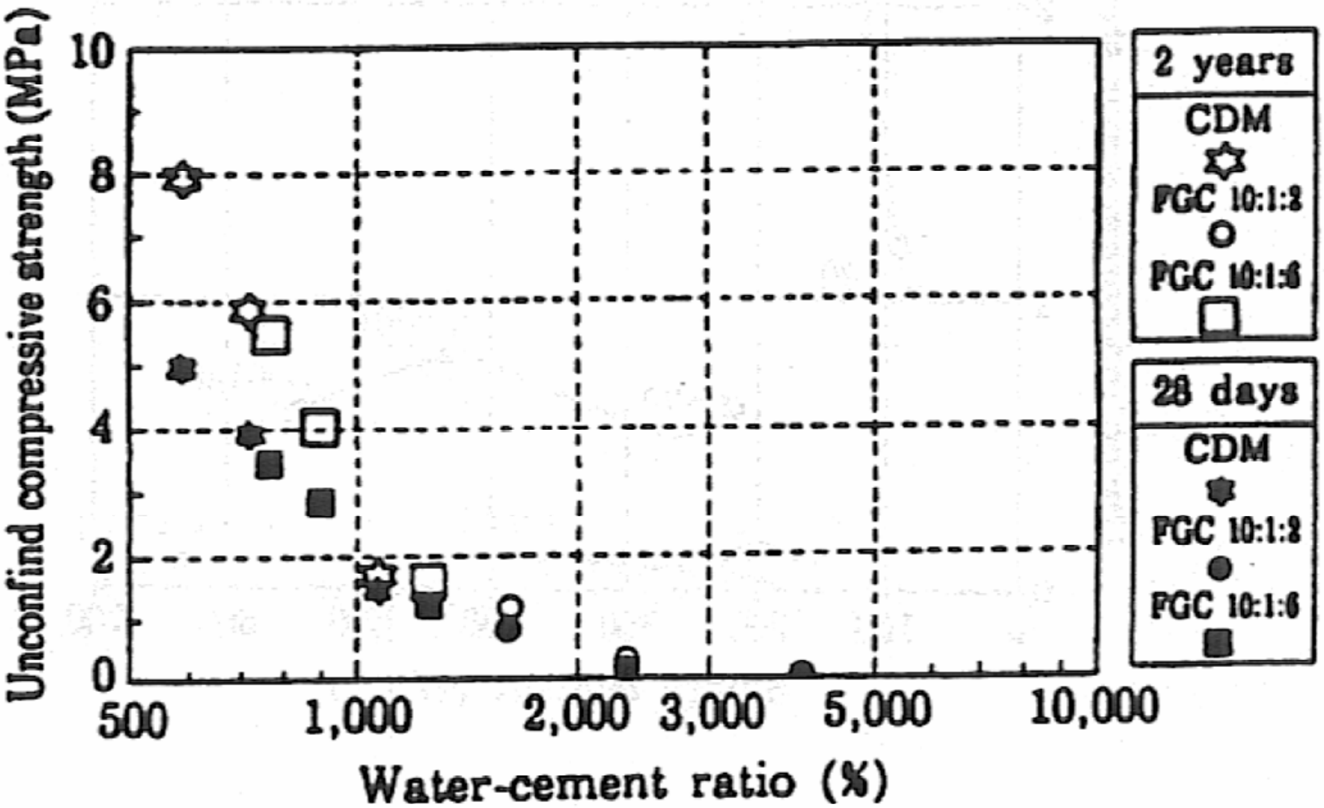


Figure 43. Relationship between water-cement ratio and unconfined compressive strength (Asano et al., 1996).

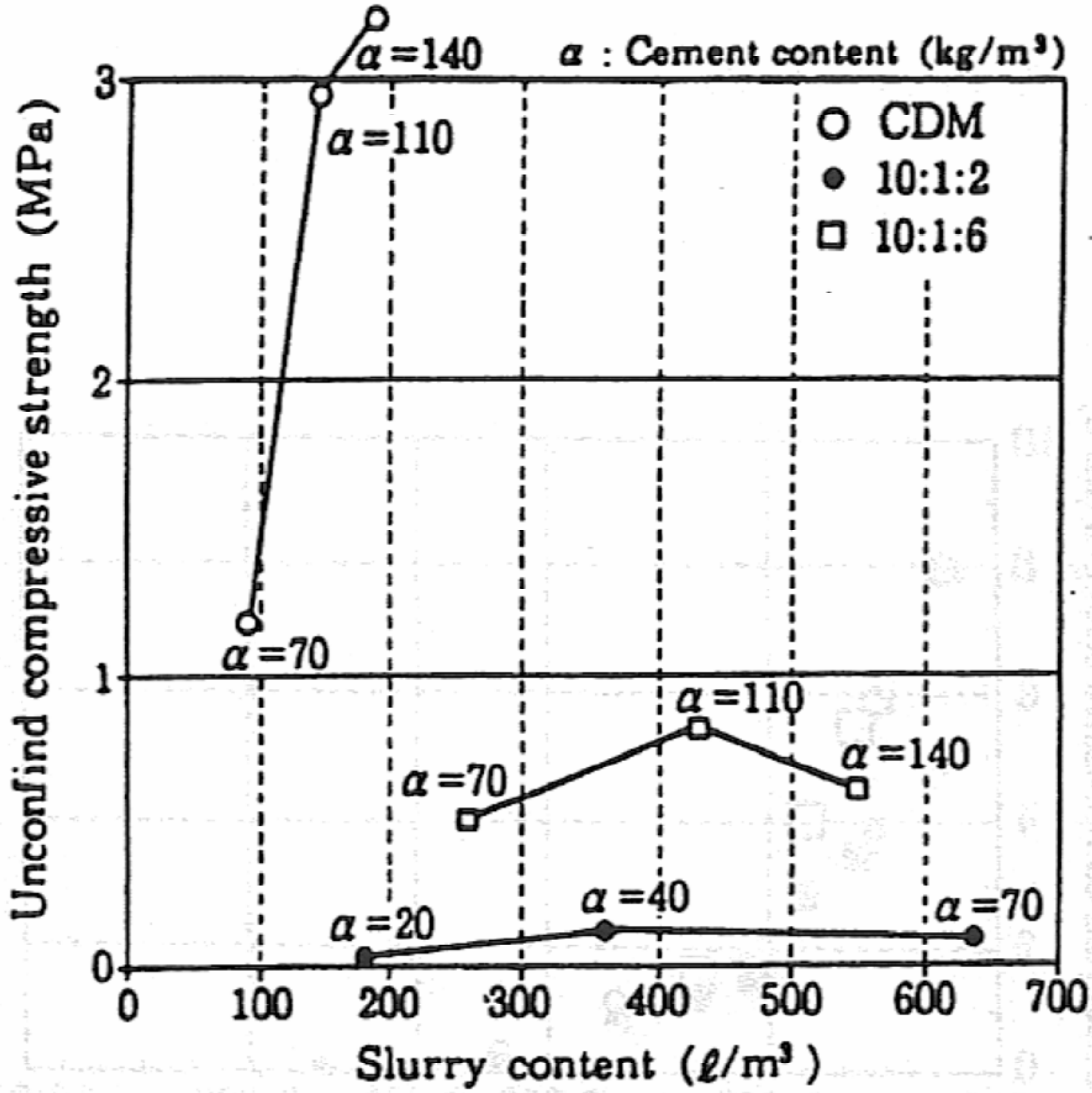


Figure 44. Relationship between slurry content and unconfined compressive strength (Asano et al., 1996).

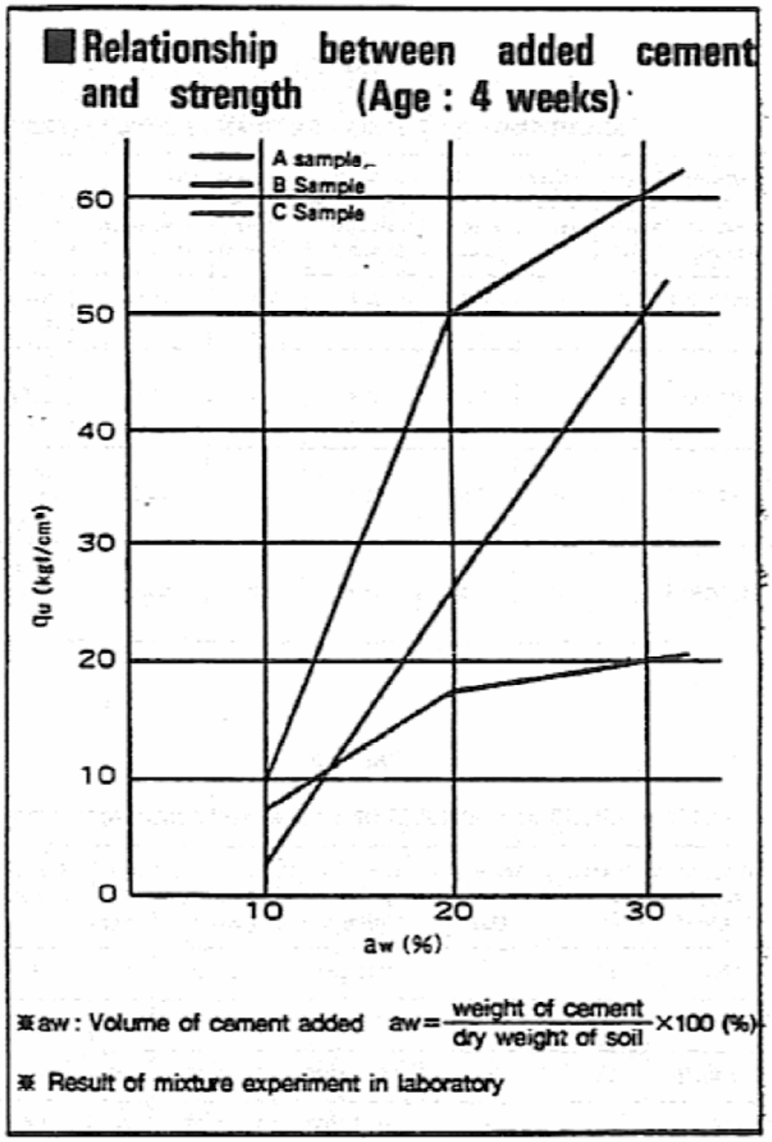


Figure 45. Relationship of treated soil strength to cement factor (CDM Association, 1994).

TABLE 1

PROPERTIES OF SUBMARINE SOILS AT YANTAI PORT

Description of soils	Water content (%)	Specific gravity	Activity* (mS/cm)	Mineralogical composition		Organic content (%)	Humus content (%)	pH value	Soluble salt content (%)
				main	secondary				
Silt	32	2.68	0.75	quartz	grundite, chlorite	1.51	0.063	7.45	0.434
Silt of low plasticity	28	2.67	0.77	quartz	chlorite	0.77	/	7.70	0.210

NOTE: * The activity of a soil is evaluated by its conductivity.
Conductivity < 0.4 mS/cm - non-pozzolana; 0.4mS/cm < conductivity < 1.2mS/cm - ordinary pozzolanicity; conductivity > 1.2mS/cm - good pozzolanicity

TABLE 2

READJUSTMENTS OF MIXING RATIO AND MIXING PROCEDURE

Time	Amount of cement (kg/m3)	Water content (W/C)	Admixture (%)	Penetration		Withdrawal		Reasons of readjustment
				speed (m/min)	revolution (r.p.m.)	speed (m/min)	revolution (r.p.m.)	
Dec. 1992	190/170	1.3	/	0.7, 1.0	25.4	1.0	25.4	Based on laboratory mixing ratio test
Apr. - June 1993	200/180	1.0	/	0.5	25.4	1.0	50.8	Strength low and poor uniformity according to the first test on field samples
July - Sept 1993	230/170	0.9	3	0.5	25.4	1.0	50.8	Strength still lower than required according to the second test on field samples
After Sept 1993	190/160	0.9	3	0.5	25.4	1.0	50.8	Strength a bit higher than required according to the third test on field samples

TABLE 3

FIELD SAMPLING AND RESULTS OF LABORATORY STRENGTH TESTS

Sampling number	Borehole number	Amount of cement (kg/m3)	Water/cement ratio	Amount of admixture (%)	Time of CDM operation (d/m/yr)	Time of sampling (d/m/yr)	Age day	Sampling rate (%)	Number of samples	Average strength (MPa)
I	1	170/160	1.3	/	7.12.1992	3.4.1993	88	78	22	0.28-21.62*
II	2	200/180	1.0	/	17. 4.1993	18. 6.1993	62	100	24	1.61
	3	200/180	1.0	/	13. 4.1993	20. 6.1993	68	100	24	2.26
III	4	230/170	0.9	3	20. 7.1993	18. 9.1993	60	100	18	3.02
	5	230/170	0.9	3	15. 7.1993	18. 9.1993	65	100	22	2.45
	6	230/170	0.8	3	16. 7.1993	20. 9.1993	66	100	21	3.87
	7	230/170	1.0	/	15. 7.1993	22. 9.1993	69	100	17	3.38
IV	8	190/160	0.9	3	25. 9.1993	15.12.1993	82	100	19	2.27
	9	190/160	0.9	3	28. 9.1993	16.12.1993	82	100	18	2.72

NOTE: * Strength differs greatly as the mixture is not uniformly mixed.

Figure 46. Field and laboratory strength variation with soil type, water/cement ratio, and cement factor (Min, 1996).

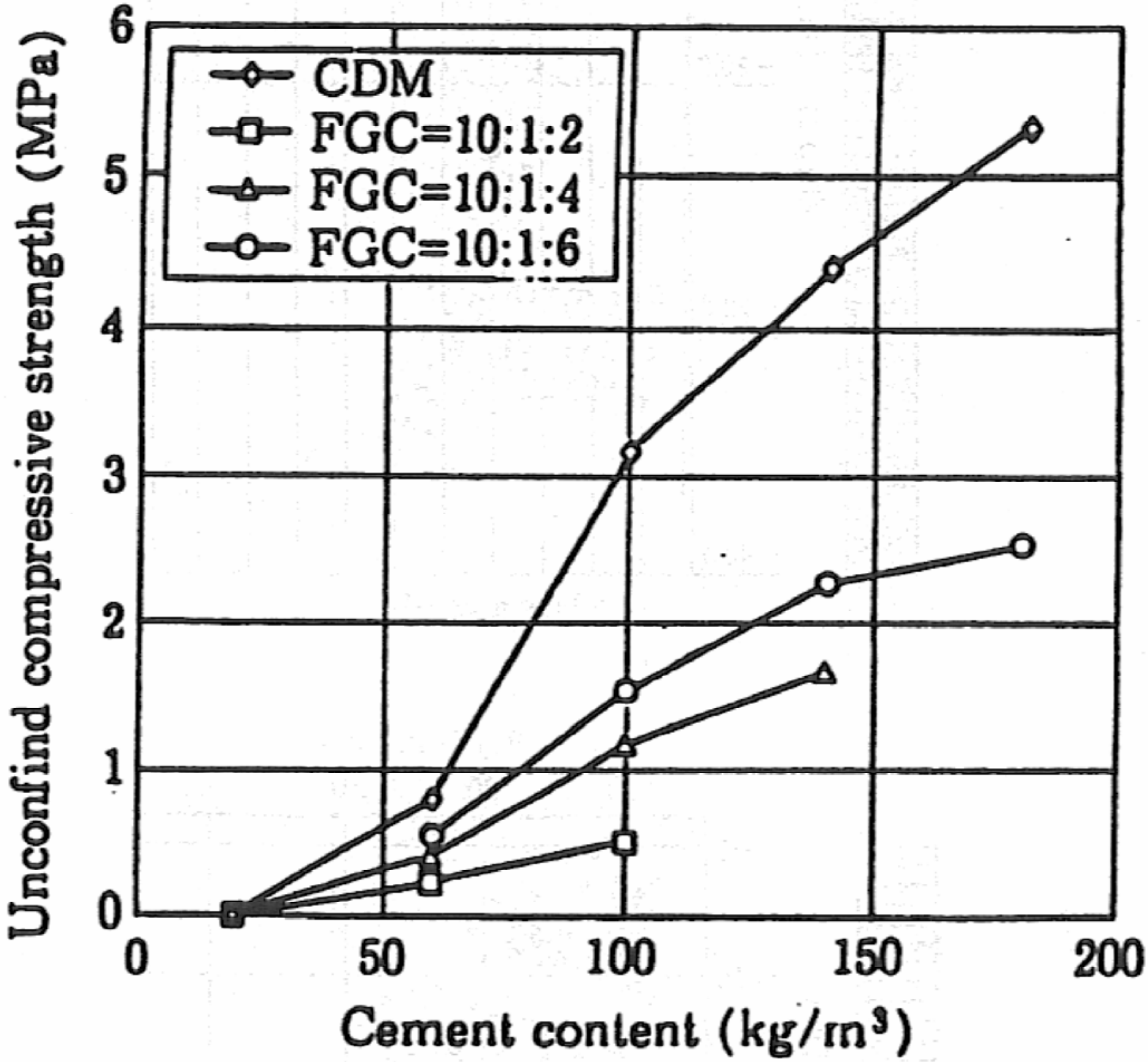
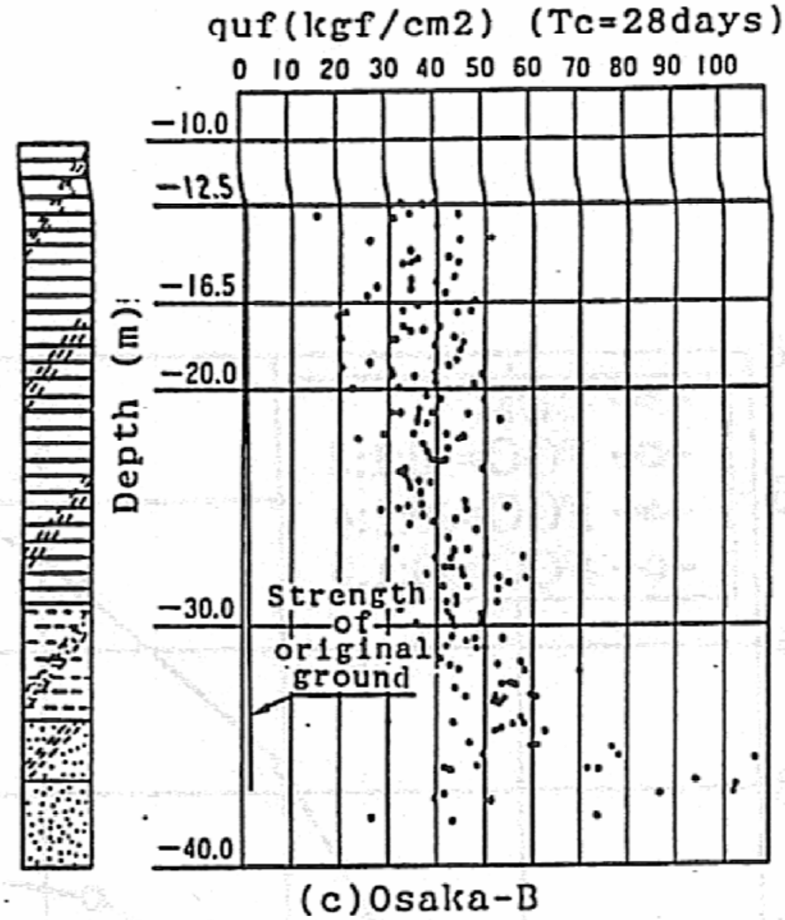


Figure 47. Variation in strength with cement content (Asano et al., 1996).



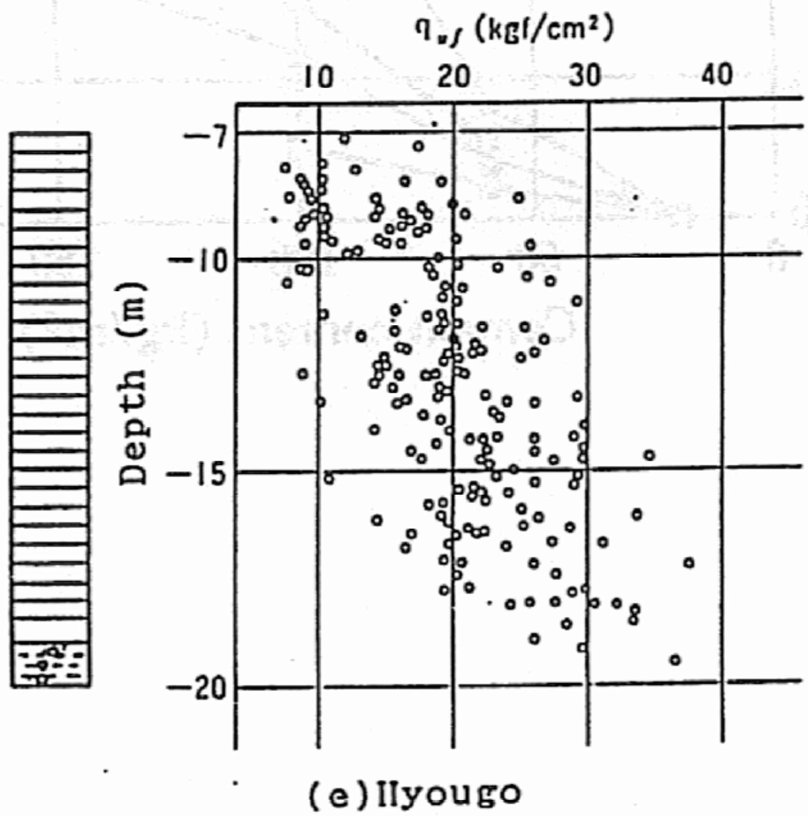


Figure 48. Distribution of strength of improved soil with depth (CDM Association, 1994).

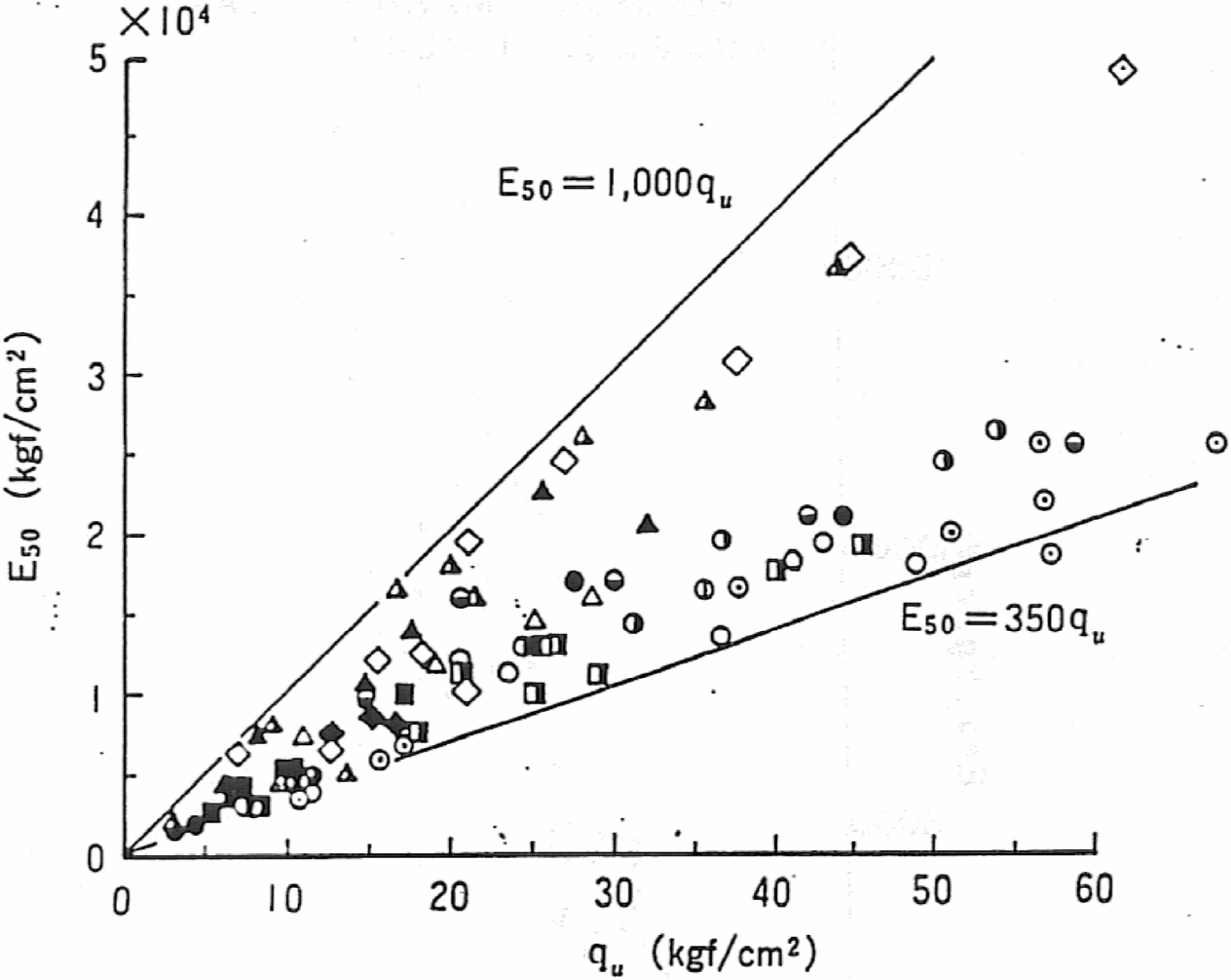


Figure 49. Relationship between strength and modulus of linear deformation (E_{50}) for laboratory improved soil (CDM Association, 1994).

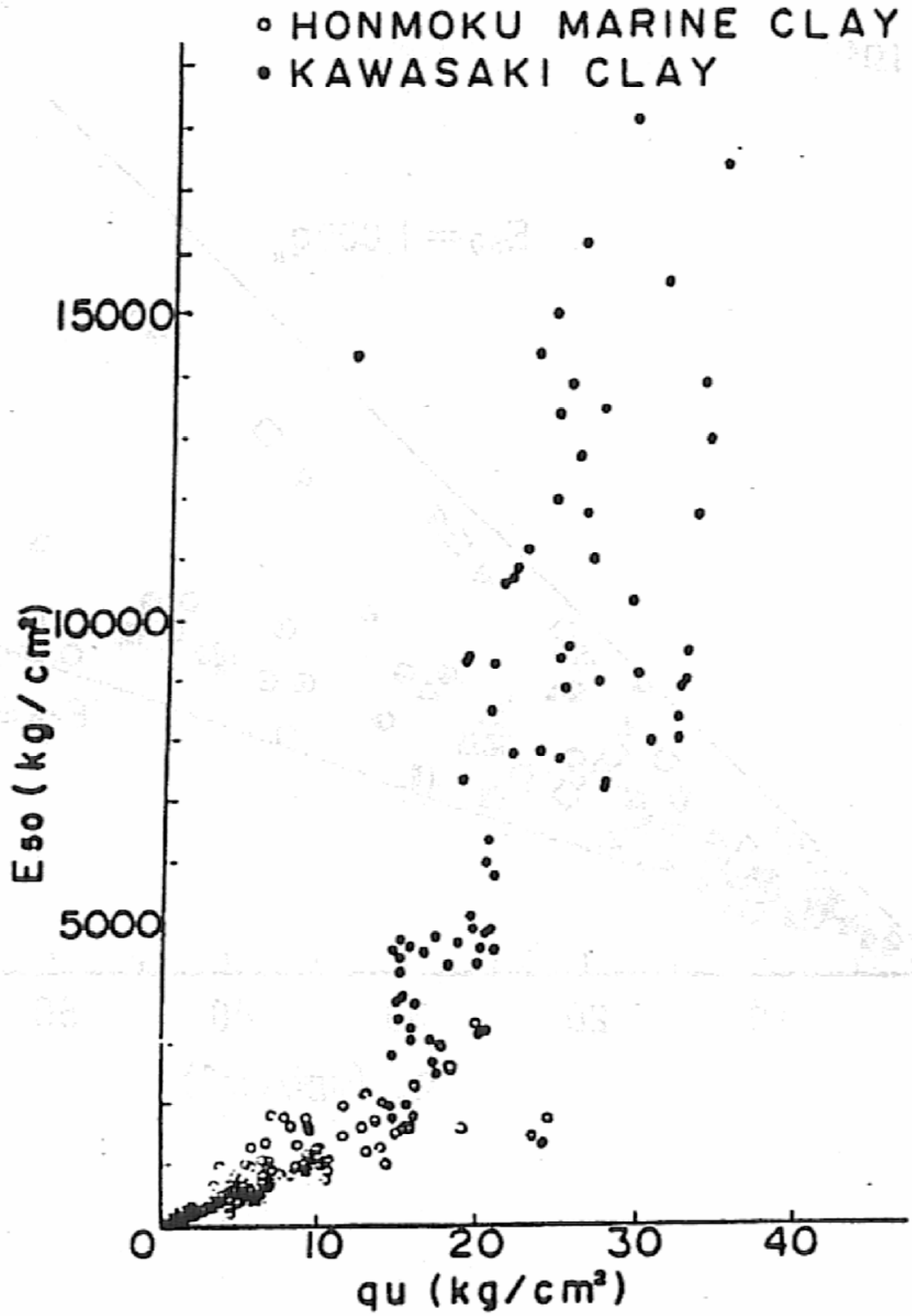


Figure 50. Relationship between strength and modulus of deformation for field samples (Okumura, 1996).

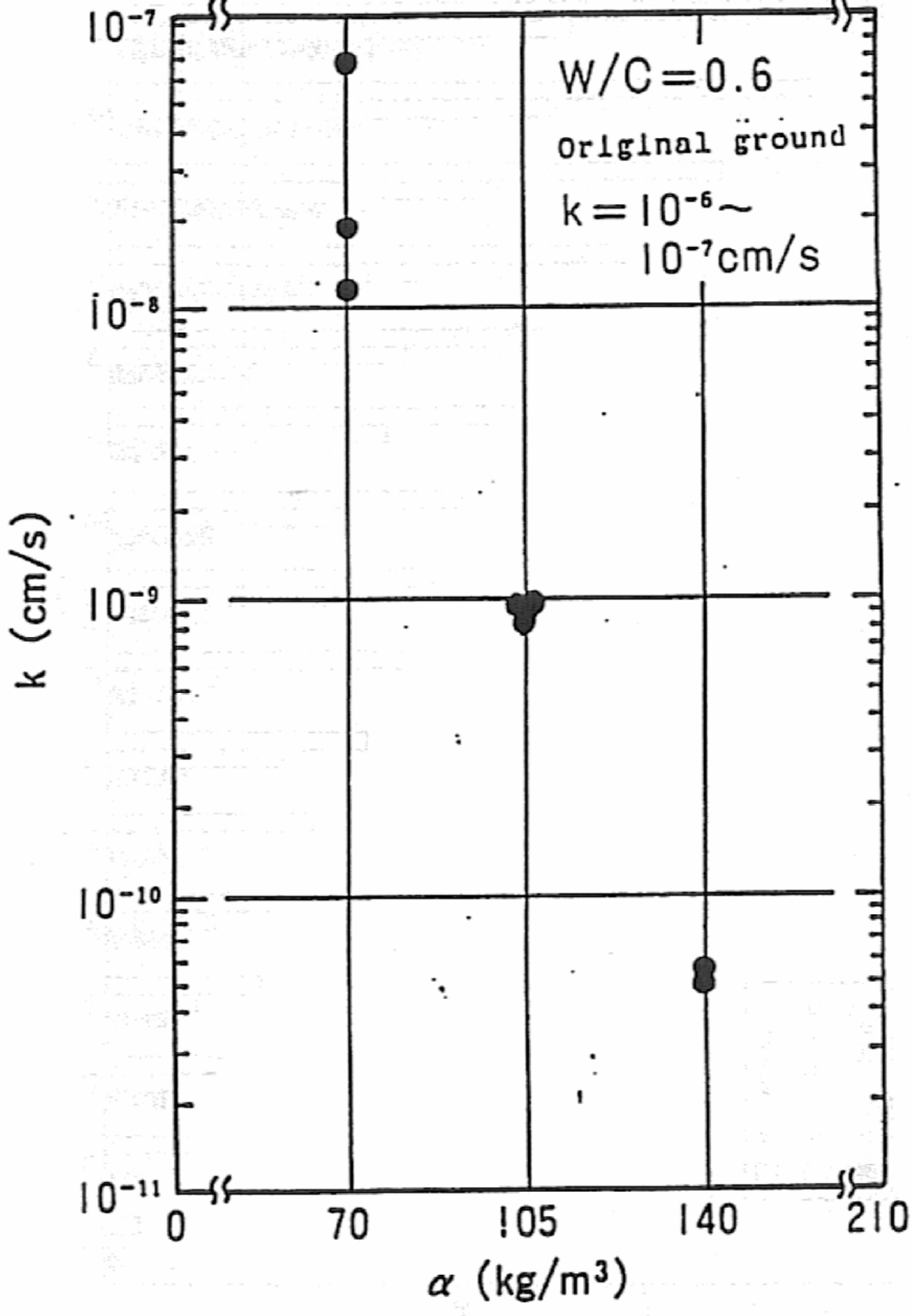


Figure 51. Relationship between coefficient of permeability and cement content for laboratory-improved soils (CDM Association, 1994).

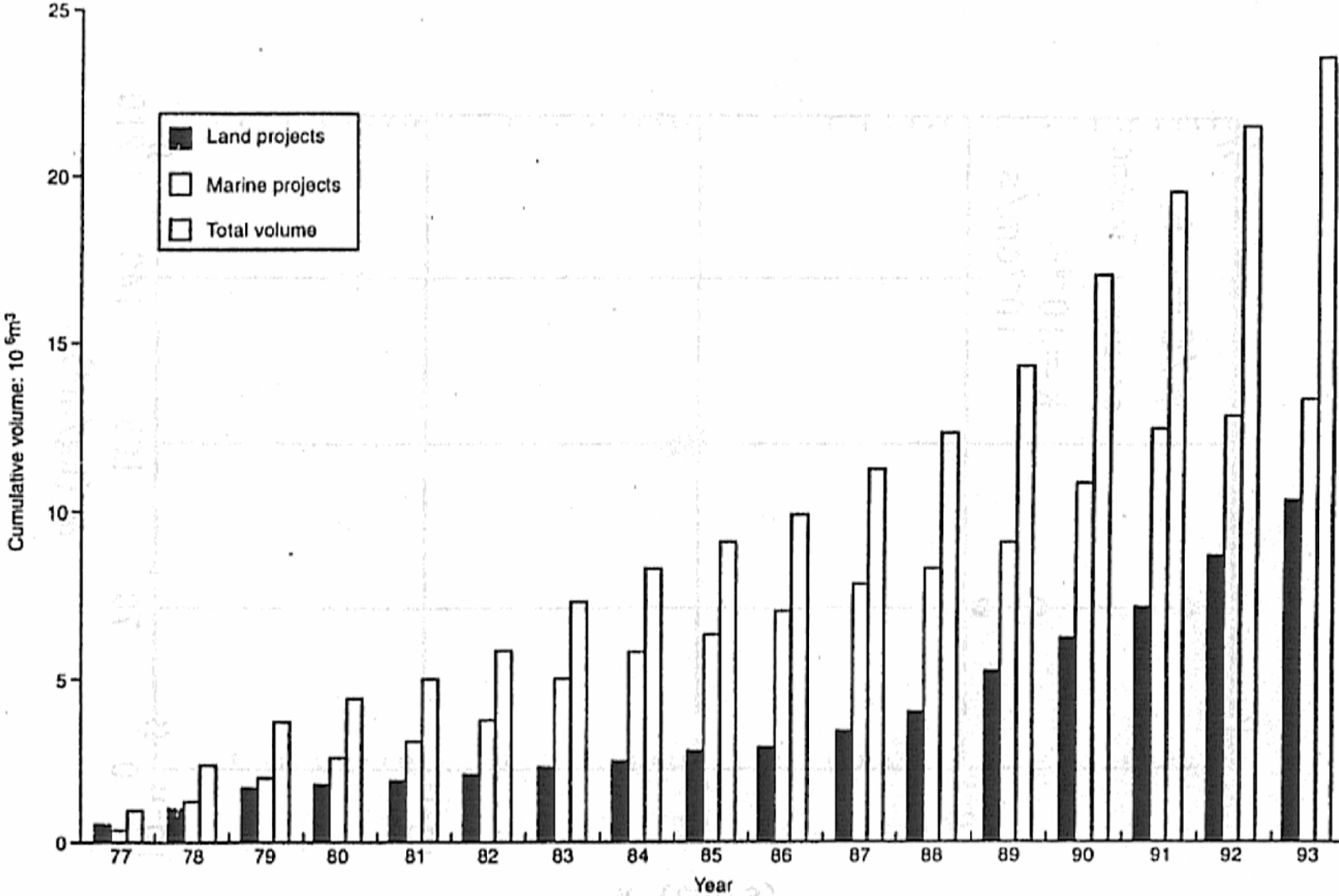


Figure 52. Volume of improved soil by the CDM method for land and marine projects (data from Okumura, 1977).

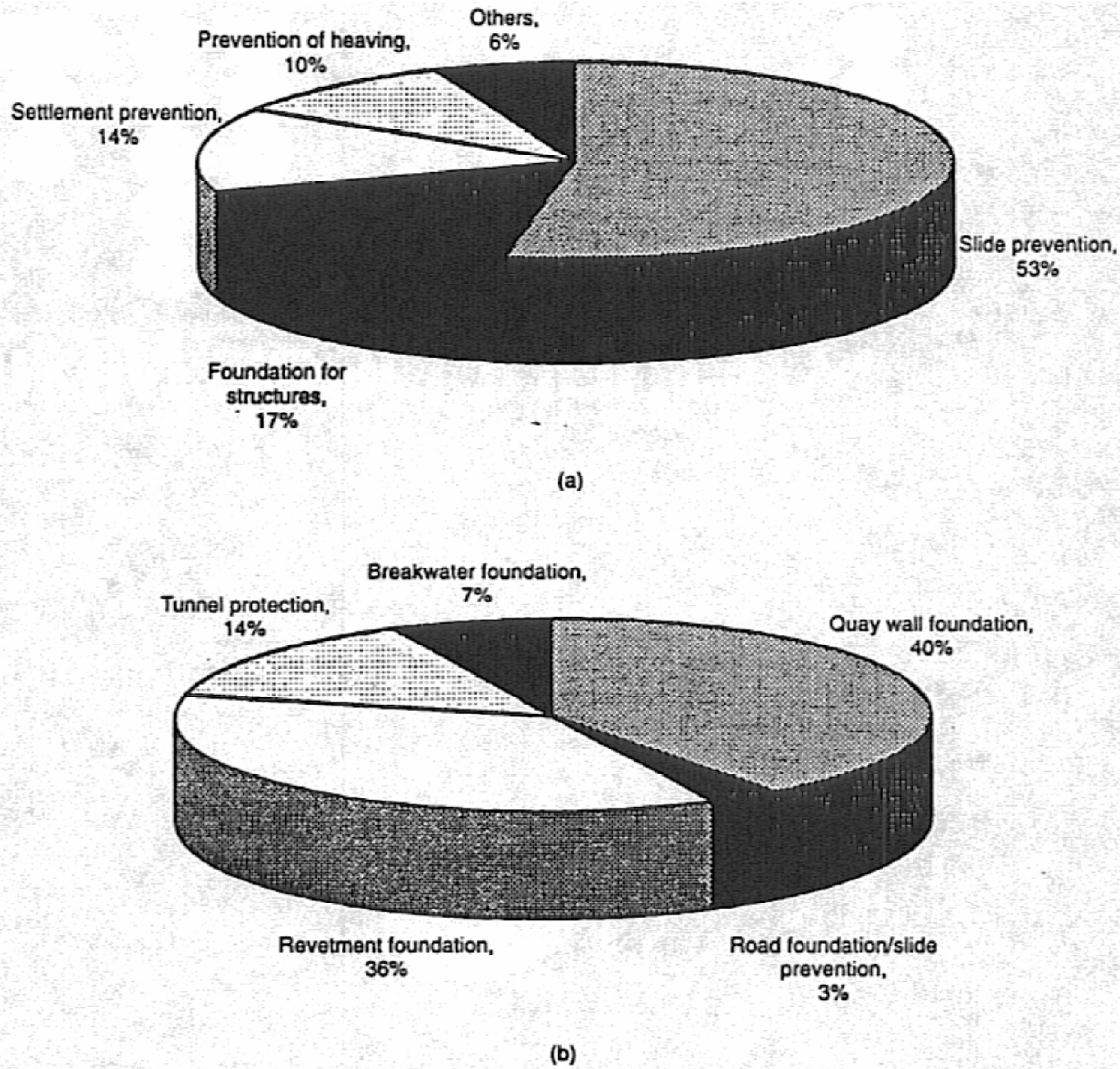


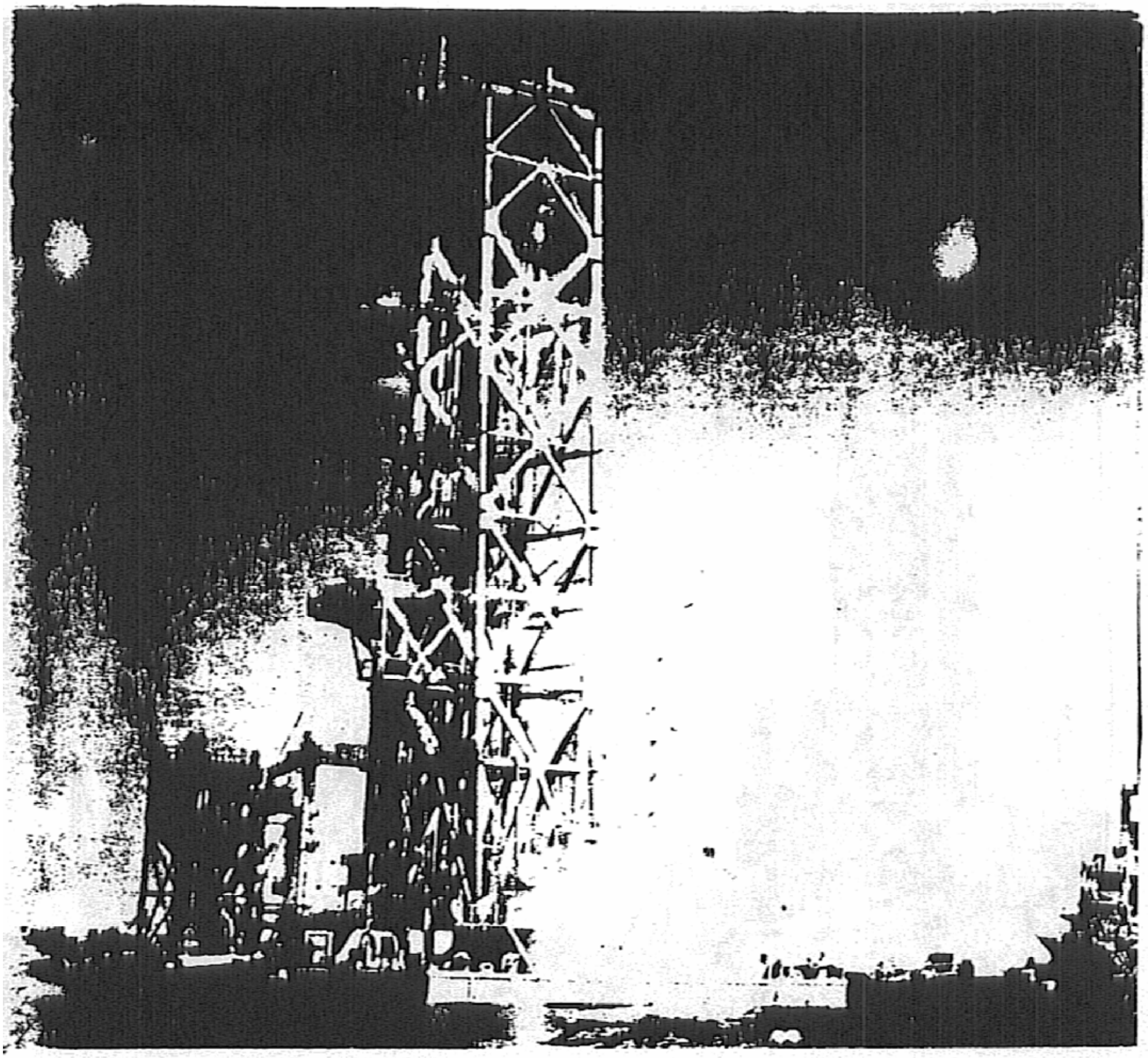
Figure 53. Deep mixing projects using CDM in Japan: (a) land projects and (b) marine projects (data from CDM Association, 1994).

Attachment 2. CDM Brochure.

CDM

Cement Deep Mixing

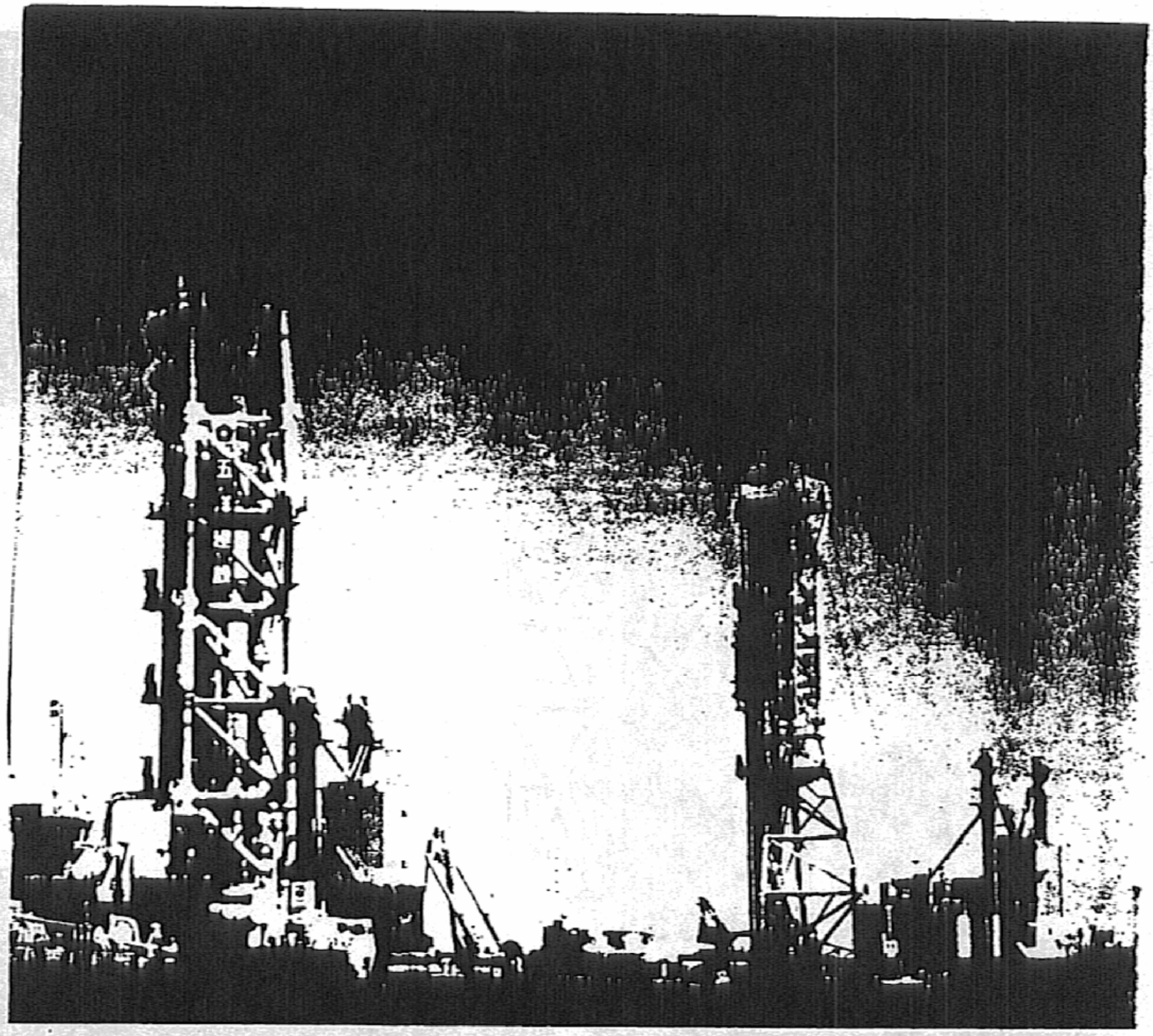
Cement Deep Mixing Method Association



A new generation soil improvement systems widely employed in the sea and on land.

Cement Deep Mixing Method ——— CDM Method

The soft and noncohesive properties of Japanese soils are well known in the world. The soft soil improvement techniques have been studied for long time in the civil engineering field in Japan, and so many methods have been developed and employed.



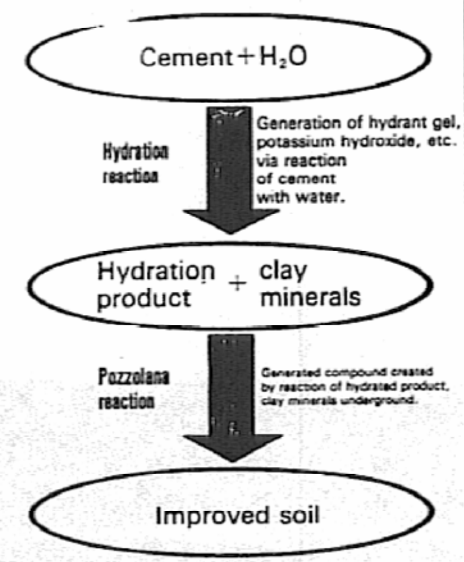
Today, the needs comes to extend areas of high quality, stabilized ground layer in short period, accompanied with mega-scale construction projects planned on the soft ground layer, besides environmental conservation is also required. To respond with the demand, a new consturuction method, "Cement Deep Mixing (CDM) method" has been developed through research and study, as well as the instruction of the Port & Harbor Reseach Institute of the Ministry of Transport and the other customers.

The CDM method is an applied chemical solidificatio technique, which inserts and mixes a cement slurry into so ground to produce a more solid ground foundation. Esta lished in 1977, the Cement Deep Mixing Method Associ tion consists of companies that joined together to promo and improve this method. So far, excellent results have bee obtained in many operations all over Japan.

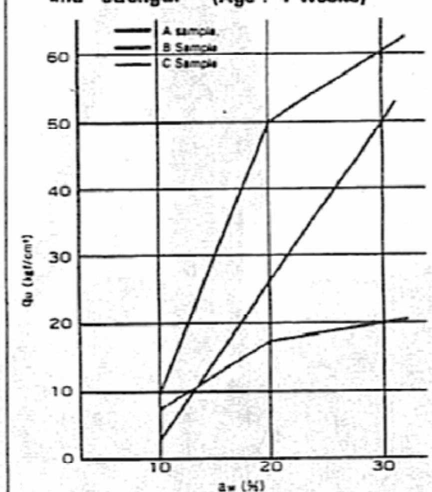
▶What does CDM method mean?

The CDM method is a soft soil stablizing method which mixes cement slurry with soft soil insitu to attain a required strength.
Soft soil is stabilized by the 2-phase chemical reaction :
First, a hydration reaction caused when the cement mixes with water, an ettringitte of capillary crystals is generated. As the age grows, the product of hydration generates a pozzolana reaction with the clay minerals in the soil.

■ Flow Chart of Stabilizing Principle



■ Relationship between added cement and strength (Age : 4 weeks)



■ aw : Volume of cement added $aw = \frac{\text{weight of cement}}{\text{dry weight of soil}} \times 100\ (\%)$

■ Result of mixture experiment in laboratory

▶Features of CDM Method

1 Required strength is surely obtainable.

Required strength can be surely obtained by setting a proper cement mixture rate suitable for the condition of the soil to be improved.

2 Reduction in project period.

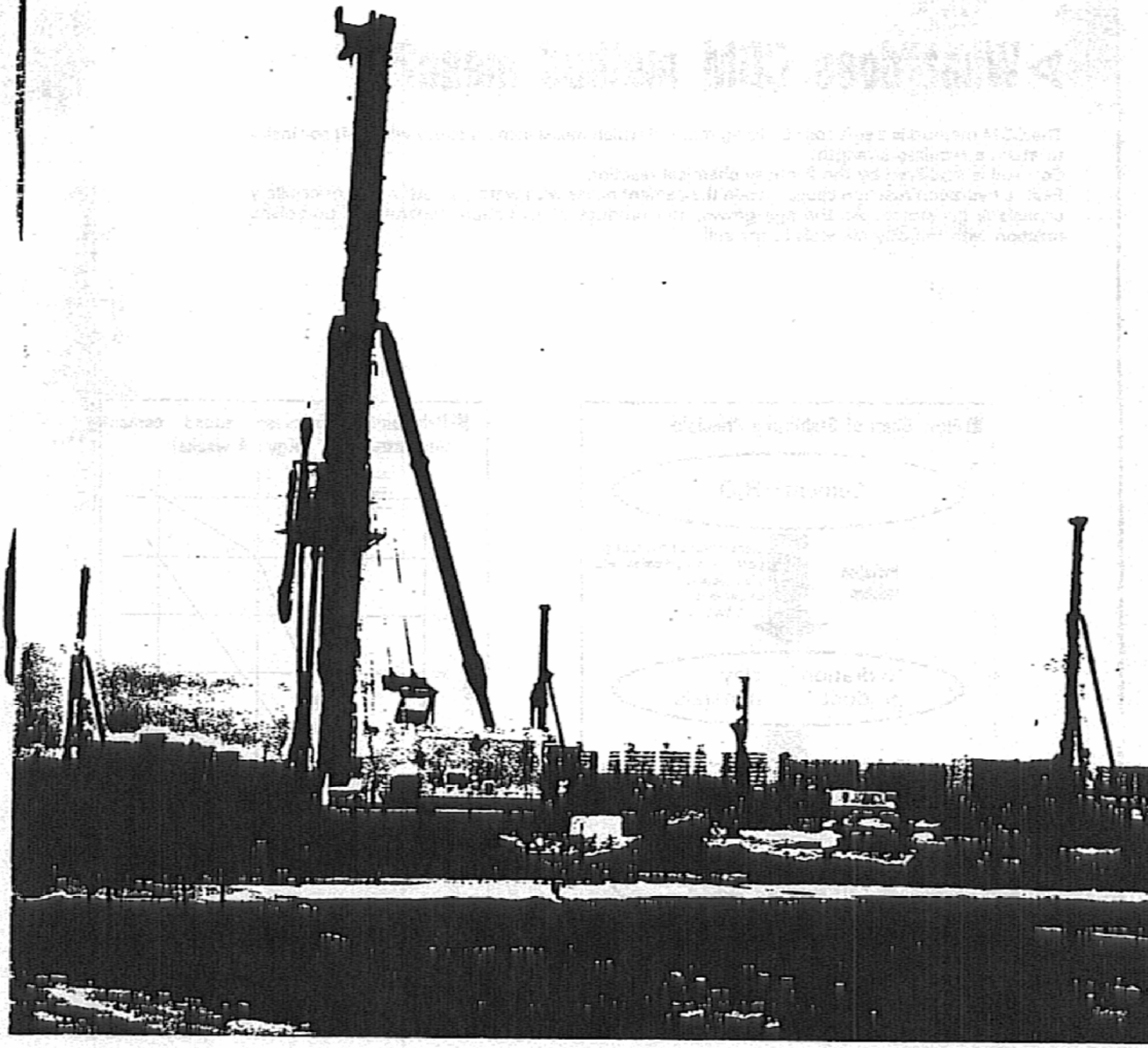
Use of an accelerating agent reduces the period to obtain a required strength. So, significant reduction in project period is available.

3 No settlement due to consolidation

The strength of the improved soil prevents settlement due to consolidation.

4 No contamination No pollution

Solidification of soft ground insitu leads to no sea water contamination or secondary pollution. In addition, the low vibration and low-noise during operation does not affect surrounding structures.



5 Variety of applications

Great power of digging and mixing enables the easy penetration through the relatively hard stratum on the way, anchorage to the bearing stratum, and improvement to various types of foundation.

6 Excellent reliability in execution control

The centralized control system for the slurry discharge, improved penetration depth, number of rotation, and the control of the slurry plants enables integrated execution control.

7 Effective use of resources

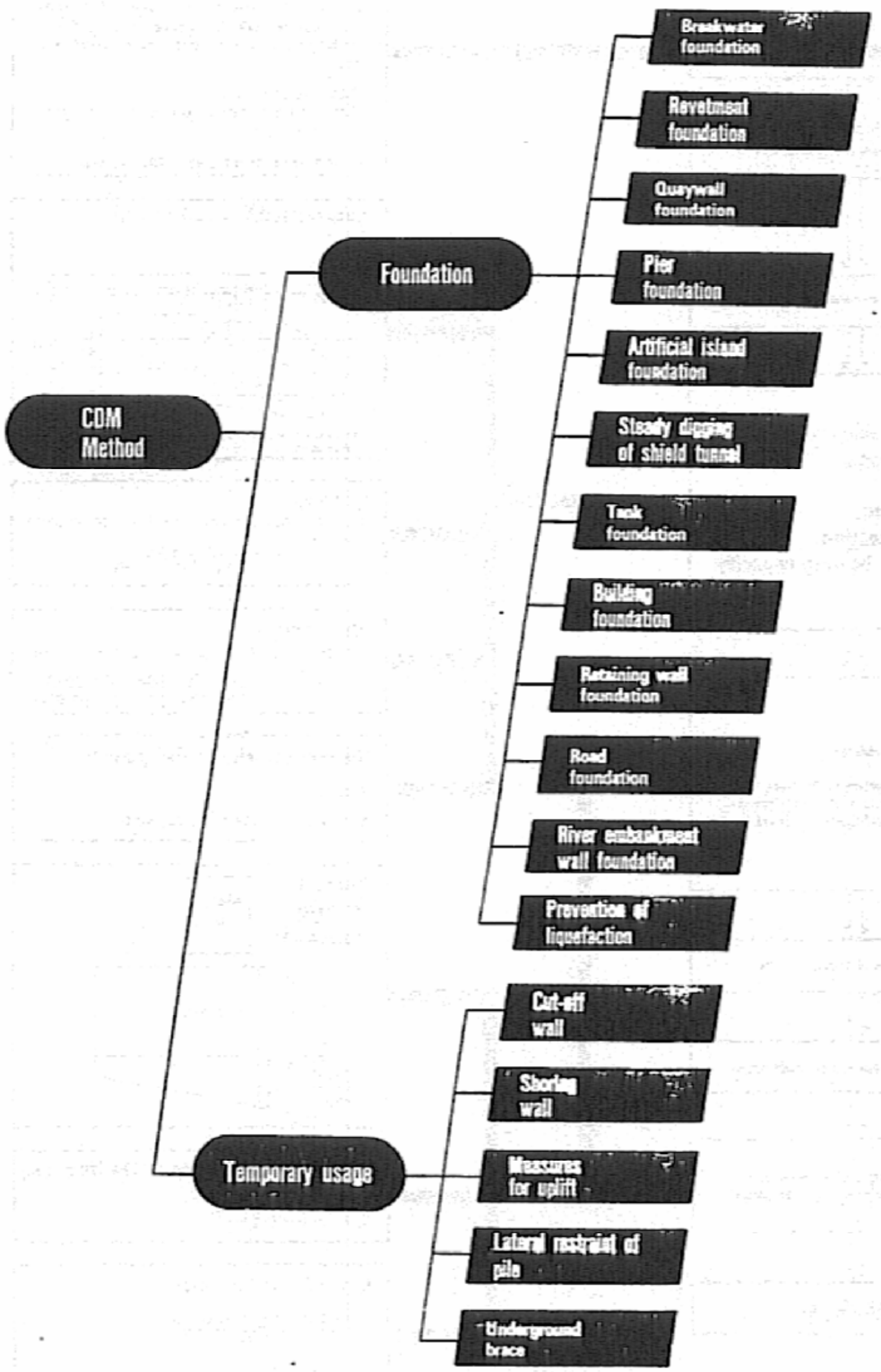
Compared to conventional methods, CDM saves resources because it stabilizes soft ground without using a great amount of sand and gravel.

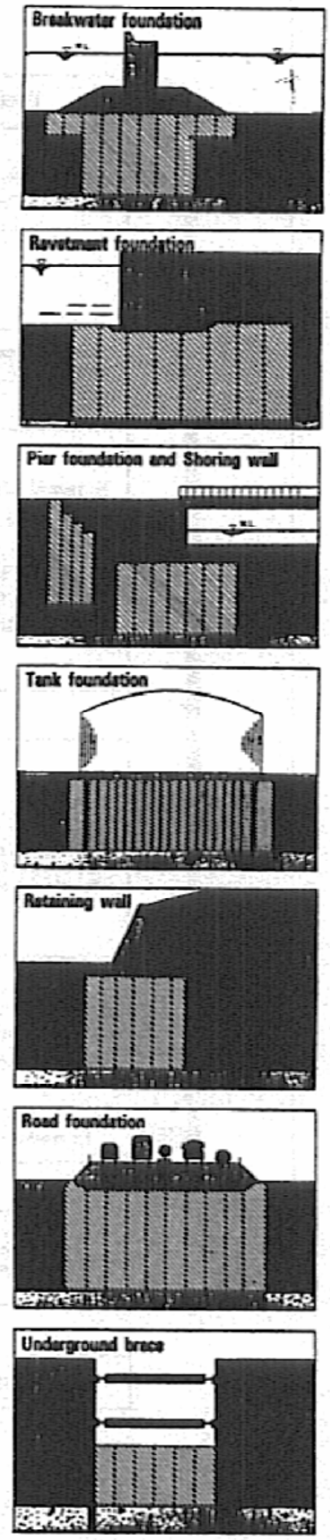
8 Cost effectiveness

Entire project costs are more effective than other methods for the greater strength obtained and less volume of ground to be improved.

▶Application of the CDM method

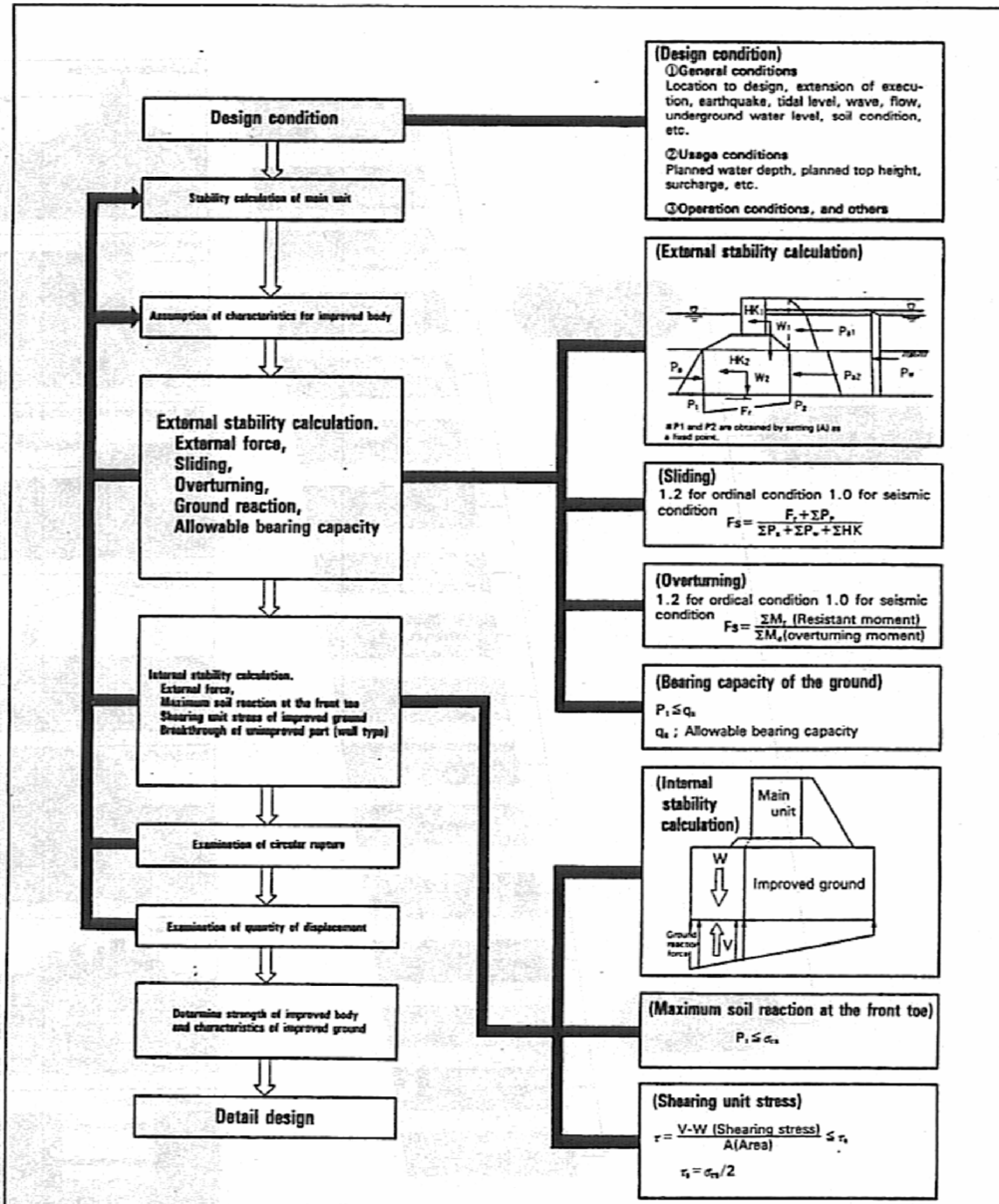
The CDM method is useful for temporarily structures, e.g., cut-off walls and shoring barriers, to ensure a steady foundation for digging, as well as the improved foundation ground for many types of structures.





▶ Design of CDM method

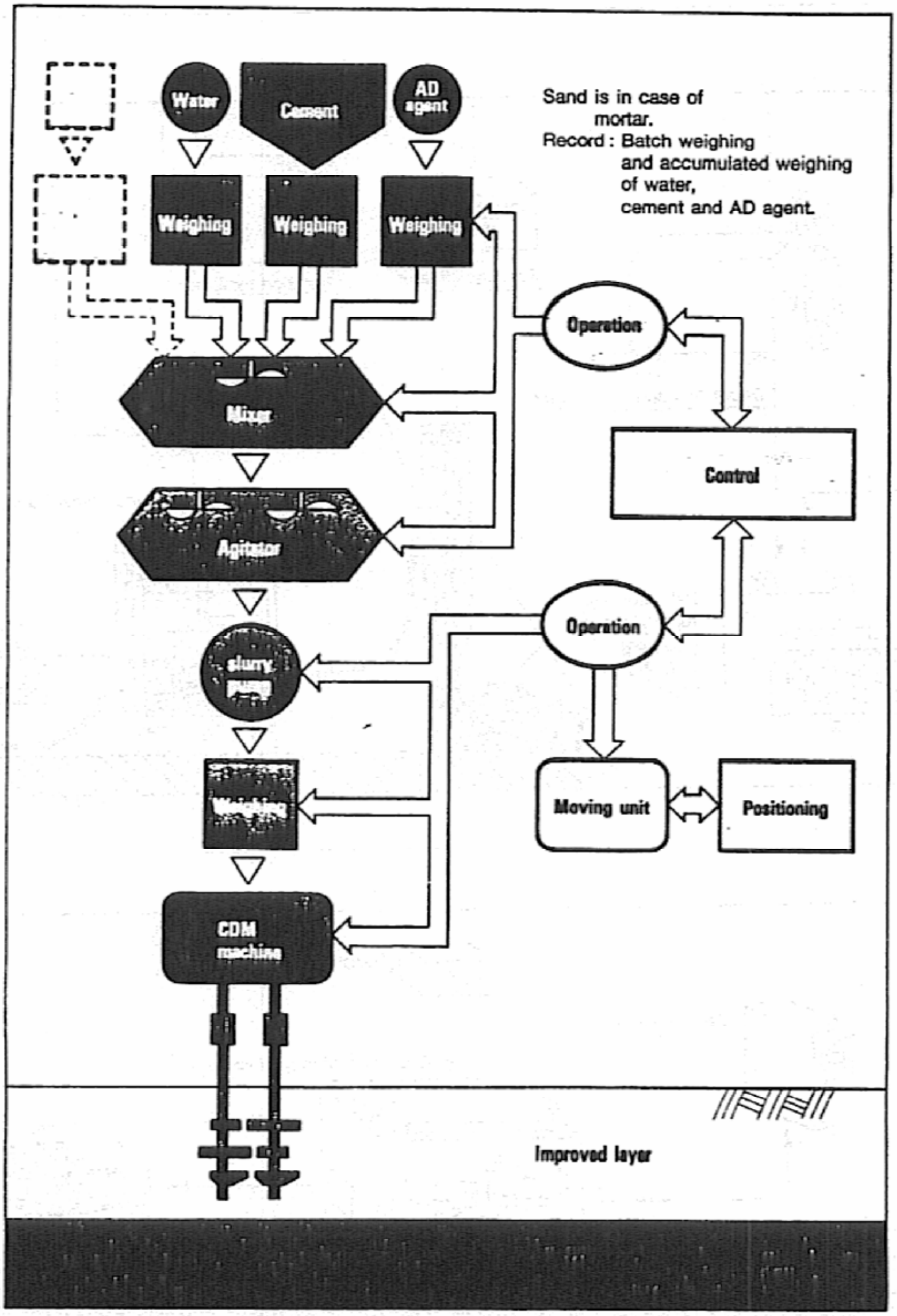
Types of improved ground by CDM method are classified into block, wall, grid, and pile. The design is based on selected type.



Procedure of designing block type and wall type

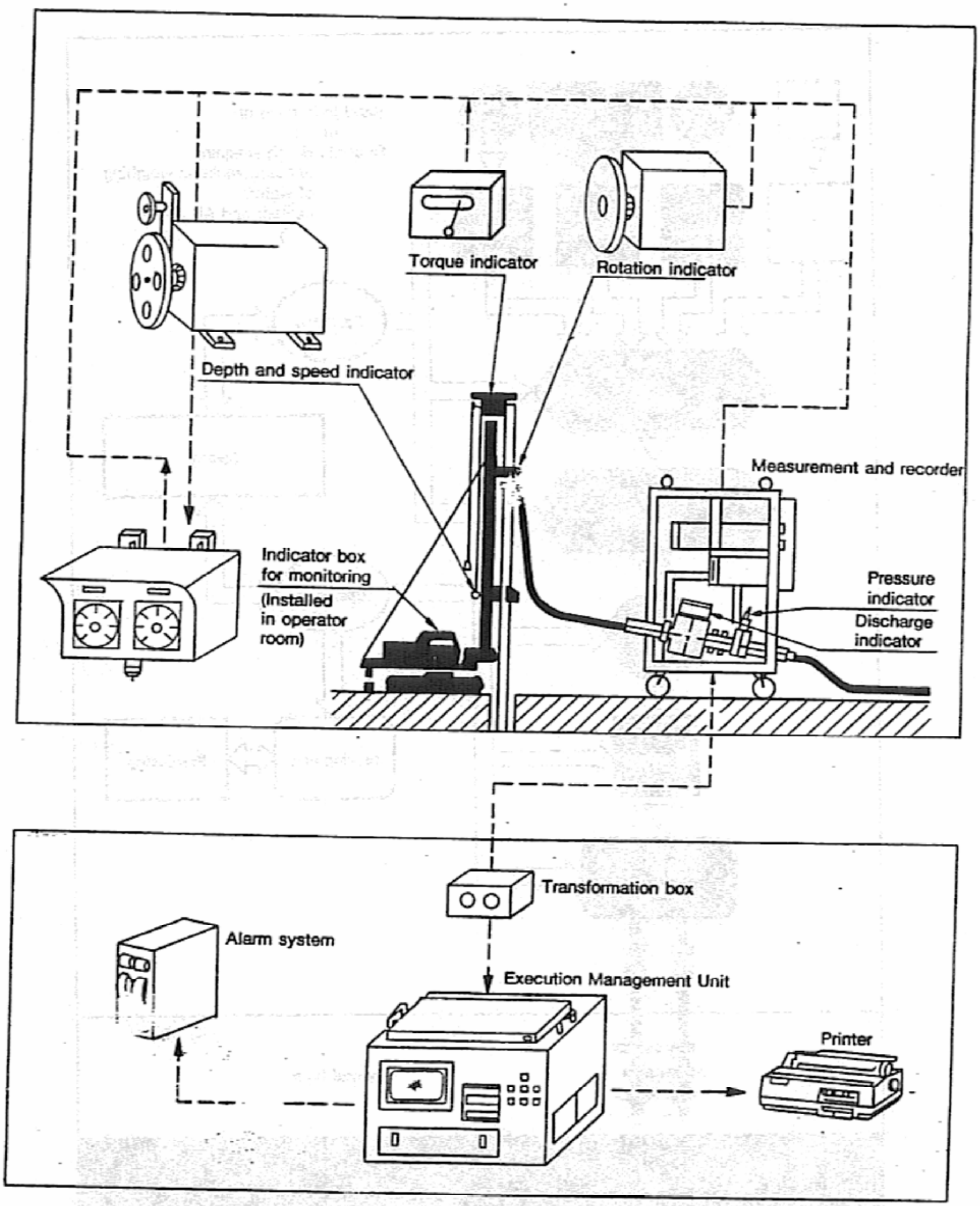
▶Procedures of CDM method

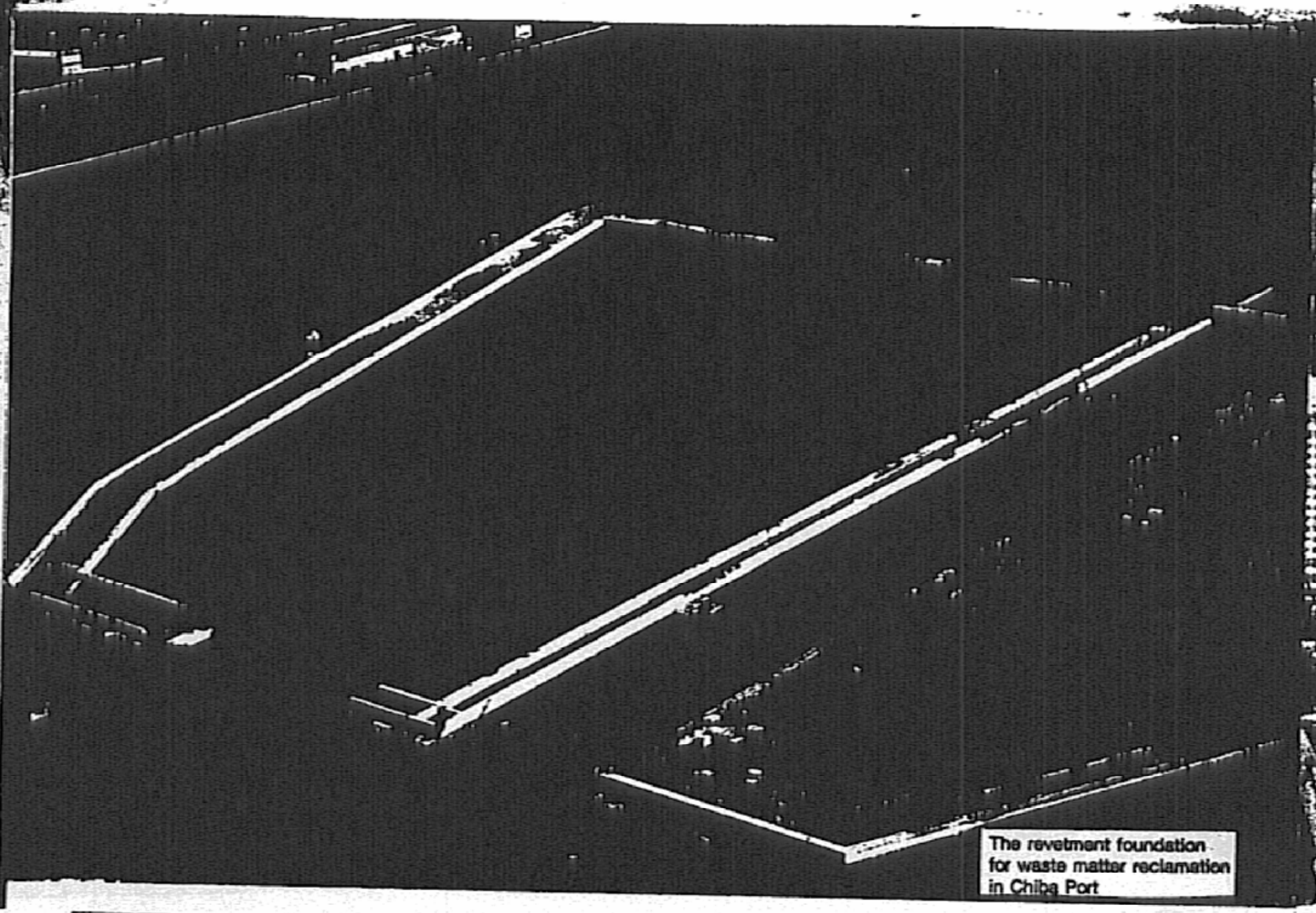
The CDM method is executed by machines dedicated to marine operation and on land operation incorporating a centralized control system, including ship guidance system, slurry plant control and operation control equipment.



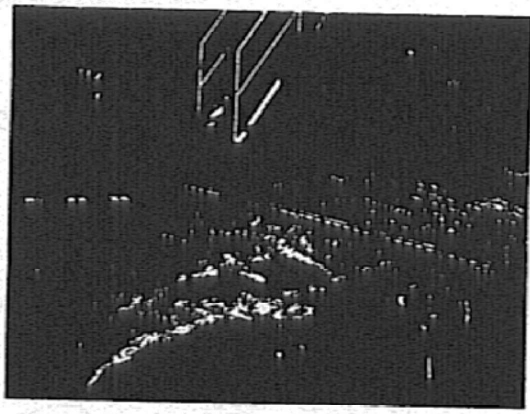
▶Centralized control System of CDM Method

The execution control system of the CDM method includes quality control and yield control. The introduction of a management system offers real-time understanding of conditions and reliable execution.



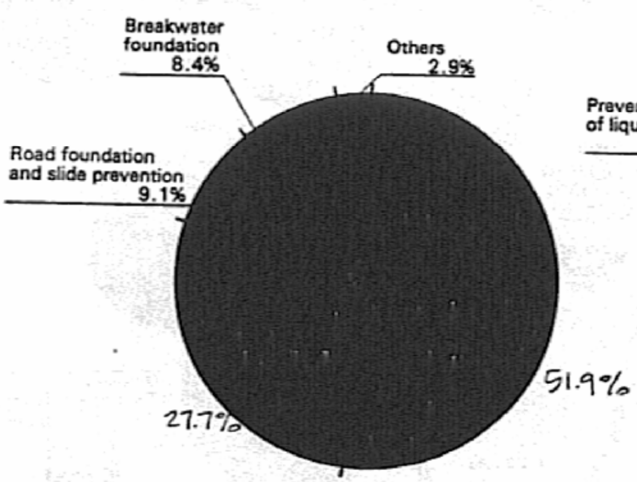


The revetment foundation for waste matter reclamation in Chiba Port

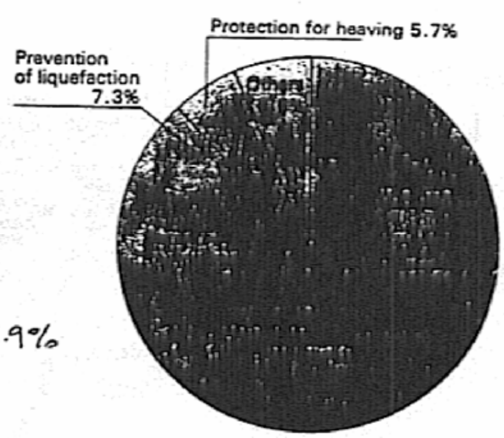


▶Achievements of CDM method

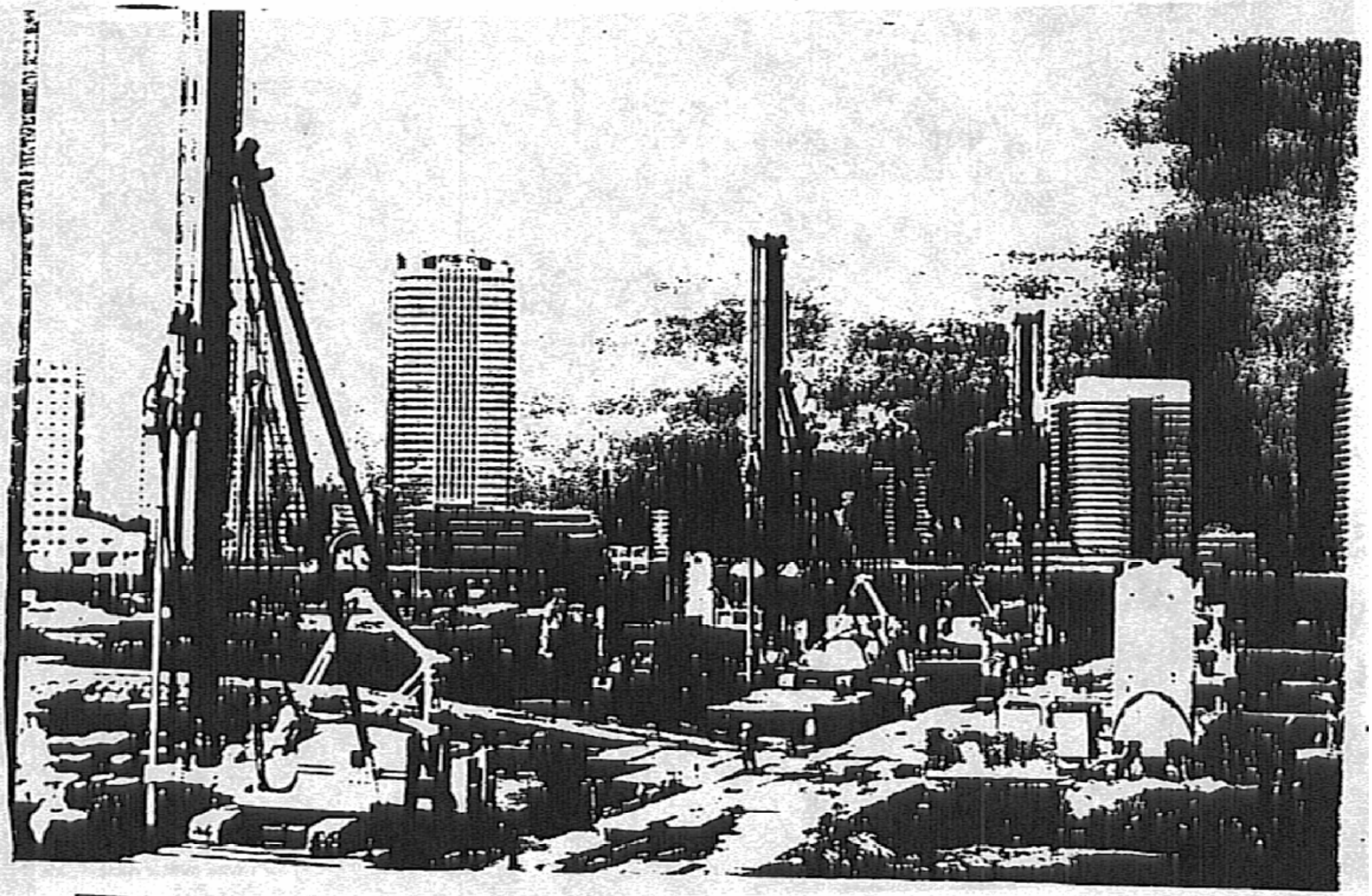
Since first practical use in 1977, CDM method has been widely employed to both in the sea and on land throughout the nation.
Until March 1995, the total volume of execution was approximately 26 million cubic meters, in both sea and land projects.

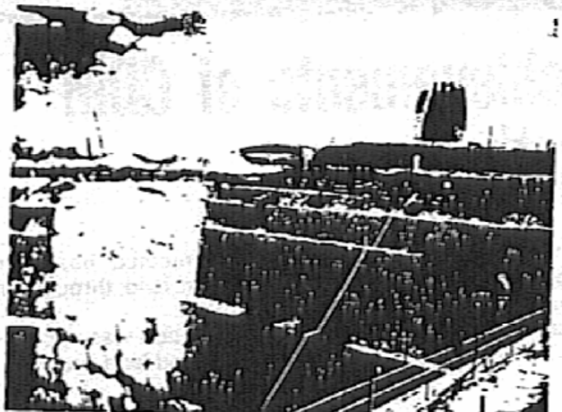


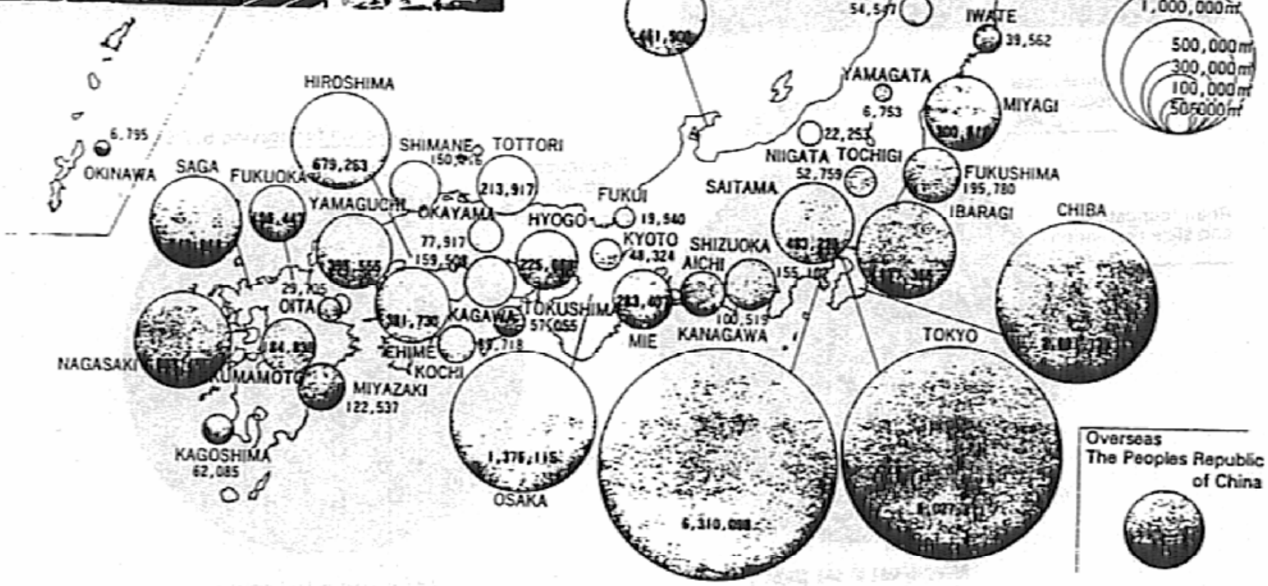
Achievement in sea projects



Achievement in land projects







Achievement of works all over Japan
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AOMORI
AKITA
54,517
IWATE
39,562
YAMAGATA
6,753
MIYAGI
ISHIKAWA
2,000,000㎡
1,000,000㎡
500,000㎡
300,000㎡
100,000㎡
HIROSHIMA
679,263
SHIMANE
TOTTORI
213,917
OKINAWA
6,795
SAGA
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OKAYAMA
77,917
159,508
HYOGO
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19,540
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48,324
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155,102
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NIIGATA
52,759
TOCHIGI
22,253
FUKUSHIMA
195,780
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CHIBA
29,725
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KAGAWA
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MIE
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CEMENT DEEP MIXING METHOD ASSOCIATION
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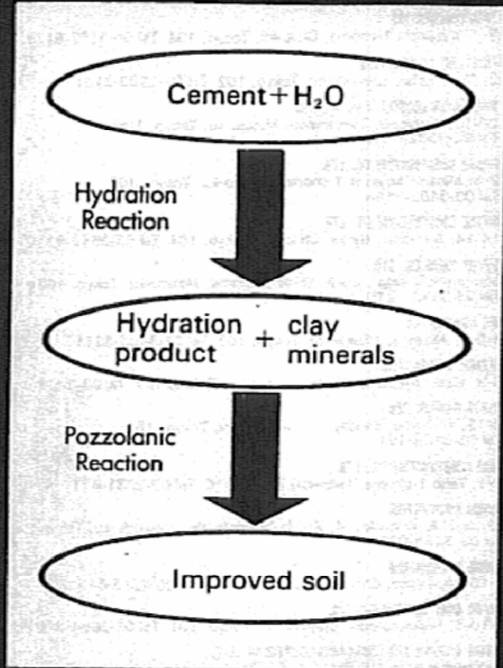
Soil Stabilization Principle



1) In Situ Soil Mix... [illegible]

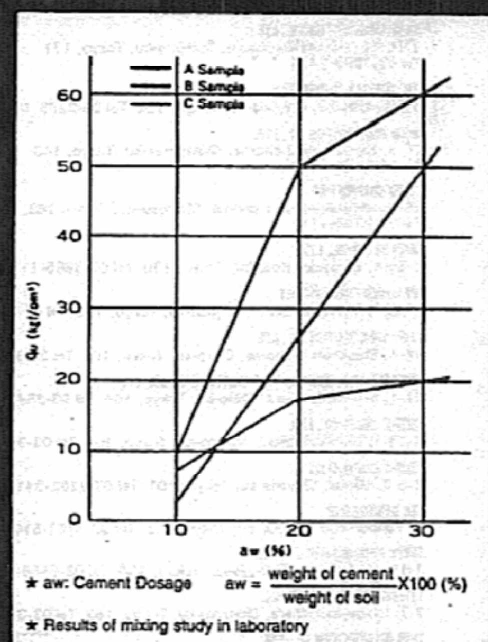
2) Proven T... [illegible]

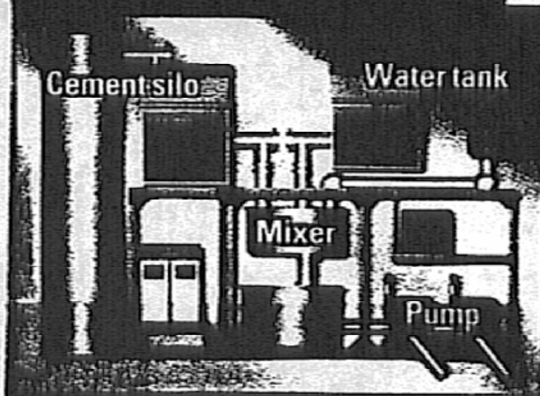
3) Relia... [illegible]

Minimum Impact to Environment

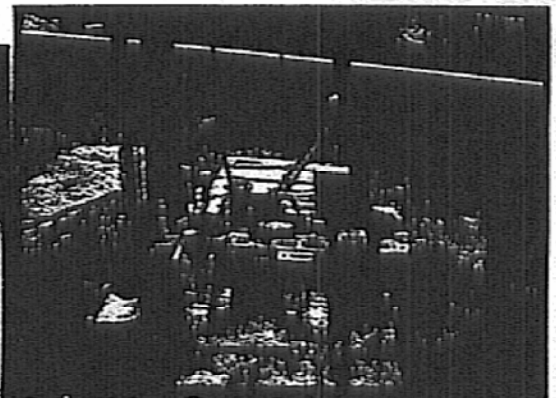
[illegible]

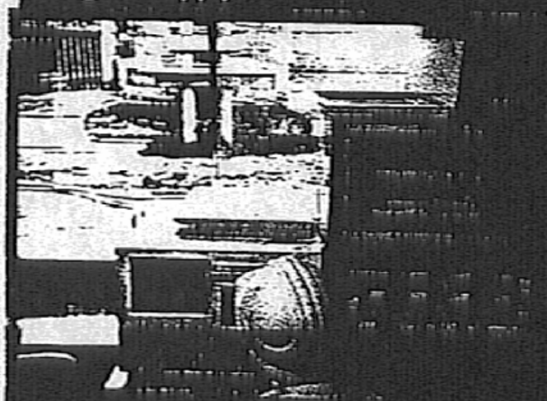
Relationship Between Cement Dosage & Strength (Age: 4 weeks)





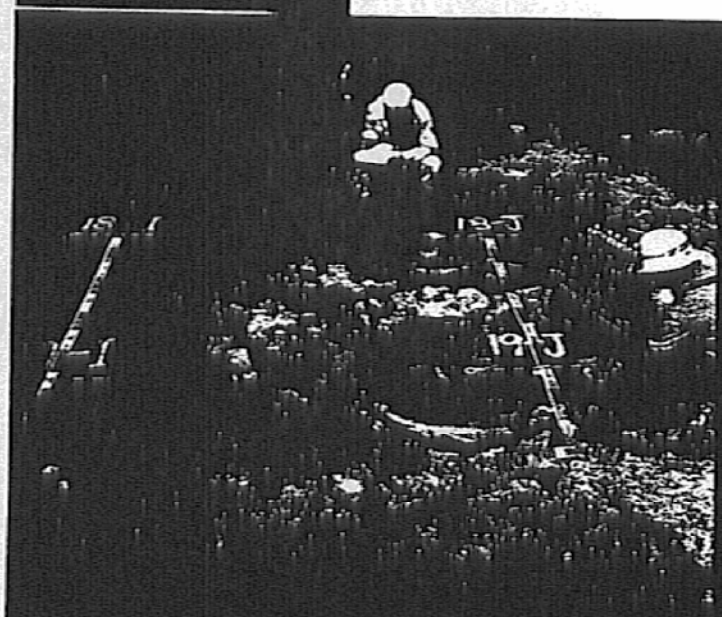
Reagent Supply


Soil Mixing Operation


Computer Control and Monitoring


In-Situ Soil Mixing

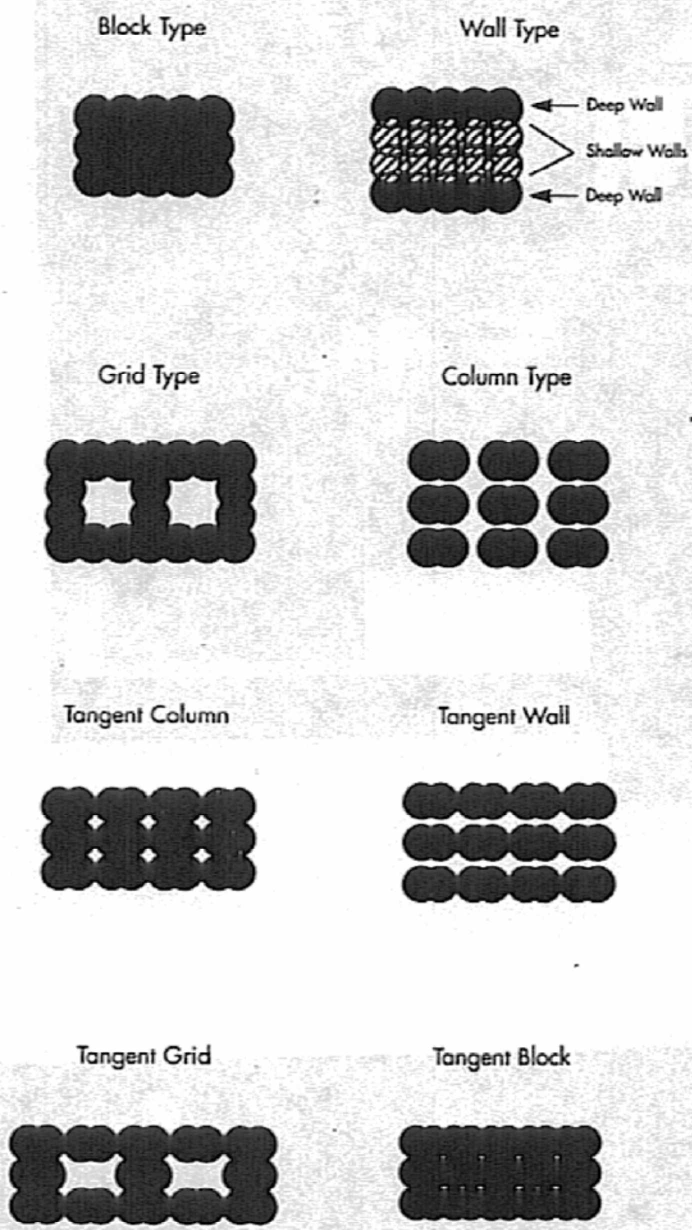
Products

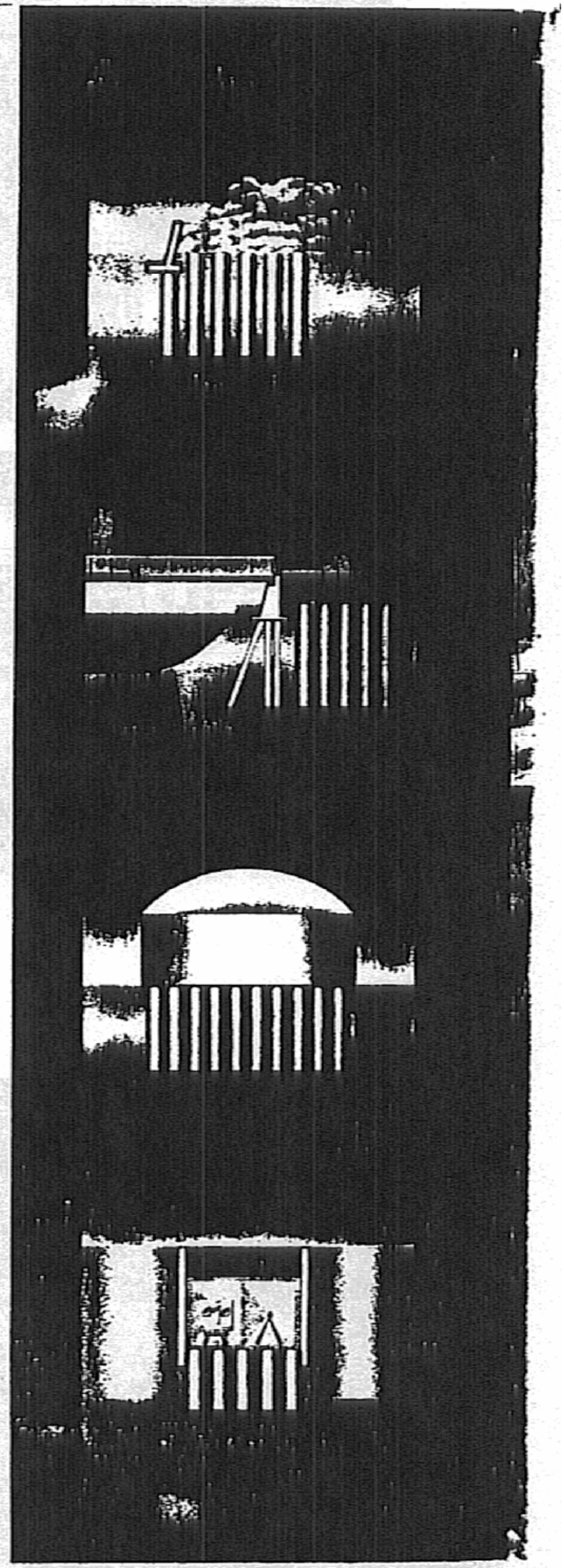


Soil-Cement Columns


Soil-Cement Columns

Basic RDM Treatment Patterns





Raito

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1. INTRODUCTION

Geo-Con, Inc. introduced their mainly WRE system on a project at San Angelo, TX, in 1988. The main purpose of the system was to provide economic stabilization of contaminated soils to 12 m in depth by using a single shaft with a relatively large-diameter mixing tool (1 to 4 m). Solidification and fixation of many contaminants in situ have met Environmental Protection Agency (EPA) standards. More recently, applications for geotechnical projections have been conducted.

2. GENERAL PROCESS (Figure 54)

The auger is rotated into the soil at about 15 rpm. Grout is injected via two ports in the mixing shaft. Alternatively, dry binder (cement and/or lime) can be added at the top of the column and then blended by vertical cycling of the mixing tool (DRE variant). Rotation and injection continue during withdrawal, and cycling up and down over certain distances is common to improve mixing efficiency and to ensure that strength or permeability performance criteria are met.

3. EQUIPMENT

Base	Typically, a crawler crane (100 to 150 tonnes) with a high-torque bottom drive turntable.
Shaft	A single shaft is suspended by cable from the crane. A mixing tool (e.g., Figure 55) is fixed to the bottom, and its exact design and dimensions are dictated by the site conditions and refinements. A shroud can be placed around the shaft to catch potentially noxious vapor releases (Figure 56).
Grout Plant	Typical grout plant (with positive displaced pumps) as used for DSM or jet grouting. Dry binder is blown in, similar to the Lime-Cement Column Process. Other equipment shown in Figure 54 may be used depending on the application (one variant uses steam or hot compressed air to extract volatile pollutants (Geo-Con, Inc., 1996). The DRE variant is used in soils and sludges with moisture contents above about 50%.
Control	Injection parameters are computer-controlled.
Production	Industrial production can vary from 500 to 1500 m^3 per shift.

4. MIX CHARACTERISTICS

Grout. Grouts of various types and compositions can be used (cement, bentonite, flyash, lime, and proprietary reagents). Dry materials and biological reagents can also be used in appropriate conditions. Cement factors are usually in the range of 240 to 320 kg/m^3, higher for increased strength or lower permeability (400 kg/m^3).

Treated Soil. In granular soils, strengths of 3.5 to 10 MPa are obtainable. In high-water-content sludges, 0.6 to 1.2 MPa is a more common range. The hydraulic conductivity can be as low as 1×10^{-10} m/s, but this is rare and expensive.

5. PATENTED/PROTECTED FEATURES

None known.

6. PARTICULAR ADVANTAGES

It is a very competitive system, allowing economic and fast treatment of a variety of soils and sludges containing a range of contaminants, including creosote, tars, organics, petroleum, et al.

7. OPERATING COMPANY

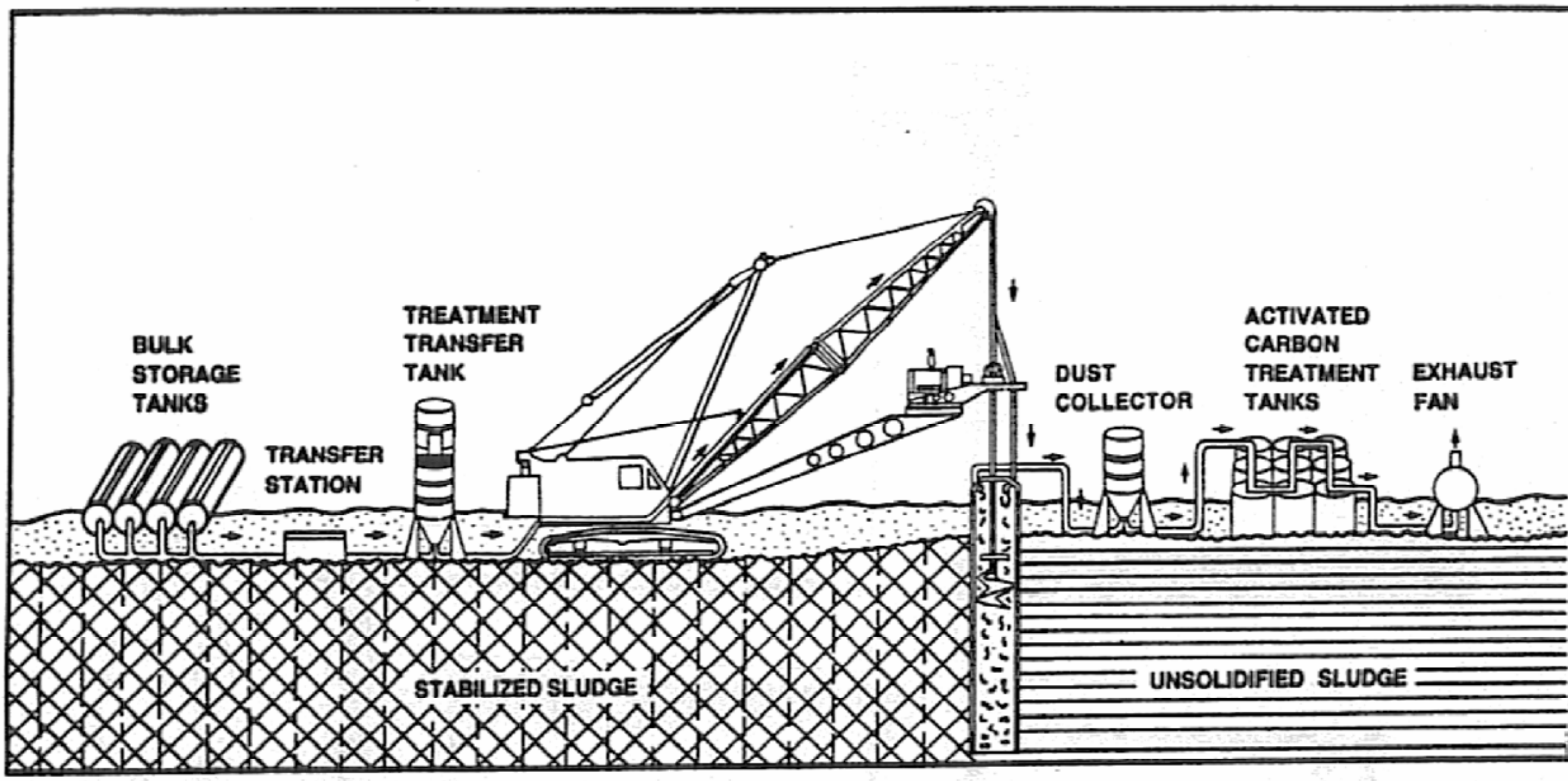
Geo-Con, Inc. of Monroeville, PA, is currently a wholly-owned subsidiary of URS Greiner Woodward Clyde. It has other offices in CA, FL, NJ, and TX.

8. REFERENCES

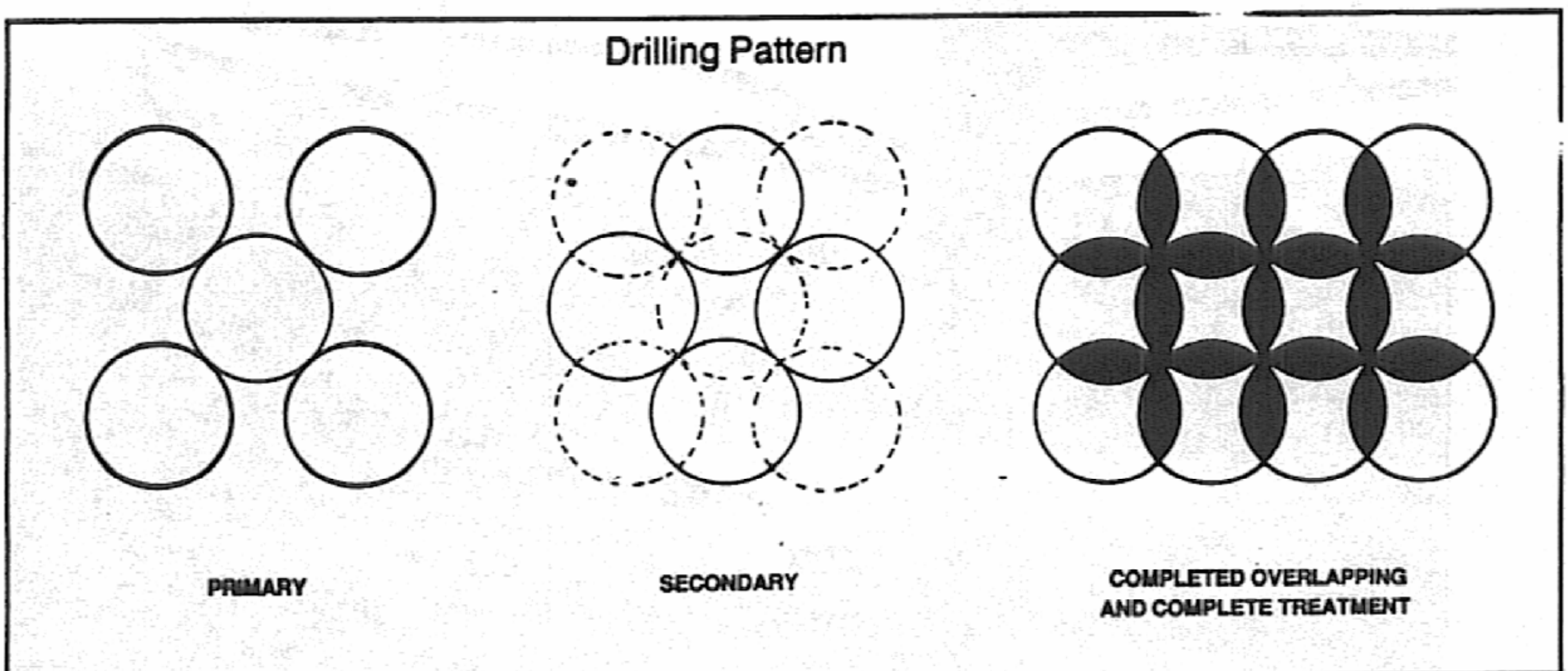
Day, S.R. and C.R. Ryan. (1995). "Containment, Stabilization, and Treatment of Contaminated Soils Using in Situ Soil Mixing," *Proceedings of the ASCE Specialty Conference*, New Orleans, LA, February 22-24, 17 pp.

Geo-Con, Inc. (1996). Promotional information.

Walker, A.D. (1992). "Soil Mixing and Jet Grouting on a Hazardous Waste Site, Pittsburgh, PA, USA," *Grouting in the Ground*. Institution of Civil Engineers, London, pp. 473-486.



Crane mounted mixing system advancing through sludge layer.



Primary and secondary overlapping bore patterns.

Figure 54. Schematic of SSM equipment and typical mixing patterns (Geo-Con, Inc., 1996).

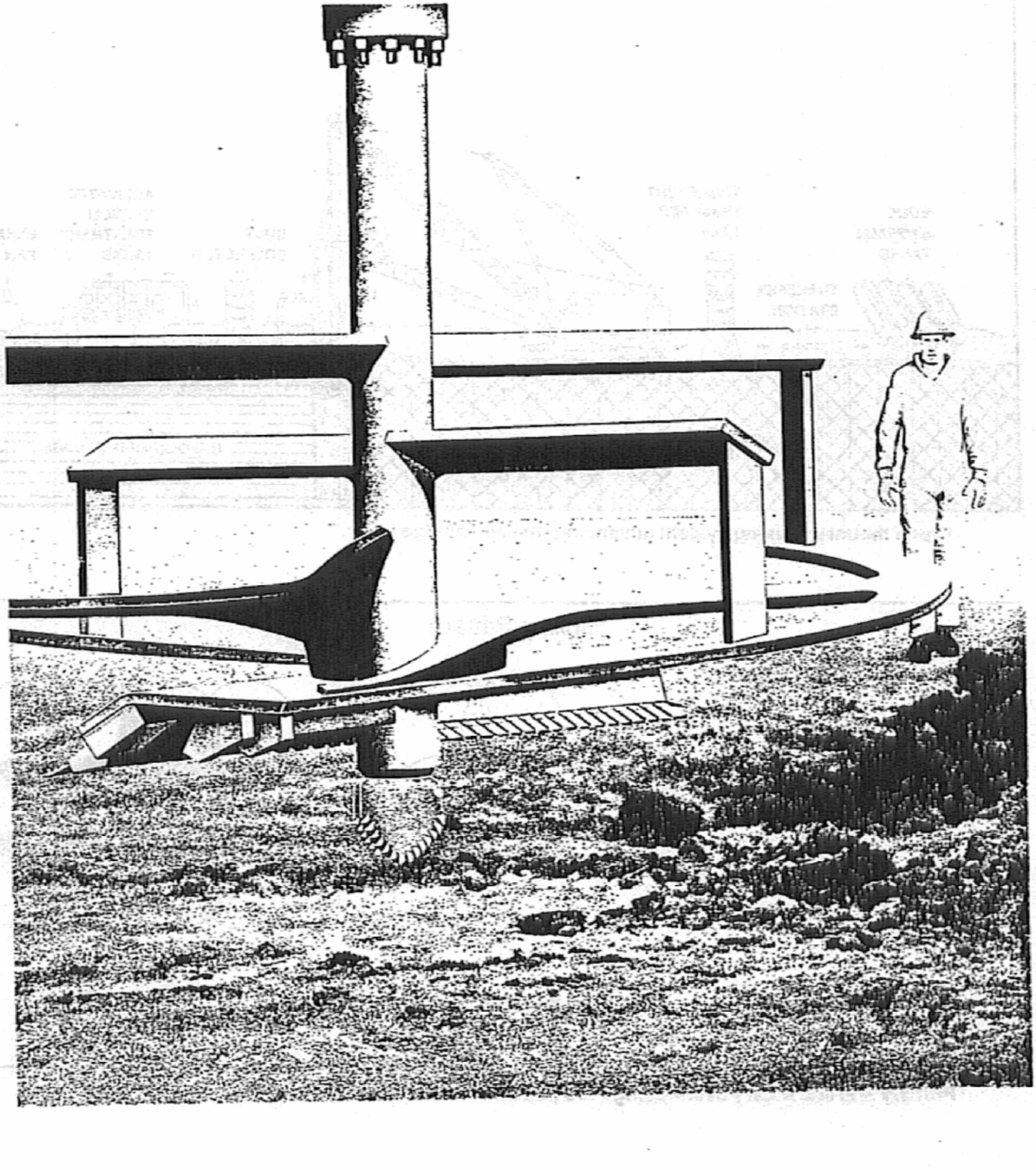


Figure 55. Lower portion of the SSM mixing tool.

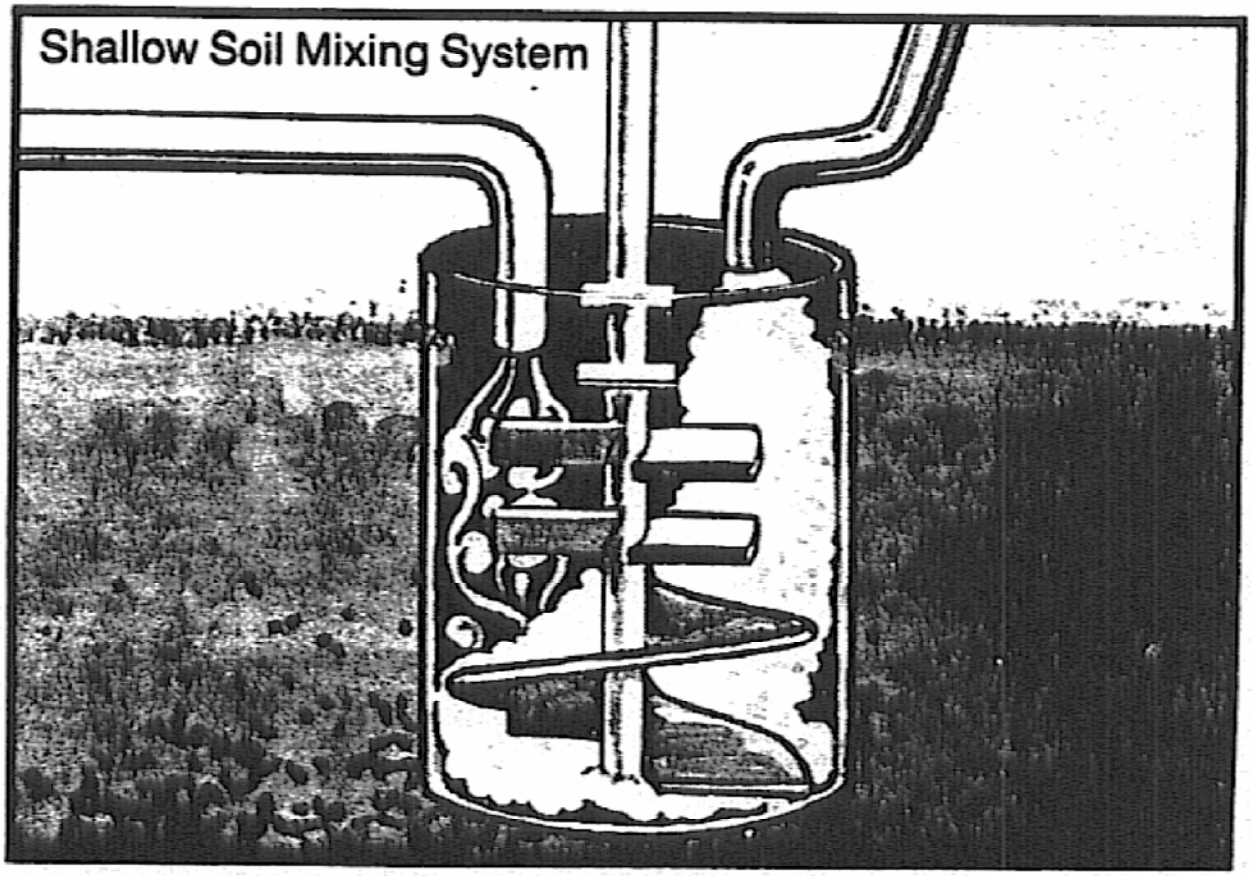


Figure 56. Shroud to capture emanating vapors and dust while treating contaminated soil and sludge up to a 10-m depth (GeoCon, Inc., 1996).

SOIL-CEMENT COLUMN (SCC) (8)

1. INTRODUCTION

This WRE system is offered in the United States by SCC Technology, Inc. in California, a subsidiary of the Japanese inventor, Tenox Corporation. It is promoted as an economic, flexible DMM variant, perhaps best suited for smaller projects, principally piled supports, in situ reinforcement, seepage barriers, and excavation support in soft clays or loose sands. Most recently (Taki, 1999), the product is referred to as a Geo-Column™ (Attachment 4).

2. GENERAL PROCESS (Figure 57)

The shaft is advanced into the ground at about 30 to 60 rpm, while grout with a low water/cement ratio is injected to provide a predetermined (low) volume ratio. Upon reaching bottom, further grout is injected and mixing continues for another minute prior to withdrawal. This occurs with reverse rotation and no further grout injection. The shaft carries a "share" blade (Figures 58 and 59) located above the drill bit that is free to rotate on the shaft. It is of larger diameter than the driven mixing blades and thus its rotation is generally restricted (Figure 60). This is the special, patented TENOBLADE, which dates from 1979 in Japan. The consequence of this action is reportedly a very thorough mechanical mixing in any soil (including clay, silt, organics, and peat above or below the water table). Given that there are three pairs of "cutting-mixing" blades, the soil is attacked six times during penetration and six times during withdrawal. Further details of the method are provided as Attachment 4.

3. EQUIPMENT (Figure 61)

<u>Base</u> Any available carrier can be used that can provide sufficient mast length, power, and maneuverability. SCC Technology, Inc. claims that this could be a crane or track rig with a top- or bottom-drive rotation. A swivel at the top of the rods allows the slurry to be injected.

<u>Shafts</u> Typically, a one-shaft set-up is used (for piles), although two can be used for ground treatment or cutoffs. These single shafts can be 0.6, 0.9, 1.0, 1.2, or 1.5 m in diameter. Double shafts are 0.8, 1.0, and 1.2 m in diameter. These can be installed to a maximum depth of 20 m.

<u>Grout Plant</u> As shown in Figure 61.

<u>Control</u> As shown in Figure 61.

<u>Production</u> During penetration (at 30 to 60 rpm), the advance rate is 1 m/min (15 to 30 mm per rotation, thus creating small-sized cuttings and therefore enhancing mixing quality). Rate of penetration in stiff clay is dependent on rotational speed, which,

in turn, will be limited by the available torque. Industrial productions of 100 m^2 of wall per 8-h shift and 25 piles, each 15 m deep, per 8-h shift have been claimed.

4. MIX CHARACTERISTICS

Grout. The water/cement (Type I-II) ratio (by weight) ranges from 0.6 for soft silts/soft clays, to 0.8 for firm clays, to 1.0 or 1.2 for sand. This is relatively low, but helps to reduce the injection volume ratio (i.e., volume of grout/volume of pile) and thus minimizes cement usage and spoil. Additives (including bentonite for cutoffs, lime or flyash for organics, marine clays and contaminated soils) and other slurries can be used, depending on the soil type to be treated and the desired result. SCC Technology, Inc.'s philosophy is to use these lower water/cement ratios to give strength while still using a low injection ratio. A cement factor of 1.5 to 3 times the required target factor is used.

Treated Soil. Strength is largely a function of initial soil type and material added as well as curing time and efficiency of mixing. A plot of strength versus cement used is shown in Figure 62. Strengths of 3.5 to 7 MPa are obtainable in sandy soil and strengths of 1.3 to 7.0 MPa are generally obtainable in cohesive soil. Soils are moved less than 1 m vertically. Permeabilities of 10^{-8} m/s can be obtained. Data from more than 2,000 projects indicate that 28-day unconfined compressive strength is 1.45 times the 7-day strength for silt and clay soils and 2 times the 7-day strength for sandy soils. Mixes with high water/cement ratios have no long-term strength gain beyond 28 days.

Shear strength is estimated as 30% UCS, tensile strength as 33% UCS, and E_{50} as 180 x UCS. Depending on the desired strength of the soilcrete column, between 150 and 400 kg/m^3 of cement is used, which corresponds to a volume of slurry of 23 to 35% of the native material, depending on the water/cement ratio (0.6 to 1.2). (Typically, a low-volume injection ratio is used to minimize cement usage and spoil, which, therefore, necessitates the use of the Share Blade action.)

5. PATENTED/PROTECTED FEATURES

The system and the drilling/mixing tools are patented in Japan by the Tenox Corporation, and are proprietary to SCC Technology, Inc. in the United States.

6. PARTICULAR ADVANTAGES

Within its geotechnical and geometrical boundaries, this DMM technique offers very high mixing efficiency, consistency and quality, and moderate (< 30%) spoil (which has a low cement content). It is also relatively cheap to mobilize ($15,000/rig) and can utilize "local" carriers and ancillary equipment (including small-scale grout plant or Readimix). Columns can be installed at any angle (up to horizontal) and can accept reinforcing steel. Quoted prices are typically $50 to

$80/lin. m of column (0.6 to 0.9 m in diameter); $70 to $100/m^2 of wall; or $40 to $60/m^2 of foundation area.

7. OPERATING COMPANIES

This process is operated in the United States by SCC Technology, Inc. The company serves 17 States. Since 1993, it has completed about 10 projects, mainly in California (Bay Area). In Japan, over the last 15 years, the annual volume of columns installed by Tenox Corporation has been $100 to $200 million, with a total of 9,000 projects competed from 1979 to 1997.

8. REFERENCES

Bell, R. and A. Dover. (1997). "Soil Cement Pile Foundation for a Large Storage Tank and Retaining Wall – Case History." *Proceedings of the Deep Foundations Institute's, 22nd Annual Member's Conference and Meeting*, Toronto, ON, October, pp. 55-66.

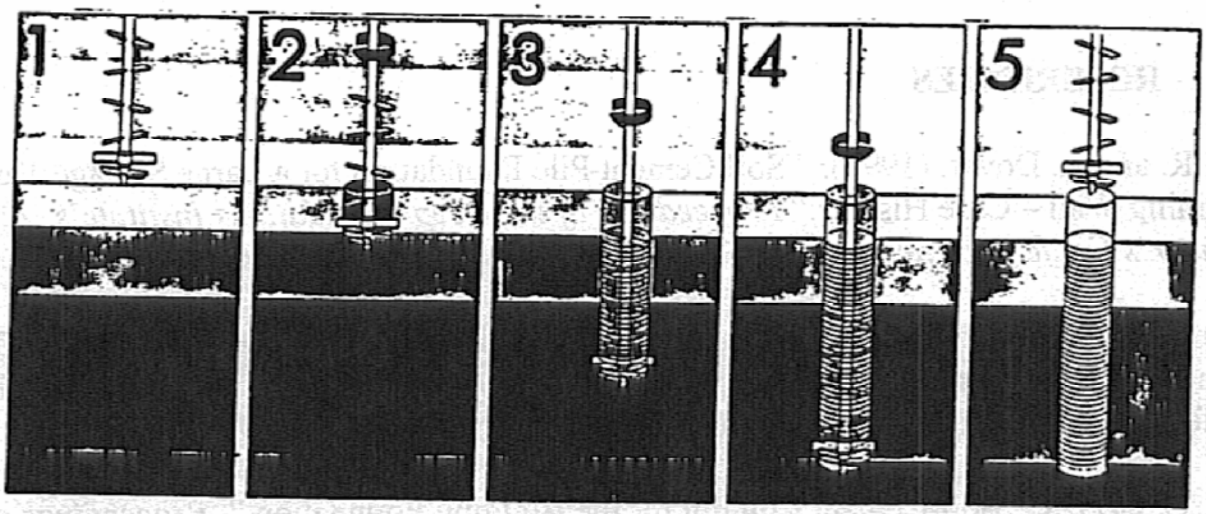
Hibino, S. (1996). "Monitoring of Subsidence of Building on Ground Improved by Deep Mixing Method." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 595-601.

Taki, O. (1992). "Soil-Cement Column for the Building Foundation." *Proceedings of the Deep Foundations Institute's 17th Annual Member's Conference and Meeting*, New Orleans, LA, October, pp. 275-289.

Taki, O. (1999). "Geo-Column." Presented at the University of Wisconsin-Milwaukee Short Course on Deep Mixing Methods, Anaheim/Orange County, CA, April 26-27, 19 pp.

Taki, O. and R. Bell. (1997). "Soil-Cement Pile/Column." SCC Technology, Inc., 23 pp.

Taki, O. and R. Bell. (1998). "Soil-Cement Pile/Column – A System of Deep Mixing." *Soil Improvement for Big Digs, Proceedings of Geo-Congress 98*, American Society of Civil Engineers, Geotechnical Special Publication No. 81, Boston, MA, October 18-21, pp. 27-40.



1. Set the auger at the center of a pile for start of driiing.
2. Drill down to the cut-off depth without grout injection.
3. Drill with injection of cement grout below cut-off depth.
4. After reaching the bottom, withdraw the auger and continue mixing in reverse rotational direction without grout injection.
5. The end of the SOIL CEMENT PILE process.

Figure 57. Production procedures (Taki and Bell, 1997).

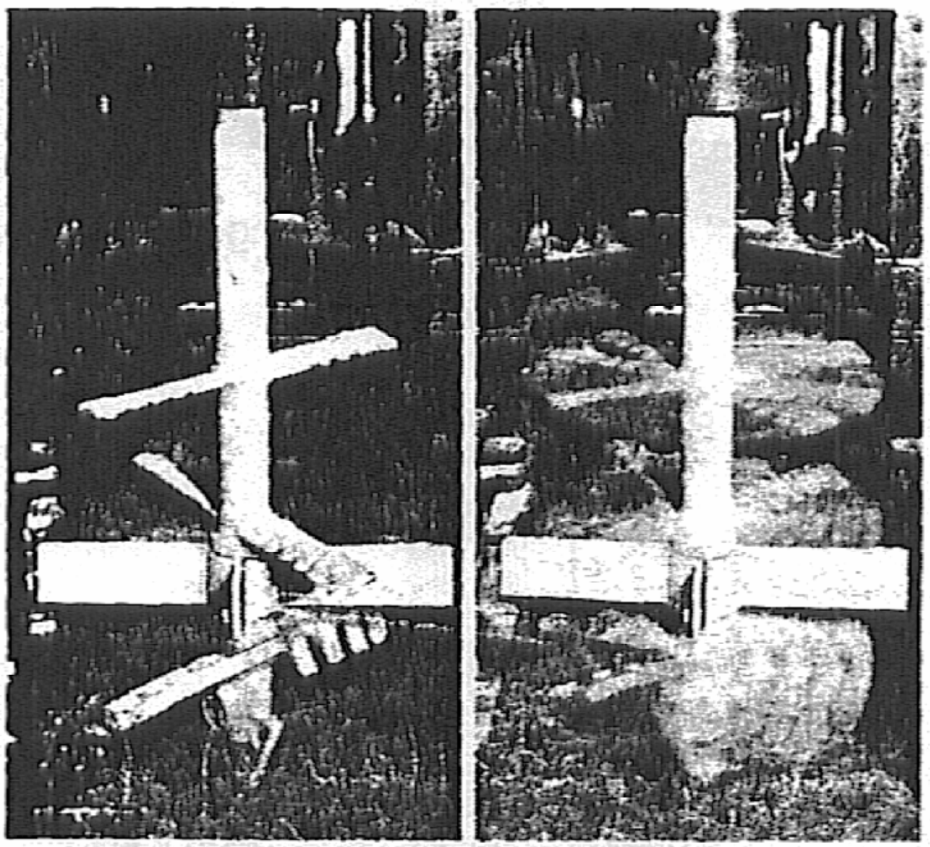


Figure 58. Mixer configuration at rest and in motion, illustrating the concept of the fixed blade (Taki and Bell, 1997).

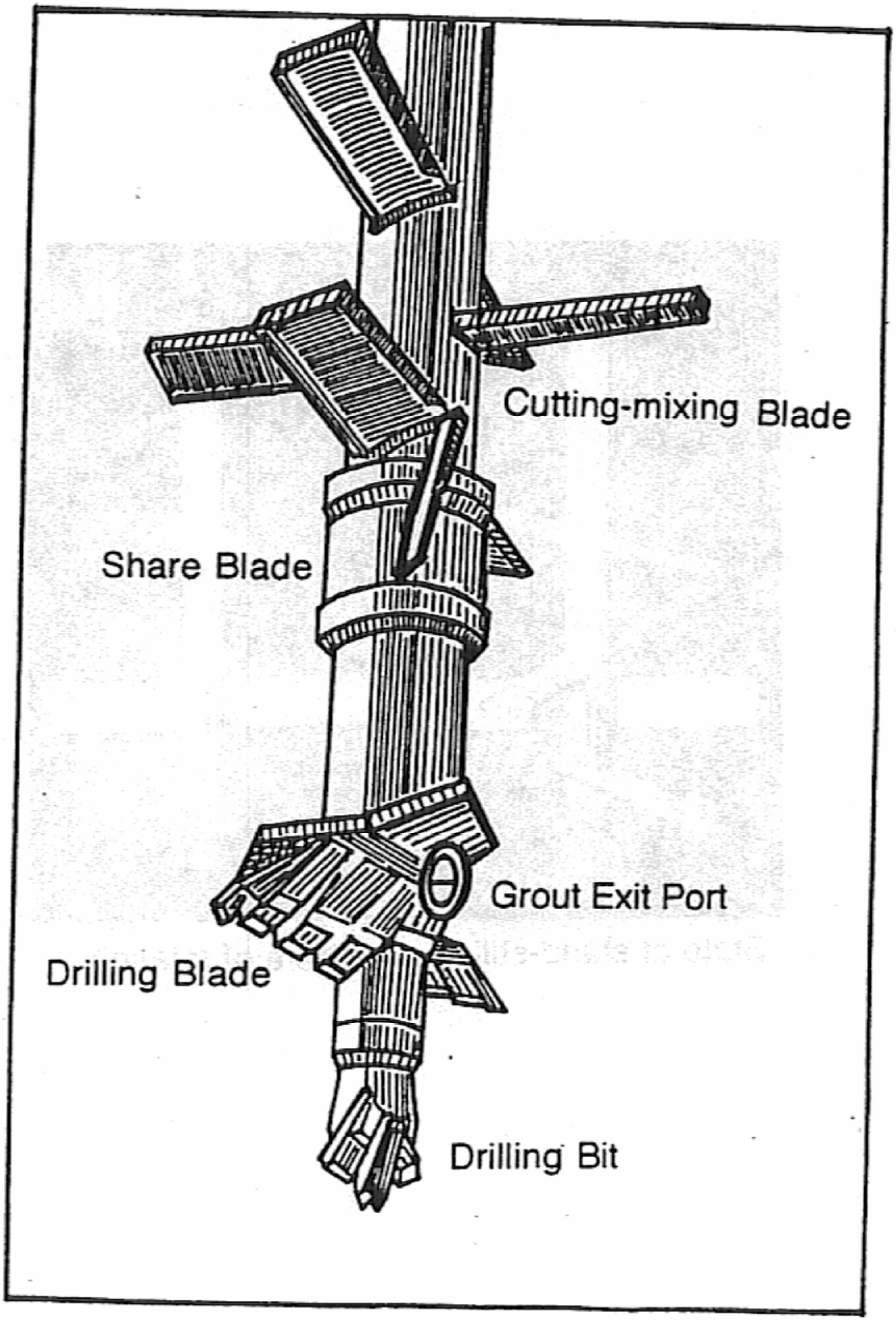


Figure 59. Special drill/mixing tool (Taki and Bell, 1997).

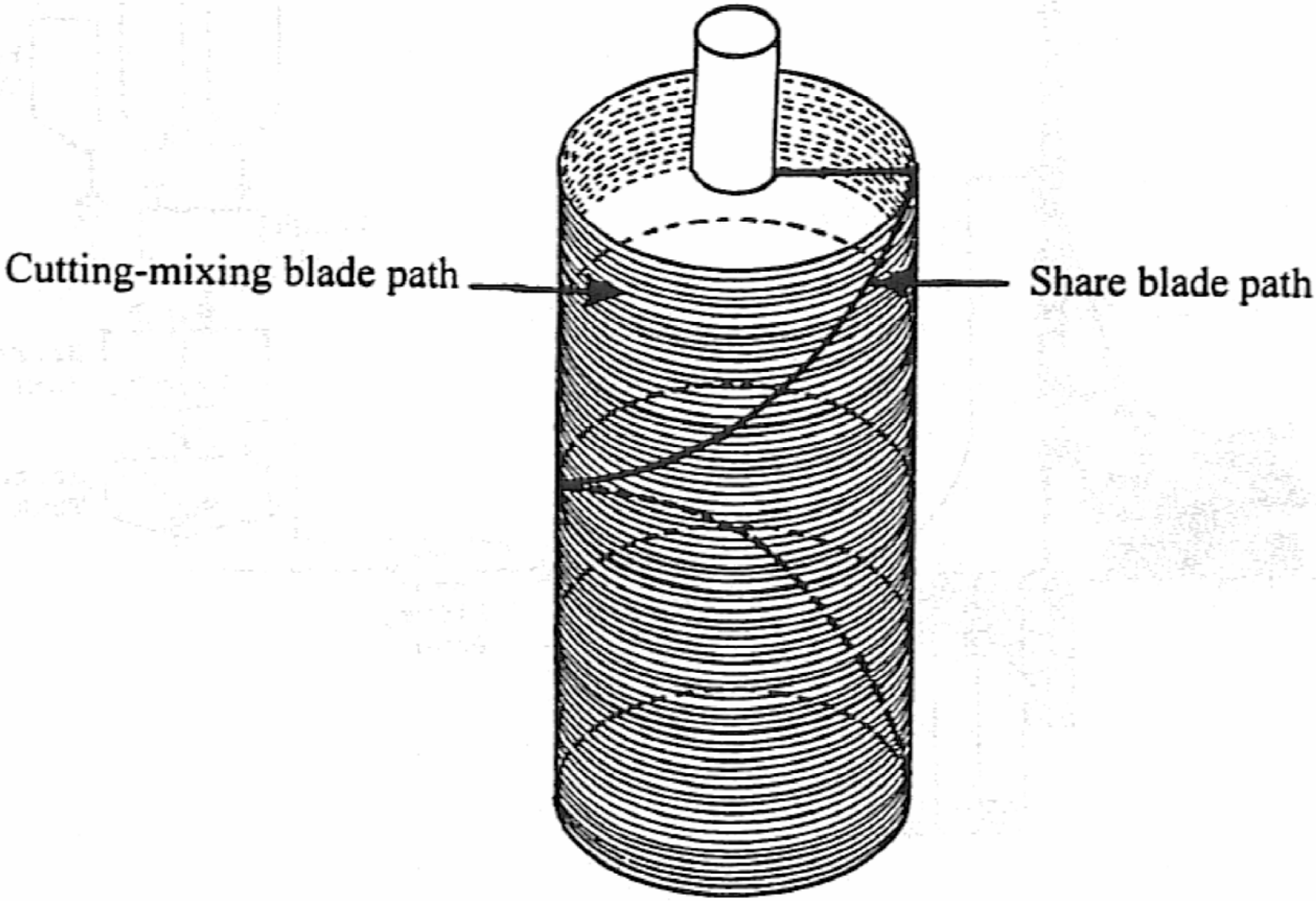


Figure 60. Drill/share blade penetration (Taki and Bell, 1997).

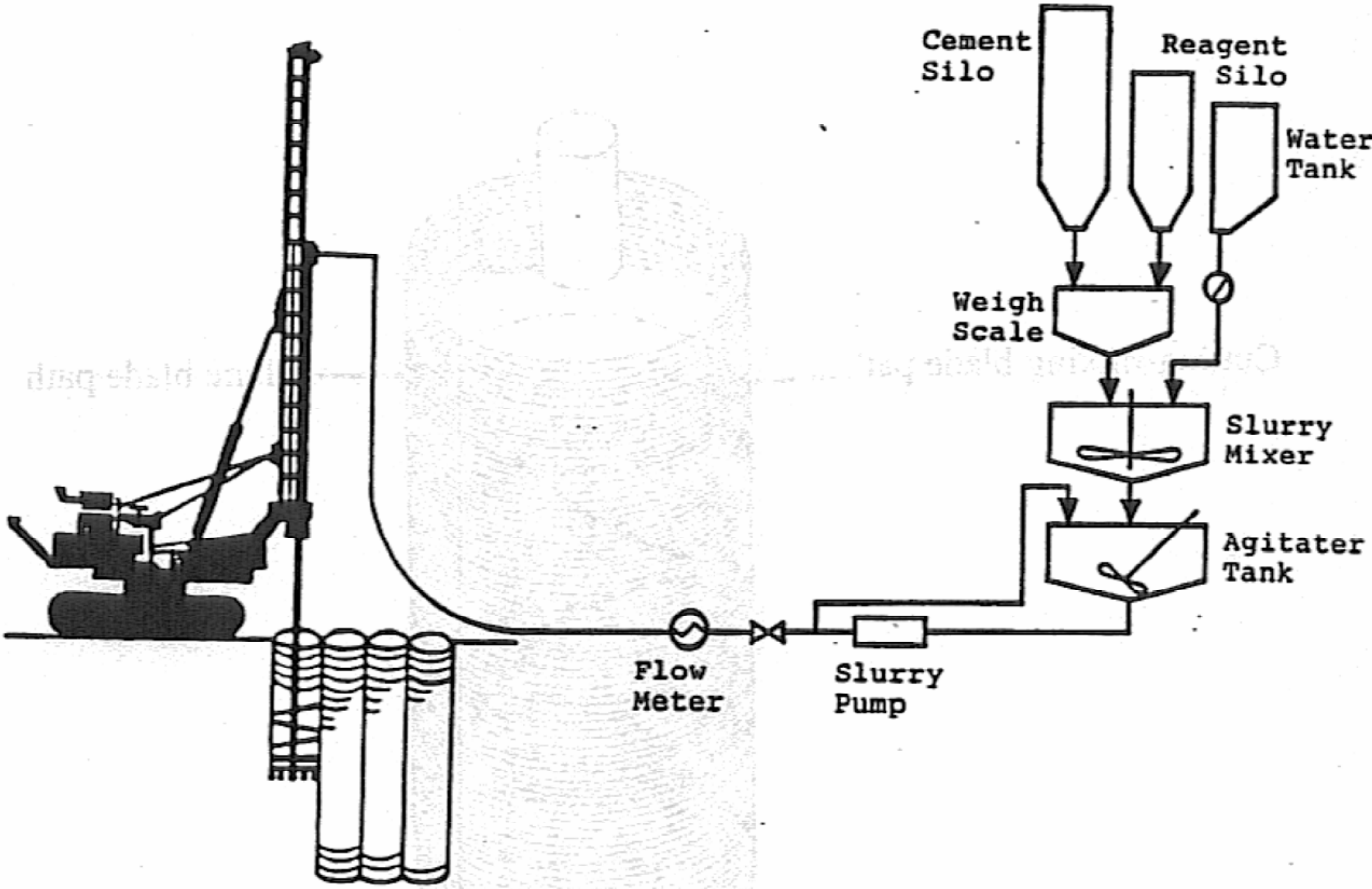
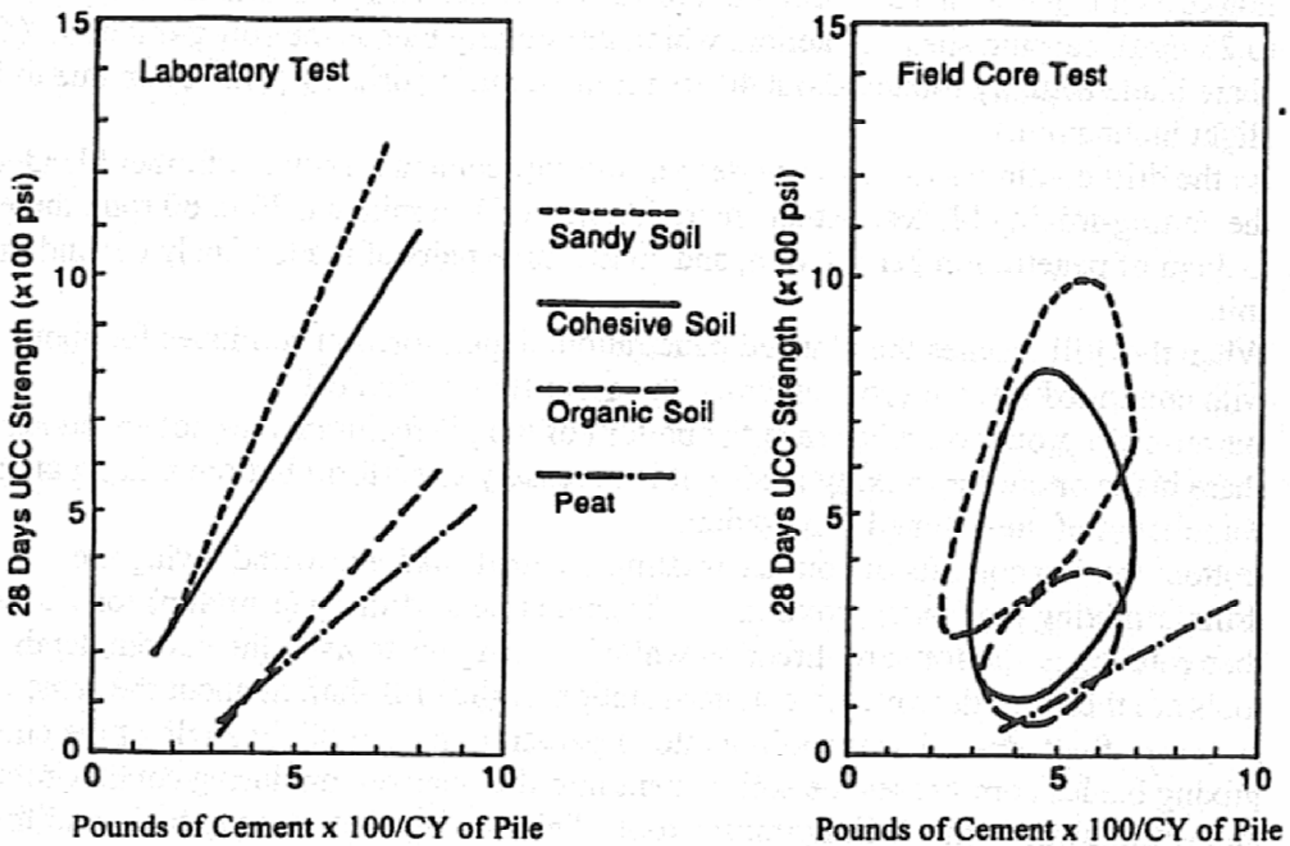


Figure 61. SCC control and grout plant facilities (Taki and Bell, 1997).



1 lb = 0.454 kg
1 yd^3 = 0.765 m^3
1 psi = 6.89 kPa

Figure 62. Relationship of unconfined compressive strength, cement content, and soil type (data developed with a water/cement ratio of 0.6 to 1.2, and a volume injection ratio of 23 to 35%) (Taki and Bell, 1997).

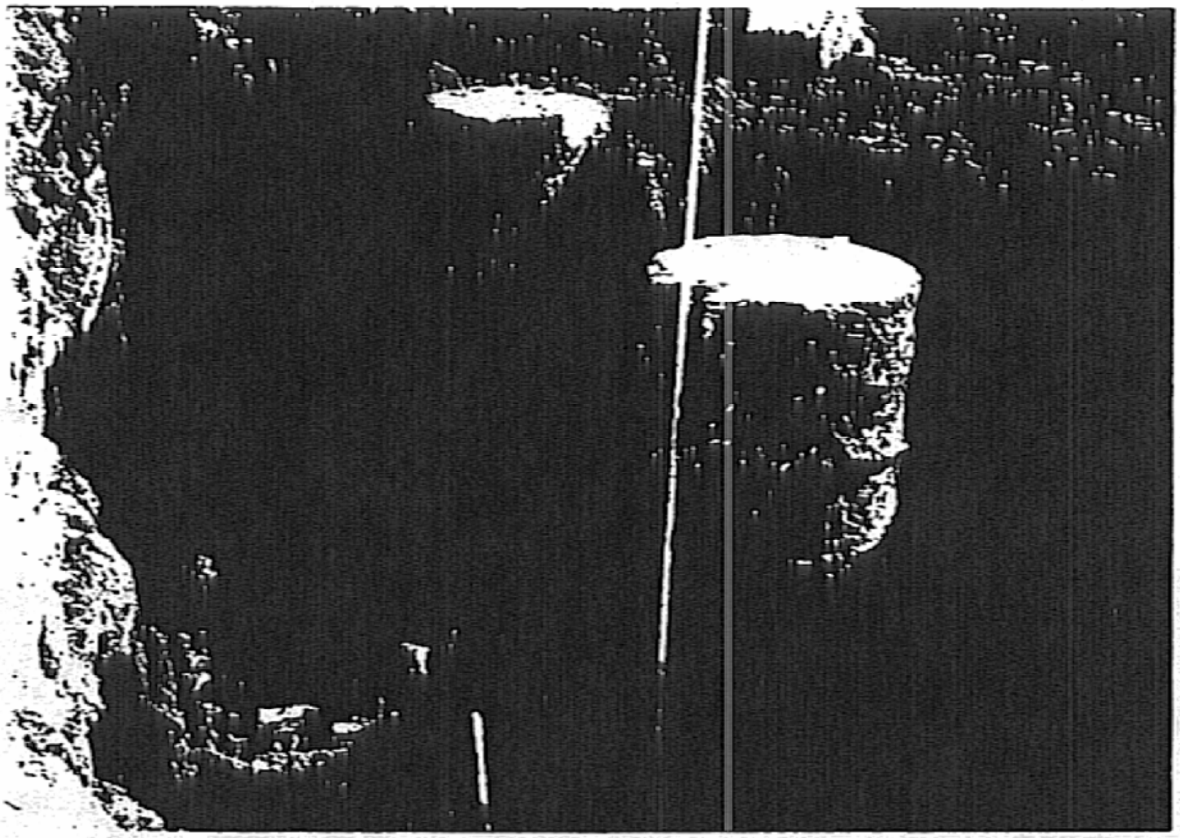
Attachment 4. SCC Technology, Inc. brochure (from Taki and Bell, 1997).

The procedure for mixing is as follows:

1. Cement grout is ejected from the grout exit port located just behind the cutting blades (5° from horizontal), where the grout mixes with the cuttings as the drill penetrates into the in situ soils. There are typically three pairs of mixing blades. The soil cuttings and grout rotate with the drill blade and are only partially mixed. The elevation on the mixing blades lifts the soil-cement during penetration and compresses (counter-rotated) it during excavation.
2. As the drill penetrates deeper, the grout-soil mixture encounters the "share blade," a non-driven blade with a 5° inclination to vertical (thickness proportional to diameter = 6 to 25 mm), causing shearing action, which thoroughly blends the soil-grout mix. (The share blade actually rotates about 40° per minute during drilling penetration due to its slight inclination.)
3. As the drill continues to penetrate deeper, the soil-cement mixture is further blended by the cutting-mixing blades. At a penetration rate of 1 m/min and 30 to 60 rpm, there is 1.5 to 3 cm of penetration per rotation, and so the three pairs of blades finely cut and mix the soil.
4. When the drill reaches the planned penetration, depth, rotation continues for about 1 min with continued flow of grout and then the grout flow is shut off.
5. Because the grout-soil mixture at the bottom of the pile/column does not encounter the share blade or cutting-mixing blades, it is necessary to perform bottom mixing after completion of the planned penetration.
6. Bottom mixing consists of counter-rotating the drill shaft and withdrawing the drilling/mixing tools at approximately the same rate as drilling (1 m/min) for 1.5 to 3 m, then rotating in the forward direction while lowering the tools to the bottom depth. The tools are then withdrawn with counter-rotation of the drill shaft at about the same rpm and rate of withdrawal as the initial rate of penetration. The slight angle of the cutting-mixing blades compresses the soil-cement into the pile/column during counter-rotation and withdrawal of the drilling/mixing tool. This is a key factor in producing uniform mixing.

It will be noted that the key element is the share blade, which is a relatively new invention. (Its name comes from the share blade on a farming plow.) The share blade is not fixed to the drill shaft, but is free from the rotation of the shaft. The share blade is slightly larger than the drill diameter so that it cuts into the side of the in situ soils. The share blade is at a slight inclination from the axis of the drill shaft (Figure 59).

The cutting-mixing blades are inclined slightly from the horizontal so that they tend to lift the soil-cement mixture when the drill is in the forward penetration direction of rotation, and to compress the mixture during withdrawal with counter-rotation.



Column Diameter : 5 feet (60 inches)

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- Pile Foundation
- Ground Stabilization
- Liquefaction Prevention
- Settlement Prevention
- Slope Stabilization
- Earth Support Wall

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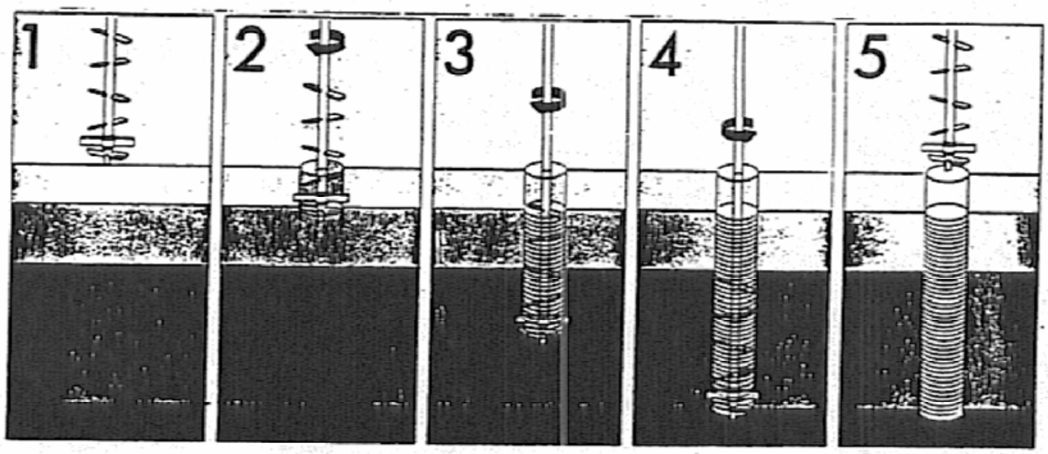
1 in = 25.4 mm, 1 ft = 0.305 m

Geo-Column™

Production Procedures



1. Set the auger at the center of a pile for start of driiing.
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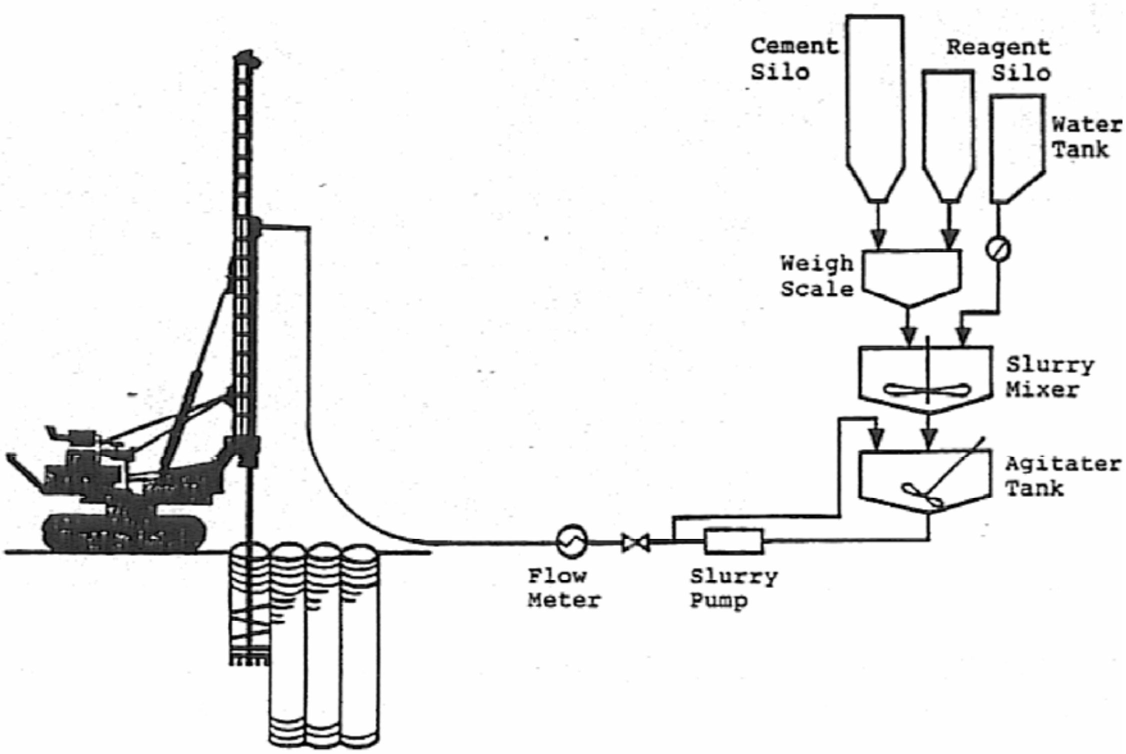
3. Drill with injection of cement grout below cut-off depth.
4. After reaching the bottom, withdraw the auger and continue mixing in reverse rotational direction without grout injection.
5. The end of the SOIL CEMENT PILE process.

System



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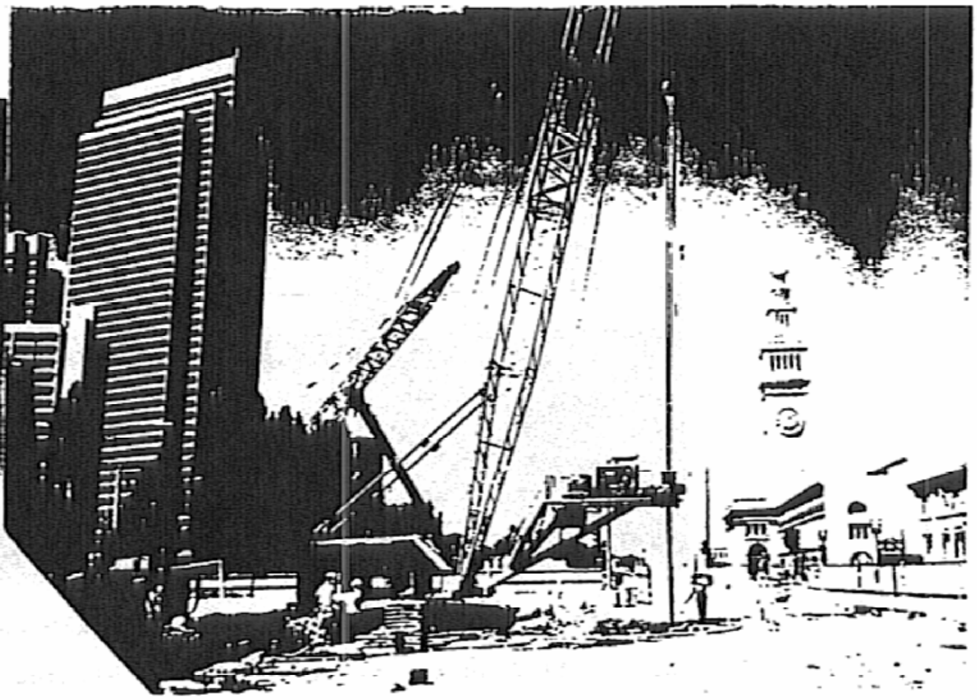
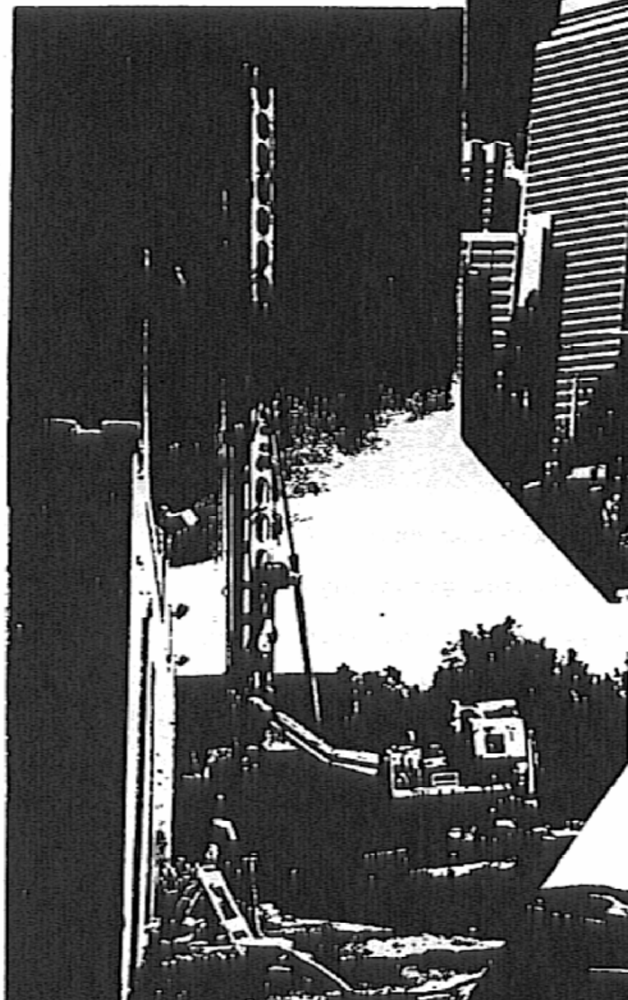
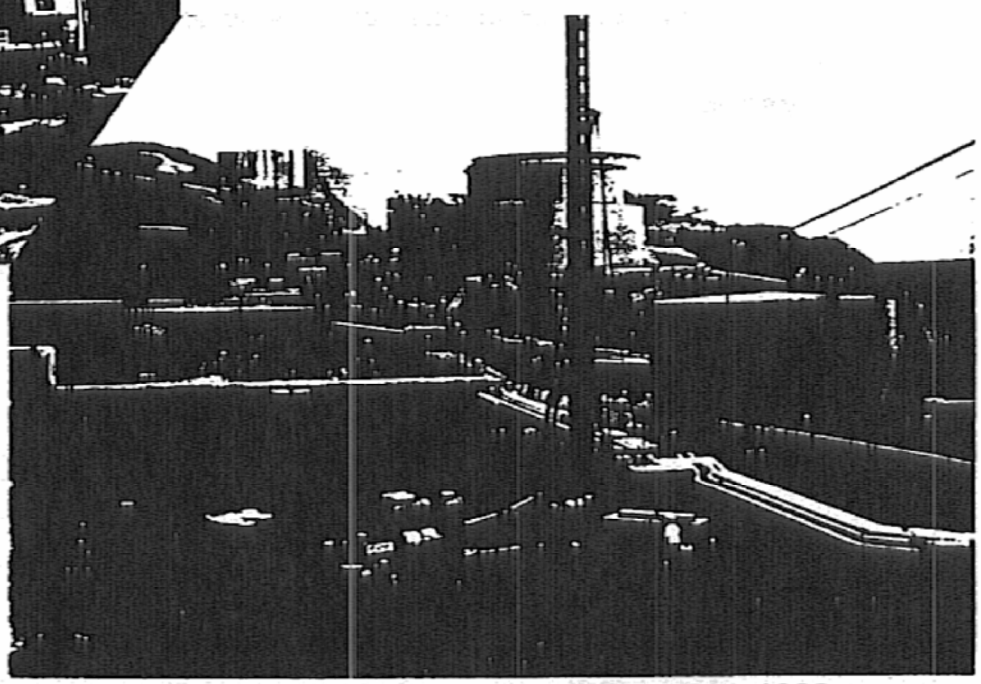


San Francisco, MUNI Metro
Seepage Cutoff 1994



Ground Stabilization
Mt. View, CA 1993



Tank Foundation, Richmond, CA 1993

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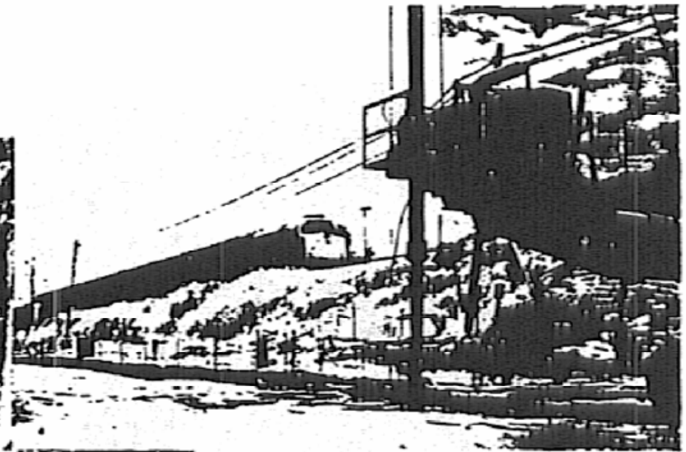
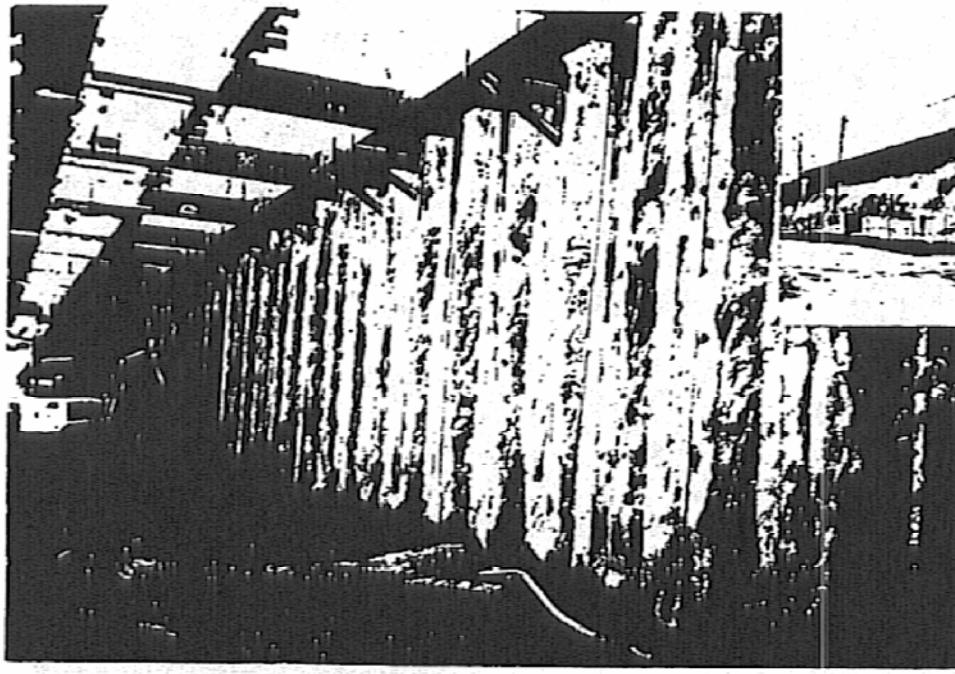
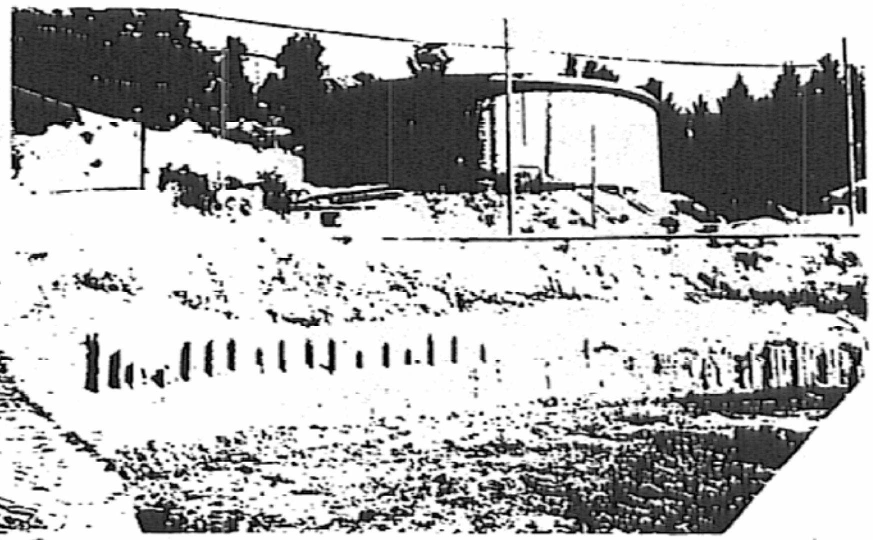
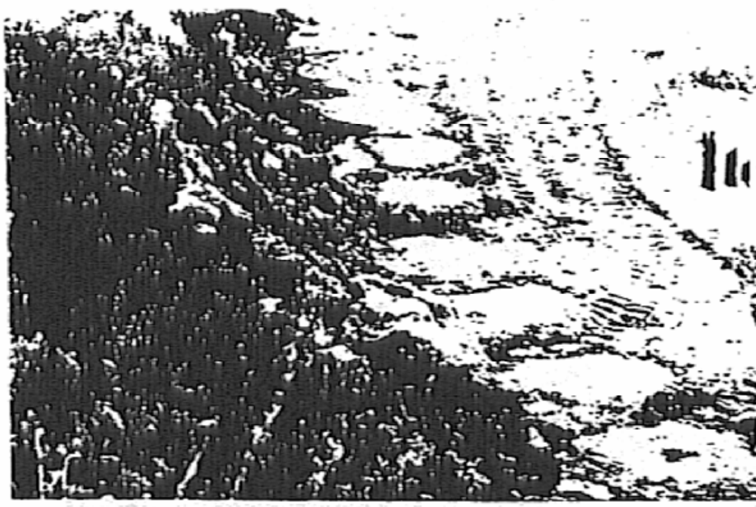




Earth Support Walls
Sewage Box Culvert
Islais Creek -B-
S.F. City/County, CA 1995





Retaining Walls
Slope Stabilization
Chevron Refinery
Richmond, CA 1995

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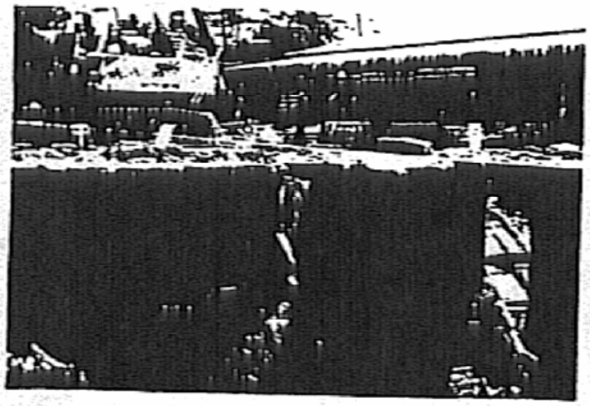
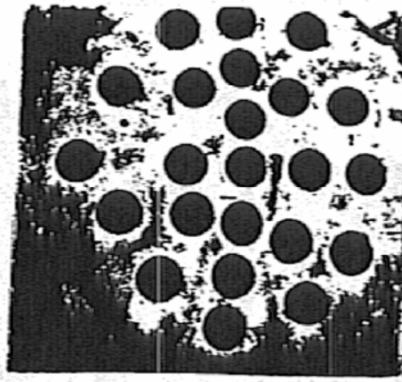
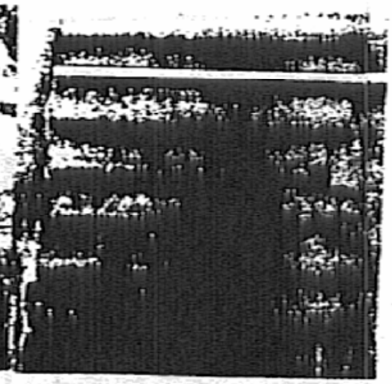
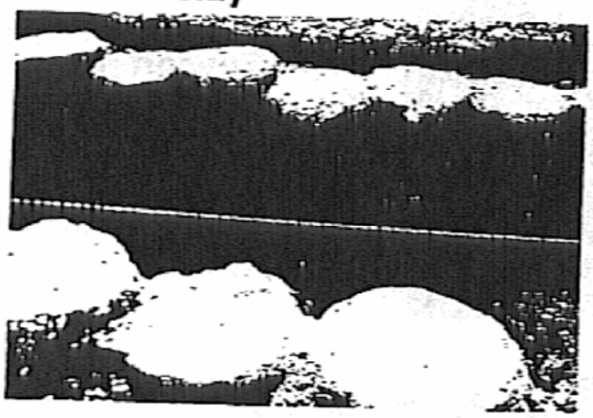
Sand

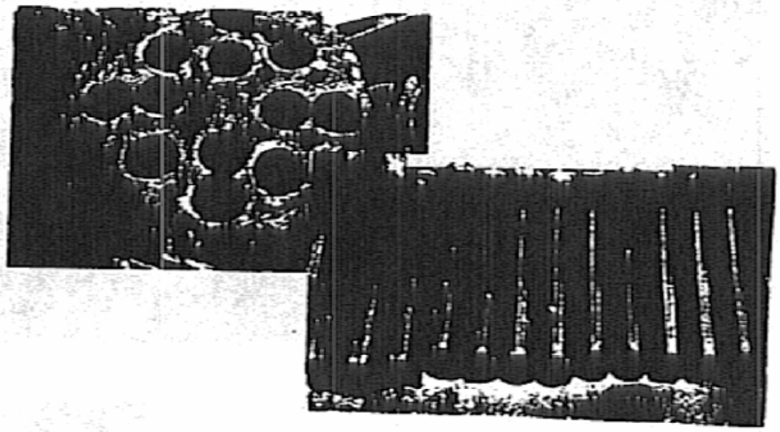




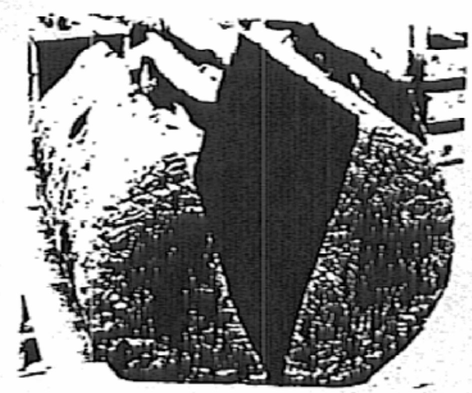


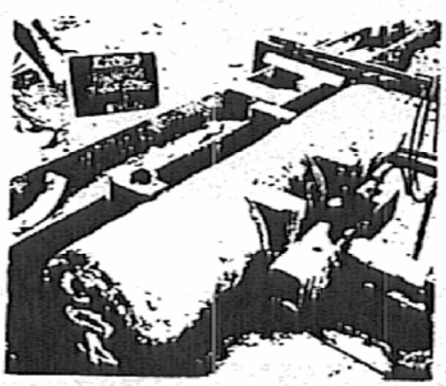
Silt and clay





Organic soil





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Geo-Column™
NEWS LETTER
September, 1998

Jefferson Avenue Underpass Cutoff Wall

In down town of Redwood City, California, project of Jefferson Avenue Underpass to the CalTrain is now on going. 50,500 SF permanent cutoff wall by Soil-Cement Columns was used because of the reductionof pumping in and after the project. And also the parts of cutoff wall are using as shoring walls.

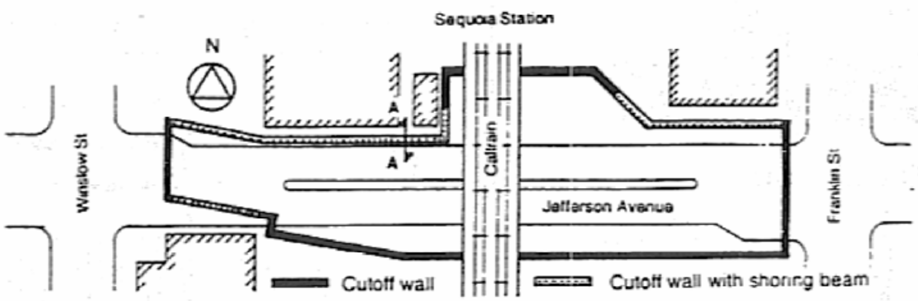


Figure 1 Plan of cutoff wall

This cutoff wall was originally designed by soil-cement columns, 30 in diameter, 2 ft center to center, 48 ft depth, 1/150 vertical and 200 psi columns strength.
Mix design by cement-bentonite were achieved to the specified 1×10^{-6} cm/sec permeability.

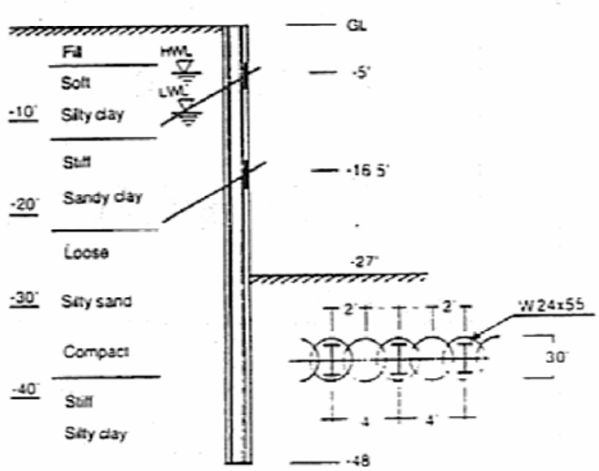
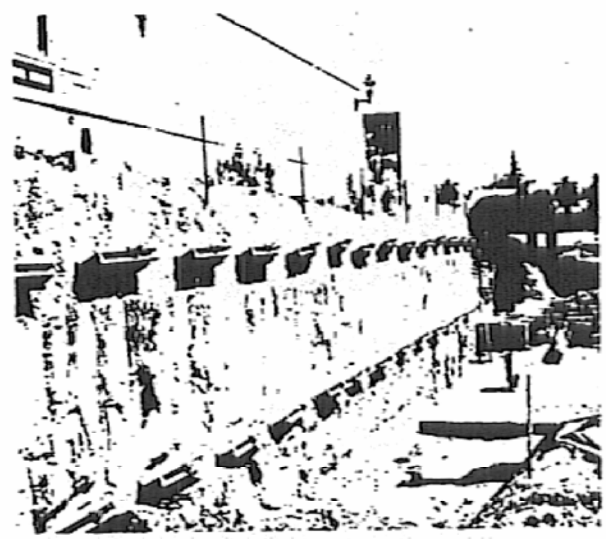


Figure 2 Detail of shoring wall (A-A)



Owner : City of Redwood City

Structural Engineer : Biggs Cardosa Associates

Engineer : Brian Kangas Foulk

General Contractor : Dillingham Construction

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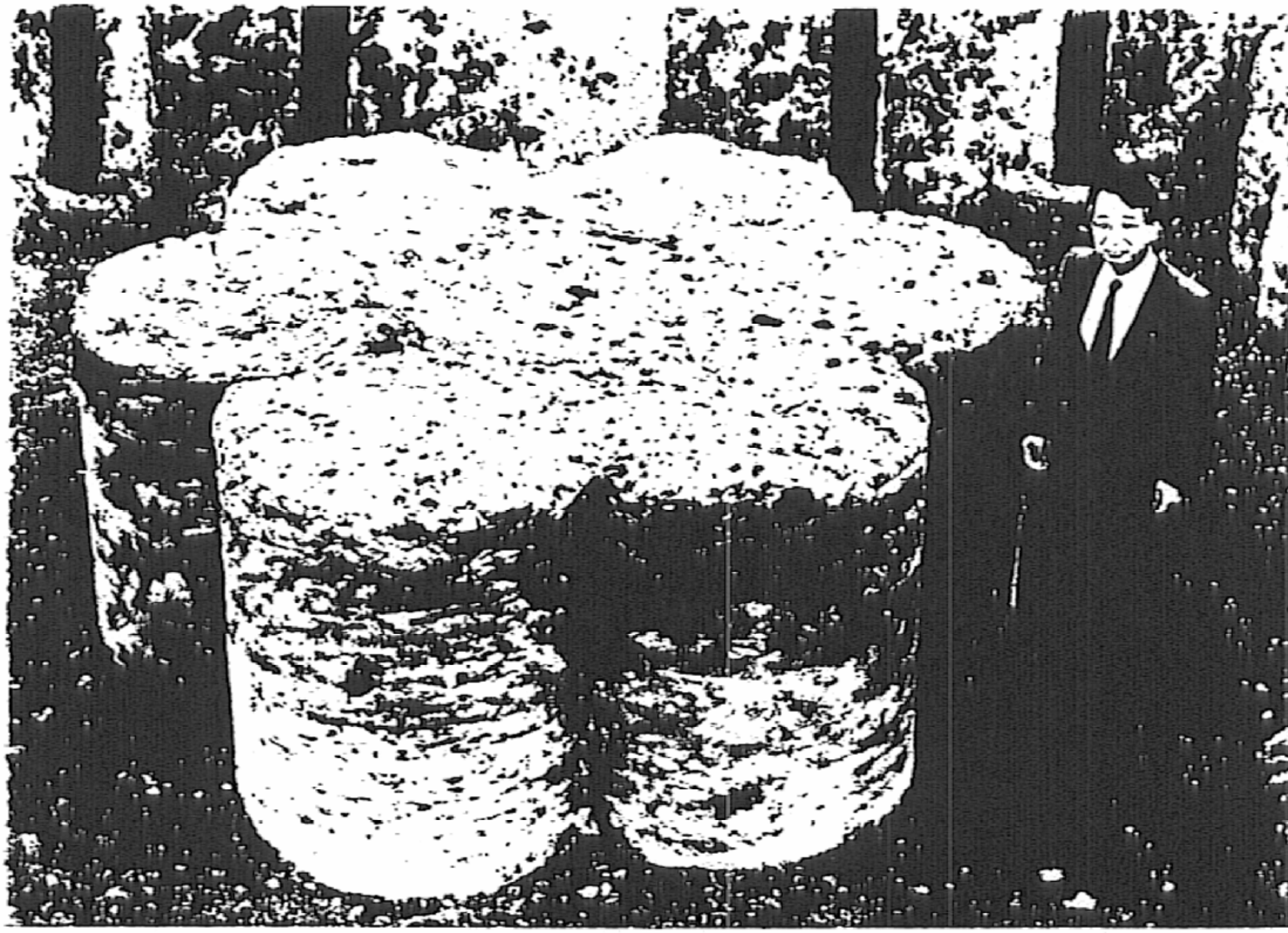

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MecTool® (9)

1. INTRODUCTION

This WRE method has been patented by Millgard Environmental Corporation in the United States. As shown in Figure 63, it was primarily intended as an environmental cleanup technique having high-volume air-handling units mounted on the crawler to provide "high-pressure injection and vacuum extraction with particulate and absorption capabilities tailored to the contaminant profile." In recent years, however, the technique has been promoted in the geotechnical market for seepage barriers, soil stabilization, and foundation construction. A companion method for marine work – Aqua MecTool® – has also been patented, which features a patented isolation mechanism which encloses the submerged tool, protecting the water above from secondary contamination. MecTool® was the winner of the 1993 NOVA award for construction innovation.

2. GENERAL PROCESS

Grout is injected through the hollow kelly bar, cable-suspended and rotated by a fixed turntable rotary drive. For "plastic soil conditions," grout is placed in a predrilled hole in the center of each element and blended with the tool, to form a larger diameter. This reportedly gives excellent control over grout and spoil quality. A proprietary additive is used in the grout which breaks down plastic soils, thereby enabling conventional WRE-type injection and mixing. Columns of up to 4.2 m in diameter are possible to depths of 25 m.

3. EQUIPMENT (Figure 63)

<u>Base</u> Suitable crawler.

<u>Shafts</u> Single, hollow with end-mounted tool.

<u>Grout Plant</u> Readimix grout fed into pumps that can deliver at up to 2 MPa.

<u>Control</u> Computer control over "major system components," also providing full documentation of the parameters of each column.

<u>Production</u> Not available.

Note that the equipment is described as complete, compact, and highly mobile, appropriate for operating in tight quarters "and ideal for pilot-scale tests."

4. MIX CHARACTERISTICS

These seem to be highly variable, and are illustrated in the following table:

Project Name	**Date**	**Diam.**	**Depth**	**Binder**	**Results**
Grand Rapids, MI	1994	2.4 m	2.7 m	Type I cf = 10%	Not available.
Charleston, SC		3.6 m	3 m	Type I + Class F ash cf = 16.3%	UCS = 2 MPa (sands) $k = 1 \times 10^{-8}$ m/s
Manitowoc, WI	1993 to 1994	2.1 m	9.6 m	60% Type + 22% ash + 9% activated carbon and 9% organophilic clay cf = 34% Note: Inject on first pass; mix on second pass.	UCS = 0.8 MPa $k = 1.8 \times 10^{-9}$ m/s
Pumpherston, Scotland		2.5 m	5 m	30% Type I; 10% Pfa; 0.5% carbon and 59.5% water (by volume) Volume factor = 23% cf = 13.2%	UCS = 2.5 MPa $k = 5.5 \times 10^{-9}$ m/s

5. PATENTED/PROTECTED FEATURES

As noted above.

6. PARTICULAR ADVANTAGES

As noted above.

7. OPERATING COMPANIES

Millgard Companies based in Livonia, MI, and Medford, MA.

8. REFERENCE

Millgard Corp. data (1993).

What is MecTool®?

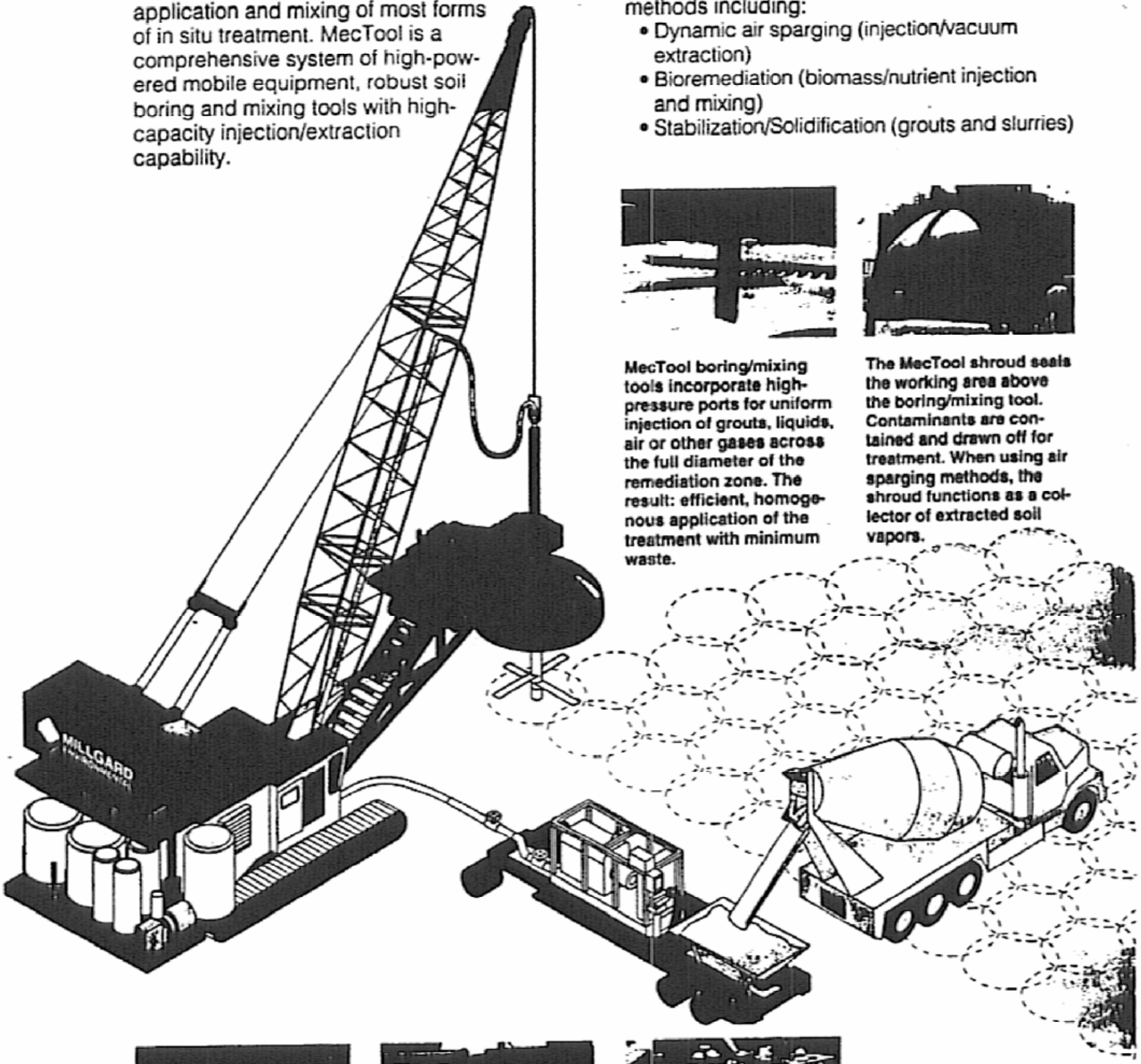
Millgard Environmental Corporation has designed and patented* an advanced remediation delivery system that provides superior application and mixing of most forms of in situ treatment. MecTool is a comprehensive system of high-powered mobile equipment, robust soil boring and mixing tools with high-capacity injection/extraction capability.

This integrated system of proven components is engineered to provide unprecedented effectiveness in the application of many treatment methods including:

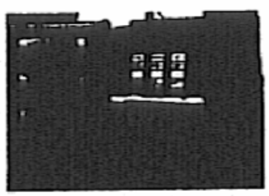
- Dynamic air sparging (injection/vacuum extraction)
- Bioremediation (biomass/nutrient injection and mixing)
- Stabilization/Solidification (grouts and slurries)

MecTool boring/mixing tools incorporate high-pressure ports for uniform injection of grouts, liquids, air or other gases across the full diameter of the remediation zone. The result: efficient, homogenous application of the treatment with minimum waste.

The MecTool shroud seals the working area above the boring/mixing tool. Contaminants are contained and drawn off for treatment. When using air sparging methods, the shroud functions as a collector of extracted soil vapors.



High volume air handling units are integrated into the MecTool rig for mobility and flexibility. A single unit provides high pressure injection and vacuum extraction with particulate and absorbtion capabilities tailored to the contaminant profile.



Major system components are controlled and monitored to provide precise delivery and full documentation of the treatment delivery process.

Reliable, high volume pumps are designed to deliver grout/slurry mixes efficiently at pressures to 300 psi. The flexible design permits efficient short-run batch delivery for pilot tests.

* MecTool: (U.S. Patent 5,135, 058).
Aqua MecTool: (U.S. Patent 5,127, 765)

Figure 63. Details of the MecTool system (Millgard Corporation, 1993).

RAS COLUMN METHOD (10)

1. INTRODUCTION

RAS (Raito Auger Shaft) Column Method is a WRE method that provides a large-diameter (1.4- to 2.0-m) column using a single-shaft, double-rod, high-speed counter-rotating system. It permits high treated soil strengths of good quality and is well suited to providing deep, pile-type foundations for a variety of structures, as well as ground improvement for other applications.

2. GENERAL PROCESS (Attachment 5 and Figure 64)

During penetration, the "excavation and mixing head" is rotated by the inner drill string with a "right turn." The three mixing wings above are rotated "left turn" (i.e., anti-clockwise) by the outer drill rod. Grout is injected via ports at the tip of the "excavation head." Depths of 24 to 28 m can be reached in soils of N value up to 30. Upon reaching target depth, the shaft is cycled up and down while additional grout may be injected.

The "excavation head" has a narrow profile blade designed to shear the soil without causing great lift. (The profile is about the same size as the diameter of the shaft.)

3. EQUIPMENT (Attachment 5)

Base	A suitable crawler crane with fixed leads weighing about 130 tonnes, providing about 175 kW; and 13 tonnes pull-down on the inner rods.
Shafts	Concentric, double tubes, counter-rotated by a special head. Mixing paddles vary from 1.4 to 2.0 m.
Grout Plant	Semi-automatic computer-controlled and monitored plant, including silos, feeds, mixer, storage tank, and pumps. Maximum capacity of mixer is 0.5 m^3/min.
Control	The construction management system exerts computer control over depth, penetration rate, withdrawal rate, rotational speed, and injection rate (Figures 65 and 66).
Production	Instantaneous production rates are 0.5 m/min during penetration and 1.0 m/min during withdrawal. Data showing production rates at three separate sites are provided in Figure 67.

4. MIX CHARACTERISTICS

Grout. Typically, neat cement grouts are used, with a water/cement ratio of 0.8. Cement factors are around 300 kg/m^3, with a grout volume ratio of 33% (one data set only).

Treated Soil. Strengths may vary from 1 to 6 MPa and will vary with distance from the center of the column (Figure 68).

5. PATENTED/PROTECTED FEATURES

RAS is understood to be patented by Raito Kogyo, Co., Ltd. of Japan.

6. PARTICULAR ADVANTAGES

Provides relatively high-strength, well-mixed, large-diameter columns even in dense soils, and so can be very competitive. The highly sophisticated computer control is typical of modern methods.

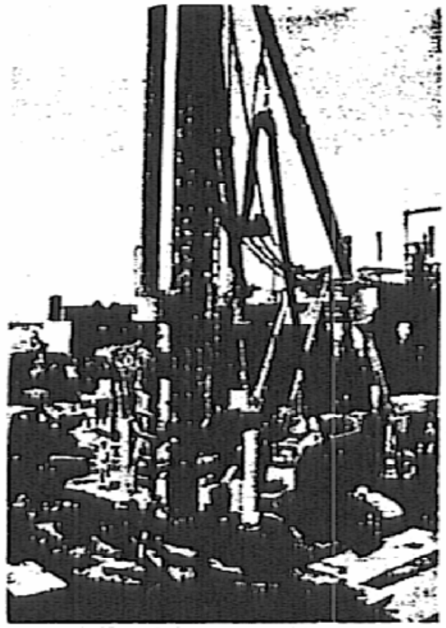
7. OPERATING COMPANIES

The Japanese parent. Raito Kogyo, Co., Ltd. is now represented in the United States. by Raito, Inc. in California.

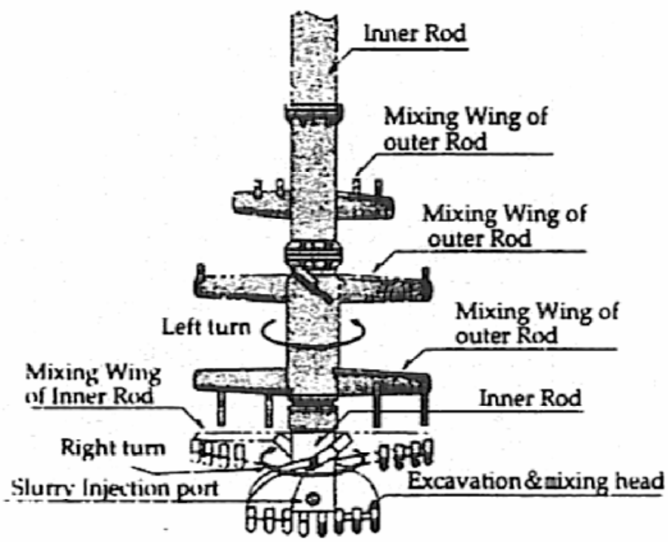
8. REFERENCES

Isobe, K., Y. Samaru. C. Aoki, K. Sogo, and T. Murawaki. (1996). "Large-Scale Deep Soil Mixing and Quality Control." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 619-624.

Raito Kogyo Co., Ltd. (Date unknown). "RAS Column Construction."



Excavation-mixing machine



Excavation-mixing rod

(1)Performance

Diameter of mixing wing,	1,400 to 2,000 mm.
Excavation mixing speed,	0.5m/min.
Pull up speed,	1m/min.
Depth of mixing.	up to 24m
Target of mixing soil,	N value up to 30 (gravel, sand layer).
Produced column strength,	1.0 to 6.0 MPa
Output of power (torque),	175kW (kN-m)
Inner pipe thrust (dead load),	about 12t
Basemachine	120t class

Figure 64. Excavation-mixing machine and rod (Isobe et al., 1996).

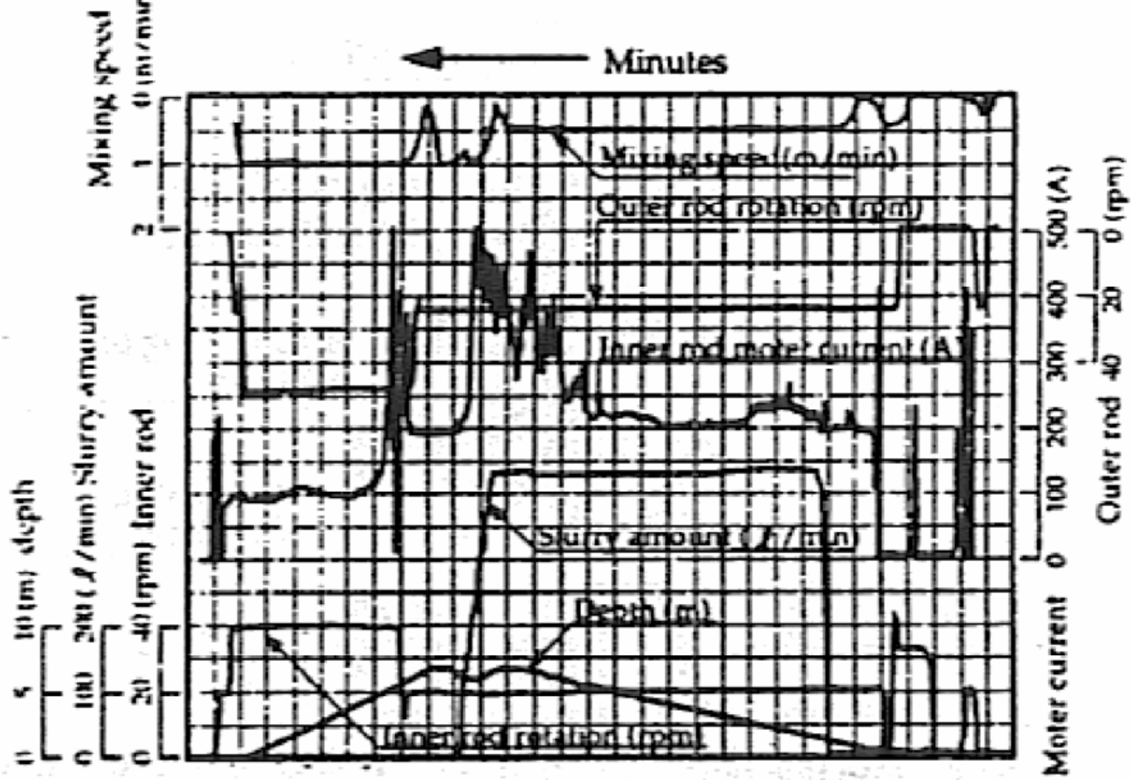
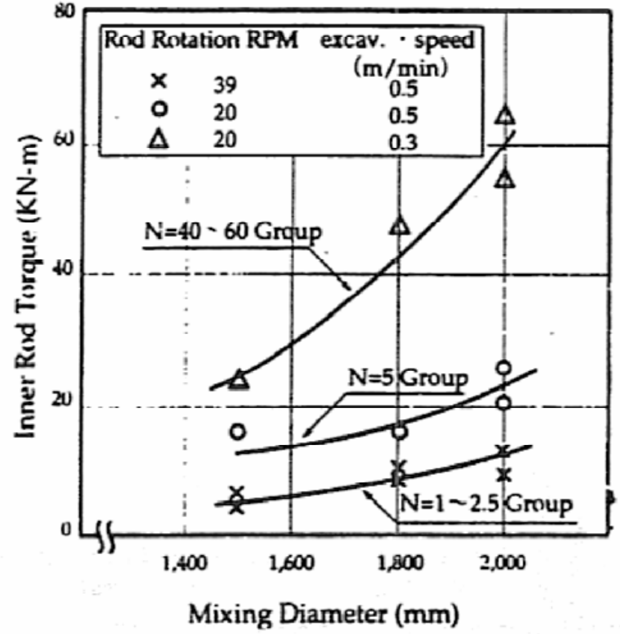
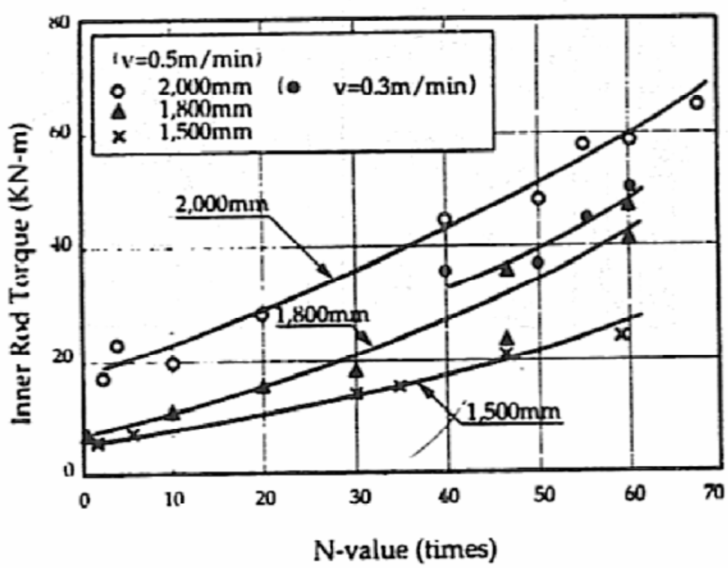


Figure 65. Oscillograph (Isobe et al., 1996).



Variation of Mixing Diameter and Rod torque



Relationship between N Valve and Rod Torque

Figure 66. Relationship of rod torque to mixing diameter and N-value (Isobe et al., 1996)

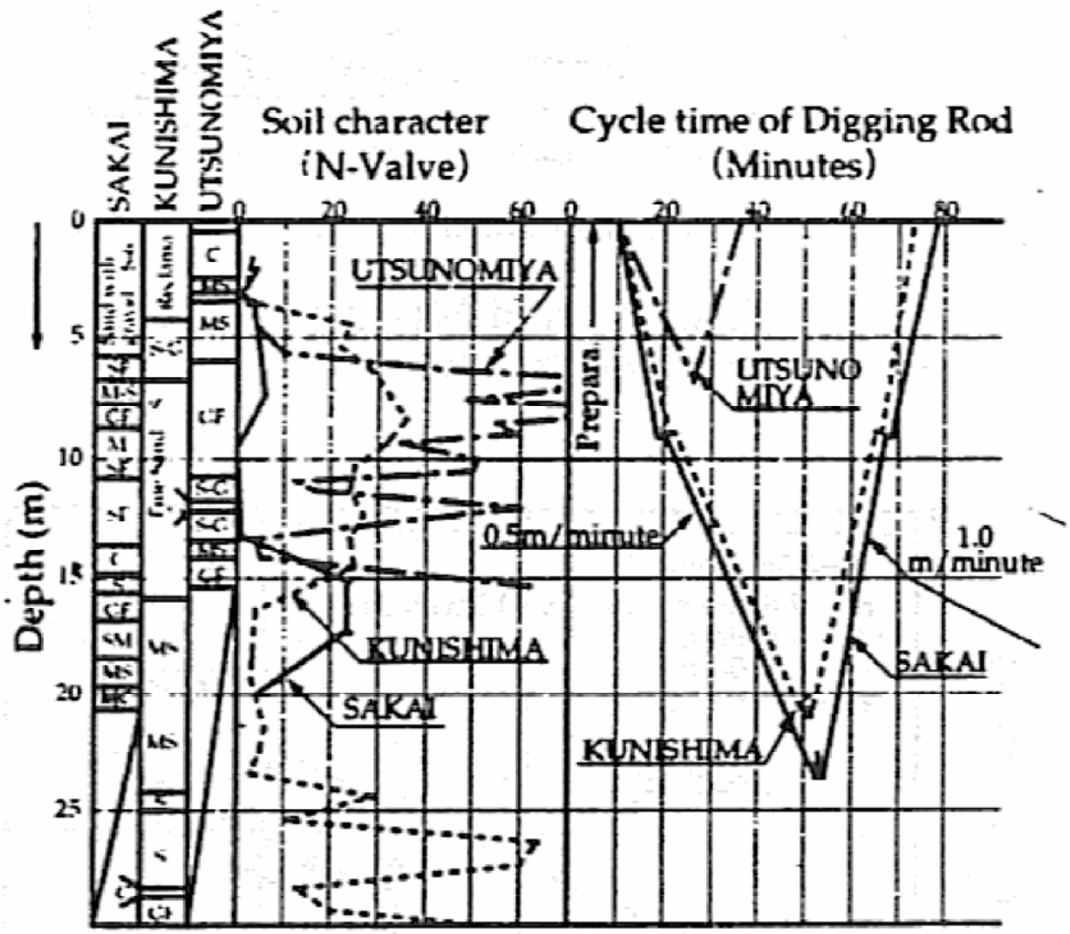
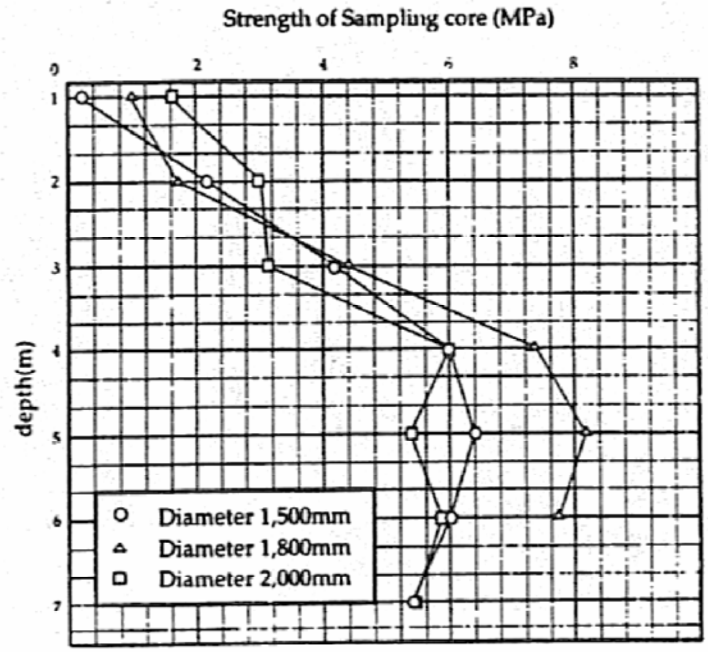
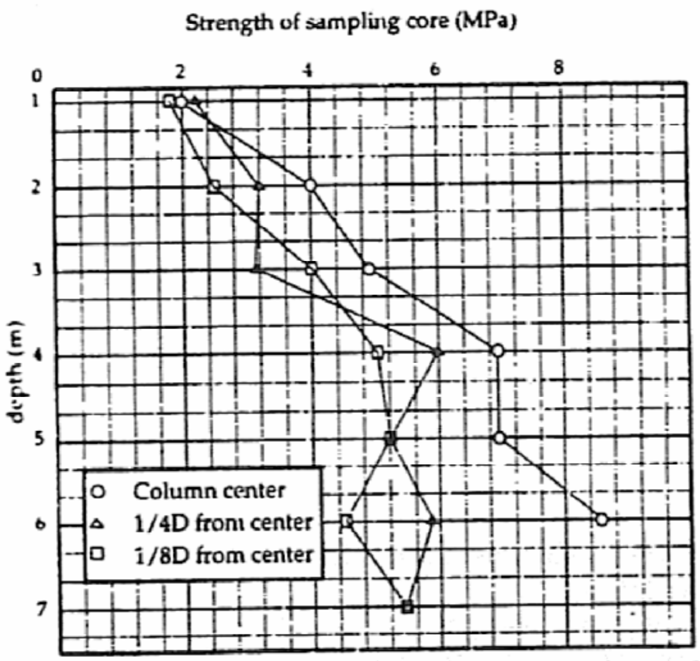


Figure 67. Soil property and cycle time of construction (Isobe et al., 1996).



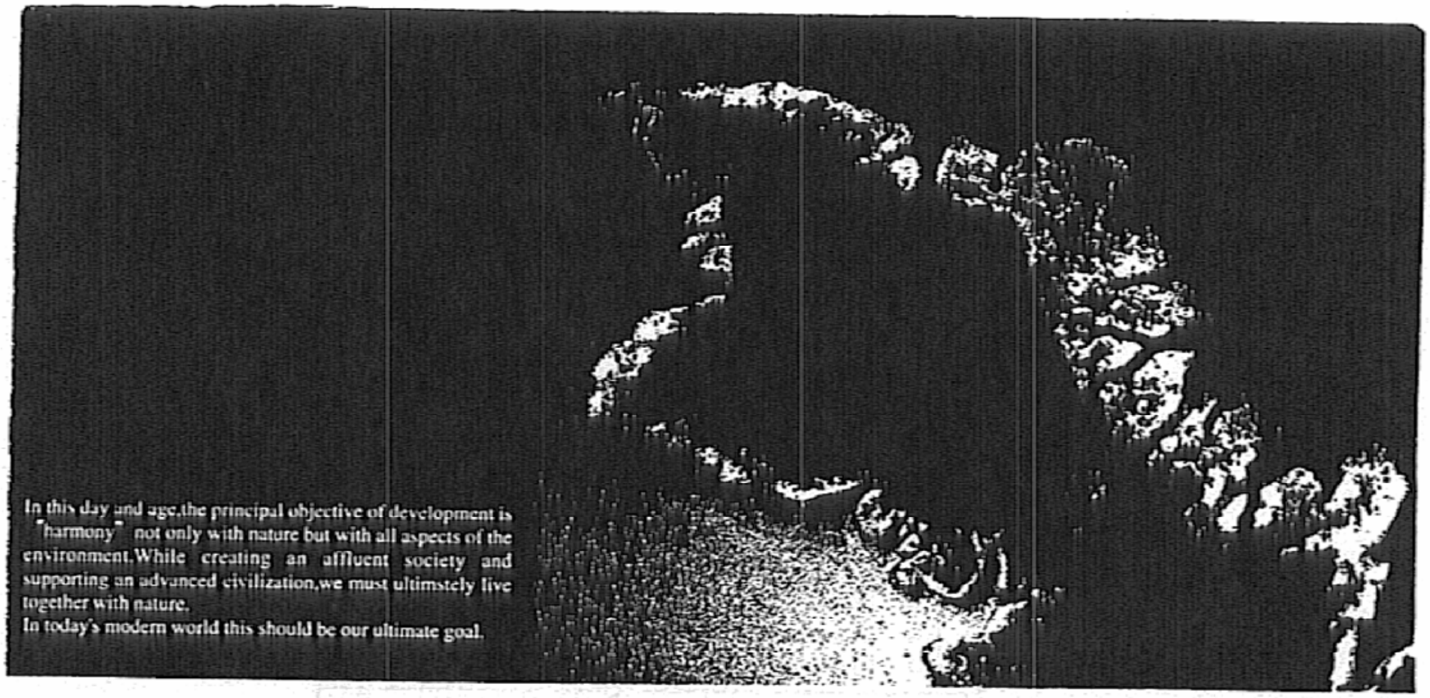
Strength of sampling core from the three columns of 1/4D from center



Strength of the three position of sampling core from the column (2,000mm)

Figure 68. Strength of sampling core from the three columns of ¼D from center, and strength of three position of sampling core from the column (2,000 mm) (Isobe et al., 1996).

Attachment 5. RAS Column Method brochure.

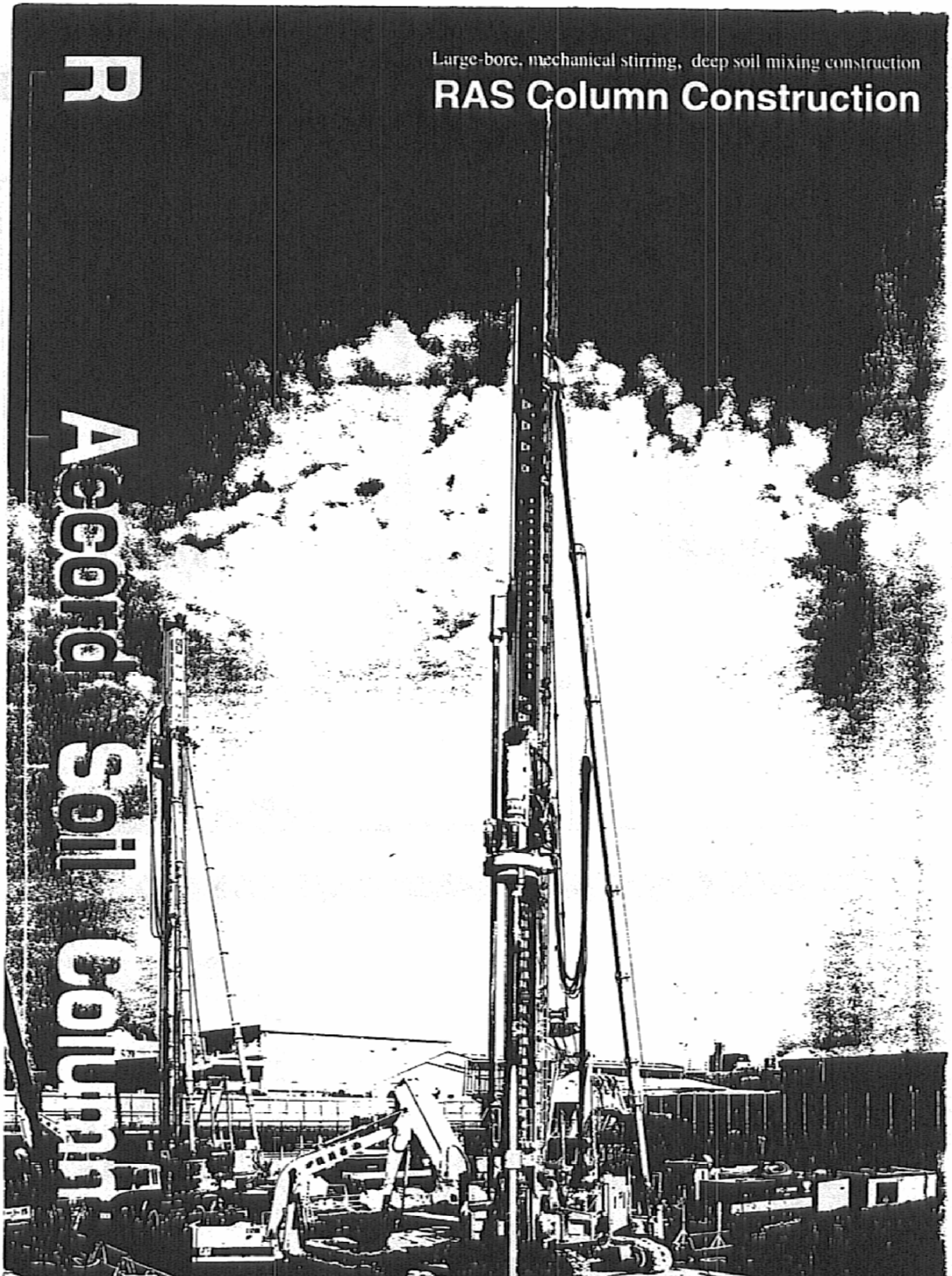


RAS Column Construction

Large-bore, mechanical stirring, deep soil mixing construction

RAITO KOGYO CO., LTD.
Head Office
2-35, Kudan-Kita 4-chome,Chiyoda-ku,
Tokyo, Japan ,Post Code 102
Phone.03-3265-2551 FAX.03-3265-0879

Raito


Large-bore, mechanical stirring, deep soil mixing construction
RAS Column Construction
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Accord Soil Column
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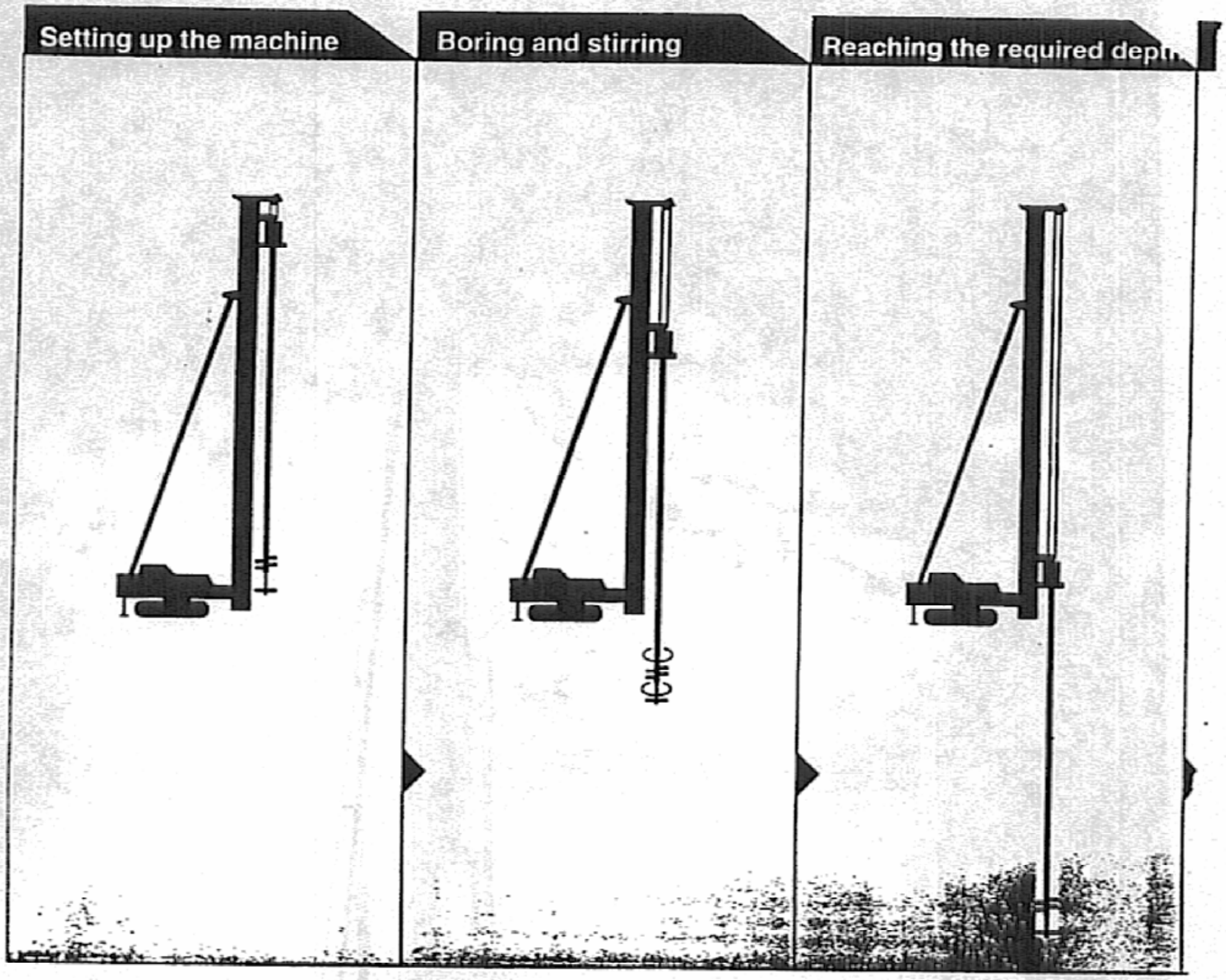
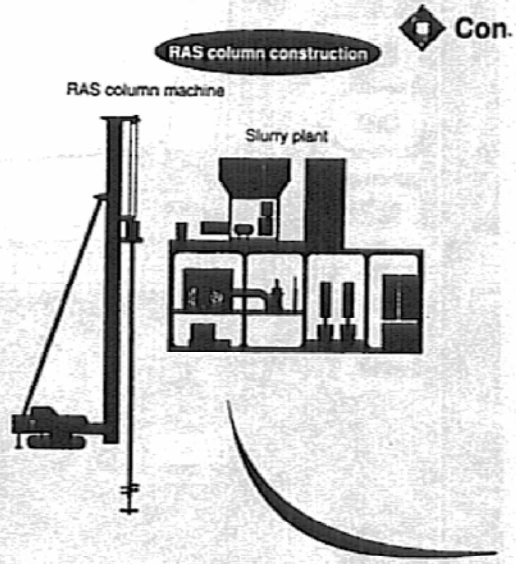
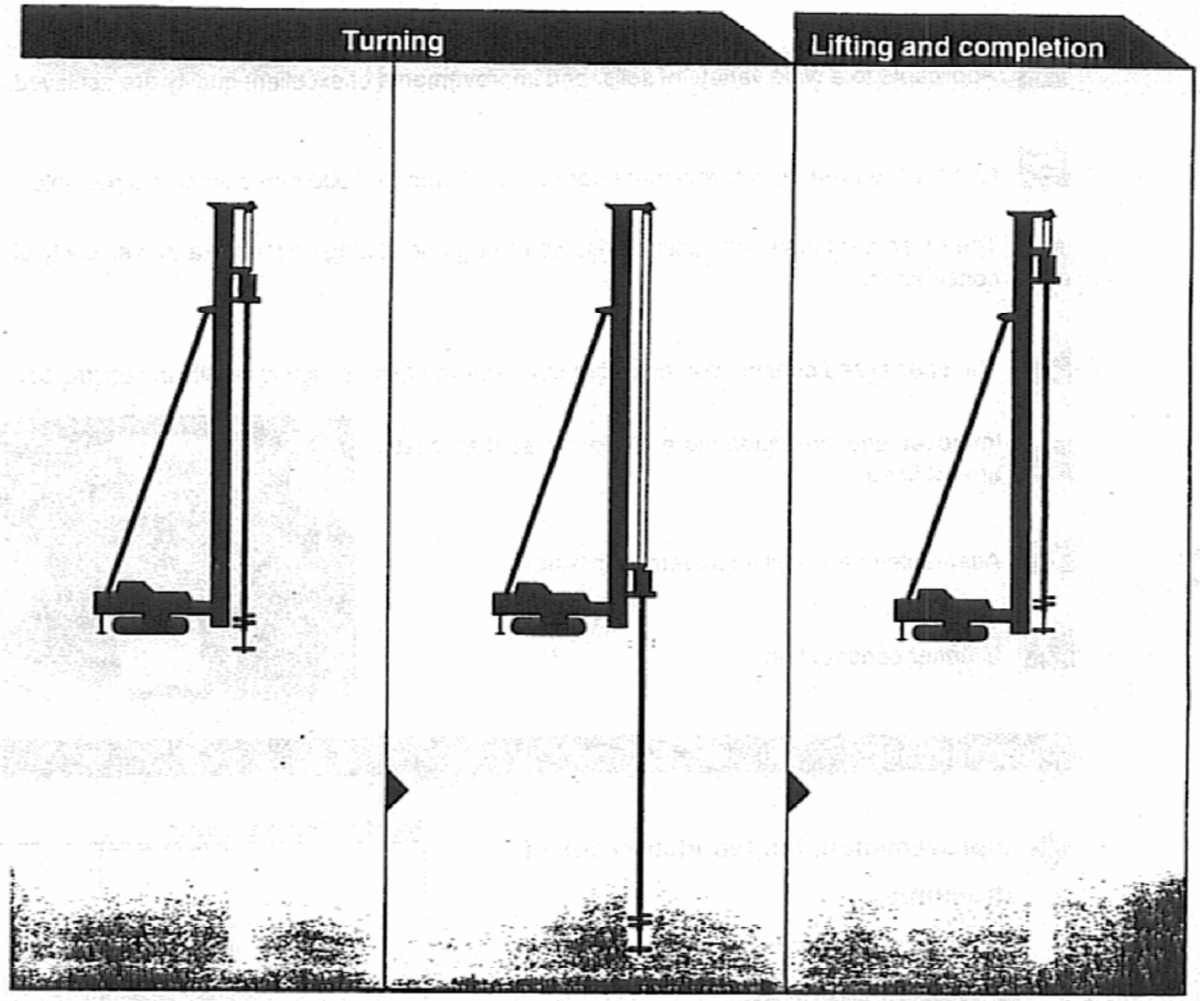
RAS Column Construction Procedure



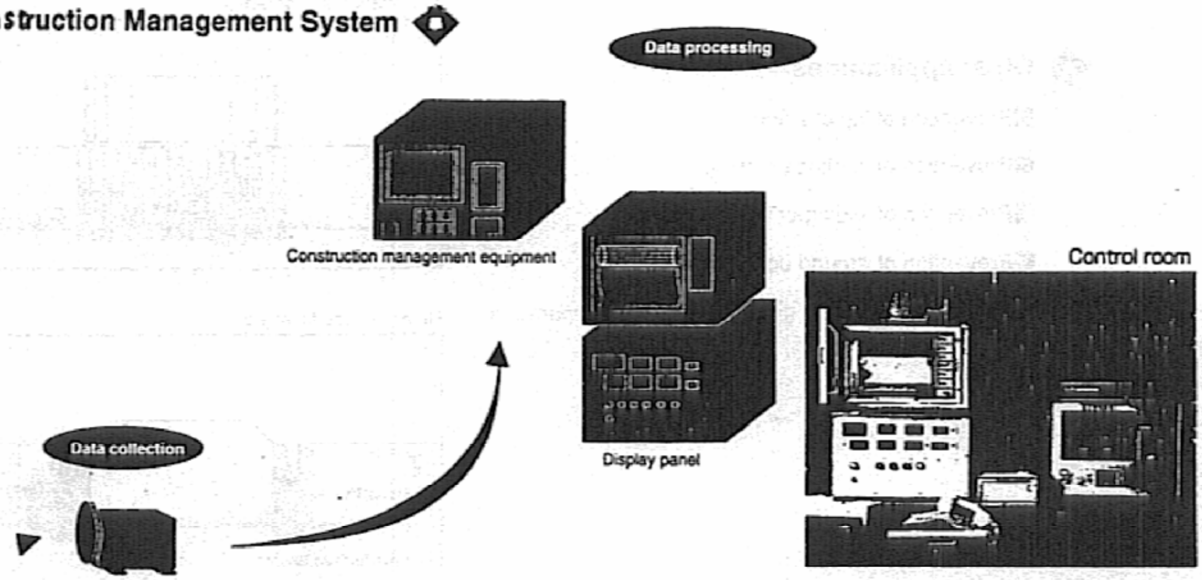
Con.

Construction



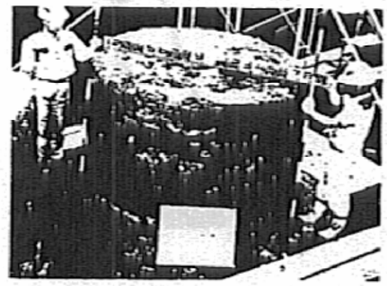


Construction Management System



Advantages of this construction method

1. Applicable to a wide variety of soils, and improvements of excellent quality are achieved.
2. Construction with an improvement bore of 1,400 mm to 2,000 mm diameter is possible.
3. The reverse rotation mechanism ensures mixing and stirring uniformity and verticality of construction.
4. The specialized construction management system ensures high reliability in construction.
5. Improvements are made more efficiently, so that costs are reduced.
6. Adaptable to any soil improvement method.
7. Greener construction



Applications

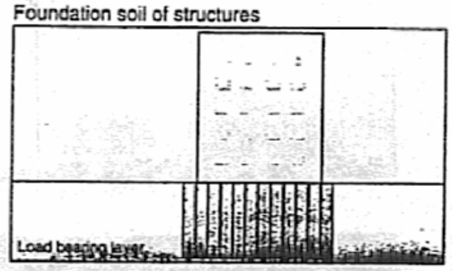
Improvement in the foundation soil of structures

- Foundation soil of structures
- Foundation soil of tanks
- Foundation soil of retaining walls
- Foundation soil of culverts

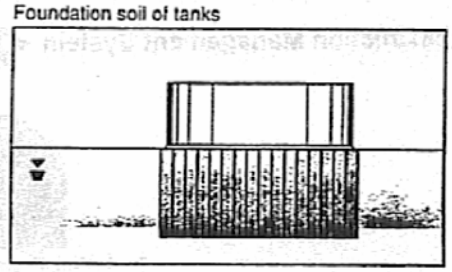
Other applications

- Prevention of liquefaction
- Prevention of subbase settling
- Prevention of sliding of banks
- Prevention of ground uplifting
- Cutting underground girders for ground preparation

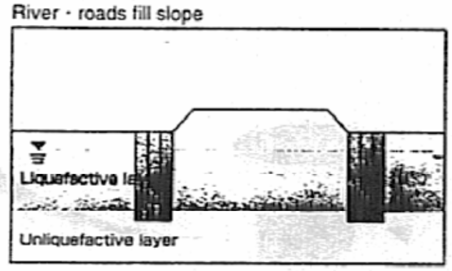
Foundation soil of structures



Foundation soil of tanks



River · roads fill slope



RECTANGULAR-1 METHOD — CUTTING WHEELS (11)

1. INTRODUCTION

This method employs two shafts with a combination of a series of horizontal mixing blades and rotated vertical vanes to create rectangular-shaped columns (Figure 69). The advantage of rectangular-shaped columns is that column elements can be created adjacent to one another to form a stabilized wall or mass without the typical overlapping and remixing required for cylindrical columns. This revolutionary new method is classified as WRE.

2. GENERAL PROCESS

Two adjacent shafts equipped with mixing blades and vanes are rotated during penetration. Cement grout is injected through nozzles at the tip of the mixing axles during penetration or withdrawal or both. The excavation auger at the tip of the mixing axles and the horizontal mixing blades make a "figure eight"-shaped column arrangement. The vertical mixing blades plane the front and back sides of this cross-section, creating a rectangular element, that is wider in the direction parallel to an axis through the mixing axles.

3. EQUIPMENT

<u>Base</u> A suitable crawler crane is used with fixed leads.

<u>Shafts</u> The mixing assembly is shown in Figure 69. Two mixing axles are used, which are connected by steel pipe to avoid rotation of the mixing axles on their own axes. A single flight auger is located at the base of each mixing axle. Cutting teeth are mounted on the leading edge of the augers. One horizontal mixing blade is mounted directly above each excavation auger, but at different elevations. These blades have a slightly larger diameter than the excavation augers to enlarge the column diameter. Vertical vane assemblies are mounted above these horizontal mixing blades. Each vertical vane comprises an 8.82-kN-m gear box with four claw-like mixing vanes on the front and back of the axle. The gearbox transfers the horizontal rotation of the mixing axles into vertical rotation of the vanes. The gearboxes share a common power source, and additional power is not required, making this equipment versatile and easy to maintain. Three additional horizontal mixing blades are mounted above each of the vertical vane assemblies. The blades and vanes on the mixing axles are offset vertically to avoid contact between them and obstruction of upward or downward flow of slurry during operation. A rectangular column 1800 mm by 1,000 mm is constructed using this equipment. Since the columns are constructed adjacent to one another without overlap, the vertical accuracy of the installation is very important to avoid space between columns and to provide adequate transfer of load between elements.

Grout Plant No data provided in the only reference found.

Control A field test was conducted to compare the work efficiency and quality of ground improvement achieved under overlap conditions ranging from no overlap to between 100 mm and approximately 200 mm of overlap. Installation of columns against an existing hardened mass was also studied. Columns were installed to a depth of 15 m in sands and silts with Standard Penetration Test blow counts (N) of 0 to 10. The installation efficiency and vertical placement accuracy were reported to be "equal to or better than the conventional methods regardless of whether overlapping was used or not." The results of the installation of columns against the existing mass were not discussed.

An inclinometer is fixed at the top of the vertical mixing unit, and deviation from the vertical axis is measured and plotted in orthogonal directions during column installation.

Production No data were provided.

4. MIX CHARACTERISTICS

No data were provided.

5. PATENTED/PROTECTED FEATURES

The vertical mixing assembly may be assumed to be patented.

6. PARTICULAR ADVANTAGES

The method creates rectangular-shaped columns that require no overlap of columns to construct walls and treated masses. There is a better transfer of forces between column elements due to their rectangular shape. No untreated soil remains between elements. A vertical convection flow of soil is generated during mixing by the vertical mixing vanes. There is good vertical control. The method should provide a high industrial production since there is no need to overlap columns.

7. OPERATING COMPANIES

Engineers from Shimizu of Japan have published the only known reference, which describes a field trail in Japan.

8. REFERENCES

Watanabe, T., S. Nishimura, M. Moriya, and T. Hirai. (1996). "Development and Application of New Deep Mixing Soil Improvement Method to Form Rectangular Stabilized Soil Mass." *Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 783-786.

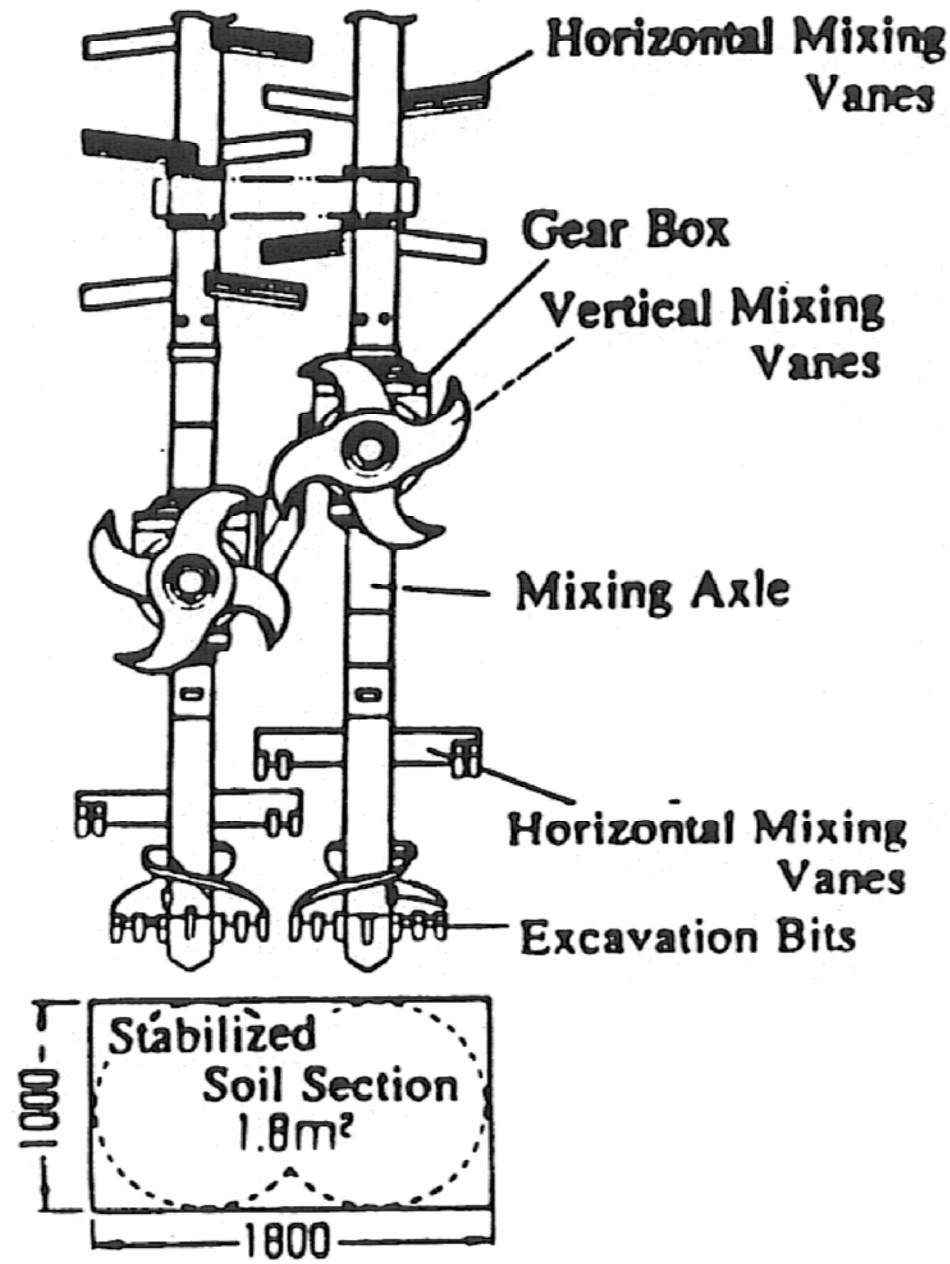


Figure 69. Schematic of mixing blades (Watanabe et al., 1996).

RECTANGULAR-2 METHOD – BOX COLUMNS (12)

1. INTRODUCTION

This WRE method produces rectangular or square columns through the use of a box that surrounds the mixing tools and contains the treated soil within this box frame. The blades mix the soil within the box, forcing the soil from the corners of the box to the center, producing a more uniform mix. The advantage of this method is that it requires less overlapping during column construction to make a block of treated soil. The development of this system is still in the experimental phase, and a laboratory model test program and two field test programs have been conducted to date.

2. GENERAL PROCESS

The mixing shaft is rotated into the ground together with the box casing, which contains the treated soil. Cement slurry is injected during penetration. The shaft is counter-rotated during withdrawal. A schematic of the installation steps is shown in Figure 70.

3. EQUIPMENT

Base	A suitable crawler crane.
Shaft	A detail of the mixing tool and box frame is shown in Figure 71. This system employs a single shaft with a 1-m-diameter mixing blade assembly consisting of four horizontal mixing blades. The blade at the tip of the mixing shaft contains cutting teeth. The box casing consists of a 1-m-square steel frame situated between the second and third mixing blades. The box casing does not rotate during mixing, but moves vertically with the mixing shaft during penetration and withdrawal.
Grout Plant	No information is available, but it is assumed to be similar to CDM.
Control	Laboratory model tests were performed, and two field test programs were conducted – one in clayey soils and one in sandy soils. The laboratory model tests were conducted on sands to investigate the mixing mechanism within the box casing and to determine the level of uniformity of the mixing within the box. The conclusion of these tests was that the soil in the corners of the box casing moves with the rotation of the agitator when the passive earth pressure of the soil is exceeded. The well-mixed material at the center of the box then moves into the corners of the box, producing a uniformly mixed cross-section as mixing progresses.

Production   Penetration and withdrawal rates from a test program conducted in clayey soils were 0.5 and 1.0 m/min, respectively. The mixing shaft rotation speed used was 30 rpm.

4. MIX CHARACTERISTICS

Grout   For the field (100 to 300 kg/m³) and laboratory (200 to 400 kg/m³) programs, the cement factor ranged from 150 to 400 kg/m³. Reported water –to-cement ratios ranged from 1.0 to 1.2.

Treated Soil   The quality of the treated soils produced during the field tests was evaluated through the following parameters:

- Comparison of the unconfined compressive strength of the core specimens recovered from near the center and from the corners of the box.
- Core recovery percentage.
- Coefficient of variation in UCS.
- Comparison of strengths of laboratory-mixed samples and core specimens.

Unconfined compressive strengths of treated clayey soils increased gradually with depth from approximately 1.2 to 4.2 MPa. Cores were also cut perpendicularly to the axis of the columns at depths of 0.9 to 1.6 m from the ground surface. Similar strengths were measured in these cores as in the vertical cores. No significant difference in strength within these transverse cores was identified from the corner to the center of the column.

The percent of core recovered from the test columns ranged from 92% to 100% in the clayey materials and was 100% in the sandy materials. No difference in core recovery was noted between the corner cores and the central cores.

The coefficient of variation of UCS was measured to be between 36.3% and 38.3%, which corresponds to a reportedly typical coefficient of variation for DMM techniques of 20% to 40%.

The field core strengths were 60% to 75% of the strengths of the laboratory-mixed samples. An estimate of 60% to 80% of the laboratory-mixed strength can reportedly be achieved in this field with "fairly good" quality control.

5. PATENTED/PROTECTED FEATURES

No patents were identified in the reference cited below.

6. PARTICULAR ADVANTAGES

Square or rectangular columns are produced; therefore, less overlapping is required. Also, the mixing efficiency seems high.

7. OPERATING COMPANY

Daisho Shinko Corp. of Japan.

8. REFERENCE

Mizutani, T., S. Kanai, and M. Fujii. (1996). "Assessment of the Quality of Soil-Cement Columns of Square or Rectangular Shapes Formed by Deep Mixing Method." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 637-642.

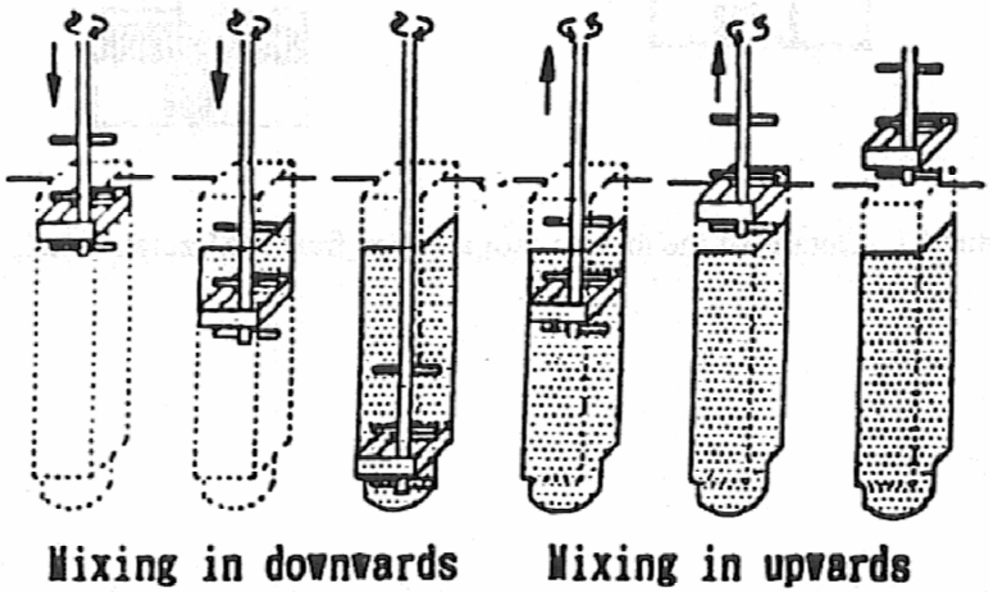


Figure 70. Schematic of installation steps (Mizutani et al., 1996).

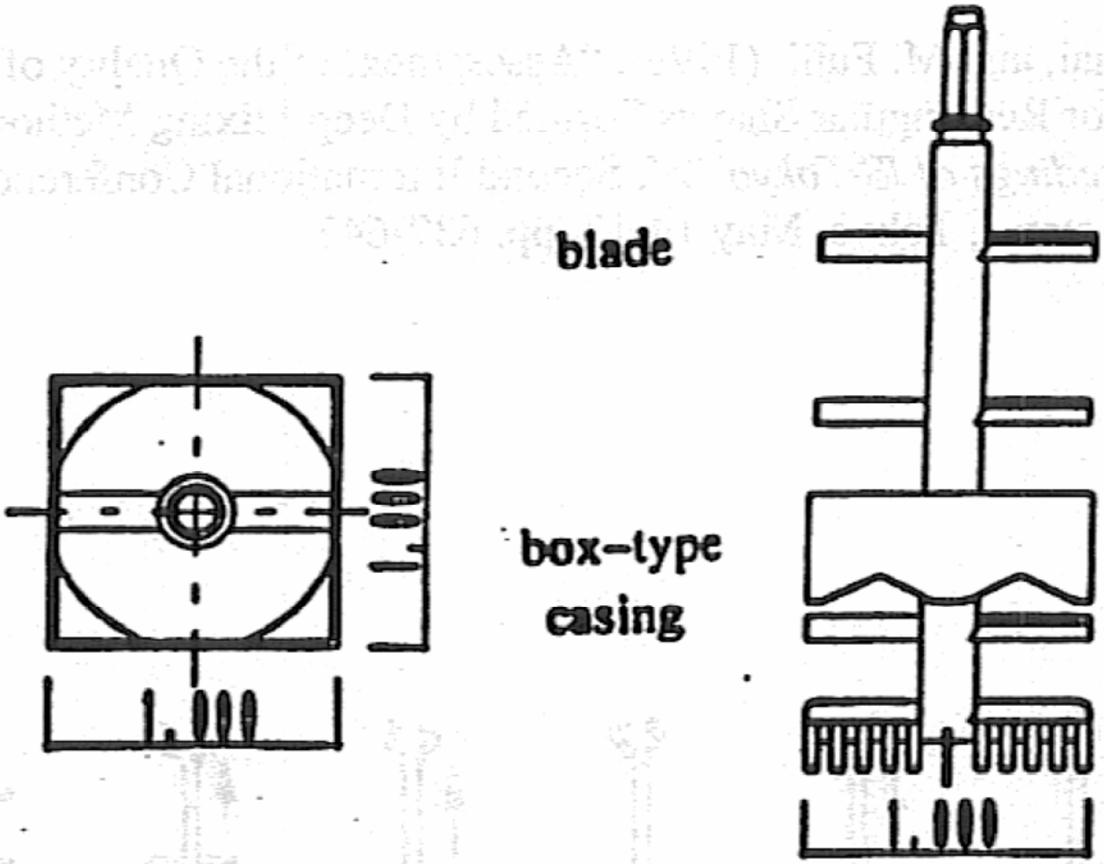


Figure 71. Details of the mixing tool and box frame (Mizutani et al., 1996).

SINGLE-AUGER MIXING (SAM) (13)

1. INTRODUCTION

This WRE method has been developed by Terra Constructors since 1995. Terra claims capabilities in both Single-Auger Mixing (SAM), with a few projects completed, and Multiple-Auger Mixing (MAM, probably a WRS method), with no case histories to date. Very little data are available.

2. GENERAL PROCESS

The SAM technique employs a large mixing tool that is rotated into the ground at 8 to 16 rpm while simultaneously injecting reagents through the tool's hollow stem. Grout can also be injected during withdrawal. The MAM technique employs a mixing tool equipped with auger flights and mixing blades that mix the soil in a pugmill-type fashion. Slurry is injected during penetration, and once the specified depth is attained, the tool is counter-rotated and withdrawn with continued grout injection.

3. EQUIPMENT

<u>Base</u> A single crane-mounted turntable is used for the SAM method (Figure 72). Where required for site logistics or safety, an extended mounting frame (Figure 73) will allow a 15-m clearance from the center of the crane to the center of the mixing tool. A set of crane-supported leads is used for the MAM method.

<u>Shafts</u> The SAM mixing tool is typically 1 to 3.6 m in diameter, selected based on soil type and moisture content. The tool has three wings, with a series of inclined cutting blades on each (Figure 74). The effective maximum depth of the SAM method is 13 m. MAM is intended to be used for projects in excess of 13 m. The MAM mixing tools are equipped with three to five small overlapping auger flights and mixing blades. These mixing tools are rotated by top-drive hydraulic motors.

<u>Grout Plant</u> A positive displacement pump is used to deliver slurry for both of these methods.

<u>Control</u> No data available.

<u>Production</u> A production rate of 380 m^3/per 8-h shift is claimed for SAM.

4. MIX CHARACTERISTICS

<u>Grout</u>. Cement grout is used mainly as the binder. However, other additives for oxidation and/or stabilization of contaminants can be used. Water/cement ratios of 0.75 to 1.0 are typically used.

The ratio of the weight of grout to the weight of soil is typically 10% to 20%. Dry reagents or gases, such as hot air or steam, may also be used in the SAM process.

Treated Soil. Unconfined compressive strengths vary depending on the soil type: up to 3.5 MPa is claimed. Permeability of the soil-cement is similar to that of the in situ soil.

5. PATENTED/PROTECTED FEATURES

These systems are not patented.

6. PARTICULAR ADVANTAGES

These systems are applicable for soils below the water table. These methods are also applicable to environmental projects. Off-gassing is greatly reduced through the use of a specially fabricated shroud (Figure 75) installed at the ground surface. Off-gasses may be drawn via a vacuum through an emission treatment system equipped with combinations of dust collectors, scrubbers, carbon filters, or thermal oxidizers.

7. OPERATING COMPANIES

Terra Constructors of Denton, TX.

8. REFERENCE

Terra Constructors. (1998). Promotional information and personal communication.

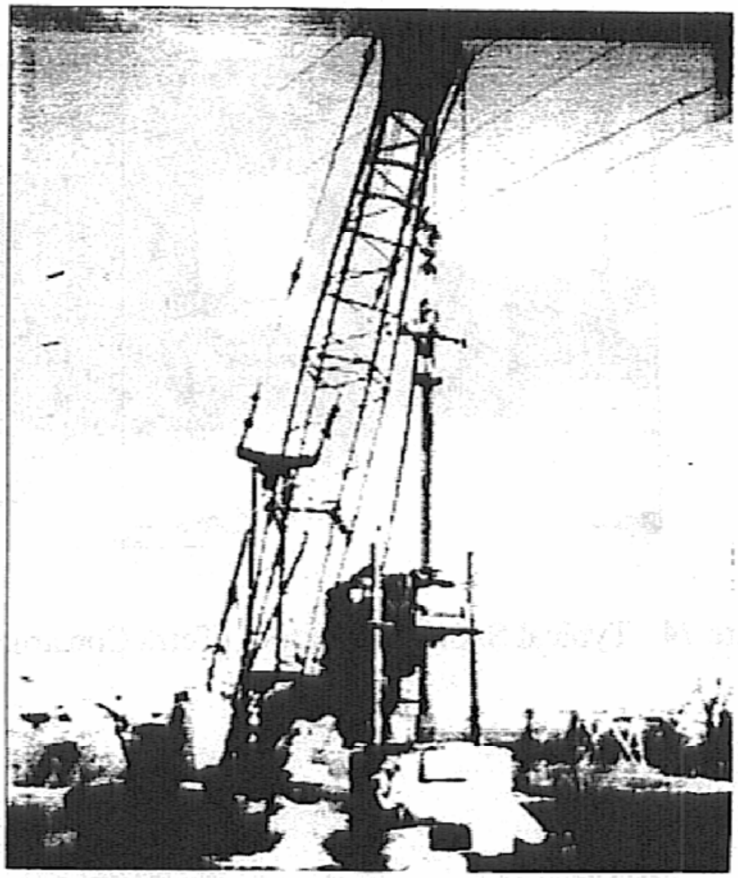


Figure 72. Soil mixing rig showing turntable (Terra Constructors, 1998).

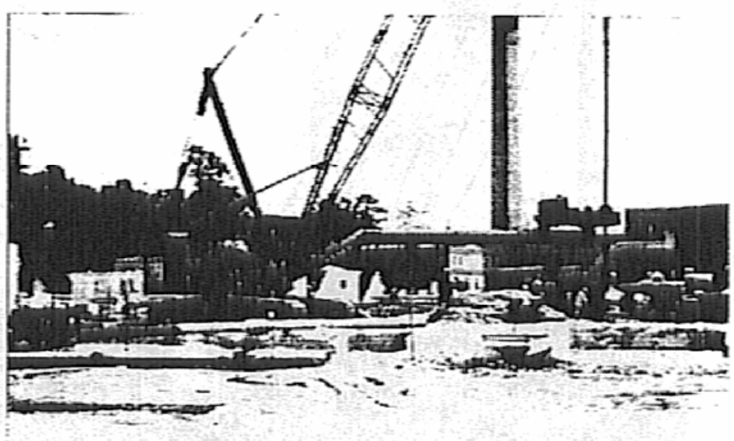


Figure 73. Extended mounting frame (Terra Constructors, 1998).

Figure 74. Typical SAM mixing tool (Terra Constructors, 1998).

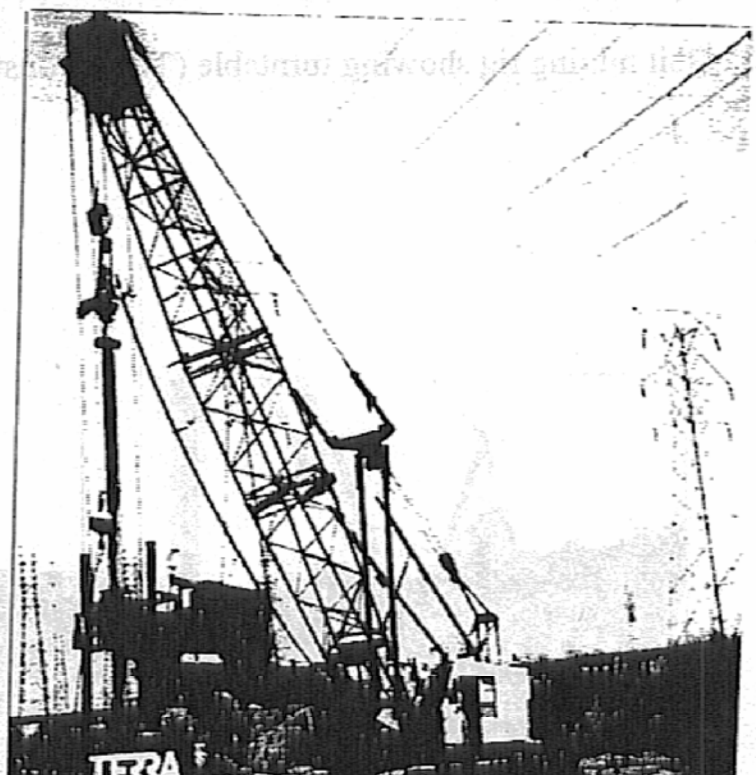


Figure 75. Typical SAM mixing rig with shroud (Terra Constructors, 1998).

CEMENTATION (14)

1. INTRODUCTION

This single shaft WRE system was developed by the Cementation Company in England in the middle and late 1980s based on continuous flight auger piling expertise and equipment. Few applications appear to have followed the original development projects, perhaps due to commercial and market pressures.

2. GENERAL PROCESS

Grout is injected during rotation to target depth. The auger is then cycled up and down several times over a vertical distance of 1 m prior to being reversed and extracted. This process is repeated at successive 1 m intervals. Two column sizes, 0.75 and 1.0 m, have been reported, although case histories have featured only the former.

3. EQUIPMENT

<u>Base</u> Crawler crane base with fixed leads and a top rotary head.

<u>Shaft</u> Comprises an unknown length of auger flight (plus drill head), followed (interrupted) by a smaller diameter continuous flight auger, which is not full length: standard drill pipe extends to the surface.

<u>Grout Plant</u> Details unknown, except that the injection pressure is high enough only to overcome line resistance (rarely above 0.05 MPa).

<u>Control</u> No details provided.

<u>Production</u> Production rates of 0.5 to 0.67 m/min for penetration and mixing are reported.

4. MIX CHARACTERISTICS

<u>Grout</u>. Cement, with or without pfa substitution is used at the lowest pumpable water/cement ratio of 0.4. A cement factor of 6% to 13% has been used, with a measured spoils volume of 7% by volume of treated soil. Cementation Company reports that, as the drilling and mixing progress, localized pore pressure variations draw water to the process as the disturbed soil dilates. The water/cement ratio of the final treated soil can therefore be as high as 2. Soils that can be treated have a Plasticity Index (PI) of less than 25% and a Liquidity Index (LI) of greater than 50%, and can range up to hard clay and dense sands.

5. PATENTED/PROTECTED FEATURES

Unknown. Probably none.

6. PARTICULAR ADVANTAGES

Virtually no leakage of grout to the surface has been reported (due to low volume ratio and shaft configuration), unless groundwater table is high and depth of treatment is considerable. Also, the use of a smaller diameter auger minimizes lateral loading of the in situ soil, which may cause heave. The system also allows specific horizons to be treated individually.

7. OPERATING COMPANY

Cementation Company is based in the United Kingdom, but is now owned by Kvaerner, a Norwegian-based, globally-active, multi-disciplinary engineering conglomerate. Applications to date have apparently all been in the United Kingdom.

8. REFERENCE

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Elliott, J.A. (1992). "Deep Mix-in-Place Soil/Cement Stabilization Using Hollow Stem Augers for Excavation at Elland, West Yorkshire." *Piling and Deep Foundations, Proceedings of the International Conference on Piling and Deep Foundations, Vol. 1*, London, May 15-18, pp. 43-50.

Greenwood, D.A. (1987). "Simple Techniques of Ground Improvement With Cement." *Proceedings International Conference on Foundations/Tunnels,* Vol. 2, pp. 8-19.

HAYWARD BAKER METHOD
SINGLE-AXIS TOOLING (15)

1. INTRODUCTION

Hayward Baker Inc., a Keller Company, has been developing various types of DMM approaches since the early 1990s. They first experimented with a small-capacity lime-column method in 1992, and in 1997, they completed rigs capable of dry and wet mixing of lime and cement for columns up to 600 mm in diameter and 20 m in depth. Based on a recent ground treatment project at Pascagoula, MS (Attachment 1), it would seem that their WRE method, called Single-Axis Tooling, is capable of producing columns up to 3.5 m in diameter and 20 m in depth, and is now a viable, competitive technique. It is believed that future developments are to continue into Wet Jet End (WJE) and Dry Rotary End (DRE) methods.

2. GENERAL PROCESS

The Single-Axis Tooling method, as observed at Pascagoula, features the rotation of a single shaft at 20 to 25 rpm under its own weight. Fluid cement-based grouts are usually injected during penetration to aid productivity and promote efficient mixing. The grout is pumped at about 600 L/min at pressures of 0.4 ±0.1 MPa. The nozzles are easily replaceable and are typically located near the tool tip. A 5-min period of injection and mixing at the bottom occurs, followed by rapid extraction during which the remaining 1% to 5% of the total grout volume is injected. The method has been developed around equipment that is readily available from other technologies (e.g., piling and grouting) and is modestly described by Hayward Baker as "low tech." Where penetration of the tool cannot be constant and uniform, top-down mixing, as just described, is used. If penetration is controllable, binder can be added during penetration (tip of the tool) and during withdrawal (top of the tool). In either case, the lowermost 1 m is repenetrated.

3. EQUIPMENT (Figures 76 and 77 attached)

<u>Base</u> An appropriate, commercially available track-mounted crane (e.g., Manitowoc 3900 or 4000) equipped with a rotary bottom-drive turntable (e.g., Watson) is used. The turntable is rated at 225 to 350 kW, providing up to approximately 610,000 N-m torque in second gear (penetration at low speed), or approximately 95,000 to 135,000 N-m torque at 40 rpm during withdrawal. If this single-crane attachment is used, down pressure is limited to 50% of the weight of the turntable. Conversely, rotary heads may have as little as 6780 N-m torque.

<u>Shaft</u> A single, 356-mm square kelly bar or a high-strength round drill pipe is used, suspended by cable through the rotary turntable. (For smaller scale operations, a standard top-drive rotary head could be used.) The actual mixer usually consists of two or three pairs of mixing blades/paddles and a lower cutting head attached

over the lower 3 to 4 m of the kelly bar, or rod. A smaller diameter rotary drill bit can be used to center the column and control vertically. Teeth are fixed to the leading edge of the cutting head. The entire configuration itself depends on the soil and the rotary capacity available, and is, therefore, project-specific and frequently field-modified continuously. Grout is injected from up to eight nozzles spaced across the cutting head diameter. Tools of 0.5 to 3.5 m in diameter are feasible, but 2.1 to 2.4 m is a typical size.

<u>Grout Plant</u> A 3-m^3 capacity jet mixer feeds into a 5-m^3 capacity paddle agitated storage tank. Small (0.75 kW) Godwin transfer pumps feed 2.5-m^3 storage tanks supplying 4JS Moyno pumps for delivery to the rig. Cement is supplied in two silos. As for the drilling rig, the grout plant components can vary flexibly – with various degrees of computer control, colloidal or jet mixers, and recirculating pump to the storage tank. Delivery pumps can be simple trash pumps or triplex piston positive displacement pumps.

<u>Control</u> Instrumentation is provided for volume and pressure recording and control at the pumps. Drill penetration data are displayed and recorded. At present, the drill rig cabin is equipped with a grout pressure gauge only – all other parameters are relayed from the pump station by telephone to the operator. A flowmeter is to be added. Wet sampling of grout and grouted soil (via a special in-hole collector) is standard. Large-diameter shafts are often sunk through treated soil to allow visual observation of the efficiency of mixing, and to permit extraction of large-scale samples for strength and deformation testing. Hayward Baker, Inc. has found that core samples always give higher strengths than grab samples, while field values are about 50% of laboratory strengths, but with a wide variation (±50% average). Pre- and post-construction cone penetrometers (CPTs) are possible for strengths less than 7 MPa. If in situ strength is expected to average 3.5 MPa or more, coring is feasible (minimum 76 mm). Recovery rates can be 25% to 100%, depending on mixing parameters and soil types. For fine sands, a grout strength of 8 MPa (specific gravity = 1.42) will provide a grouted soil strength of greater than 2 MPa. The most efficient method of evaluation is to drill a shaft into overlapping columns. This allows visual inspection of drill cuttings, shaft integrity and homogeneity, and sampling of the mixed and stabilized soils.

<u>Production</u> Penetration rates range between 0.3 and 0.6 m/min, depending on the soil, and withdrawal rates are several times faster. Depending on site conditions, treated volumes of 250 to 500 m^3/shift (i.e., more than 150 lin. m) can be achieved with one rig. A productive site may use upwards of 180 tonnes of dry materials per shift. Costs may range from $30 to $400/$m^3$.

4. MIX CHARACTERISTICS

<u>Grout</u> Cement-based grouts are used; the exact formulation reflects the desired properties of the treated soil. For example, bentonite, flyash, lime, blast furnace

slag, and other materials may be blended with the cement and water. A choice in one specific project with a low-strength criterion is a 3:1 slag/cement mix, with a 1.33 water:solids ratio. Cement factors of about 150 kg/m^3 of treated soil are typical (grout volume ratio of 15% to 30%). Binder can account for up to 50% of the cost.

<u>Treated Soil</u> Strengths in granular soils in the range of 3.5 to 10 MPa are feasible. In saturated, cohesive soils, strengths of 0.2 to 1.4 MPa can be achieved (dependent on mix design, injection parameters, soil plasticity, and moisture content).

5. PROTECTED/PATENTED FEATURES

The Hayward Baker Method has evolved over a series of projects (both dry/wet lime-cement columns, and the larger diameter mixed columns) dating from 1990, using mechanical resources and grouting expertise from within the Keller Group of companies. It is available for use only by the members of that group (worldwide) in general, and by Hayward Baker, Inc. in North America in particular.

6. PARTICULAR ADVANTAGES

The system is robust, simple, flexible, and competitive to depths of 15 to 20 m in appropriate soils. It produces moderate spoil volumes (up to 30%) depending on the grout volume ratio.

7. OPERATING COMPANIES

As in Section 5 above.

8. REFERENCES

Site-specific information available from the staff at Hayward Baker, Inc.

Burke, K., A. Furth, and D. Rhodes. (1996). "Site Remediation of Hexavalent Chromium in a Plater's Sump: Heavy Metal Chemical Fixation – A Case History." PSC 17th Annual AESF/EPA Conference on Pollution Prevention and Control, February, Orlando, FL, 10 pp.

Hayward Baker, Inc. (1998). Promotional information.

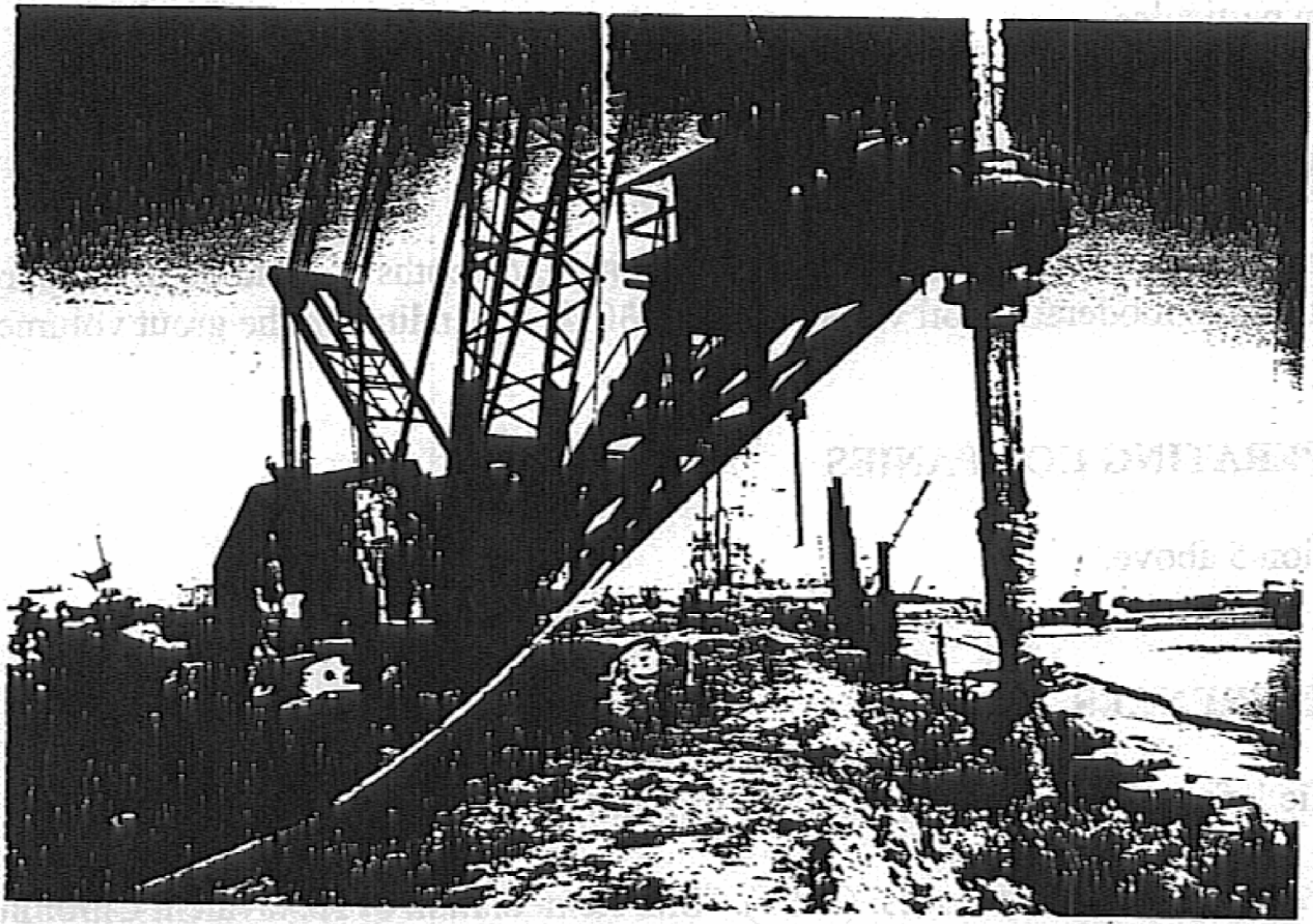


Figure 76. Single Axis Tooling rig (Courtesy of Hayward Baker, Inc.)

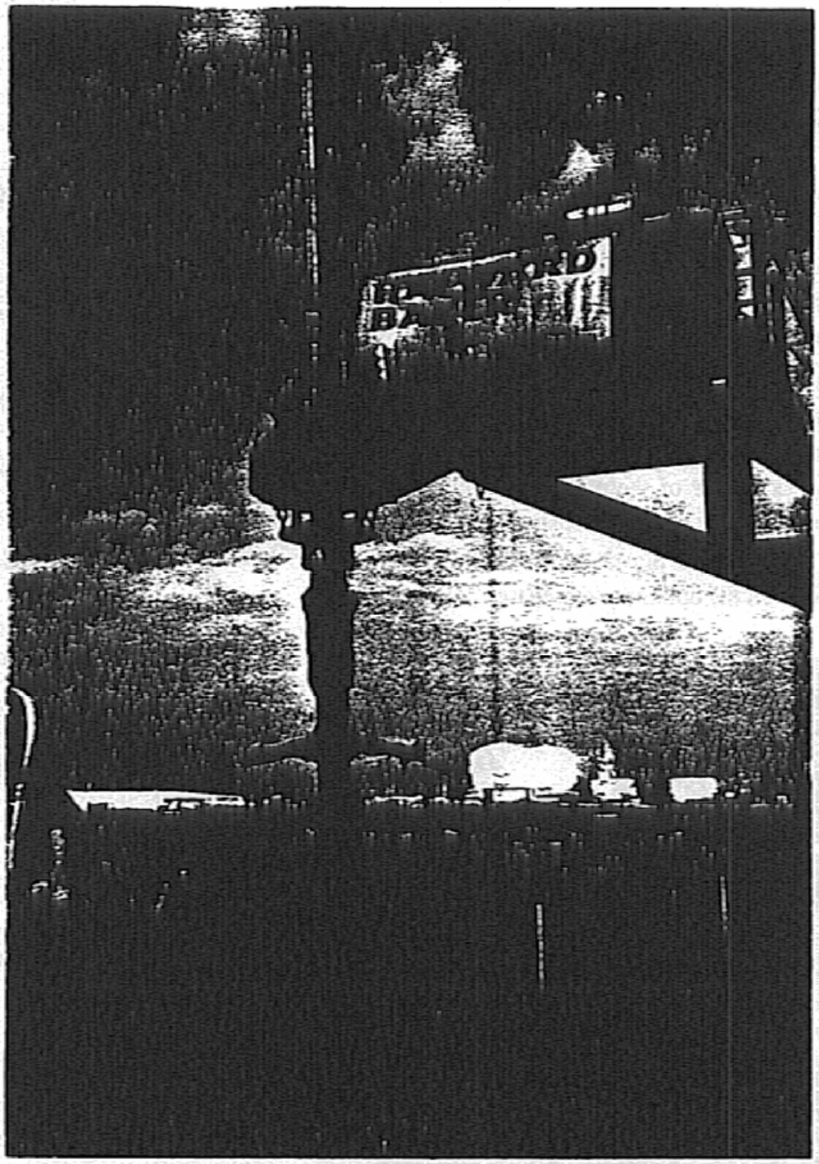


Figure 77. Single Axis Tooling mixing tool (Courtesy of Hayward Baker, Inc.)

Attachment 6.
Hayward Baker, Inc., Project summary.

HAYWARD BAKER

KELLER

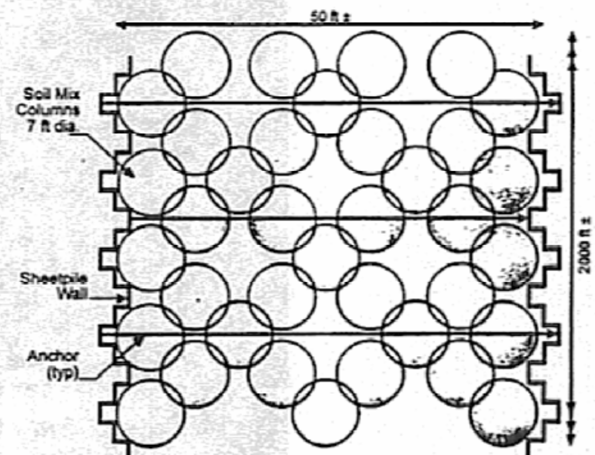
Project Summary

Soil Mixing

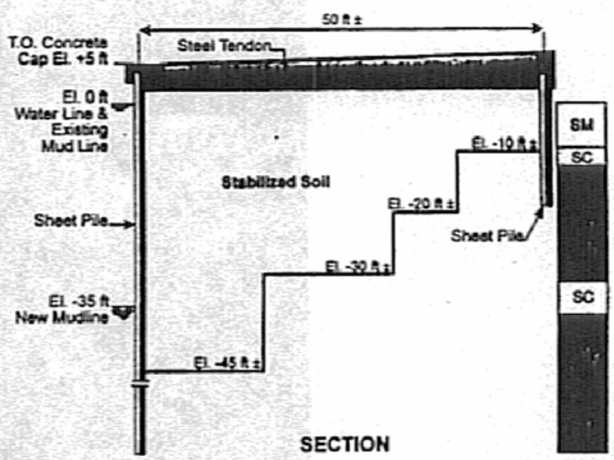
HAM Marine Facility, Pascagoula, Mississippi

HAM Marine Inc. is developing a peninsula of property at the mouth of Bayou Casotte. This requires deep water berthing and unloading capability for the operations associated with the design, construction, and repair of deep water drilling platforms.

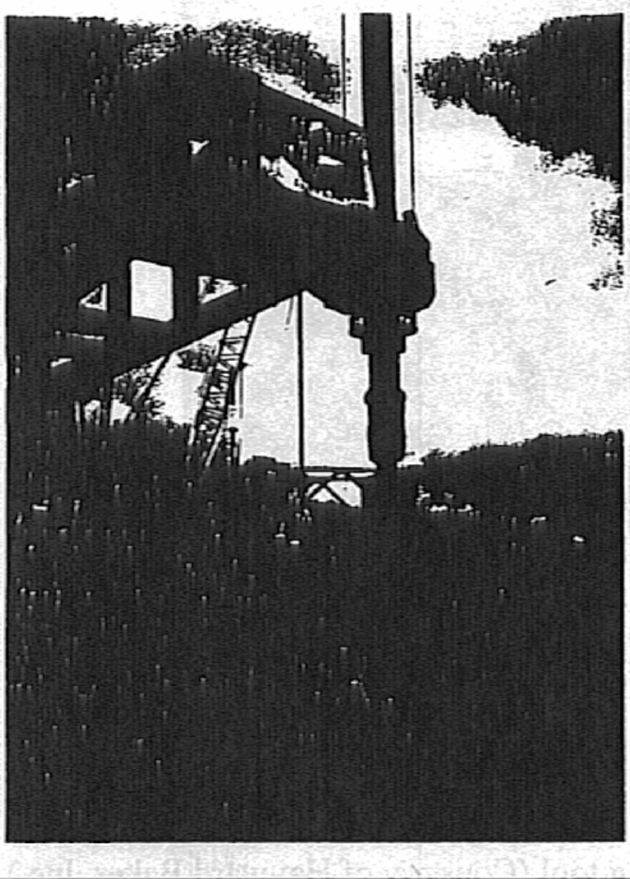
The subsurface conditions of the property are typical of river and marsh deposits of the region. The highly stratified and variable soil consists of organics, silts, clays, and sands. The very weak nature of these materials required special attention in the design of the wharf structure to prepare an economic solution. Lyle Stover Engineering Inc. of Mobile, AL, reviewed all the options and prepared a design



PLAN



SECTION



Left: Soil Mixing in progress at Ham Marine Facility in Pascagoula, MS.

Owner
Ham Marine Inc.
Pascagoula, MS

General Contractor
W.G. Yates & Sons
Pascagoula, MS

Engineer
Lyle Stover Engineering
Mobile, AL

Geotechnical Engineer
Thompson Engineering Testing Inc.
Mobile, AL

that includes ground stabilization by soil mixing, behind an anchored sheet pile wall.

The stabilized soil system provides greatly reduced earth pressures on the wall, while at the same time offering a stable support platform, 50 ft wide, along the approximately 2,000 lf of new bulkhead.

Soil Mix Design

The total project includes stabilization of over 10,500 yd^2 of platform to variable depths up to 50 ft. (see plan and cross section). Prior to production, Hayward Baker developed a variety of grout mix designs and tested their performance. Several grout designs were selected to mix with the two most difficult soils to treat on site, namely a soft, slightly organic, silty clay and a medium stiff to stiff clay. From these results, a grout material emerged that was clearly the most effective for both of these soil conditions.

Construction

The 7-ft diameter tool selected provided the mix energy required and the geometry that best fit the treatment plan controlled by the piling layout. The construction consisted of a double row of columns on the inboard and outboard sides, with a cellular arrangement between (see plan view). Sequence of construction and layout ensured adequate overlap. Upon completion of the ground improvement and the anchored wall system, the outboard soils will be dredged to elevation -35 ft.

Quality Control and Quality Assurance

Wet samples from various depths were retrieved from soil mix columns, cured and laboratory tested for 7, 14 and 28-day unconfined compressive strength. Average 28-day UCS for the project was 170 psi. Grout slurry unit weight (or density) was measured every 15 minutes.

Standard Penetration and Cone Penetrometer Testing were performed to assess improvement levels for acceptance by the owner.

***Soil Mixing** is a ground improvement technique involving the mechanical in situ mixing of soil with cementitious materials using a hollow stem mix tool. The injection of the binder material may be in the form of either a slurry or dry powder. Sets of one to three shafts with mixing tools up to eight ft in diameter are used to mix soft and loose soils to depths up to 100 ft. As the tool is advanced into the soil, the hollow stem is used as a conduit to pump grout and mix it with the soil in contact with the tool. Single columns and/or panels are created with the process as the tools are worked in overlapping configurations. A range of unconfined compressive strengths between 10 and 500 psi is possible depending on the native soil type. Interconnection of columns and panels affords many geometries that are useful for civil engineering purposes, including gravity walls, cellular improvement, retaining walls, foundation support and other in situ structures.*

ROTOMIX (16)

1. INTRODUCTION

This WRE method was developed by Inquip Associates in 1990. This method has been used in conjunction with Inquip's slurry wall techniques to create composite soil structures for retaining walls and foundations. It has also been used with soil vapor extraction, zero valent metals, and biological agents for environmental applications. Projects have been completed in the United States and Canada. Very limited information was available from this contractor.

2. GENERAL PROCESS

The process employs a single rotating shaft (5 to 45 rpm) to penetrate the ground with grout injection.

3. EQUIPMENT

<u>Base</u> A suitable crawler crane about 165 tonnes.

<u>Shaft</u> A single shaft contains a bit with paddles. The column diameters range from 1.2 to 4.8 m. The effective maximum depth ranges from 3 to 30 m, depending on the auger diameter used and the nature of the ground.

<u>Grout Plant</u> No data provided.

<u>Control</u> No data provided.

<u>Production</u> No data provided.

4. MIX CHARACTERISTICS

<u>Grout</u> Typically, cement grout is used with water/cement ratios that range from 0.8 to 2.0. Biological agents have been used in environmental applications.

<u>Treated Soil</u> Typical cement factors used are in excess of 100 kg/m^3. The volume ratio is greater than 15%. Unconfined compressive strengths of treated soil are reported to be greater than 0.1 MPa and have permeabilities less than 1×10^{-8} m/s.

5. PATENTED/PROTECTED FEATURES

Methods and techniques are reported by Inquip to be proprietary to them.

6. PARTICULAR ADVANTAGES

Inquip claims good penetration and mixing are achieved. The use of dry binder injection is also possible for treating sludges.

7. OPERATING COMPANIES

Inquip Associates of McLean, VA, and Santa Barbara, CA, who operate in the United States and Canada.

8. REFERENCE

Inquip Associates. (1998). Promotional information.

SPREAD WING (SWING) (17)

1. INTRODUCTION

This method employs a spreadable mixing blade or wing and the option of using jetting to further expand the column diameter. The advantage of the spreadable wing is that the blade can be retracted and only the pilot hole drilled through the competent soil, but expanded within the layer to be treated. The mixing unit can be inserted through narrow subsurface passages to reach treatment areas where the wing can be opened within a horizon free from obstructions. Jet grout nozzles on the outside edges of the unit allow further expansion of the column diameter, providing tight contact of treated soil with adjacent columns or existing structures. Column diameters of 0.6 to 2 m can be produced by mechanical mixing, and jetting (at 20 to 40 Mpa ± air) further expands these diameters to approximately 3.6 m. This method is classsified as WJE.

2. GENERAL PROCESS

Figure 78 shows and describes the procedure for column construction. The steps (Figure 79) (Yang et al., 1998) are:

1. Drill pilot hole down to base of zone to be treated, with the swing blade in the vertical (closed) position, parallel with the drill shaft.
2. Extend the wing.
3. Ream upwards to top of treated zone with the high-pressure jet.
4. Lower tool again to bottom of zone, and commence grout injection and mixing during withdrawal plus jet grouting, if needed.
5. Upon reaching the top of the treatment zone, retract reamer and remove shaft.

3. EQUIPMENT

Base — Base equipment consists of a crawler-mounted machine with a fixed vertical lead. One inner rod is connected to the control unit of the expandable blade and operated by a hydraulic system inside a gearbox. Expansion of the blade is controlled mechanically, and therefore the blade position can be monitored and verified at the ground surface. No specific details are provided in the literature regarding power requirements and capacities.

Shaft — Figure 80 shows the mixing unit. The diameter of the mixing tool is 0.6 m with the blade retracted, and the diameter is 2 m with the blade fully expanded. The method of ground treatment that uses mechanical mixing only was developed in 1984 and is referred to as SWING. Nozzles were added in 1986 at the end of the mixing blade to provide a two-fluid jet grouting system capable of producing increased column diameters of 2.4 to 3 m. Jet pressures of about 20 MPa are used in this revised method, which is referred to as SWING-JET. Jet pressures were increased to 40 MPa in 1988 in a variation called SWING-MJET. A three-fluid system was developed in 1991, referred to as SWING-HIJET, capable of producing columns 3.2 to 3.6 m in diameter. The high jet system is similar to conventional jet grouting equipment.

Grout Plant — Typical DMM or jet grout unit.

Control — Computer control of mixing, drilling, and injection parameters.

Production — Instantaneous production of 12 to 30 min/m has been reported. This is relatively slow, but would be offset by the system's other advantages.

4. MIX CHARACTERISTICS

Grout. — Little data are available. However, Kawasaki (1996) reports on the use of a retarded slurry, with a cement factor of 450 kg/m^3, at Kinko Bridge, Yokohama. Typical figures may begin at 200 kg/m^3. Other test data indicate pumping rates of 48 to 108 L/min.

Treated Soil — Soil-cement columns created by SWING consist of two zones: an outer zone produced by jet mixing and an inner zone produced by mechanical mixing. The unconfined compressive strength (q_u) of the inner mechanically mixed zone ranges from 0.4 to 4.4 MPa. The outer jet mixed zone exhibits a lower strength than the inner zone for a column produced with the same water/cement ratio. For preliminary design, maximum unconfined compressive strengths of 1.5 MPa for sandy soils and 1.2 MPa for cohesive soils can be assumed for soils treated by jet mixing. For practical applications, these columns can be considered as composite columns, and an average strength can be assumed for the entire column. The ratio of field strengths to laboratory strengths is 0.5 to 1.

The modulus of elasticity of the outer jet mixed zone can be estimated as $E_{50} = 100q_u$. The E_{50} for the inner mechanically mixed zone is lower than that produced by the CDM method, which is 400 to 600 q_u, and is closer to that produced by DJM, which is $150q_u$.

The majority of the applications of the SWING method have been for the treatment of soft ground as opposed to reducing permeability, and so no data are available.

5. PROTECTED/PATENTED FEATURES

There is a SWING Association in Japan that protects the technology.

6. PARTICULAR ADVANTAGES (Figure 81)

SWING has the advantages of a jet grouting system in that a smaller diameter hole (0.6 m) is required for the drill rod, allowing structural underpinning and better penetration through difficult, harder soils. The treated column size can be increased by increasing jet mixing pressure. Due to jet mixing, the treated zone can provide good contact with adjacent underground structures. The mixing blade can be opened in designated horizons only, which saves cement, time, and spoil. The method is also advantageous for treating clays with strengths greater than 0.05 MPa, since initial drill torque requirements are minimized.

7. OPERATING COMPANIES

Taisei Corporation and Raito Kogyo Co., Ltd., both of Japan, are two of the larger members of the SWING Association, founded in the late 1980s and which now has 17 members. Operation of this technology outside of Japan is unknown thus far, although Raito Kogyo Co., Ltd. is represented in the United States by Raito, Inc., in California.

8. REFERENCES

Kawasaki, K., H. Kotera, K. Nishida, and T. Murase. (1996). "Deep Mixing by Spreadable Wing Method." *Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 631-636.

Yang, D.S., J.N. Yagihashi, and S.S. Yoshizawa. (1998). "SWING Method for Deep Mixing." *Soil Improvement for Big Digs*, Geotechnical Special Publication No. 81, Geo-Institute of the American Society of Civil Engineers, Boston, MA, October 18-22, pp. 111-121.

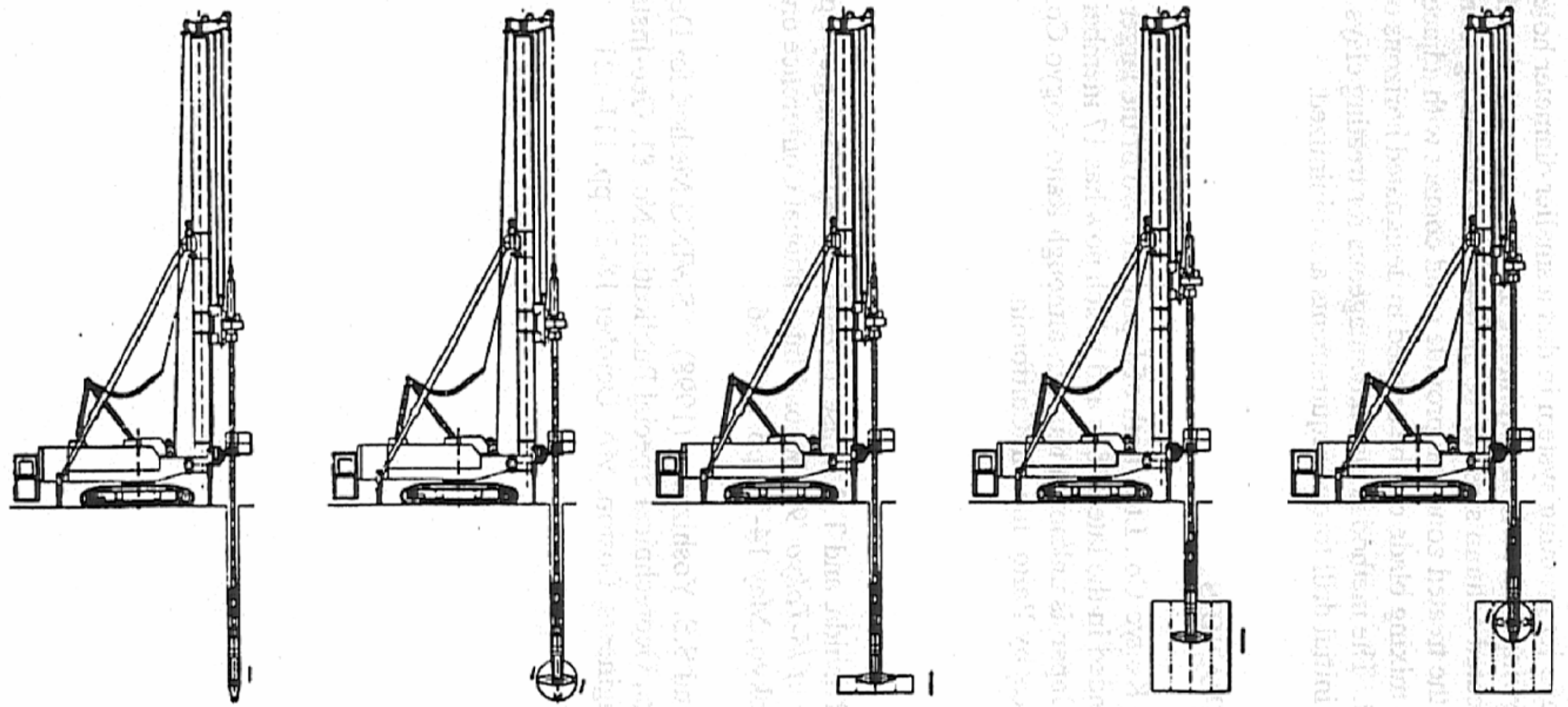


Figure 78. Procedure used for Spread Wing column construction (Kawasaki et al., 1996).

1) Drilling of Pilot Hole
Drill the pilot hole with water to the bottom of soil layer to be treated.

2) Expanding the SWING Blade
Expand the SWING blade while rotating the shaft.

3) Pre-drilling the Treatment Zone
Pre-drill the zone to be treated upward using SWING blade and high-pressure jet. Lower the blade down to the bottom while keeping the blade at expanded position and shaft rotating. Grout may be injected during the downward drilling.

4) Injecting and Mixing
Inject the grout from the blade and high-pressure grout jet from the edge of the blade and perform both mechanical mixing and jet mixing.

5) Extract SWING Blade
Rotate the SWING blade back to the shaft after soil mixing.

6) Retrieving the Shaft
Withdraw the shaft to the ground surface.

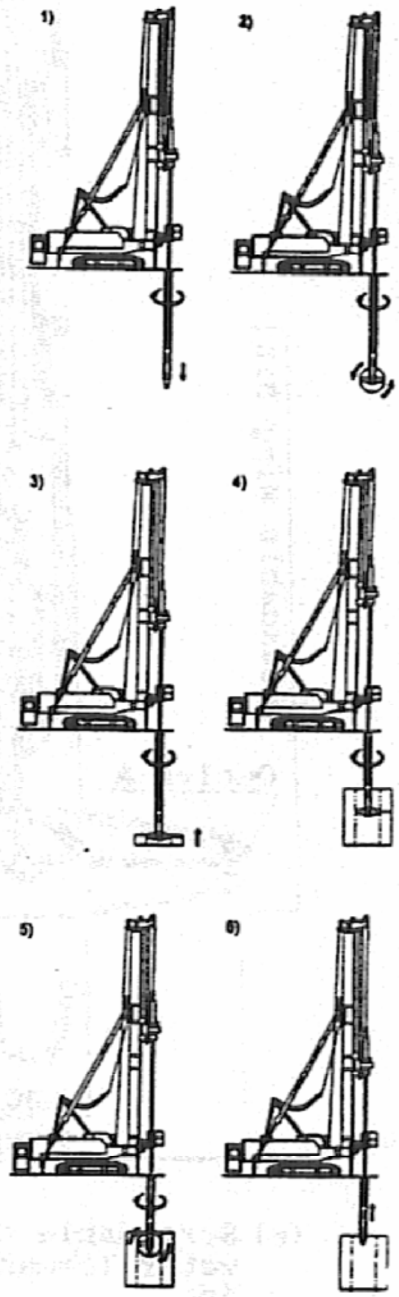


Figure 79. Installation procedure (Yang et al., 1998).

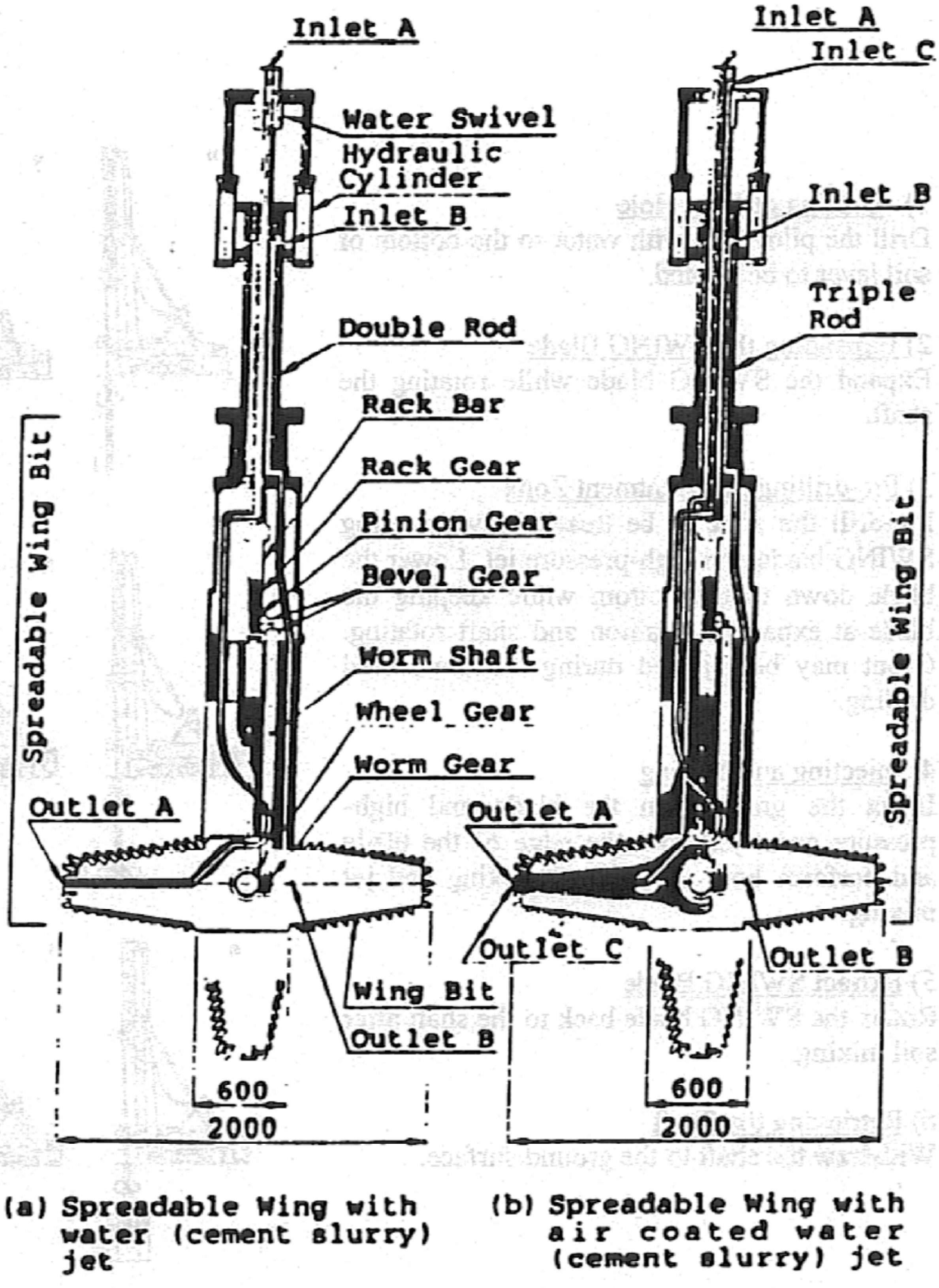


Figure 80. Mixing unit used for Spread Wing Method (Kawasaki et al., 1996).

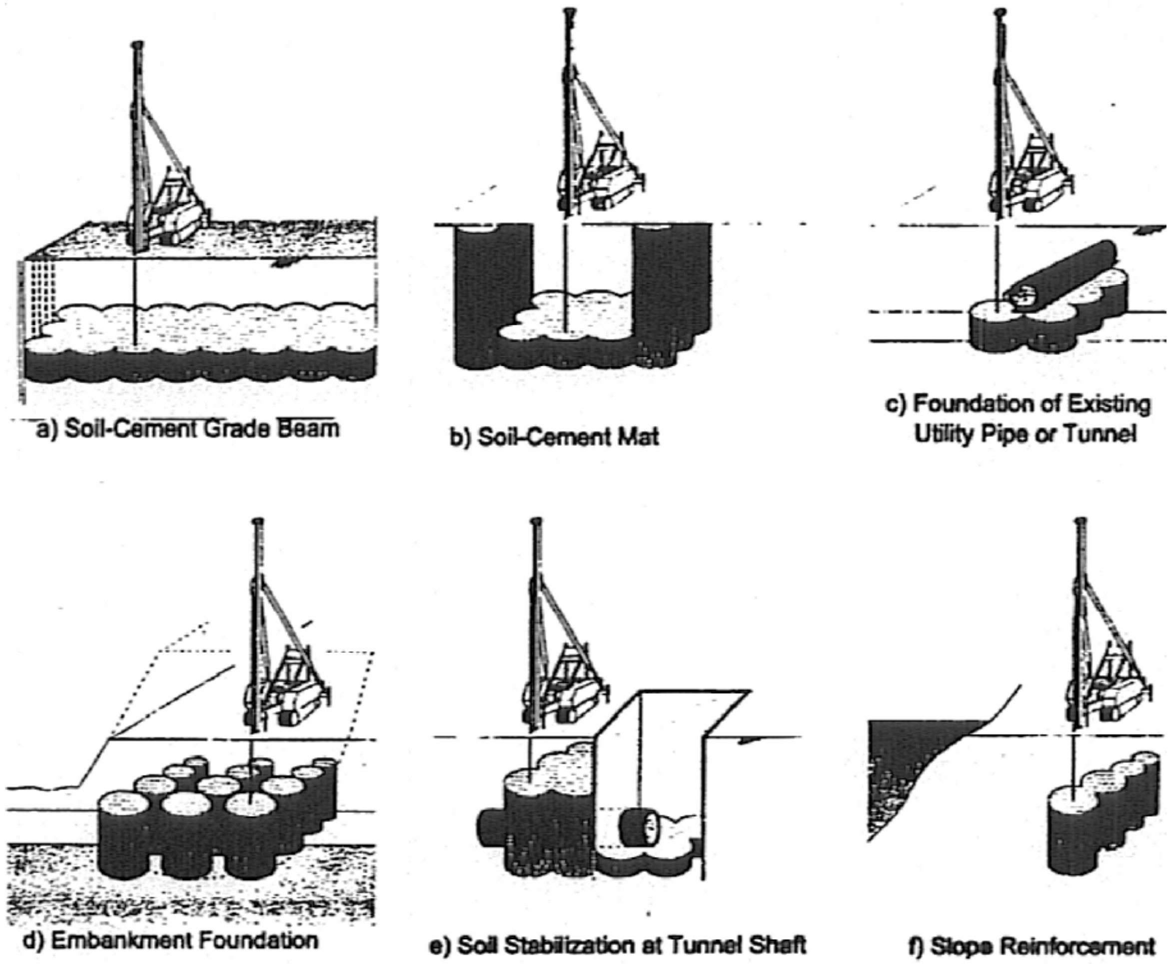


Figure 81. Application of SWING Method (Yang et al., 1998).

JACSMAN METHOD (18)

1. INTRODUCTION

This system is classified as WJE. JACSMAN is an acronym for Jet And Churning System MANagement. The JACSMAN system was developed to solve problems inherent to both mechanical deep mixing and jet grouting. With mechanical deep mixing, it can be difficult to create tight joints and work close to underground structures. With jet grouting, it is difficult to guarantee a constant column diameter. With the JACSMAN system, columns are constructed using a combination of cross-jet grouting and deep mixing This combination can construct a treated mass with firm joints between columns, columns of controlled diameter, and uniform quality as a result of the cross-jetting. There is a JACSMAN Association in Japan.

2. GENERAL PROCESS

Grout is injected at low pressures through nozzles on the cutting blade during penetration. Upon reaching the bottom of the hole, the unit is withdrawn while cement grout is cross-jetted into the soil at a high velocity. The resulting column is larger than a mixed column and can be constructed close to sheet pile walls or solid piles (Figures 82 and 83). A maximum depth of 20 m can be reached.

3. EQUIPMENT

Base — Large crawler-mounted crane.

Shafts — The two counter-rotating shafts are mounted 0.8 m apart. Each shaft contains three 1-m-diameter blades: one lower penetration/soil shearing blade containing low-pressure discharge nozzles, and two mixing paddles containing high-pressure grout nozzles. Cutting teeth are mounted on the leading edges of the blades to facilitate excavation and break-up of the soil. Two high-pressure nozzle configurations were evaluated: one nozzle at one end of each blade for a total of four nozzles and one nozzle at each end of each blade for a total of eight nozzles.

The nozzles on the upper blade are oriented to discharge downward at an angle of 60°, and the nozzle(s) on the lower blade are angled upward at 60°. This allows the jetted slurry to intersect at a given distance from the shaft.

The jetted streams of slurry lose power when they collide, and the diameter of the column is maintained uniformly accurately. The cross-jetting also increases the degree of mixing in the column.

During penetration, mechanical mixing and low-pressure jetting produces a treated mass with nominal dimensions of 1 m x 1.8 m. The treated area is 1.5 m^2, with the individual columns (each formed by a 1-m-diameter blade on shafts separated by 0.8 m) overlapped by 0.2 m. The rotation rate during penetration and withdrawal is typically 20 rpm.

The treated mass formed by mechanical mixing and high-velocity jetting on withdrawal is approximately 1.9 m + 2.7 m for a treated area of 5.66 m^2 with individual column overlap of 1.1 m.

Grout Plant — Material storage silos, batching system, slurry mixer, agitator tank, low- and high-pressure grout pumps.

Control — No data available.

Production — Penetration rate is 1 m/min, and the withdrawal rate can be varied from 0.5 m/min to 1.0 m/min.

4. MIX CHARACTERISTICS

Grout. The water/cement ratio of the mix used for the prototype test was 1.0. Approximately 200 L/min of grout was pumped to each shaft. The jetting was conducted at pressures of 30 MPa. On some of the tests, compressed air at 1 m^3/min was injected with the grout. The grout flow to each jet varied from 75 to 150 L/min. The cement volume reported per cubic meter of treated soil was 200 kg/m^3 for the jetted section and 320 kg/m^3 for the mixed portion of the column.

Treated Soil. The prototype test was conducted in a layered soil consisting of fill, clay, and silty sand. Soil data and subsequent UCS results are shown in Figure 84. Strength values ranged from 1 to 6 MPa. The effect of air entrainment is shown in the data in Figure 85: the solid points represent columns formed without air, the open points represent columns formed with air. This prototype test was conducted to:

- Investigate the ability to control column size.
- Investigate the effectiveness of the "cross-striping" action of the jets.
- Determine the system's ability to construct columns adjacent to underground structures, such as sheet piles and other piles. Figure 86 shows the column layout for this portion of the test.

The investigation was conducted by installing columns using various methods and equipment configurations. Table 6 shows the test variables for the test columns.

The pump pressure was adjusted during testing to allow the same flow rate of cement slurry (volume/hour) to be jetted through the two different nozzle configurations (four nozzles/shaft vs. eight nozzles/shaft). The same water/cement ratio (1.0), was used for the mechanical mixing portion (discharged through the low-pressure jets on the lower-most mixing blade on each shaft and the cross-jet mixing portion. A cement factor of 200 kg/m^3 was used for mechanical mixing during penetration. The test variables are listed in Table 6. The test results are as follows:

- The four-nozzle configuration made larger columns than the eight-nozzle configuration, although both transmissions produced the same volume of slurry.
- The columns had uniform diameters.
- Desired column diameters can be achieved by injecting air during jet grouting.
- The effect of lift velocity on column diameter is less pronounced on the four-nozzle system than on the eight-nozzle system. Column size decreased with increased lift velocity using the eight-jet system, whereas column diameter remained relatively unchanged for the four-jet system.
- The strength of columns formed using the four-jet system is greater than the strength of columns formed using the eight-jet system.
- The strength of columns jetted using air was less than the strength of columns jetted without air.
- Mechanical mixing showed equal or higher strengths compared to jet mixing.
- The overlapping of columns was satisfactory.
- Satisfactory contact can be achieved between the columns and adjacent underground structures.

5. PATENTED/PROTECTED FEATURES

Presumed protected by the researchers' companies. The development of this technique is quite recent, although Nicholson et al. (1997) claim that about 20 projects had been completed in Japan by 1996.

6. PARTICULAR ADVANTAGES

The system is capable of treating larger volumes of soil per pass, overlapping columns together with adjacent columns and/or existing underground structures, and it requires less open space in untreated areas.

7. OPERATING COMPANY – GEOGRAPHIC RANGE

The only English language paper found was authored by Fudo Construction Co., Tokyo and Chemical Grout Company, Tokyo, members of the JACSMAN Association. Understood to operate only in Japan.

8. REFERENCES

Miyoshi, A., and K. Hirayama. (1996). "Test of Solidified Columns Using a Combined System of Mechanical Churning and Jetting." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 743-748.

Nicholson, P.J., B.H. Jasperse, and M.J. Fisher. (1997). "Economical Alternative for Containment Barriers." International Containment Technical Conference and Exhibit, St. Petersburg, FL, February.

Table 6. Installation parameters for the various test columns (Miyoshi and Hirayama, 1996).

STEP	Case No.	Penetration		Lifting			
		Penetration velocity V(m/min)	Quantity discharge q(l/min)	Lift velocity V(m/min)	Jet volume q(l/min)	Jet pressure P (N/cm²)	Air volume (m³/min)
Test 1	1-1	1.0	200 ×2	0.5	75 ×8	3000	1.0 ×8
	1-2				150 ×4		1.0 ×4
	1-3				75 ×8		——
	1-4				150 ×4		
Test 2	2-1	1.0	200 ×2	1.0	75 ×8	3000	1.0 ×8
	2-5				150 ×4		1.0 ×4
	2-2			0.5	150 ×4	3000	1.0 ×4
	2-3						——
	2-4	1.0	200 ×2	0.5	——	——	——
Test 3	3-1 ~ 3-9	1.0	200 ×2	0.5	150 ×4	3000	1.0 ×4

Jet vol., Air vol. : jet vol/a nozzle x nos. of nozzles

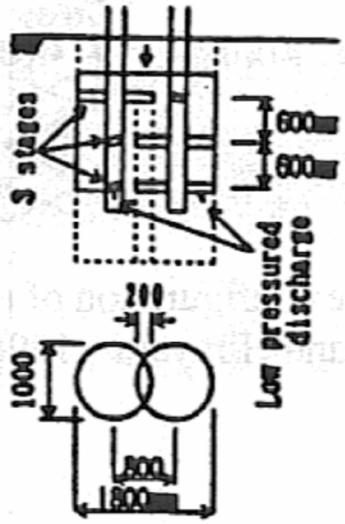
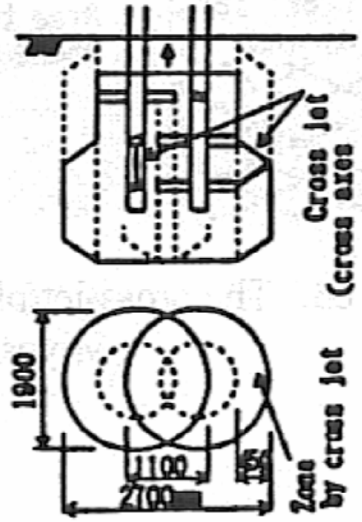
	Penetration (mechanical mixing)	Lifting (cross jet operated)
Method of work 2-rods, 80cm apart		
Elevation velocity	V = 1.0 m/min	V = 0.5 m/min
Rotation of rod	R = 20rpm	R = 20rpm
Diameter	ϕ_P = 1m(A_P =0.785m²) × 2	ϕ_P = 1.9m(A_P =2.83m²) × 2
Quantity of cement slurry	q=200 ℓ/min × 2	pressure q=150 ℓ/min × 4nozzle P= 3000N/cm² (air vol:q=1 m³/min × 4nozzle)

Figure 82. General configuration of the mixing and jetting unit for the JACSMAN system (Miyoshi and Hirayama, 1996).

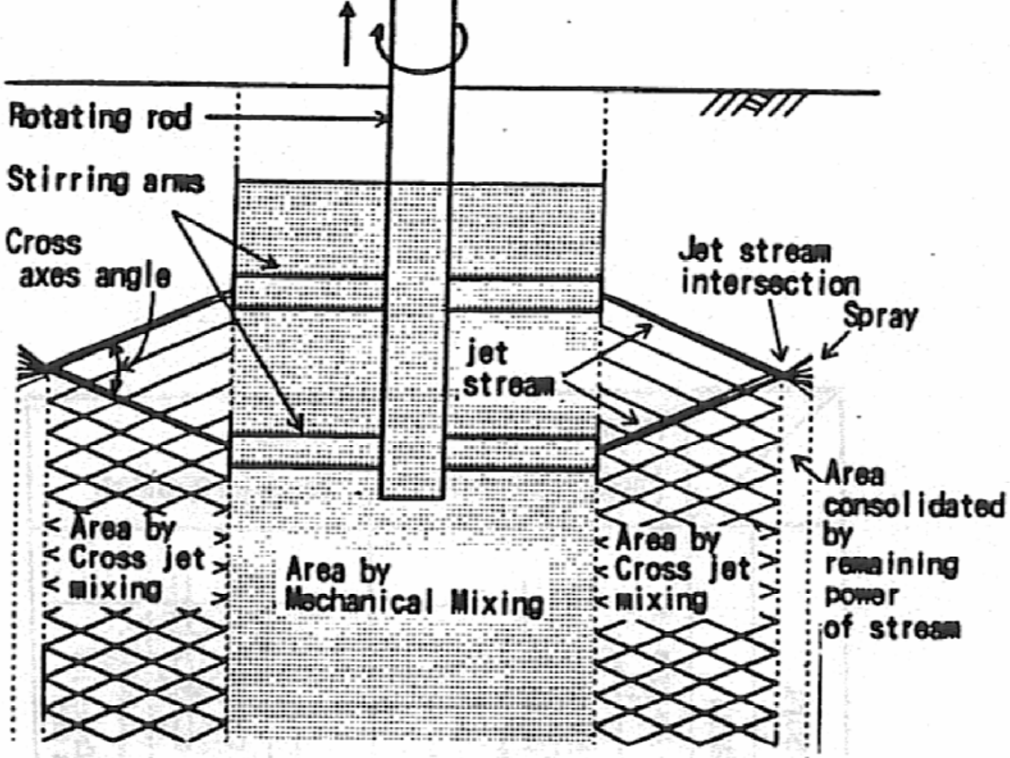


Figure 83. The cross-jet/blade configuration of the JACSMAN system (Miyoshi and Hirayama, 1996).

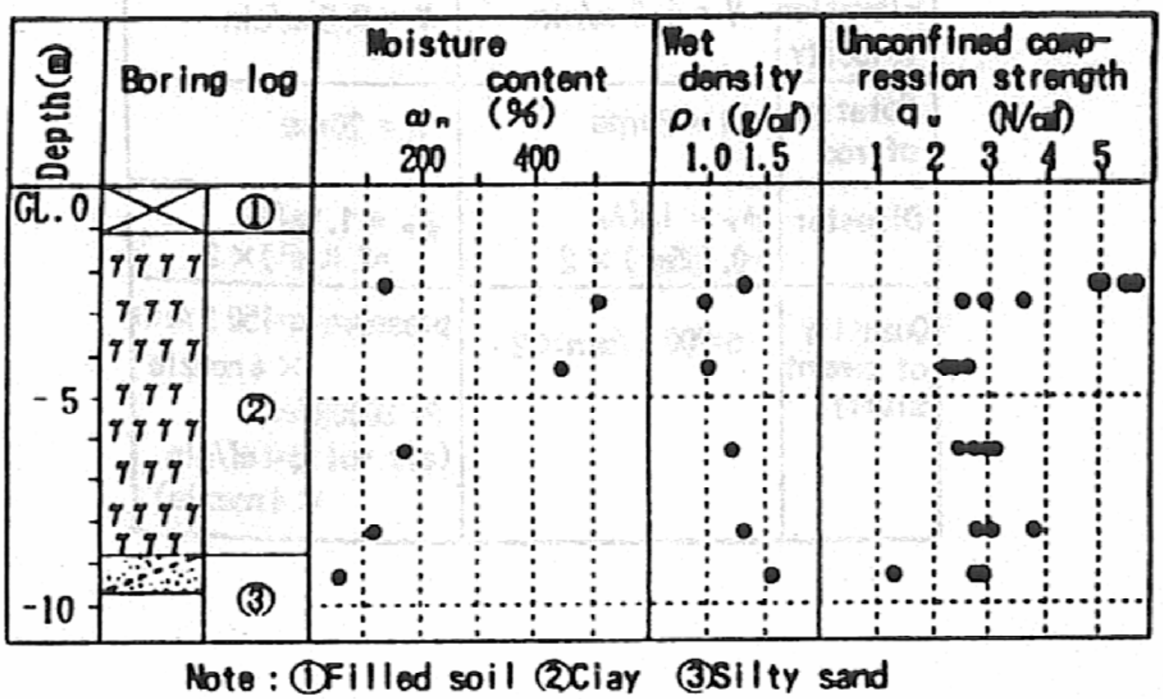


Figure 84. Soil data and UCS results for prototype test (Miyoshi and Hirayama, 1996).

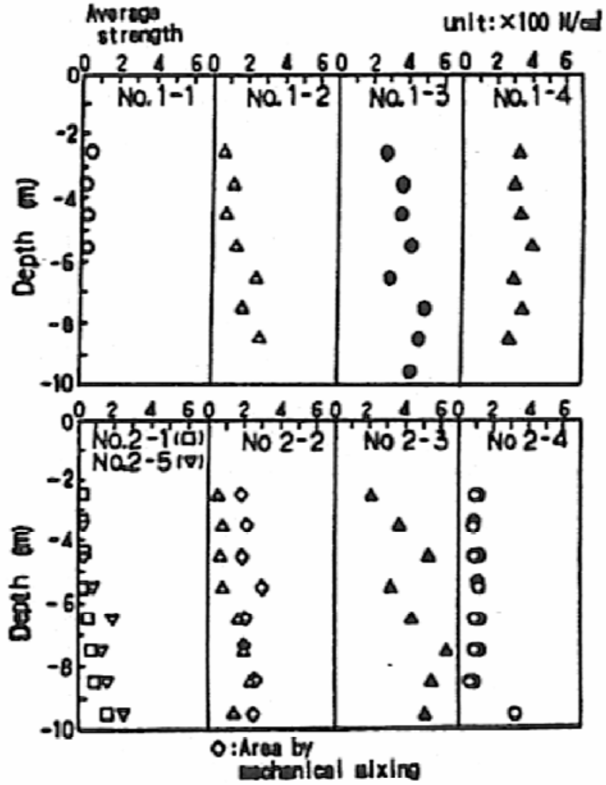


Figure 85. Effect of air entrainment on strength (Miyoshi and Hirayama, 1996)

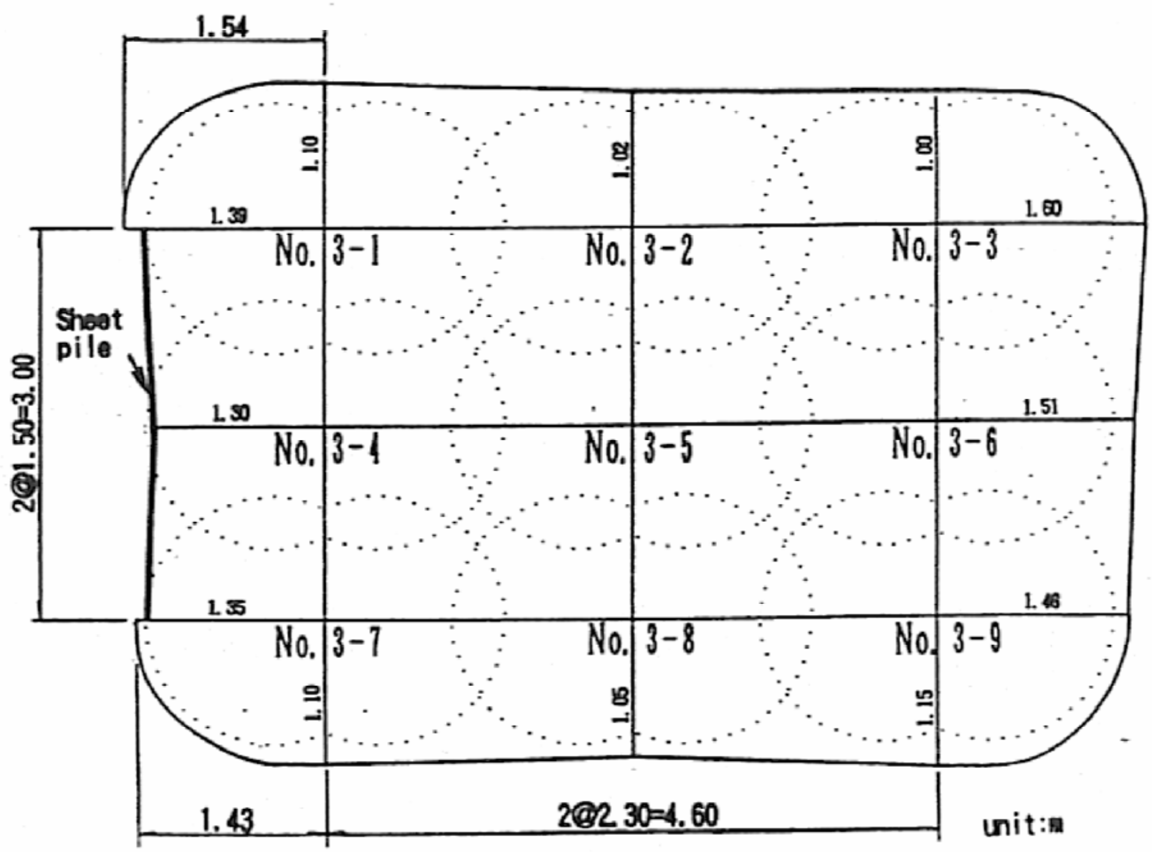


Figure 86. Test column layout (Miyoshi and Hirayama, 1996).

LDis SYSTEM (19)

1. INTRODUCTION

With conventional jet grouting methods, large volumes of soil are removed and ground displacement can be great. The Low Displacement Jet Mixing (LDis) system was developed and tested to reduce the volume of material displaced by the jet as well as to reduce ground movement. Assuming it is legitimate to regard this as a Deep Mixing technique, it can be classified as WJE. Development is in the prototype stage.

2. GENERAL PROCESS

The mixing tool (Figure 87) is rotated while apparently injecting some volume of grout. The ground is penetrated to the base of the zone to be treated. The tool is then withdrawn to the surface to further break down and remove soil. The mixing tool then re-penetrates to the base of the treatment zone and upon withdrawal, cement slurry is injected at high pressure via lateral jets. Injection pressures of 40 MPa were used. The general process is illustrated in Figure 88. The intent of this method is to remove the same volume of ground as the volume of slurry injected and thus prevent lateral or vertical displacement.

3. EQUIPMENT

<u>Base</u> The major equipment used in this technique is listed in Table 7. The equipment is similar to a conventional jet grouting system.

<u>Shafts</u> The addition of a single-auger flight located directly above the jet ports distinguishes this system from conventional jet grouting equipment. The mixing tool is shown in Figure 87.

<u>Grout Plant</u> Assumed similar to jet grouting equipment.

<u>Control</u> Assumed equivalent to usual jet grouting.

<u>Production</u> Production rates are lower than with conventional jet grouting techniques due to the double-pass required to loosen the soil and their grout. Withdrawal speed is the same as for penetration, at approximately 0.33 m/min. However, overall production decreases to about 55% that of jet grouting.

4. MIX CHARACTERISTICS

Grout. A grout injection rate of 100 L/min was reported for the test columns. Approximately 1.5 m^3 of slurry was added to form a column 1 m in diameter and 5 m long, i.e., 300 L/min or a volume ratio of just under 40%.

Treated Soil. Reported strengths of treated soil are approximately 2 MPa. As noted above, the intent of this method is to remove the same volume of ground as the volume of slurry injected. The method, through testing, was determined to be 90% effective, i.e., it removed 1.35 m^3 of soil when 1.5 m^3 of grout was injected.

To measure the level of ground movement, inclinometers were installed at the test site at the locations shown in Figure 89. A series of five columns were installed by the conventional method, and five columns were installed by the LDis method. Displacements at depth due to the LDis columns were reduced to 1/6 that of the conventional jet grouting method.

5. PATENTED/PROTECTED FEATURES

Assumed to be protected by the developers (particular to LDis: other features as for jet grouting).

6. PARTICULAR ADVANTAGES

The technique imparts less disruption to adjacent structures. Heave is better controlled, and spoils volume is low.

7. OPERATING COMPANY

Onoda Chemical Co. of Japan.

8. REFERENCE

Ueki, H., K. Hasegawa, K. Suzuki, and M. Bessho. (1996) "Development of a High-Pressure Jet Mixing Method for Displacement-Reducing." *Grouting and Deep Mixing, Proceedings of IS-Tokyo '96*, Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, pp. 767-772.

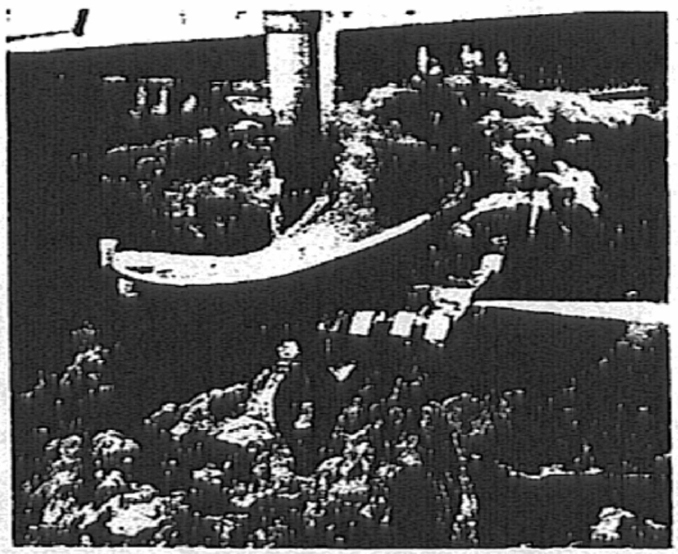


Figure 87. Soil-removing disk (Ueki et al., 1996).

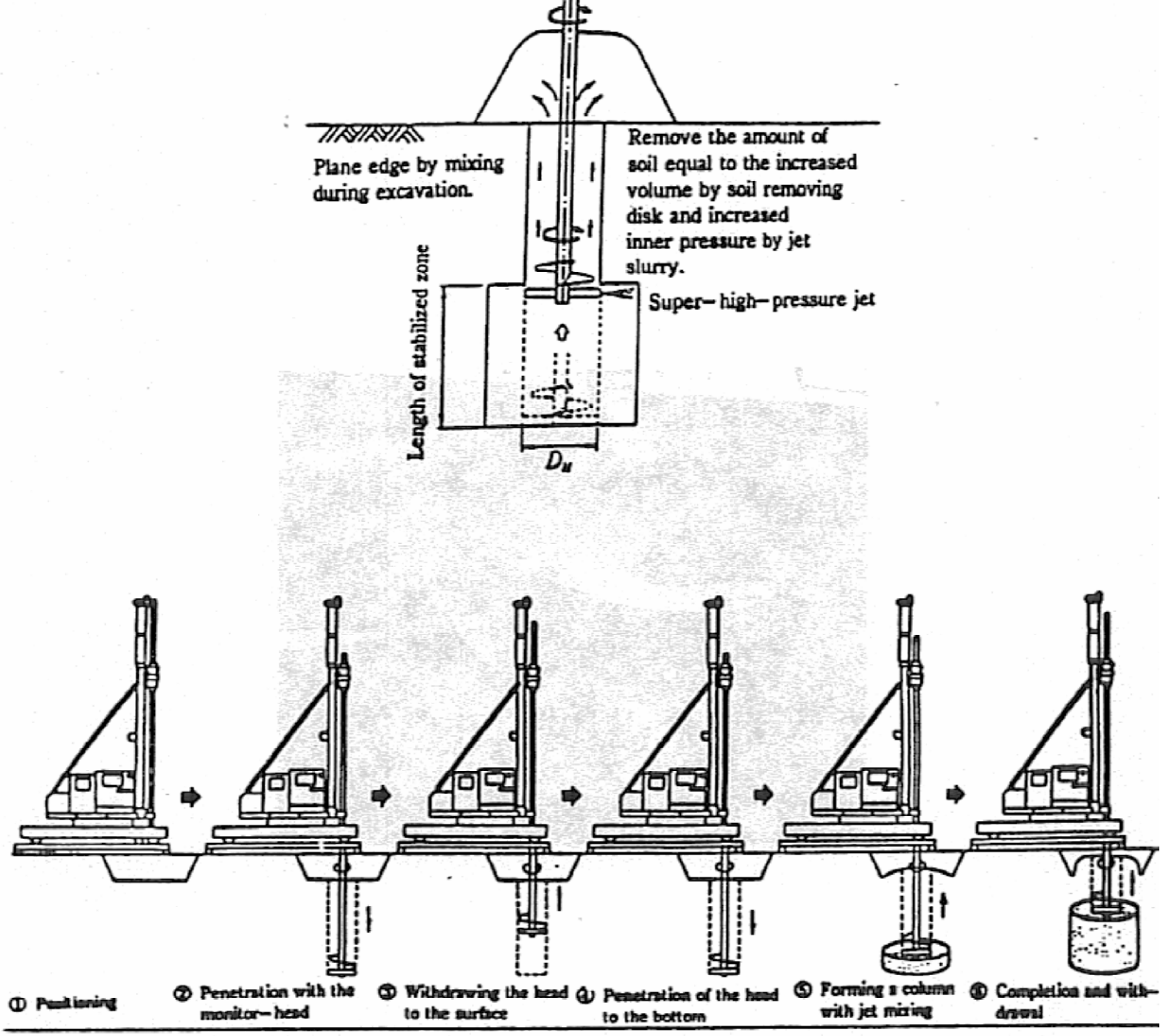


Figure 88. LDis system and general processes involved in forming an LDis column (Ueki et al., 1996).

Table 7. List of the major equipment (Ueki et al., 1996).

equipment	specifications	capacity (kW)
Automatic mixing plant	mixer 1.5 m³ agitator 2 m³ with a meter of water and hardening agent	15.6
Hardening agent silo	30 ton with SC	15.4
Super-high -pressure pump	30 to 40 MPa	110
Water tank	10 m³	—
Flow gauge	0 to 200 l/min	—
Jet mixing equipment	3.5 m stroke 3 to 40 rpm	30
Slide base (driving equipment)	automatic travelling	—

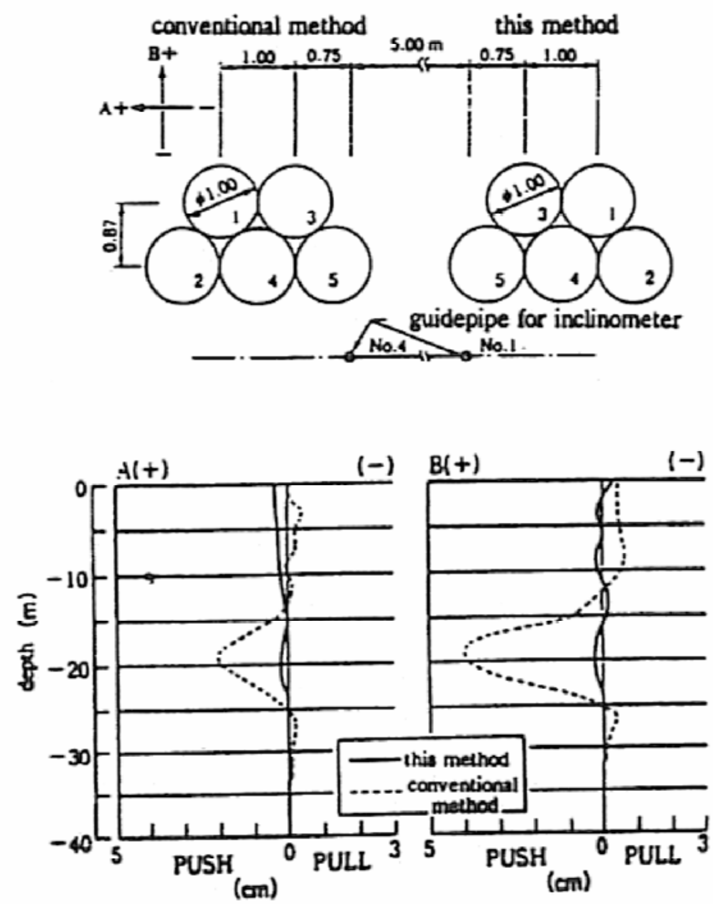


Figure 89. Plan of the test execution and measured cumulative displacement by the conventional method and this method (Ueki et al., 1996).

1. INTRODUCTION

The GeoJet system is classified as WJE. A "processor," comprising an auger flight or a pair of swings (Figures 90 and 91), is located at the bottom of the hollow-stem mixing rod. Attached to the auger flight or wings are high-pressure grout nozzles. During rotation of the mixing rod, the processor mechanically cut the soil, which is then hydraulically mixed by high-velocity grout injected into the soil-cement column at relatively high volumes, with a high degree of computer control, process repeatability, and verification documentation. The concept was developed in the early 1980s as a way of installing piles without the disadvantages associated with pile-driving methods, and still focuses most applications in that arena, although other applications (e.g., earth retention) have been conducted.

2. GENERAL PROCESS

The processor is rotated and lowered, cutting the soil at 50 to 75 mm per rotation. Simultaneously, grout is injected at about 700 to 750 L/min from the processor at pressures of 10 to 35 MPa (typically 15 MPa) to blend the soil and grout. The slurry injection rate is slowed as it is withdrawn from the hole and backfill grout is injected at low pressure. The whole zone is formed in one continuous pass and is controlled by a microprocessor. The process is so swift that this computer control is essential. The 486k unit samples parameters every 6 s to permit adjustment of key construction parameters, e.g., pump pressure, drill speed, and drill torque, in order to ensure that predetermined density and strength targets are efficiently met.

3. EQUIPMENT

<u>Base</u> The equipment consists of a 110-tonne crawler-mounted crane with fixed leads, which carries an 600-kW generator delivering power to all systems, including a 225-kW rotary turntable (Figure 92) and 350-hP grout pump. A bottom drive turntable of 43,000 N-m is capable of rotation speeds during mixing of 150 to 200 rpm (most recently, the trend has been toward using 90 rpm, especially when the larger diameters are used).

<u>Shafts</u> The drilling and mixing system includes a single shaft with auger flights or blades located at the bottom of the shaft. The drill rod is 152 mm in diameter, 50 mm thick. The processor, producing columns 600 to 1200 mm in diameter, usually 900 to 1200 mm, is fitted with teeth, depending on the soil. Cutting of the soil is accomplished by the wings. Teeth or blades are attached to the leading edge of the processor to help penetration and aid mechanical mixing. The exact nature and composition of the processor is varied, depending on soil conditions (a recent version resembles an SSM tool). Wings range in size from 400 to 1220 mm in diameter. Depths of 45 m are obtainable, but 25 m is a typical maximum pile length.

Grout Plant — Mixing is accomplished by the high-pressure/velocity grout, which is provided by a jet grout mixer (about 1150 L/min) with recirculating capabilities. A horizontal triplex grout pump is capable of pumping at pressures greater than 40 MPa, typically 15 MPa, mounted to the crane, and at a typical rate of about 550 to 750 L/min. A 220-`bulk cement storage "guppy" (i.e., 1-day capacity) delivers grout at 100 kPa into 1.1-tonne holding tanks from where it is pumped at 200 kPa to the mixer. The grout plant has three pumps: one each for grout, water, and recirculation, and the plant includes a nuclear densometer to continuously monitor the density of the grout. The nozzles in the processor typically have carbide inserts to combat the erosive action of the grout. The mixer is also referred to as RCM (Halliburton's Recirculating Cement Mixer).

Control — During installation, the microprocessor analyzes rotation rate, penetration rate, slurry pressure, torque, crowd force, and treated soil volume and density as a function of depth during the construction of each element. The computer reacts to changing ground parameters and adjusts injection parameters to maintain specific treated soil properties in different strata. Rotation is stopped automatically if treated soil parameters exceed preset limits. The system is equipped with a microprocessor to monitor and control the entire process given the very fast penetration rates achievable. An automated spotter/positioning system is also provided. The operator control panel has a touch screen. Typical verification documentation is shown in Figures 93, 94, and 95.

Production — Industrial production rates in excess of 150 m/h and 1100 m/shift have been achieved. Instantaneous rates include 2 to 12 m/min (penetration), and 15 m/min (withdrawal). Set up time between holes is commonly 1 to 2 min. As in most DMM methods, penetration rate is controlled by rotational speed, among other things. For cohesive soils, chip sizes per blade per rotation are limited to about 10 to 15 mm.

4. MIX CHARACTERISTICS

Grout. To date, only grouts consisting of cement and water have been injected. The water/cement ratio of these grouts can vary from 0.5 to 1.0.

Treated Soil. Strengths in Beaumont Clay at the Tidwell, TX, site ranged from 4.83 to 10.3 MPa. Strengths in the San Francisco Bay Mud deposits of 0.7 to 5.5 MPa have been recorded, the actual value is controllable via the injection parameters. The amount of material pumped is dependent on the soil type and strength requirements of the soilcrete column. Cement factor is typically 150 to 300 kg/m^3. Test of piles installed using the GeoJet system have been described by Reavis and Freyaldenhoven (1994). Prof. L.C. Reese of the University of Texas has also been closely involved in development. The relatively high strengths for the columns in clay are largely due to the high degree of mixing imparted by the rapidly rotating shaft. The volume ratio is 20% to 40%.

5. PATENTED/PROTECTED FEATURES

The blade design, computer system for controlling drilling and injection parameters, and process are patented. A total of five patents are currently in place for the GeoJet system (Nos. 4,793,740; 5,396,964; 4,604,003; 4,958,962; and 5,890,844), and three patents are pending.

6. PARTICULAR ADVANTAGES

The system is capable of very high output, providing high-quality/high-strength mixing with low vibration, low noise, and no loss of ground or heave. Good performance has been observed within 0.8 m of existing structures. Soft rock (e.g., shales) can be penetrated. Computer control and uniformity/repeatability of product are excellent. A high degree of Quality Assurance/Quality Control is provided. A high grout:soil bond (in piling applications) is achieved. The system produces low waste volumes (20% to 30% of ground treated). This technique does not need casing for pile installation in caving soil.

7. OPERATING COMPANIES

The equipment is owned and operated by Condon Johnson Associates of Oakland, CA. They have the license from the inventor, Lonnie Schellhorne of California, to operate the equipment in five western States. Trevi-ICOS Corporation of Boston, MA, is licensed to use GeoJet elsewhere in the United States and overseas.

8. REFERENCES

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Gillette, T. (1994). "Houston Bridge Piles Drilled Using High-Pressure Water/cement Slurry." *Roads and Bridges*, September, pp. 44-47.

Johnson, J. (1999). "Geo-Jet." Presented at the University of Wisconsin-Milwaukee Short Course on Deep Mixing Methods, Anaheim/Orange County, CA, April 26-27.

Reavis, G., and F.C. Feyaldenhoven. (1994). "GEOJET Foundation System." *Geotechnical News*, Vol. 12, No. 4, December. "Geosystems Issue," Ed. by M.E. Caves, pp. 56-60.

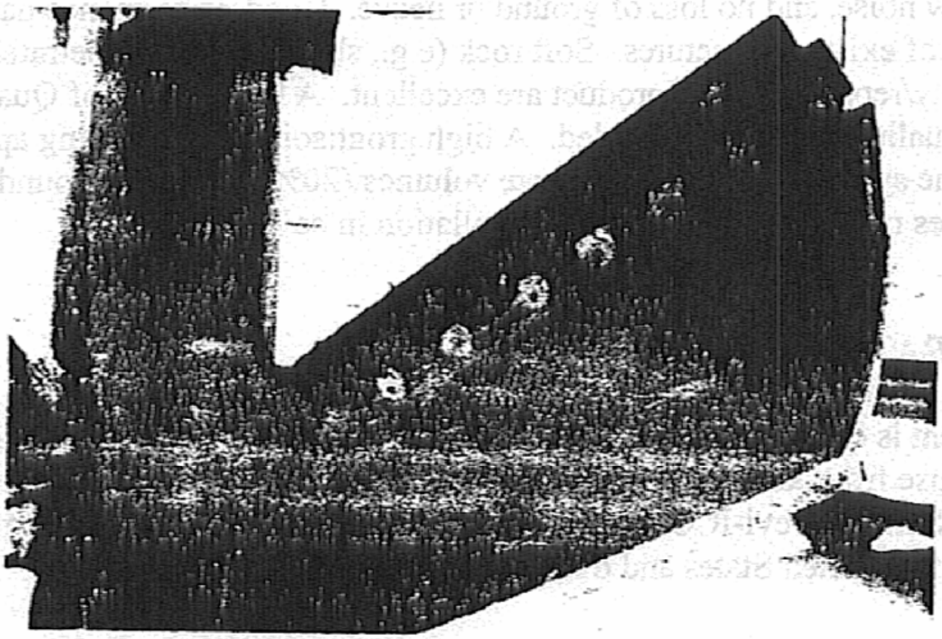

Figure 90. Mixing wings at the end of the hollow-stem kelly.

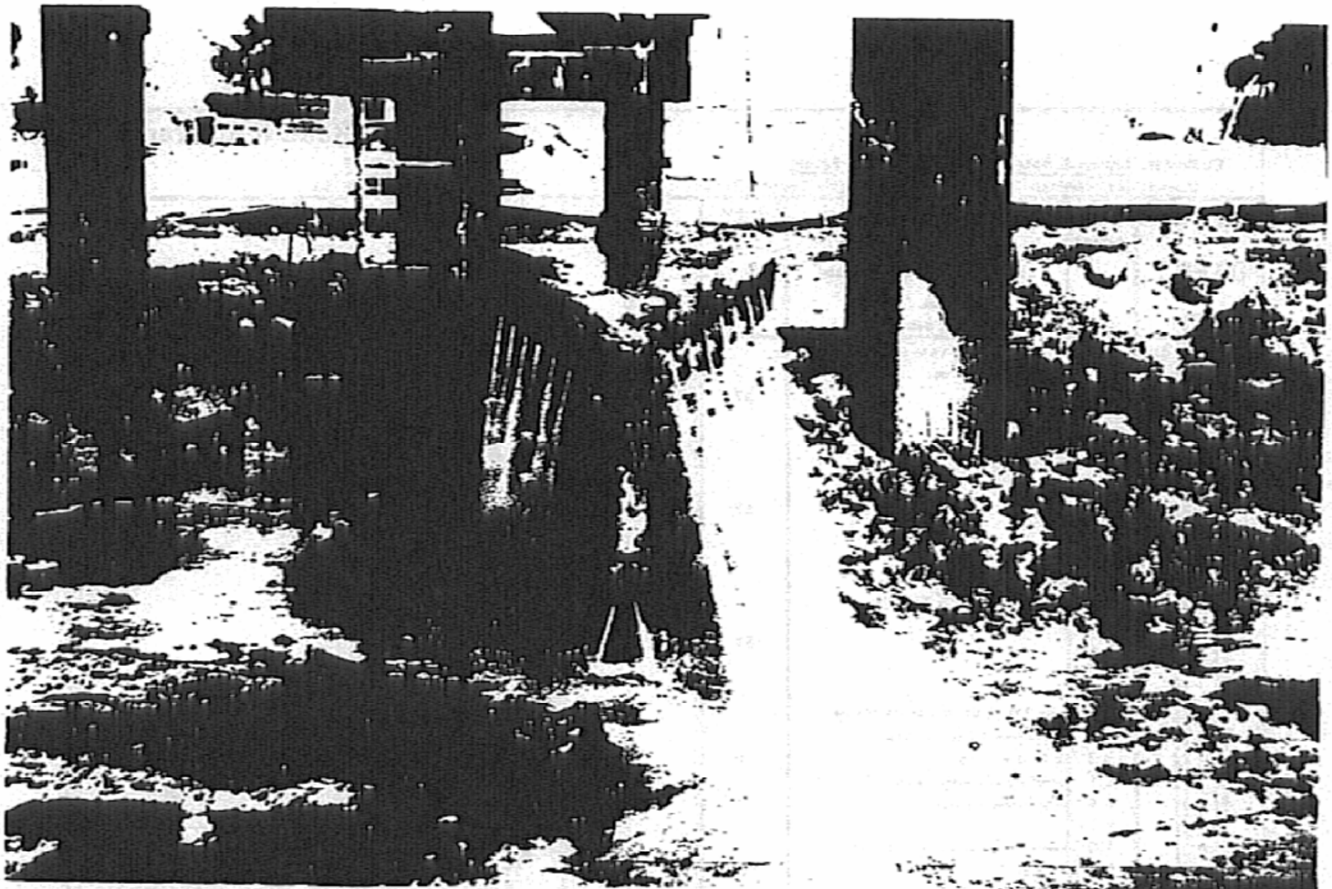

Figure 91. GeoJet processor (Courtesy of Condon Johnson Associates).

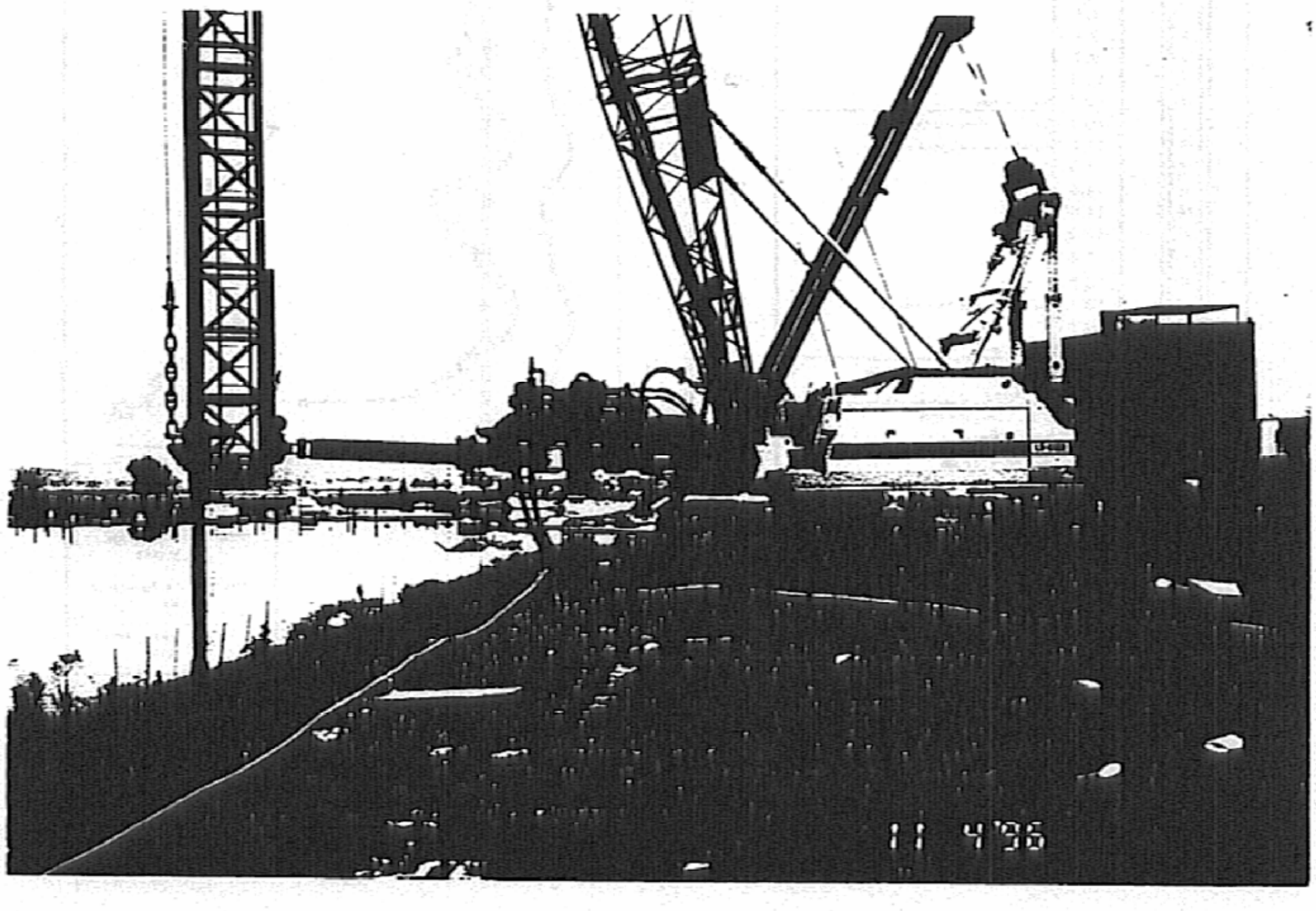

Figure 92. GeoJet equipment (Courtesy of Condon Johnson Associates).

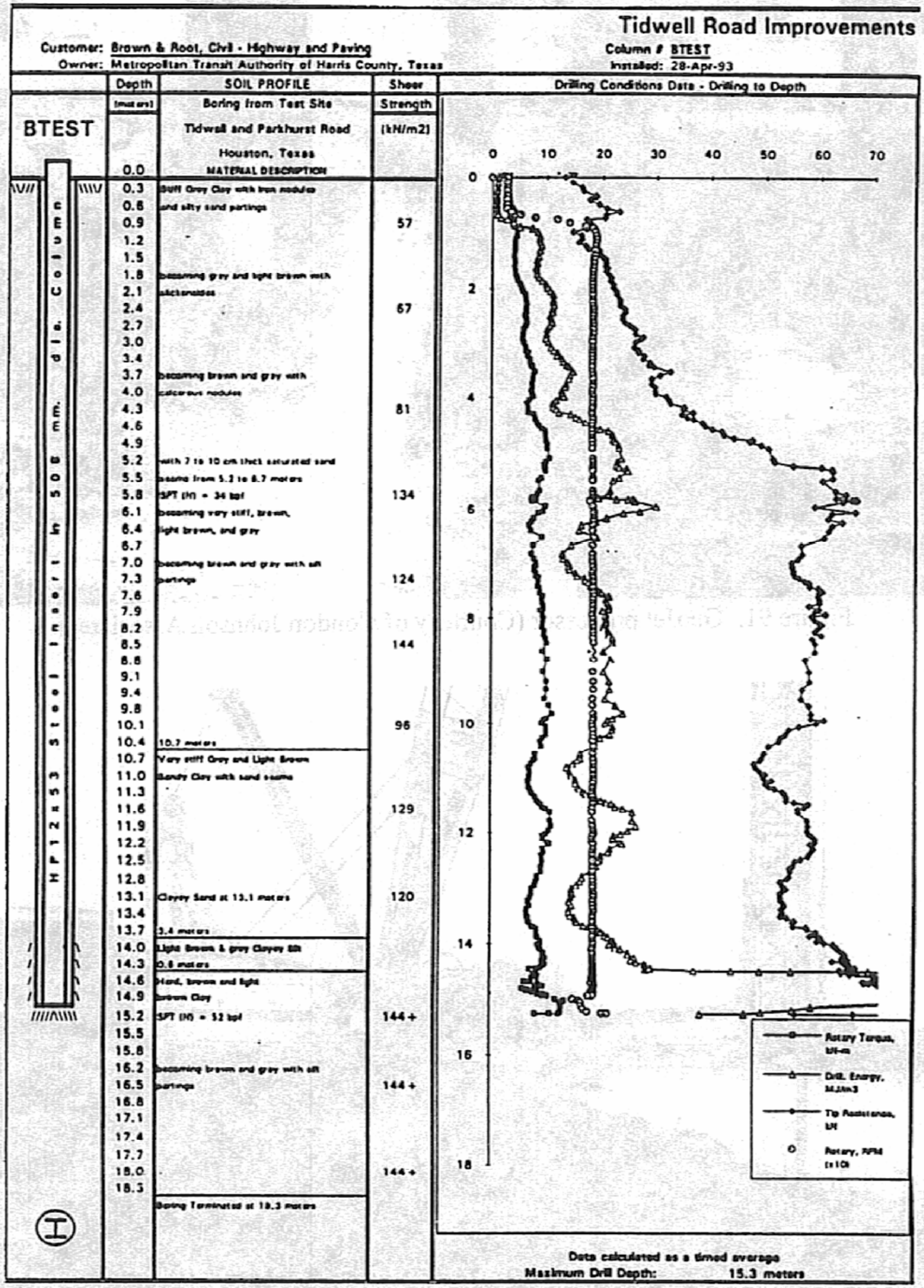

Figure 93. Verification documentation plotted with soil profile (1 of 2 pages).

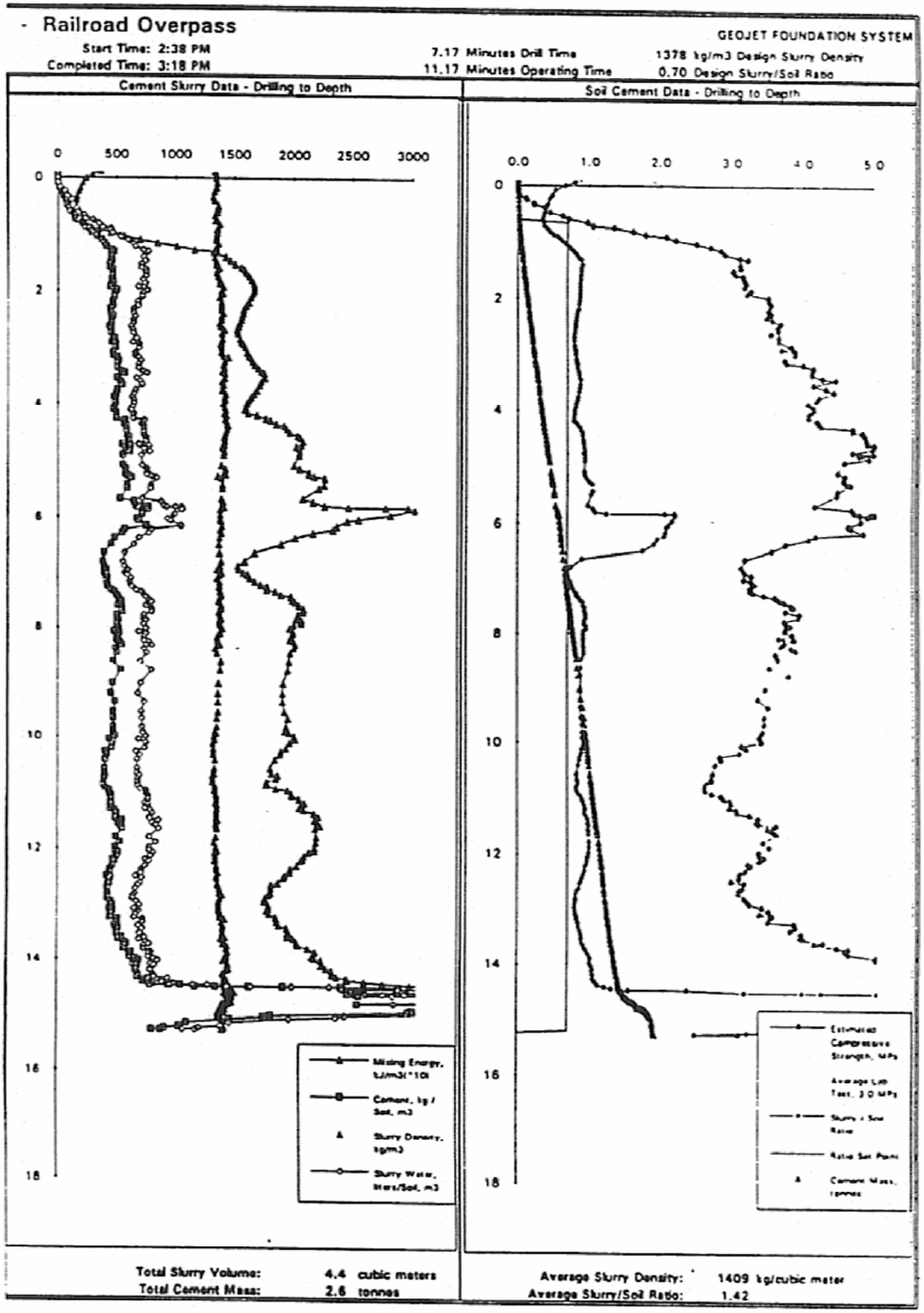

Figure 93. Verification documentation plotted with soil profile (2 of 2 pages).

Geo-Jet ™ Production

Tooling Performance Specification

Inputs Column

Augar diameter inches	24
Diameter of jets pilot	0.125
Num of jets on pilot	3
Diameter of jets main processor	0.125
Num of jets on main prosessor	8
Diameter of jets gel breaker	0.125
Num of jets on gel breaker	0

Calculated Column

Vol. per.lineal ft. cu.ft.	3.14

Pilot Performance

Pilot jet flow G.P.M. ea.	16.20
Pilot jet flow, tool total G.P.M.	48.61
Cement solids lbs. per gal.	6.09
Required SPM pump H.P. for pilot	[illegible]

Main Processor Performance

Main jet flow G.P.M. ea.	16.20
Main processor jet flow, tool total G.P.M.	129.61
Cement solids lbs. per gal.	6.09
Required SPM Pump H.P. for main processor	[illegible]

Gel Breaker Performance

Gel breaker jet flow G.P.M. ea.	16.20
Gel breaker jet flow, tool total G.P.M.	0.00
Cement solids, lbs. per gal.	6.09
Required SPM Pump H.P. for gel breaker	[illegible]

Tool Totals

Total slurry flow G.P.M.	178.22
Total H.P. Calc	[illegible]
Total engine H.P. required	[illegible]

Slurry Spec.

Slurry P.S.I.	2100
Slurry density P.P.G.	12.50
Percent cement solids by soil vol.	20%

Feed Rate

Required lbs. cement solids per. lin. ft.	59.06
Required slurry gals. per. lin. ft.	9.69
Total slurry req. for hole Gals.	348.91
Feed Rate Feet per Minute	18.39

Inputs-Feed

Number of cutter faces	2
Tool R.P.M.	91

Job Info.

Hole depth feet	36
Retract F.P.M.	50
Avg. set-up time on next hole, MIN.	1.5
Production Shift length,Hr.	7
Calculated Production Shift length, MIN.	420

Calculated Feed

Chip thickness, inches per REV., per face	1.21
Feed rate F.P.M.	18.39
Drilling time per hole, Min	1.96
Total retract time Min.	0.72
Total cycle time Min.	4.18
Total columns per shift	101
Total Lin.Ft. Per Shift	3619

Quantities

Required Cement per hole in Lbs.	2,126
Sacks per. hole	23
Sacks per shift	2,274
Tons per shift	107
Gallons of Slurry Per Shift	35,077

Figure 94. Verification documentation – tooling performance specification.

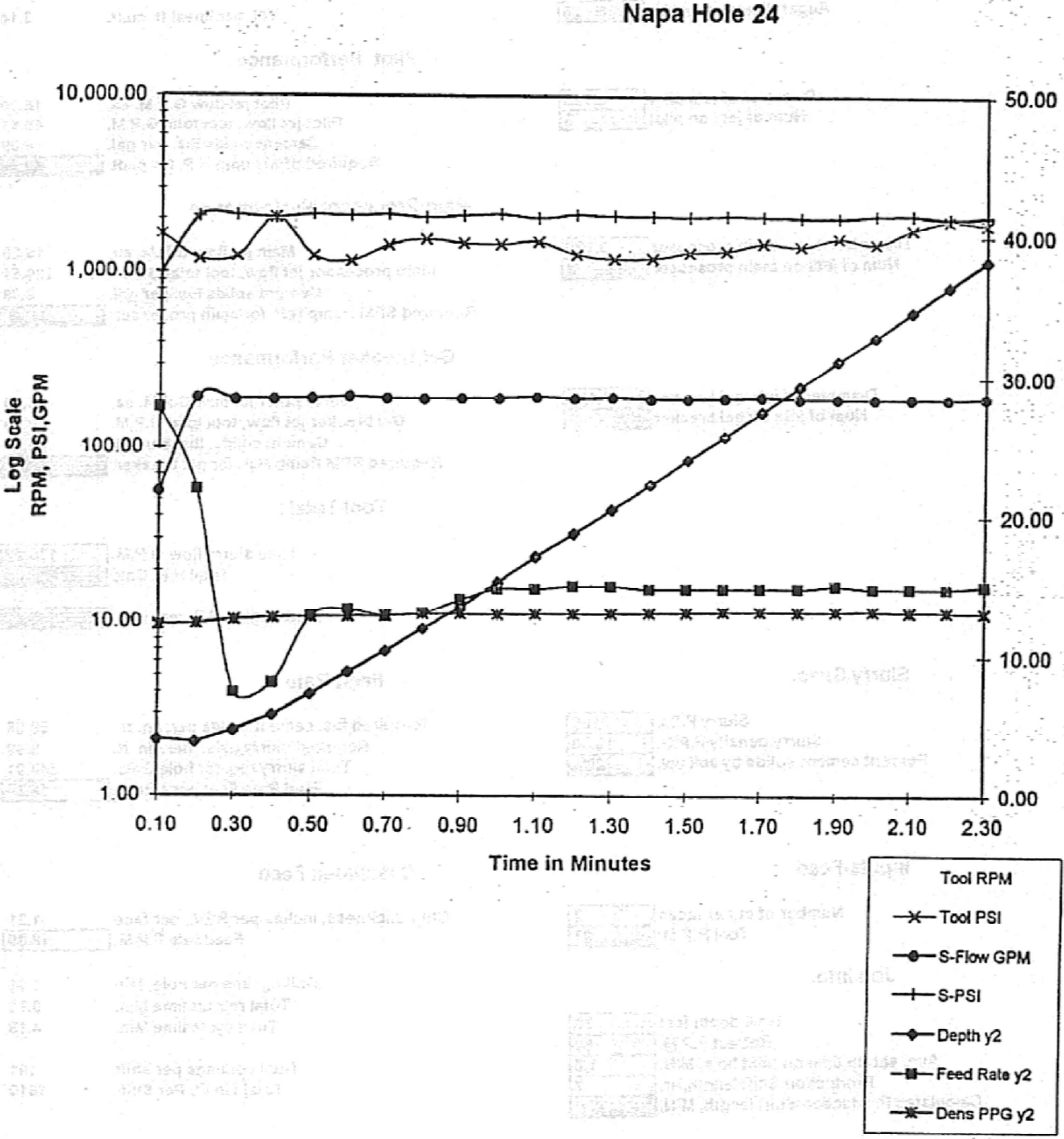

Figure 95. Verification documentation – drilling parameters versus time (Johnson, 1999).

Hydra-Mech^{SM} (21)

1. INTRODUCTION

This technique is classified as WJE and involves a combination of mechanical mixing and hydraulic jetting to form an enlarged column. Development of this method was undertaken during construction of a test wall by DSM methods at the National Geotechnical Experimentation Test Site in College Station, TX.

2. GENERAL PROCESS

Drilling is performed to the bottom of the hole using water, bentonite, or other drill fluid. Mixing commences at the bottom of the hole. Grout is introduced through the shaft at low pressure, and simultaneously, high-pressure grout (400 bar) is injected through nozzles at the outer edge of the mixing tool. The mechanical mixing and low-pressure grout injection create a mixed column equal in diameter to the mixing tool. The high-pressure cement expands the diameter of the column. At the bottom, the shaft is cycled three times through a 6-m-long "enlarged zone" (Figure 96). Mechanical mixing occurs smoothly in the center of the column, and chunks of material are forced to the perimeter, where disaggregation occurs by the jets. Treatment with the high-pressure jets can be switched on and off throughout the depth of the column to create plugs of treated soil (Figure 97).

3. EQUIPMENT

<u>Base</u>	110-tonne crane with a top rotary head or table-mounted rotary drive.
<u>Shafts</u>	This technique employs a single shaft, fitted with 1.2-m-diameter paddles and a 0.9-m-diameter auger. Eight 2-mm "hydra nozzles" are located on the outer edges of the mixing tool.
<u>Grout Plant</u>	3.8-m^3 lightning mixer fed from silos with weight-batching control. Progressive-cavity, low-pressure pumps (DMM) and triplex pumps (jetting).
<u>Control</u>	Computer-controlled grout delivery system.
<u>Production</u>	Industrial productivities of 200 to 500 m^3 per shift are feasible.

4. MIX CHARACTERISTICS

<u>Grout</u>. The same cement slurry is used for the mechanical mixing and the hydraulic jetting. A cement slurry with a water/cement ratio of 1.0 to 1.75 is used.

Treated Soil. The cement factor used in the test wall was 100 to 120 kg/m^3. Unconfined compression strengths of core samples obtained from this test wall were on the order of 2.8 MPa. Visual observations showed very efficient mixing of slurry and soil.

5. PATENTED/PROTECTED FEATURES

The system has been protected by Geo-Con, Inc.

6. PARTICULAR ADVANTAGES

Hydraulic expansion of the mechanically mixed section allows column sizes to be increased 0.6 to 1.2 m beyond the auger size. Hydraulic jetting results in very homogeneous mixing, and allows intimate inter-column contact. Fast introduction of grout results in faster mixing and therefore costs that are two to three times lower than jet grouting. No compressed air is used in this system.

7. OPERATING COMPANY

Geo-Con, Inc. is based in the United States, with offices in CA, FL, NJ, PA, and TX. Geo-Con operates within the United States, but has international capability.

8. REFERENCES

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Nicholson, P.J. and B.H. Jasperse. (1998). "Hydraulic and Mechanical Cement Soil Mixing." Deep Mixing Methods short course presented by the University of Milwaukee-Wisconsin, Milwaukee, WI, August 27-28.

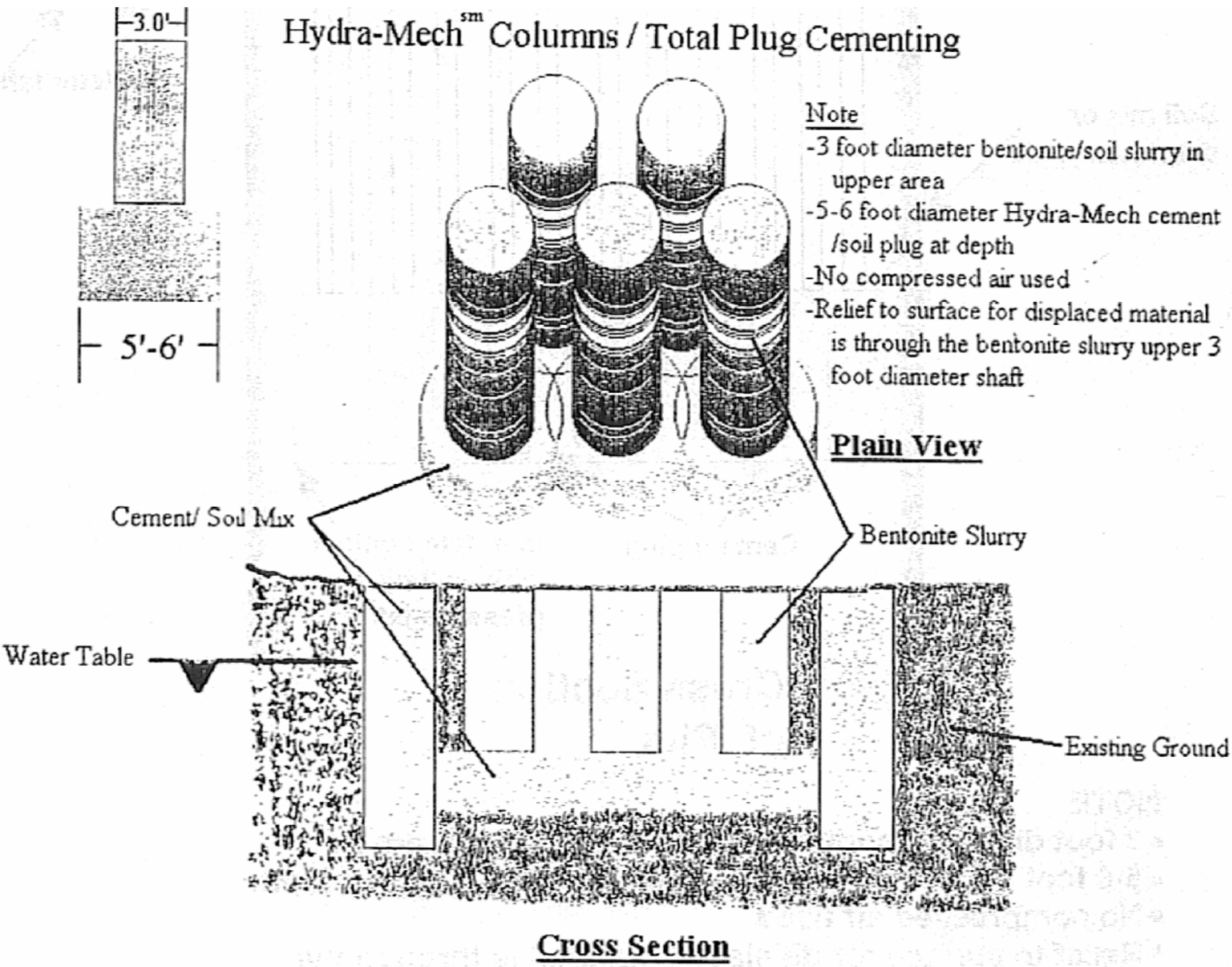
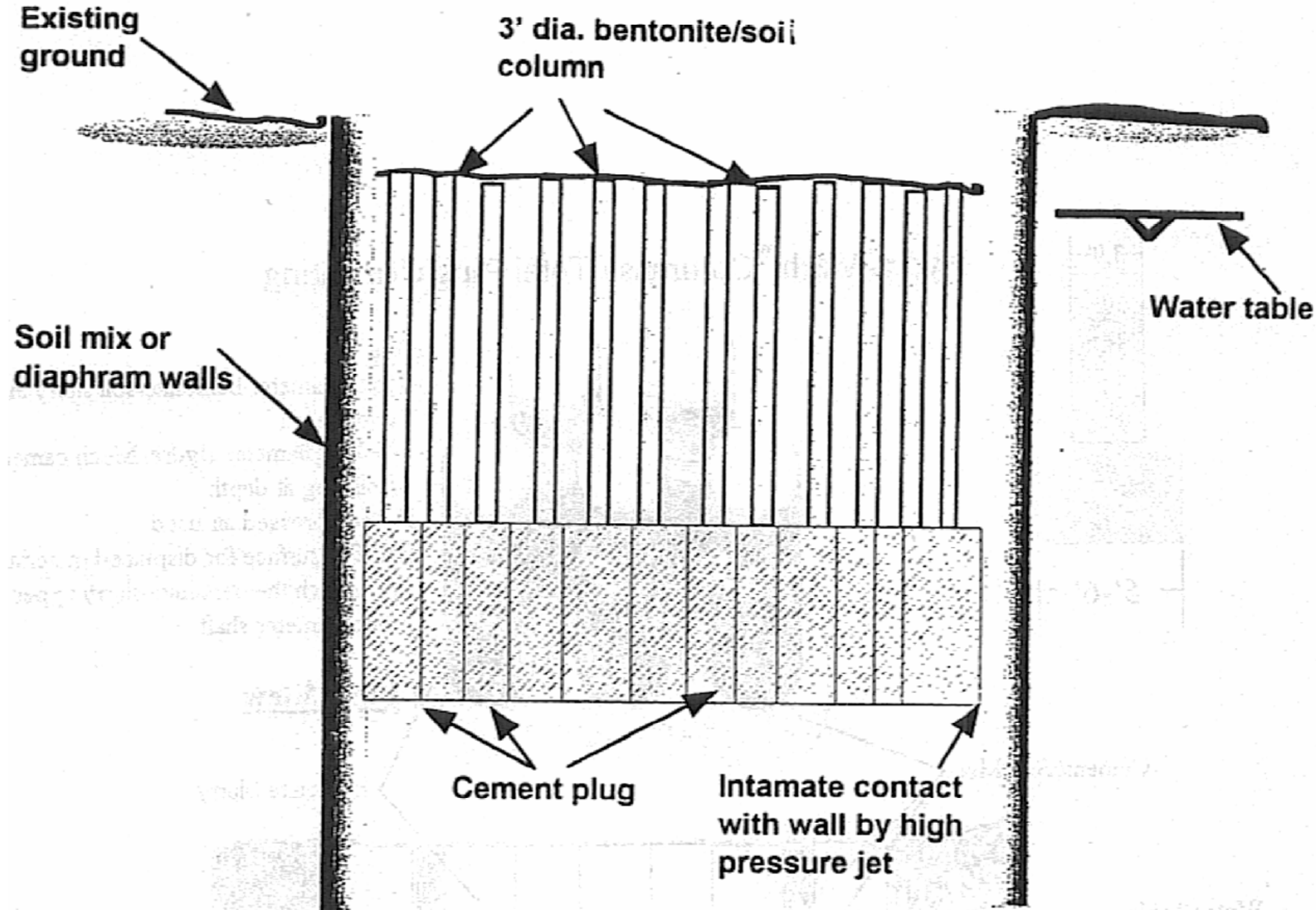


Figure 96. Total plug cementing using Hydra-Mech^{SM} (Geo-Con, Inc., 1998).



Cross Section of Pits

NOTE

- 3 foot diameter bentonite/soil slurry in upper area
- 5-6 foot diameter Hydra-Mech$_{m}$ cement/soil plug at depth
- No compressed air used
- Relief to surface for displaced material is through the bentonite slurry upper 3 foot diameter shaft

Figure 97. Creation of impervious plugs using Hydra-Mech^{SM} (Geo-Con, Inc., 1998).

DRY JET MIXING – DJM (22)

1. INTRODUCTION

The Dry Jet Mixing method, as practiced by numerous major contractors within the DJM Association in Japan (Attachment 1), is classified as DRE. It is a method of soil treatment whereby cement or other dry, powdered material is blended pneumatically with soft soil of high moisture content. The introduced binder chemically reacts with the soil, producing a stronger, more stable material. In general, less cement is added per volume of treated soil than in Deep Mixing methods that use slurry. Considering this and the fact that the binder is dry, much less spoil is created than by wet methods. It is used only on land-based projects. The technique was developed by the Construction Ministry of Japan from 1977 to 1979 in an integrated technical development project known as "Development of New Soil Stabilization Techniques" and was operational by 1981. There are about 60 to 70 rigs of various types currently active in Japan. It is most frequently used to treat liquefiable sands, organic soils, peats, and very soft silts or clays with water content in excess of 100%, below or close to the water table.

2. GENERAL PROCESS

The general process (Figure 98) involves penetrating the soil with the rotating mixing shaft at 24 to 32 rpm using compressed air to prevent choking of the jet nozzles. Some binder may be injected during penetration. Upon reaching the bottom of the hole, the unit is counter-rotated at up to 64 rpm and withdrawn while dry materials are injected under compressed air from nozzles located in the upper mixing blade (Figure 99). Usually, two shafts are used, each with two or three pairs of blades. The shape of the mixing blades is such that a cavity is created beneath the blade during rotation. As the blade turns, the air pressure drops within this cavity, into which dry reagent is therefore deposited. The compressed air used to carry the dry materials passes upward along the shaft and is vented through a valve in the particle collection shroud located at the ground surface.

3. EQUIPMENT (Tables 8 and 9 and Figure 100)

Base — The base equipment comprises custom-built, crawler-mounted, or (rarely) skid-mounted cranes. The rotation motors and gear boxes are permanently located near the base of the rig, thus lowering the center of gravity and improving stability when tracking on unleveled ground.

Shafts — The mixing system (one or two shafts) consists of the drive unit, the drive shaft, the cutting and mixing blade, and grout nozzles. The mixing unit is composed of two or three pairs of blades mounted on each of the shafts. The blades have a narrow profile and do not develop any soil-auguring action. The standard blade is 1 m in diameter, and the maximum depth is 33 m. The spacing of the mixing units on the dual-mixer models can be 0.8, 1, 1.2, or 1.5 m and the maximum

	depth capacity is 33 m. The heavy rotation motors and gear boxes always remain at the bottom of the mast thus, promoting mechanical stability during all phases of construction.
Binder Plant	The plant supplying the binder consists of material storage silos, an agent delivery system, a generator, and an air compressor.
Control	Advanced automatic monitoring gives continuous and accurate records of the construction depth, rpm, penetration and withdrawal rates, and volume of binder.
Production	Typically, 50 to 55 min are required to install a 9-m column, allowing 6 to 8 min to detach/add rods. Productivity is 35% to 40% lower in low headroom conditions. Instantaneous penetration is 0.5 m/min, and 3.0 m/min during withdrawal.

4. MIX DESIGN CHARACTERISTICS

Injected Materials. Reagent used depends on properties of soil to be treated and the purpose of the treatment. Binder particle size is less than 5 mm. Cement, cement-based reagent, slag cement, and lime are most frequently used (90% of all applica-tions), followed by slag, flyash, and gypsum (Figure 101). Quicklime is used in marine clays with very high water content; cement factors can be adjusted between strata and vary as follows:

- Cement: 100 to 400 kg/m^3 for in situ sand and fine-grained soil
  200 to 600 kg/m^3 for peats and organics
- Lime: 50 to 300 kg/m^3 for soft marine clay soils

Cement-based reagents are effective for treating most types of soils, including peat and organic soils.

Treated Soil. The amount of binder introduced depends on the soil conditions and desired properties of the treated soil. Unconfined compressive strengths range typically from 2 to 20 MPa (see CDM for general properties). The ratio of 28-day to 7-day strengths is about 1.5 (Figure 102). Strength gain in DJM is faster than for slurry methods. The shear strength ranges from 1 to 6 MPa, which is approx-imately 2.0 to 3.4 times less than the UCS (Figure 103). The tensile strength is 10% to 20% UCS, with this ratio decreasing as UCS increases (Figure 104). Modulus of elasticity (E_{50}) ranges from 50 to 200 times q_u (Figure 105). Permeability data are not available, although Yang et al. (1998) note that the permeability of DJM-treated ground is higher than that produced by slurry methods, and may be "considered semi-permeable."

In appropriate conditions, the efficiency of mixing is high. For highly plastic cohesives, lumps will remain. The system produces little spoil.

5. PATENTED/PROTECTED FEATURES

There are two basic patents (presumably on the blade depth and on the electronic control systems) and many supplementary patents.

6. PARTICULAR ADVANTAGES

Many kinds of solid agents can be used, and the amount of construction materials needed at the site is reduced. The "closed system" of transport and injection results in little dust, and soils can be stabilized without producing waste. The method provides high mixing efficiency, uniform quality, and higher early strength. Binder dosage can be varied depending on soil, and cement dosage can be controlled reliably, at different depths, without affecting productivity. The operation is automated and therefore controlled and verified reliably. The work site is clean since water is not used, and no human handling of materials is needed. The system produces low noise, low vibration, and no heaving. A single-shaft machine has been developed (DJM1070E) for use in relatively low head conditions, and all machines are relatively mobile. The equipment can work in soft ground without stability concerns or further settlement or damage to sensitive soil.

Experience since 1980 includes 1.845 million m^3 of treated ground per year in almost 300 jobs, with a total of 15.9 million m^3 in 2,345 jobs by the end of 1995.

7. OPERATING COMPANIES

The DJM technique is operated by a collection of Japanese contractors who are members of the DJM trade association. They operate in Japan. (See Figure 106 for annual output.) The most recent DJM manual notes 64 members with about the same number of drill rigs available. Since 1998, this system has been offered in the United States by Raito, Inc.

8. REFERENCES

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Table 8. Specification of DJM equipment (DJM brochure, 1996).

	機種 Type	DJM1070	DJM2070	DJM2070L	DJM2090	DJM2090L	DJM2110
改良機本体 Mixing machine	撹拌軸数 Number of shaft	1 本	2 本		2 本		2 本
	軸間距離 mm Distance of shaft	–	1,000 1,200 1,500		1,000 1,200 1,500		1,000 1,200 1,500
	標準撹拌翼径 mm Diameter of standard blade	1,000	1,000		1,000		1,000
	最大貫入深度 m Maximum working depth	20	23	26	30	33	33
	撹拌軸回転速度 rpm Rotating speed of blade	5～50	21, 48(50Hz)		32, 64(50Hz)		32, 64(50Hz)
	撹拌軸最大トルク kgf-m (KN-m) Maximum torque	2,000 (19.6)	2,000 (連続定格) (19.6)		2,520 (連続定格) (21.7)		3,080 (連続定格) (30.2)
	貫入引抜速度 m/min Velocity of penetration or withdrawal	0～7.0	0.5～3.0		0.5～3.0		0.5～3.0
	原動機～駆動方式 Rotating method	電動機・油圧 Electric motor～hydraulic motor	走行、昇降：ディーゼル・油圧 Moving, up down: Engine～hydraulic motor 撹拌：電動機 Rotating: Electric motor		走行、昇降：ディーゼル・油圧 Moving, up down: Engine～hydraulic motor 撹拌：電動機 Rotating: Electric motor		走行、昇降：ディーゼル・油圧 Moving, up down: Engine～hydraulic motor 撹拌：電動機 Rotating: Electric motor
	原動機出力 Out put	75kW	ディーゼル：130PS (114kW) Engine: 電動機：55kW×2台 Electric motor:		ディーゼル：130PS (114kW) Engine: 電動機：90kW×2台 Electric motor:		ディーゼル：130PS (114kW) Engine: 電動機：110kW×2台 Electric motor:
	走行形式 Moving method	スキッド油圧式 Skid type	クローラ式 Crawler type		クローラ式 Crawler type		クローラ式 Crawler type
	全装備重量 kgf Total weight	21,000	67,900	70,000	85,300	90,000	92,800
	接地圧 kgf/cm² Contact ground pressure (KPa)	0.24 (23.5)	0.81 (79.4)	0.83 (81.3)	0.98 (96.0)	1.03 (100.9)	1.06 (103.9)
プラント改良材 Agent handling plant	改良材供給機 Agent feeder	2.0m³×1台	2.0m³×2台		2.0m³×2台		3.5m³×2台
	施工管理計器 Control machine	1式	1式		1式		1式
	改良材サイロ Agent silo	30t 1基	30t 1基		30t 1基		30t 1基
	空気除湿機 Air drier	2.2kW×1台	2.2kW×2台		2.2kW×2台		2.2kW×2台
	レシーバタンク Air tank	4m³×1台	4m³×2台		4m³×2台		4m³×2台
付属機器 Others	空気圧縮機 Air compressor	7kgf/cm² (686KPa) 10.5m³/min ×1台	7kgf/cm² (686KPa) 10.5m³/min ×2台	7kgf/cm² (686KPa) 10.5(17.0*)m³/min ×2台	7kgf/cm² (686KPa)** 17.0m³/min ×2台		7kgf/cm² (686KPa)** 17.0m³/min ×2台
	発動発電機 Generator	125kVA×1台 60kVA×1台	300kVA×1台 60kVA×1台		350kVA×1台 60kVA×1台		500kVA×1台 60kVA×1台
	バックホウ Back hoe	0.6m³×1台	0.6m³×1台		0.6m³×1台		0.6m³×1台
	ホイールクレーン Wheel crane	油圧式 4.8t吊 ×1台	油圧式 4.8t吊 ×1台		油圧式 4.8t吊 ×1台		油圧式 4.8t吊 ×1台
	敷鉄板 mm Iron plate	1,500×6,000×22 ×15枚	1,500×6,000×22 ×50枚		1,500×6,000×22 ×50枚		1,500×6,000×22 ×50枚

*：( )内数値は最大深度23mを超える場合について適用

**：土性等によっては高圧空気圧縮機を必要とする。

Table 9. Characteristics of dry agent handling plant (DJM brochure, 1996).

	機　種 Type	DJM1070	DJM2070, 2070L	DJM2090, 2090L	DJM2110
供給機 Agent feeder	有効貯蔵量 m³ Stored volume	2	2 × 2 台	2 × 2 台	3.5 × 2 台
	供給能力 kg/min Feeding ability	25 ~ 120	(25 ~ 120) × 2	(25 ~ 120) × 2	(25 ~ 120) × 2
	空気消費量 Nm³/min Consuming air volume	2 ~ 9	(2 ~ 9) × 2	(2 ~ 9) × 2	(2 ~ 9) × 2
	最大使用空気圧 kgf/cm² Maximum compressed (KPa) air pressure	7.0 (686)	7.0 (686)	9.8 (960)	9.8 (960)
	寸法 mm (全長×全幅×全高) Size (L×W×H)	2,400×1,800×3,650	4,400×2,500×3,650	4,400×2,500×3,650	5,185×2,555×4,980
	全体重量 kg Total weight	3,000	5,100	5,600	6,500
サイロ Agent silo	貯蔵量 ton Stored weight	30	30	30	30
	寸法 mm (全長×全幅×全高) Size (L×W×H)	6,500×2,500×2,600	7,000×2,500×2,600 (但しスクリュコンベアは含まず)	7,000×2,500×2,600 (但しスクリュコンベアは含まず)	7,000×2,500×4,175 (但しスクリュコンベアは含まず)
	全体重量 kg Total weight	7,500	8,000	8,000	8,200

(注) 記載の仕様は改善のため予告なく変更することもあります。

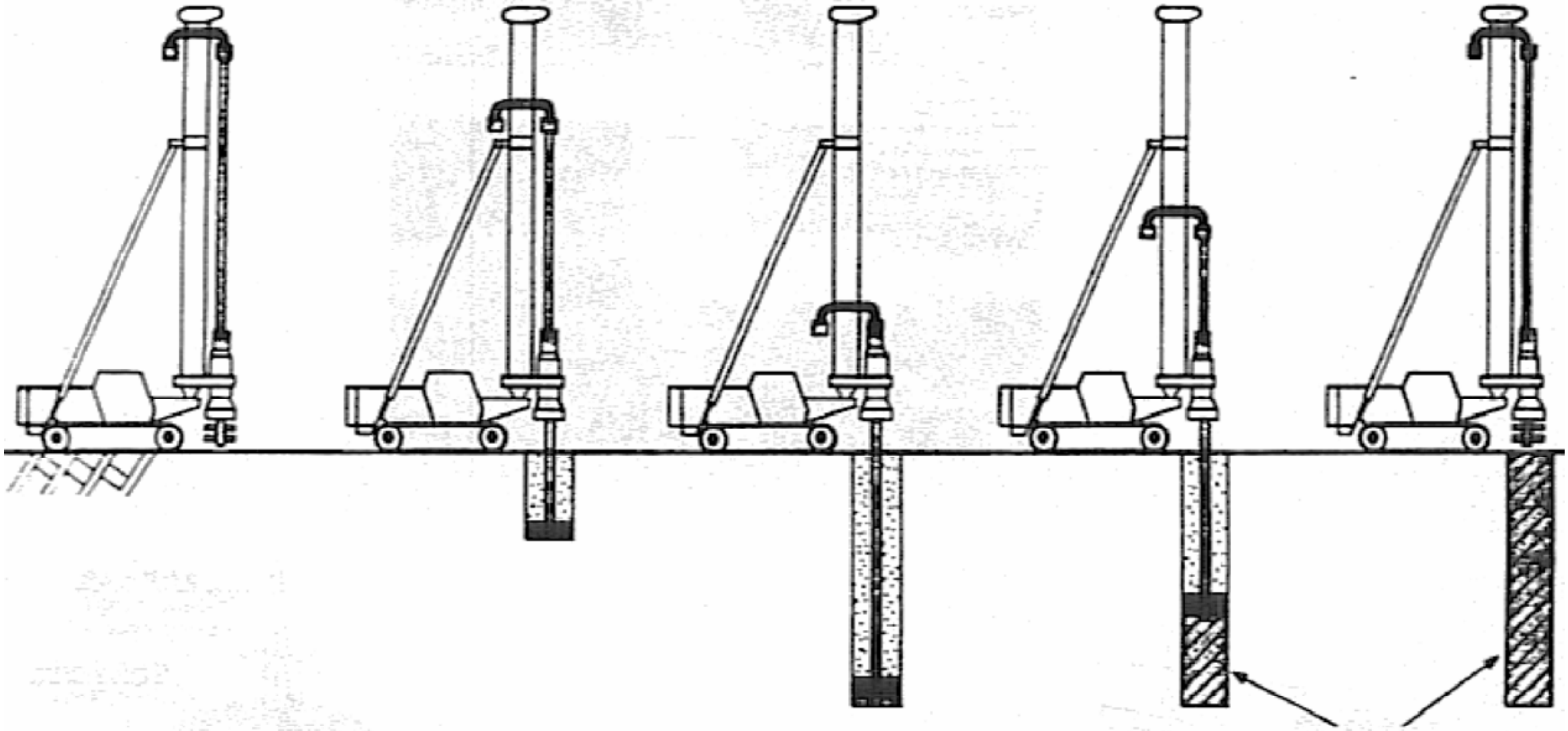
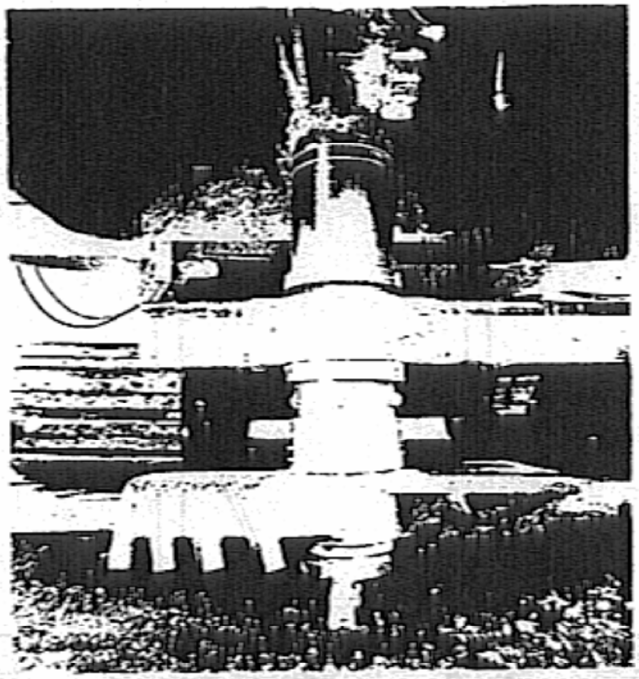


Figure 98. Concept of installation (DJM brochure, 1996).



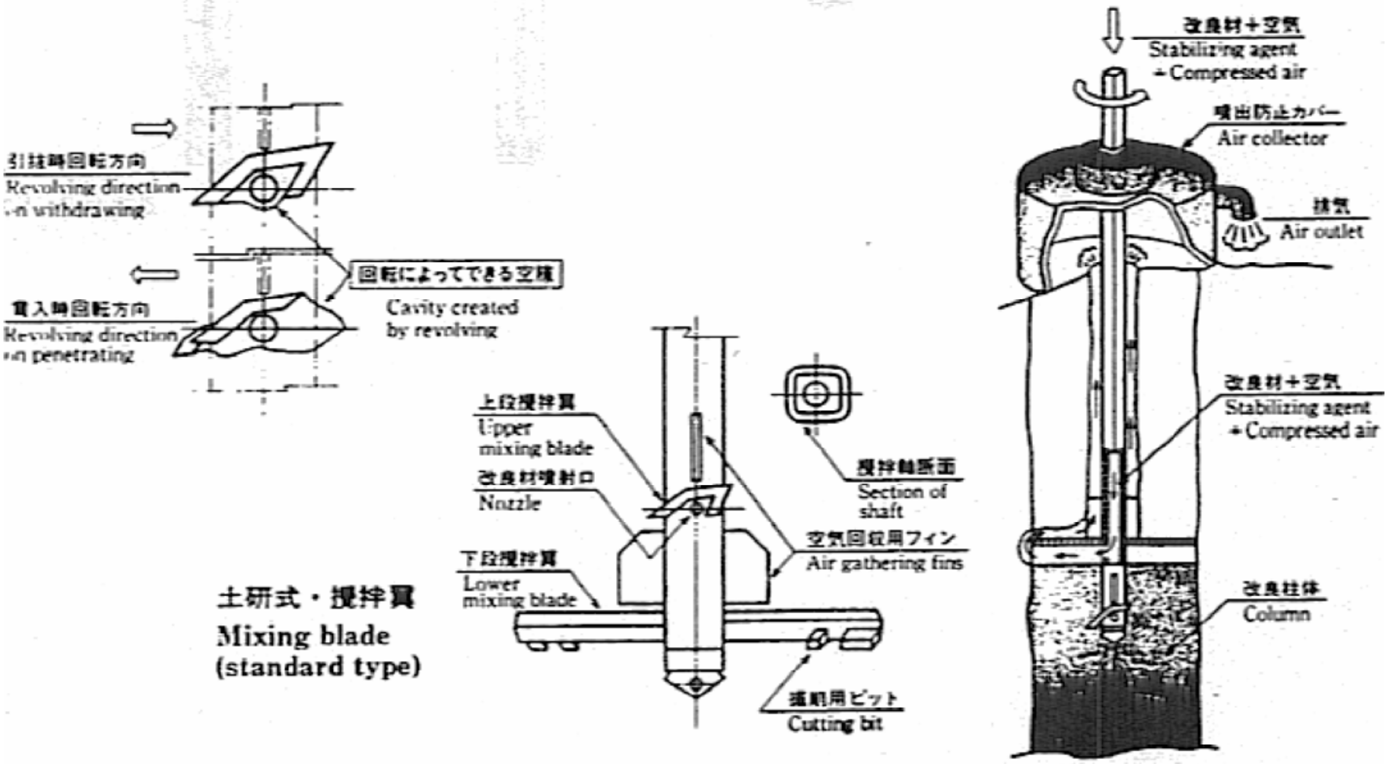


Figure 99. Details of mixing blade (DJM brochure, 1996).

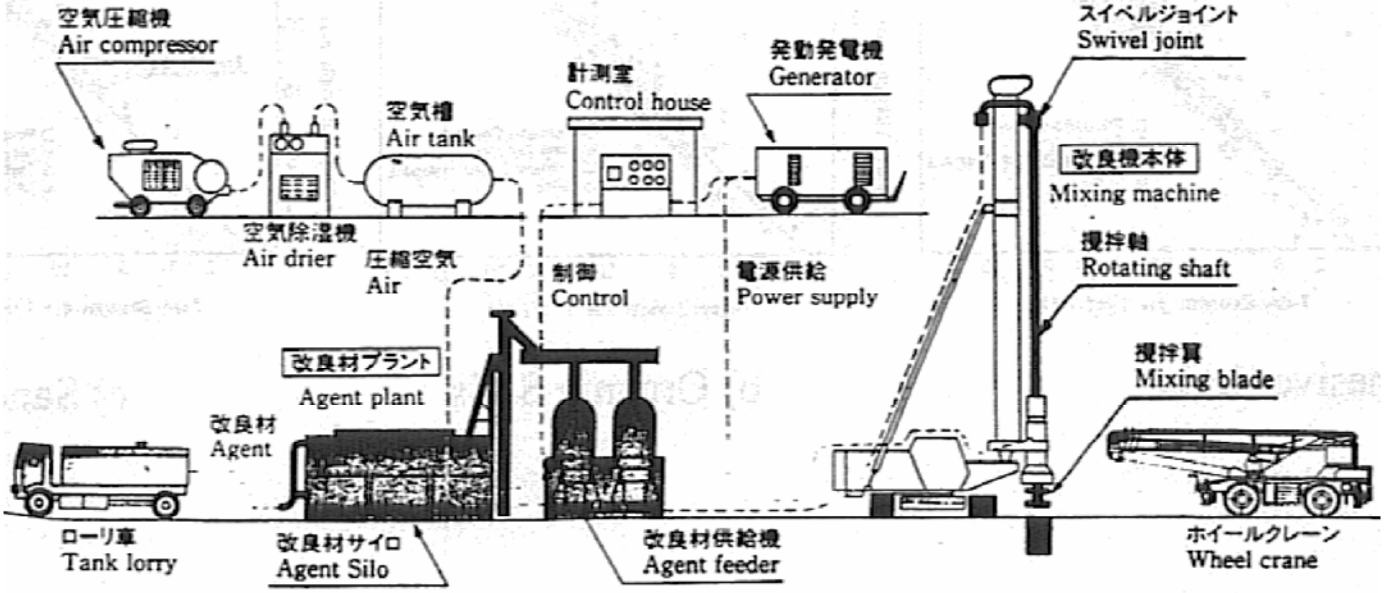


Figure 100. Details of DJM equipment (DJM brochure, 1996).

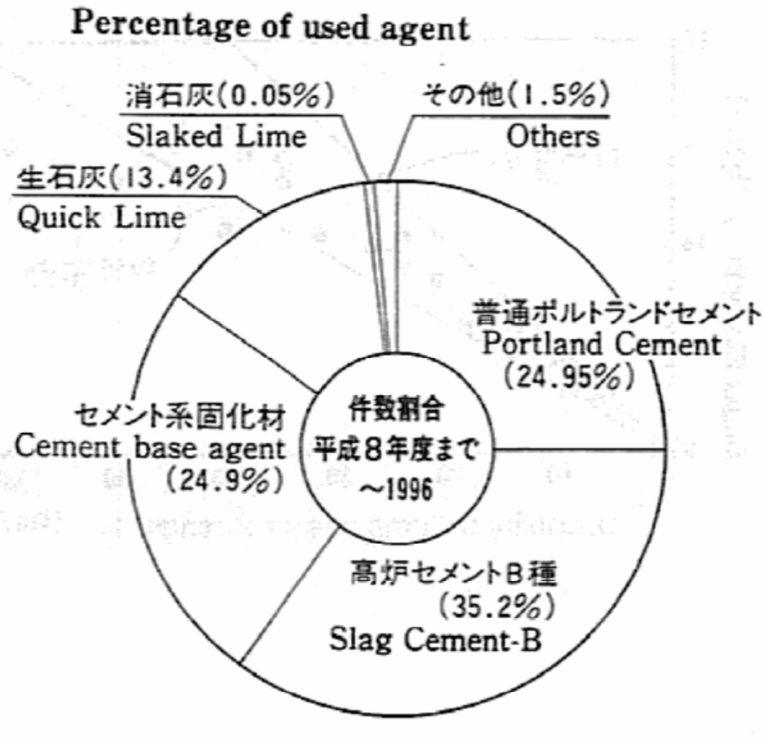


Figure 101. Types and quantities of dry agents used (DJM brochure, 1996).

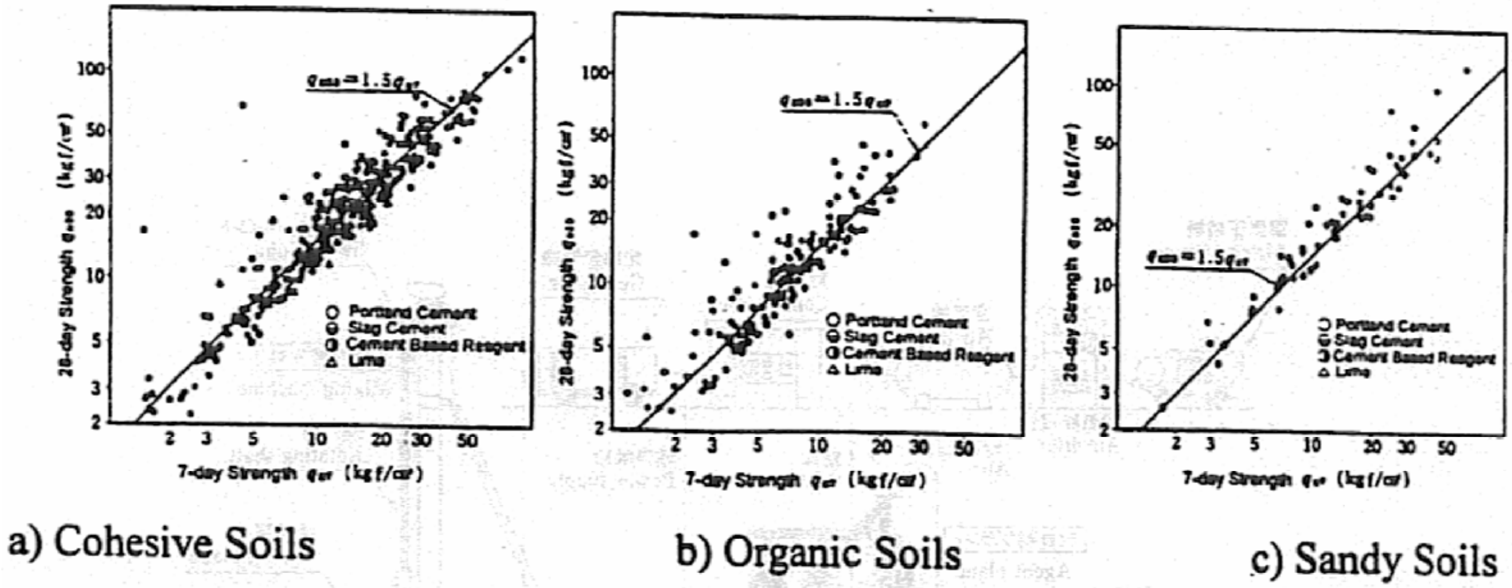


Figure 102. Relationship between 7-day and 28-day strengths (after DJM Association, 1993).

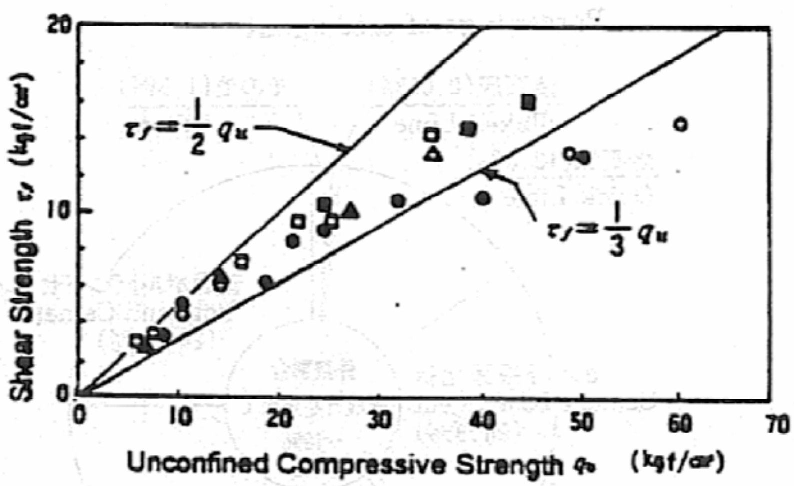


Figure 103. Relationship between shear strength and unconfined compressive strength (after DJM Association, 1993).

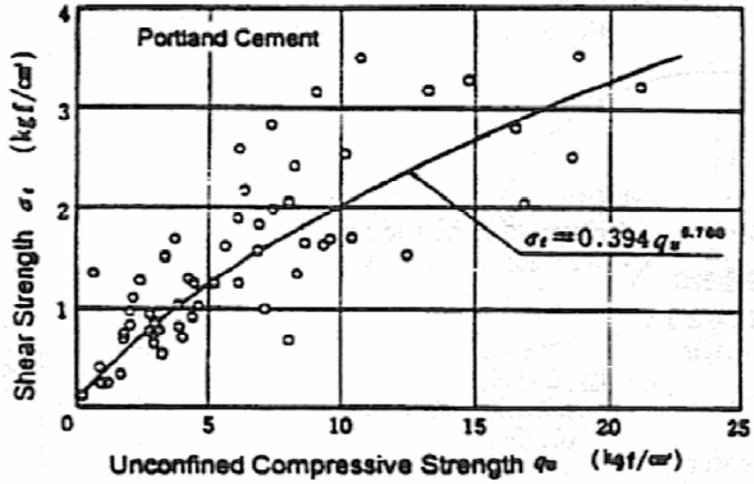
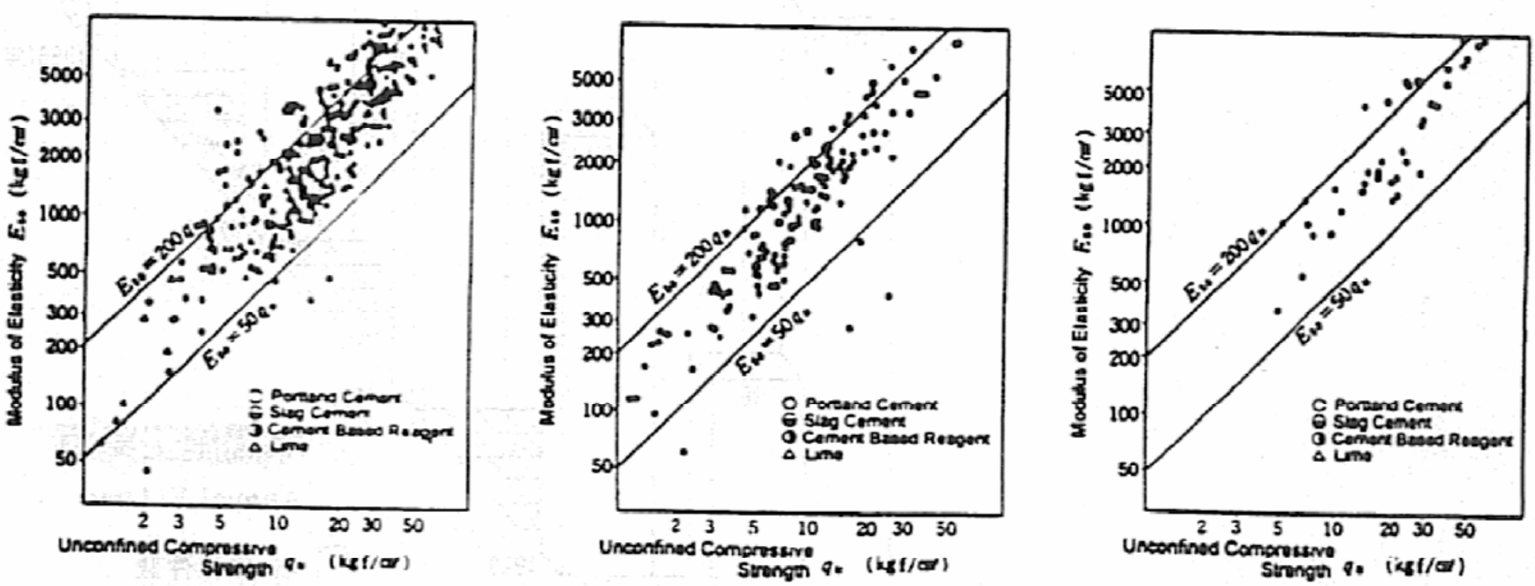


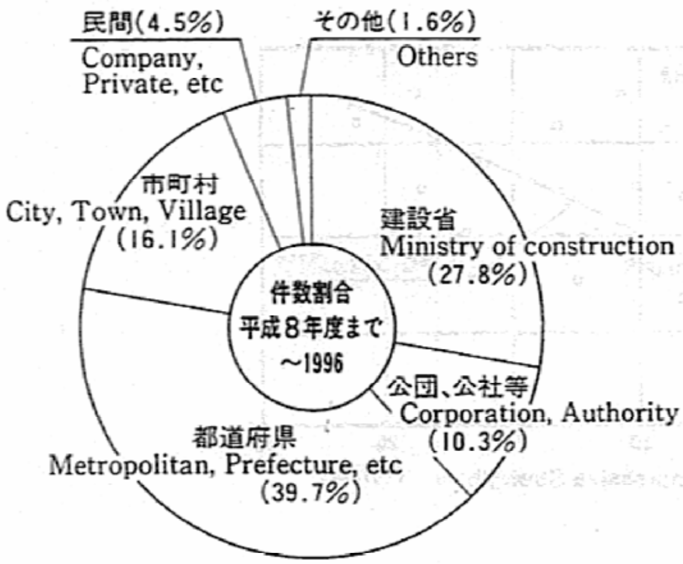
Figure 104. Relationship between tensile strength and unconfined compressive strength (after DJM Association, 1993).



a) Cohesive Soils b) Organic Soils c) Sandy Soils

Figure 105. Relationship between E_{50} and unconfined compressive strength (after DJM Association, 1993).

Percentage of owner or employer



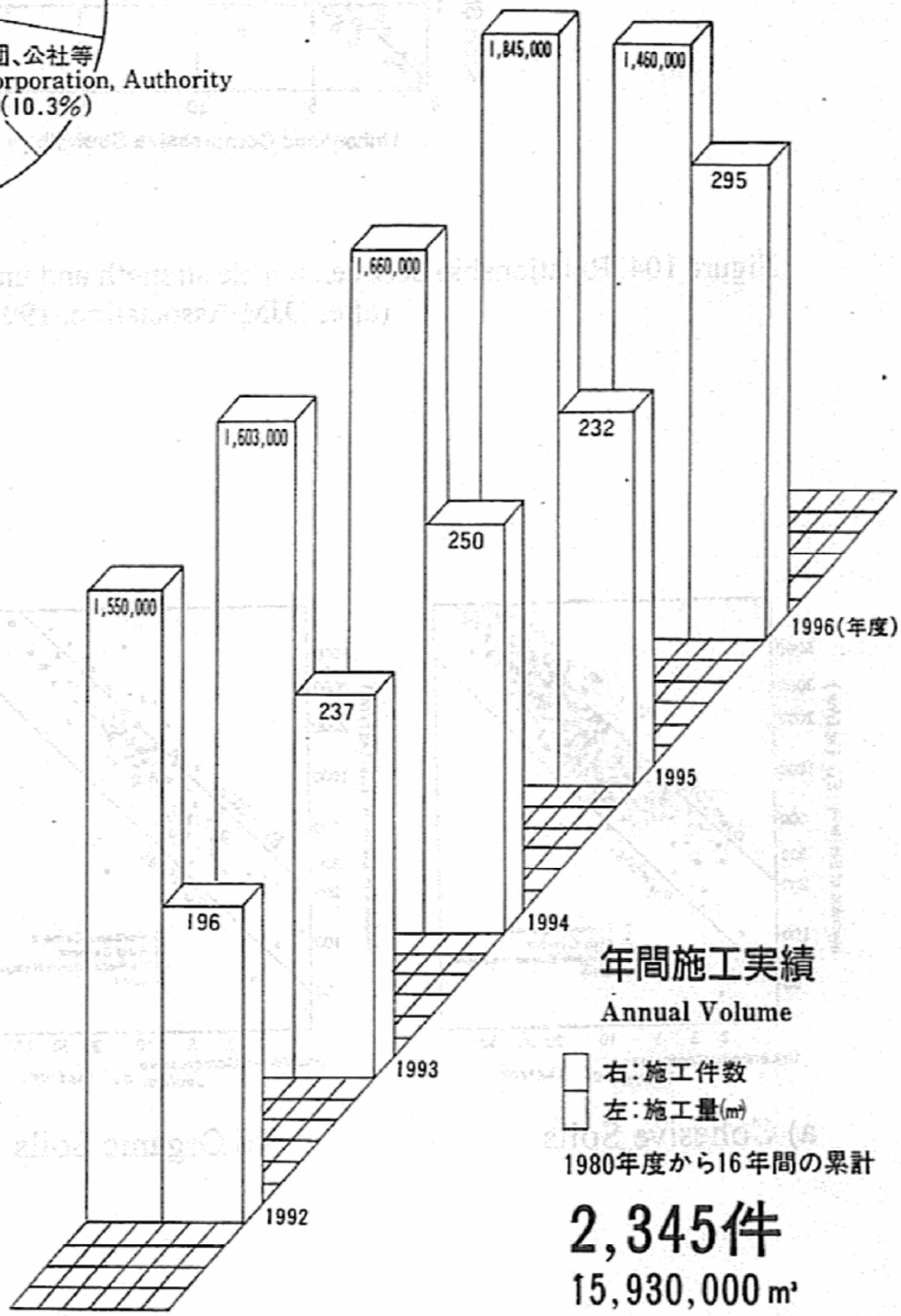
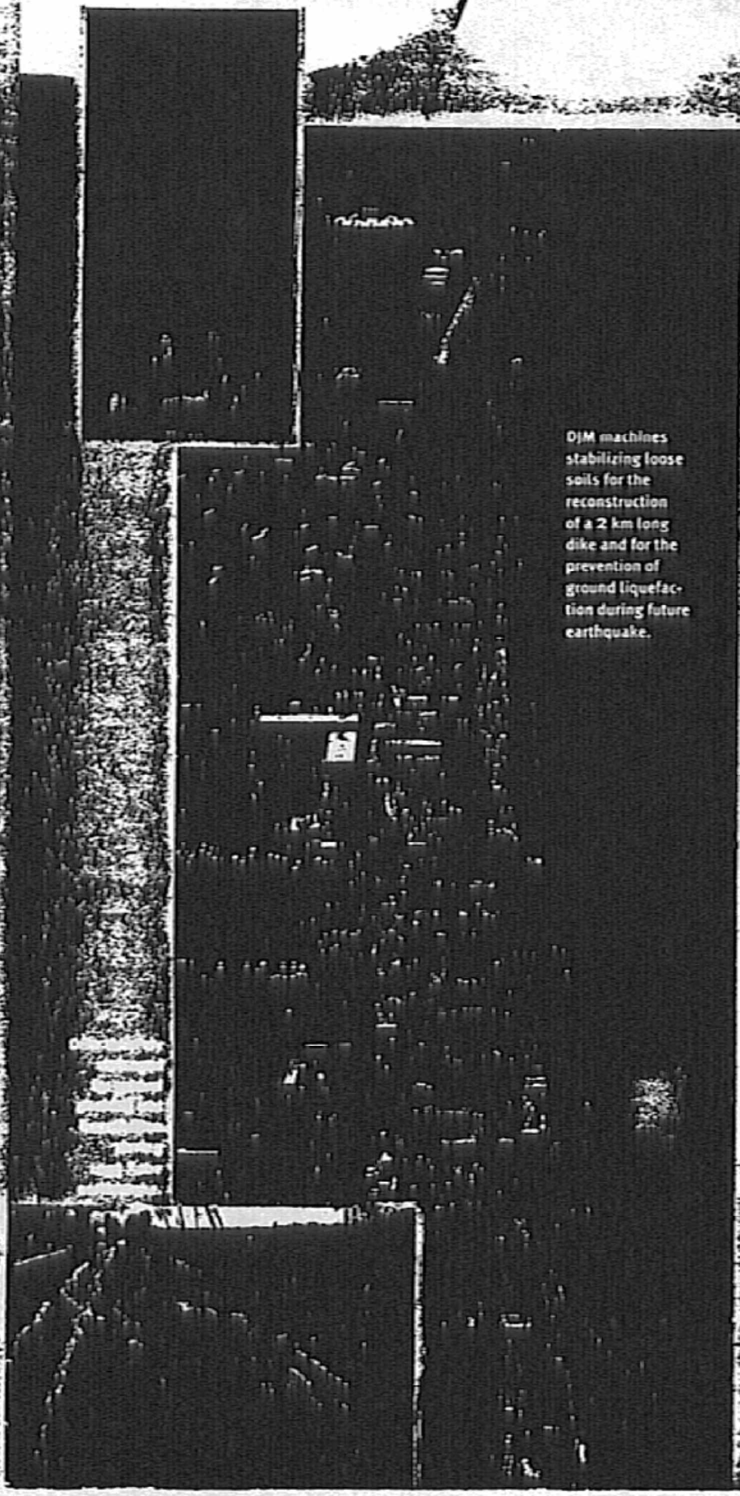


Figure 106. Annual output of DJM (DJM brochure, 1996).

Attachment 7. DJM brochure.

DJM SYSTEM



DJM machines stabilizing loose soils for the reconstruction of a 2 km long dike and for the prevention of ground liquefaction during future earthquake.

Dry Jet Mixing Method [illegible]

1. [illegible]
Dry Jet Mixing (DJM) uses mixing blades [illegible] reagents, such as cement or lime, with [illegible] increase the strength and reduce the [illegible] of soft ground.

2. [illegible]
In addition to cement and lime, other [illegible] particles with sizes less than 1 mm can be used. [illegible] and quantity of reagent used are dependent [illegible] properties and purposes of soil treatment.

3. [illegible]
The mixing action of the blades creates an even distribution of reagent in the soil. According to the soil [illegible] the reagent dosage can be adjusted to different soil [illegible]

4. [illegible]
DJM employs a highly advanced automatic [illegible] system which provides continuous and accurate [illegible] of the soil mixing depth, penetration and withdrawal speeds, blade rotation speed, and reagent injection [illegible]

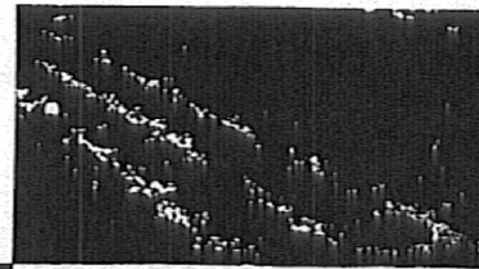
5. [illegible]
DJM does not need water for slurry preparation. [illegible] without water keeps the site clean and also [illegible] the quantity of construction spoils.

6. [illegible]
DJM uses a closed system to transport and [illegible] into the soil. Thus, little dust is introduced into the air. The operation is safe and creates a minimal amount of [illegible] and ground vibration.

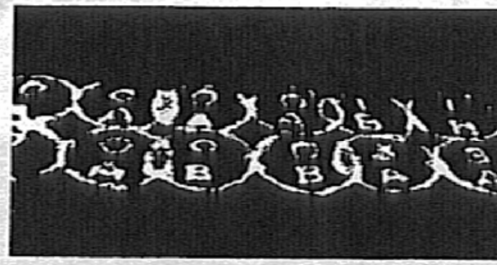
7. [illegible]
The mixing machine used is mobile [illegible] to the next soil mixing location [illegible] is automatic which [illegible] efficiency.

ARaito

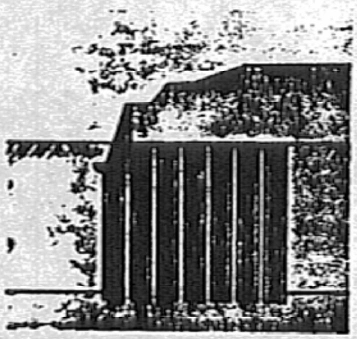
PRODUCTS



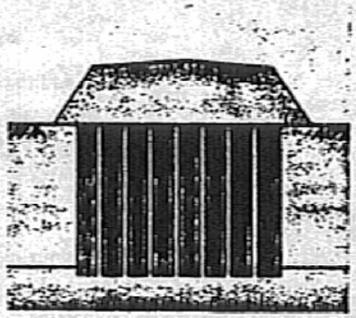
DJM soil-cement columns



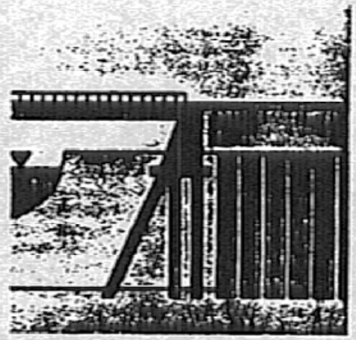
DJM soil-cement panel



Prevention of slope failure for high embankment

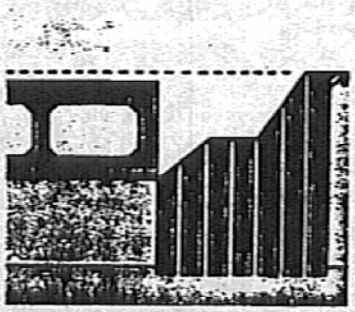


Prevention of slide failure for embankment and reduction of settlement

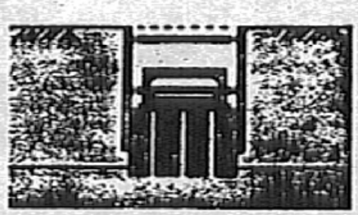


Prevention of slide failure for abutment and reduction of settlement for embankment

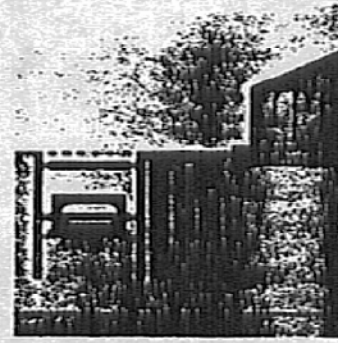
APPLICATIONS



Stability of excavated slope



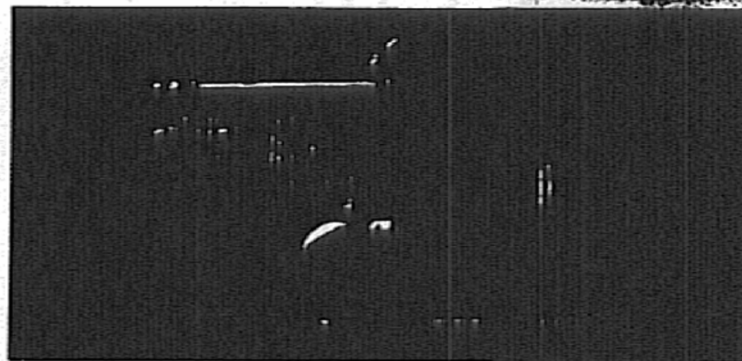
Reduction of settlement for underground structure



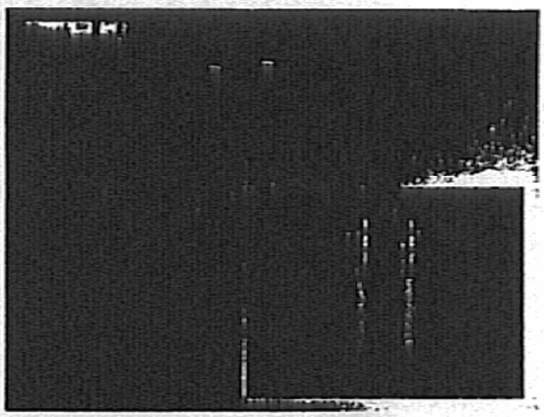
Prevention of adverse effects to adjacent structure

Raito

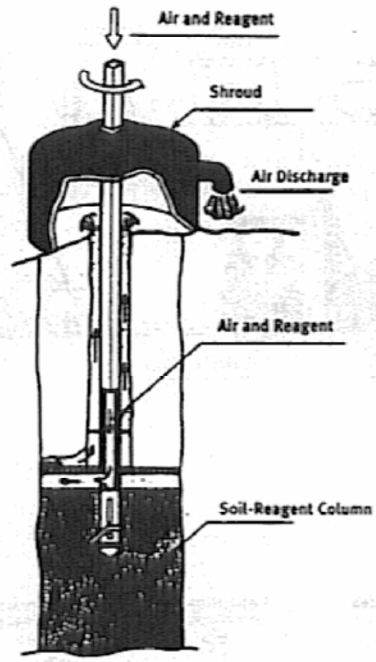
REAGENT SUPPLY & SOIL MIXING



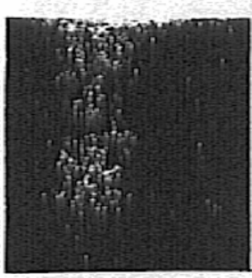
Reagent feeder and silo

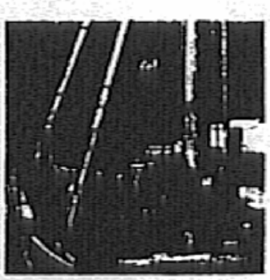


In situ soil mixing



Reagent delivery and mixing



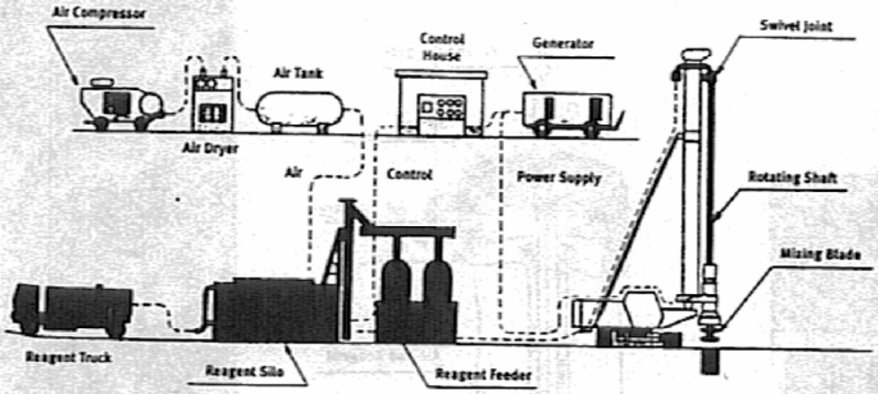


River bank ground reinforcement

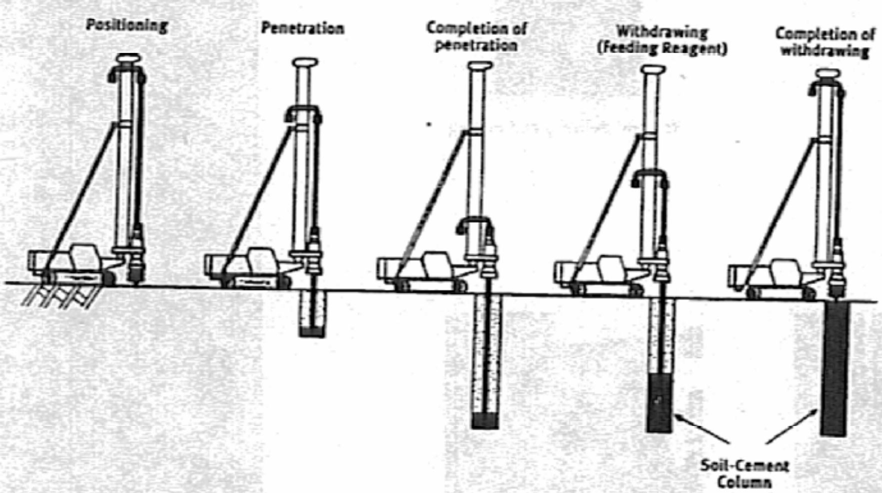
Soil improvement behind bridge abutment

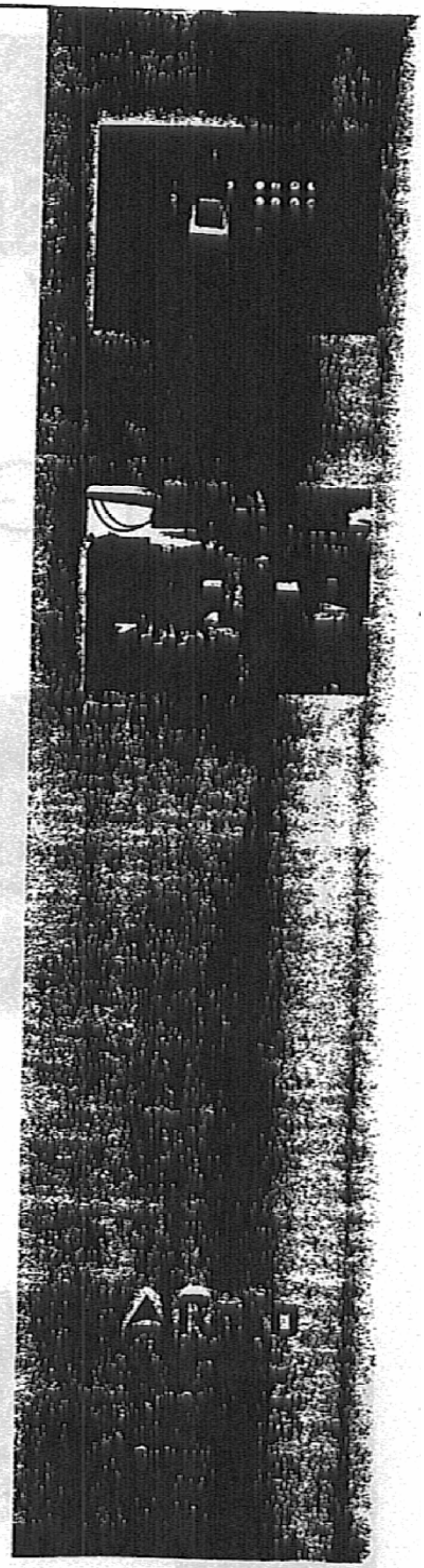
DJM SYSTEM & WORKING PROCEDURE

Line-Up of DJM System



Working Procedure





NORDIC LIME – CEMENT COLUMN METHOD (23)

1. INTRODUCTION

This method is undertaken by a number of large Swedish and Finnish contractors, both in Scandinavia and elsewhere. It is one of the oldest and best researched Deep Mixing Methods, used primarily (90% of the applications) to install treated ground columns in soft cohesive and/or organic deposits to reduce settlement and improve stability. It is classified as DRE since dry materials (principally a cement and unslaked (quick) lime) are blown into the soil during extraction of a rotated tool that mixes the soil only at the tip, as shown in Figure 107.

In its earliest days (dating from laboratory research in 1967 and field research in 1974), only quicklime was added to treat 500-mm-diameter columns to 10 m depth in soils generally finer than in Japan. The exothermic reaction of $CaO + H_2O = Ca(OH)_2$ is stable in the long term where the soil pH is 5 or more and a surplus of calcium ions exists. (There is history of 25 years without signs of decay.) However, in recent years, there have been major advances in equipment (mainly due to the Finnish contractor, YIT, and the Swedish contractor, Stabilator Attachment 1), and in materials (use of cement with the lime), so that now virtually all applications use lime-cement in various percentages (Figures 108 and 109).

Unlike in Japan, where original research into the use of quicklime was soon overcome by the use of CDM and DJM methods, largely cement-based, the cost of lime in Scandinavia is generally lower than that of cement, and the high-humidity problems inherent in Southeast Asia are not encountered.

2. GENERAL PROCESS

The crawler-mounted, self-contained rig (Figure 110) rotates a tool (Figure 111) to target depth (typically ≤ 25 m) at 100 to 200 rpm (typically 130 to 170 rpm). Compressed air is introduced during this process to break up the soil structure and to keep the injection ports clear. Dry materials are then blown in as the tool is rotated in the opposite direction at 120 to 150 rpm and withdrawn. The compressed air pressure is gradually reduced as the tool nears the surface (from 0.5 to 0.7 down to 0.15 MPa), while the air typically discharges to the surface around the drill rod from all depths.

Originally, columns of 500 mm diameter were installed, but now 1.2 m can be reached, although 600 mm remains the most common (Figure 112), and 800 mm is also popular, especially in the United States.

Strong reliance is placed on computer control and data display in real time.

3. EQUIPMENT

Base — The earliest equipment was relatively light with a 10-m depth capacity. Rathmeyer (1996) notes that a "new era" started in 1990 with the introduction of "technically advanced" machinery from Finland that permitted larger diameters (to 800 mm), independent feeding of at least two different dry binders simultaneously, rotational speeds in the range of 130 to 200 rpm, withdrawal rates of 10 to 15 mm/s (15 to 20 mm/rotation), and depths of up to 25 m. Typical details are provided for a contemporary Stabilator machine in Figure 113. The operator's cabin is often overpressured to prevent dust ingress. The newest machines can reach 30 m in appropriate soils, although 25 m is a practical maximum.

Shafts — Rods can be square in section (120 mm), bottom rotated, or round (100 to 125 mm in diameter) with top drive. The former permit air to escape from the ground more easily during drilling. The tool outlet is 25 mm in diameter.

Grout Plant — In the traditional system, the lime and cement are provided from separate 3.5- to 5-m^3 tanks and are mixed in a closed-system tank (1.5 to 2.5 m^3), eliminating the risk of dust leakage during installation. There is a dryer on the compressor (6 m^3/min at 6 bars) (to prevent hydration of the quicklime) and a 3-mm sieve/filter. The tanks have load cells. A curtain is placed around the carrier to prevent wind acting adversely on the load cells. Materials are provided in 30- to 40-m^3 storage containers. In the newer version, there are two units: one "installer" and one "carrier." The carrier contains two 10-m^3 tanks each and a compressor, and is in radio contact with the installer. The carrier is operated from the installer, both of which are crawler-mounted.

Control — The computer system provides real-time control of the processes (especially rate of materials injected), as well as records of quantities of materials, rate of injection, rpm, withdrawal rate, air pressure, materials composition, and depth. The drill has automatic verticality control set up (±¼°).

Production — Instantaneous penetration rates are about 150 mm/rotation going down (varies with the soil) and 15 mm/rotation on withdrawal. A 15-m-long column can be installed in 5 min.

Industrial production of 400 to 1,000 lin. m per 8-h shift (600 mm diameter) is common and is dictated by the type of soil, amount of additive, and column diameter in particular.

4. MIX CHARACTERISTICS

Injected Material. The binder content is typically 35 kg/m of column, with a range of 20 to 60 kg/m. For 600-mm-diameter columns, the content is 23 to 28 kg/m (typically a 50:50 ratio of lime to cement) and for 800-mm-diameter columns, the content is up to 50 kg/m (typically a 50:50 ratio of lime to cement). Lime is unslaked, with granular particles normally less than 1.5 mm in size.

The materials commonly used now are lime and cement with a 50:50 split (up to 75:25). Holm et al. (1983) described earlier work with lime only, and lime/gypsum (75:25) (recommended for long-term stability), now superseded. Cement is found to be essential, especially in organic soils for strength and durability.

Current binder content values equate to 80 to 150 kg/m^3 of soil. In general terms:

100 kg/m^3 = 7% of the dry weight of silty soils
= 10% to 12% of the dry weight of clay soils
= up to 100% of the dry weight of peats

Experiments continue with different cementing materials, such as flyash, and slag cement. Very little spoil is generated and mixing is typically very efficient.

Treated Soil. Generically, results depend on:

- Soil (especially the water content), which explains strength variability with depth.
- Type and amount of material injected (below the minimum quantity, there is no improvement), otherwise, shear strength and E-value increase with cement content.
- Temperature.
- Effective in situ stress.
- Age.

Cement causes relatively rapid gain of strength due to its reaction with the moisture in the soil. Lime generates longer term pozzolanic reaction. Tests and theory indicate an optimum lime content in most conditions of 10% to 15%.

The maximum design shear strength (taken as 50% UCS) is typically 0.10 to 0.13 MPa, but can vary in the field from 0.1 to 1.0 MPa. Pressuremeter tests have been conducted and results indicate shear strengths of 0.5 to 0.7 MPa.

Rajasekaran et al. (1996) recently experimented with lime additives for soft marine clays in the laboratory. They found a strength increase of 8 to 10 times, a compressibility reduction of 2 or 3 times, and a reduction of PI from 53% to 30% after 45 days.

Esrig (1997) stated that the C_u (column strength). for treated columns was approximately 10 (high organic clays) to 50 (silty clay) times the soil C_u. Also, E = 50 to 200 times C_u

Sources of actual treated soil data include:

- Rathmayer (1996) – UCS vs. water/cement ratio, also shows the role of organics (Figure 114).
- Stabilator (1997) – Shear strength with time (Queens West project, Brooklyn) (Figure 115).
- Huttunen and Kujala (1996) – Properties of various treated peats (Figures 116 and 116b).
- Swedish Geotechnical Institute (1996) – Shear strength with different additive contents with time, in different soils (Figures 117a and 117b).
- Holm et al. (1981) – Reported that for lime columns in very soft clay, the compression modulus of the columns was 500 to 3000 C_u.
- Åhnberg et al. (1995) – Strength vs. water:binder ratio for different soils.
- Esrig (1999b) – Unconfined shear strength (half the unconfined compressive strength) for different treated soil types (Figure 118).

Regarding permeability, it was originally reported that pure lime columns, due to mixing inhomogeneities, and center hole "weakness" were up to 1,000 times more permeable than the native clays and that other additives resulted in less permeable columns. When calculating the settlements with time, the permeability of lime columns is assumed to be 1,000 times higher than the clay. For lime-cement columns, the factor is 400 to 500. A vast amount of research has been conducted, as summarized by Holm, Rathmeyer, Åhnberg, Esrig, and others. For U.S. soils, Esrig (1997) provided details of the preliminary tests for I-15, Salt Lake City, UT. In addition, research is ongoing, as reflected in the current Swedish and Finnish programs. Åhnberg et al. (1994) provided a comprehensive summary of research trends, see Figure 119.)

5. PATENTED/PROTECTED FEATURES

The method is only used by a relatively small number (less than 10) of Swedish and Finnish contractors. No restrictive patents are believed to now exist (Esrig, 1999a).

6. PARTICULAR ADVANTAGES

The process is fast and economical, giving low to moderate strengths. The technique is excellently researched and well understood, allowing design and cost optimization. The market is served by competent and innovative contractors, backed by Government agencies, with a long record of successful case histories. The method has low vibration, low noise, and minimal surface spoils. The column spacing, diameter, and depth are adjustable. Computer control and construction data display in real time.

However, depth is limited to a maximum of 30 m and the most appropriate applications are in relatively soft, cohesive and/or organic soils, and loose to medium dense sands less than 1 m above the water table. Low- to medium-strength columns are suitable for ground improvement only; and relatively economic supplies of quicklime are required, unless cement columns alone are required.

7. OPERATING COMPANIES

The active companies are based in Sweden and Finland where 60% of the current annual market is found. The balance is historically in Southeast Asia, with minor amounts more recently in the Baltic countries. Recent U.S. demands (e.g., I-15, UT and BART, San Francisco, CA) offer considerable opportunities in other countries, such as the United States. Stabilator now has an office in Queens, NY.

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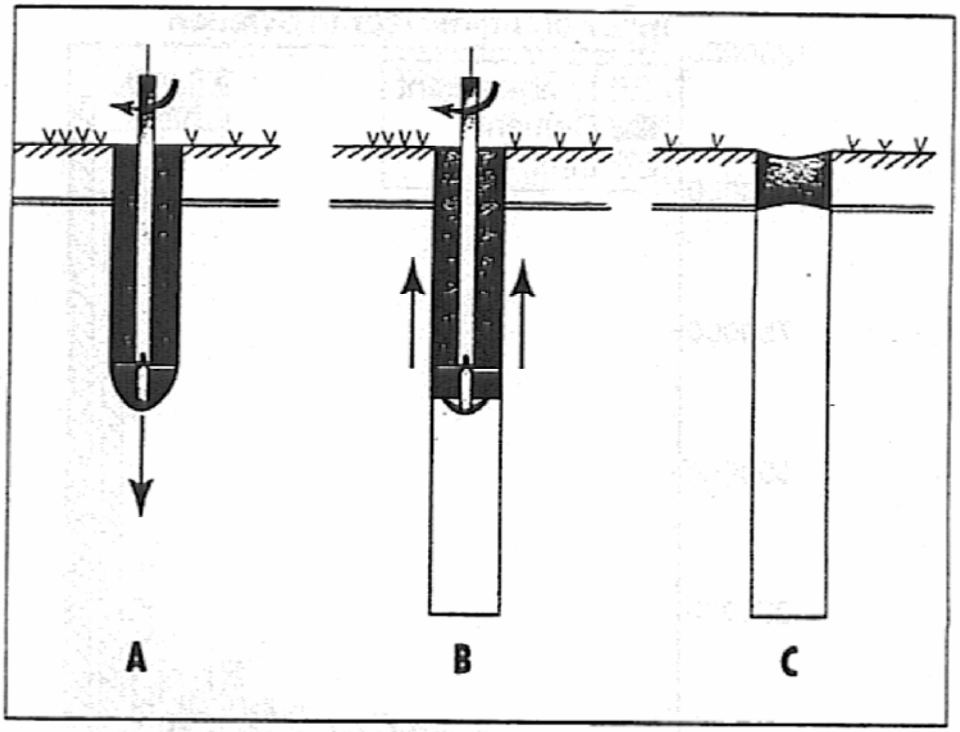


(A) Mixing tool is inserted to prepare the soil. (B) Lime and cement are injected and mixed as tool is rotated and raised. (C) Depths of completed columns are predetermined and controlled by on-board computer.

Figure 107. Installation procedure (Stabilator, 1996).

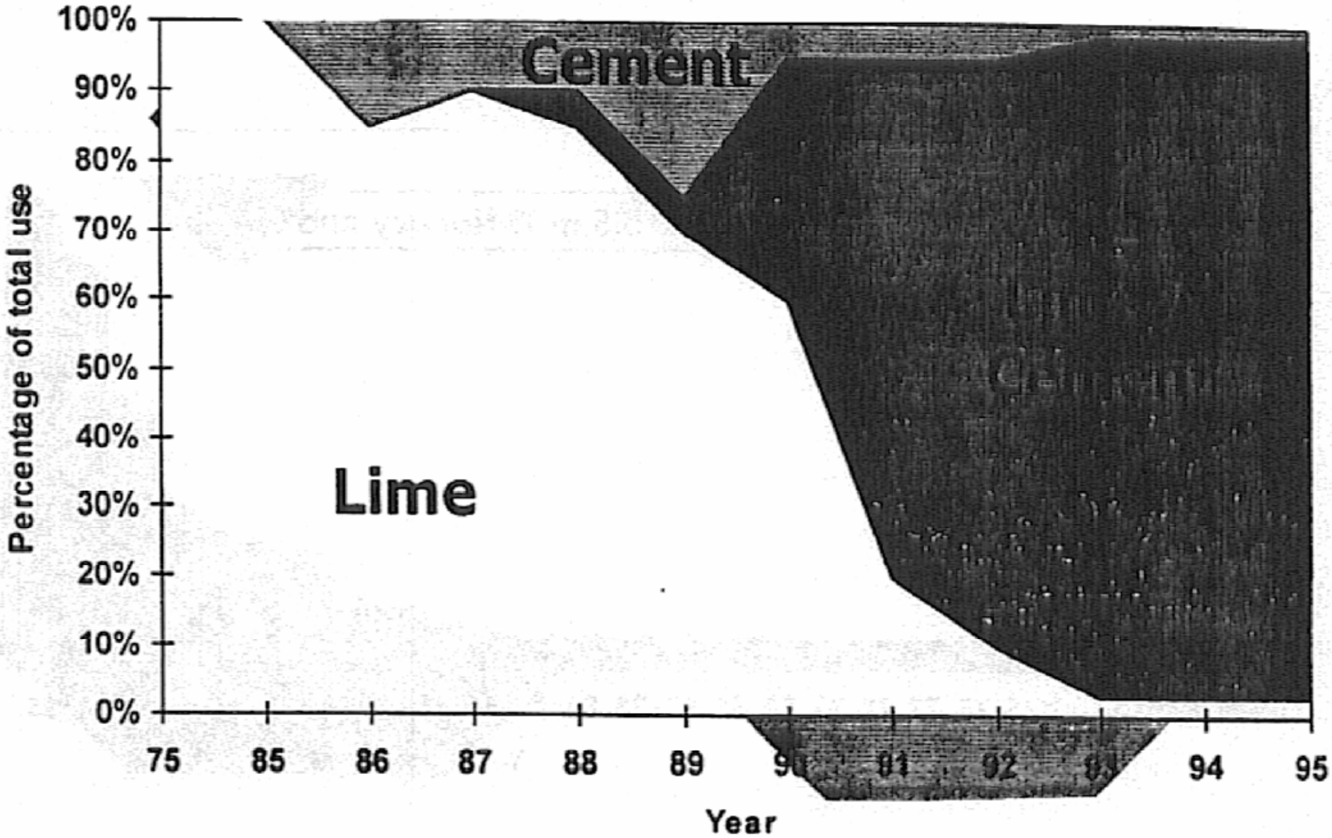


Figure 108. Changes in the use of additives over time (Esrig, 1999b).

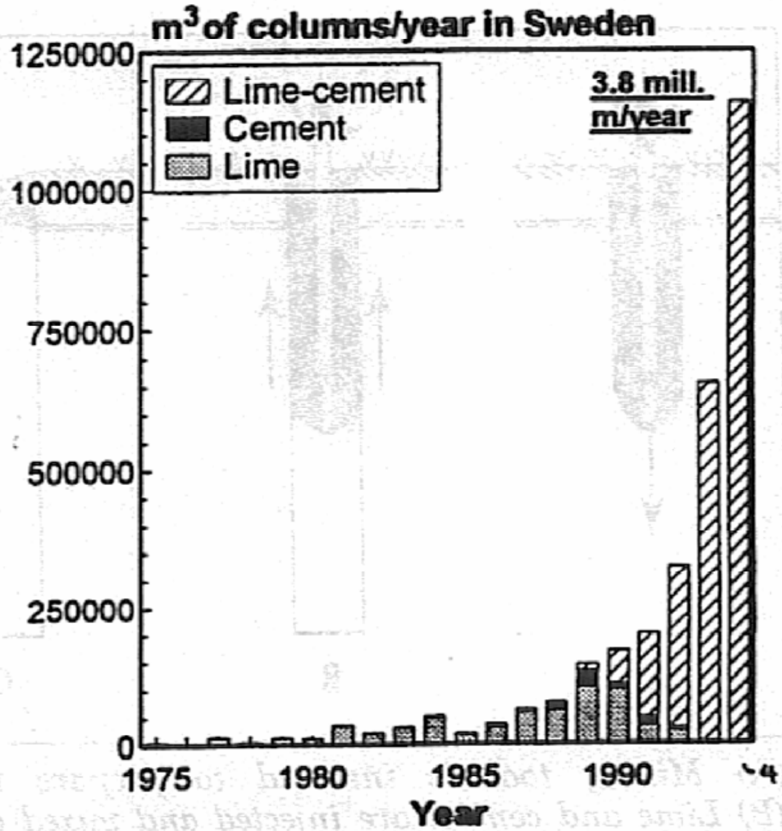


Figure 109a. Use of different stabilizing agents for deep stabilization of soils in Sweden, 1975-1994 (Åhnberg et al., 1994).

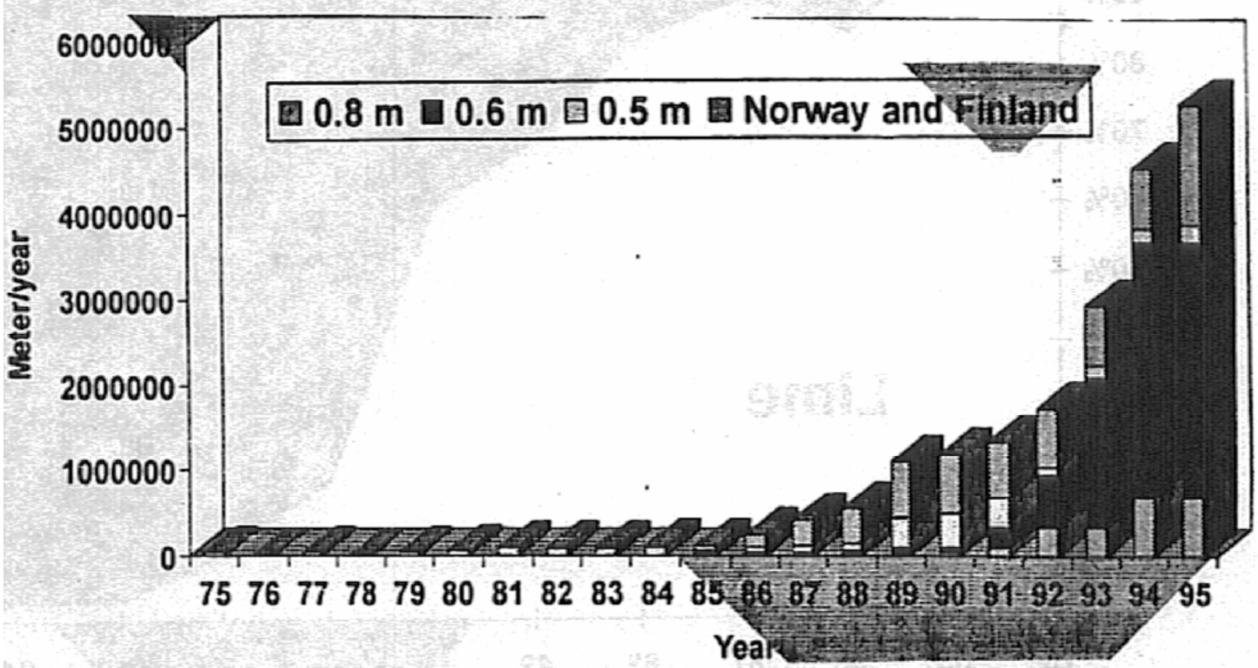


Figure 109b. Column production in Scandinavia (Esrig, 1999b).

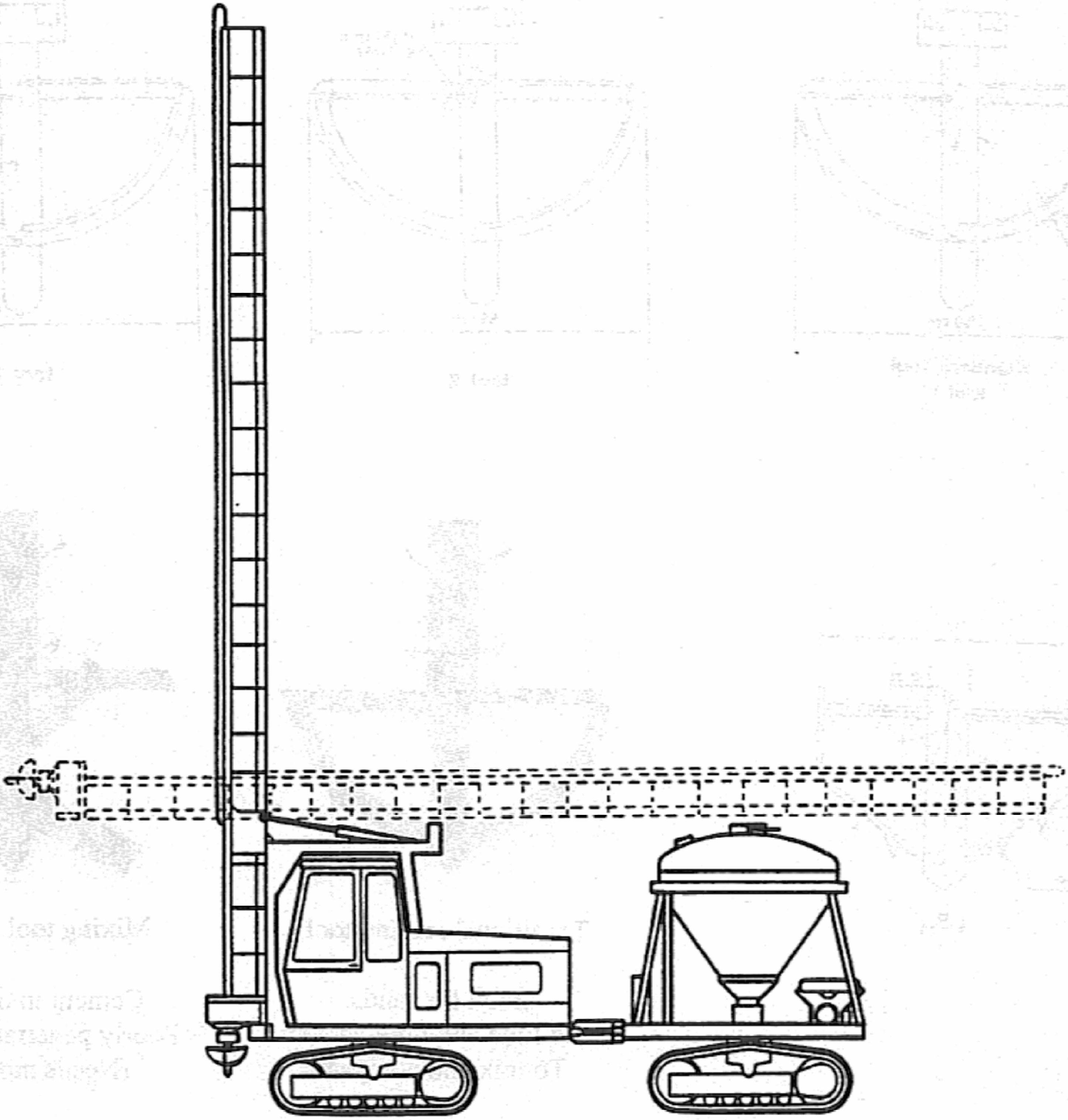
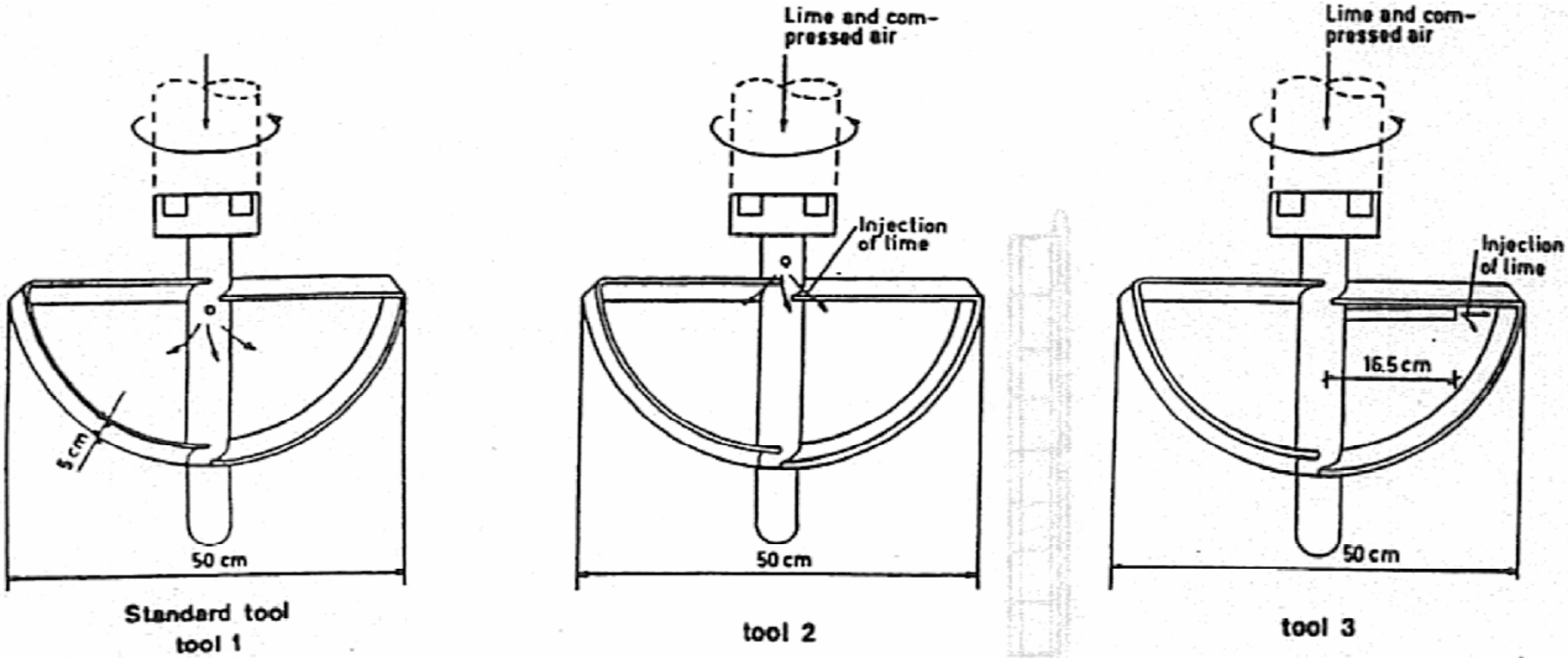
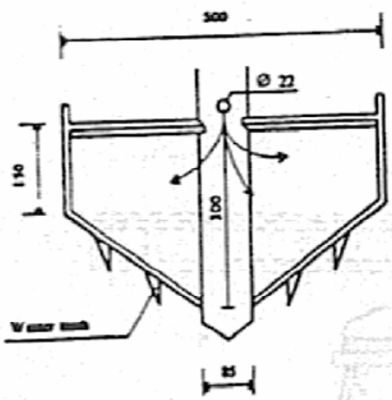
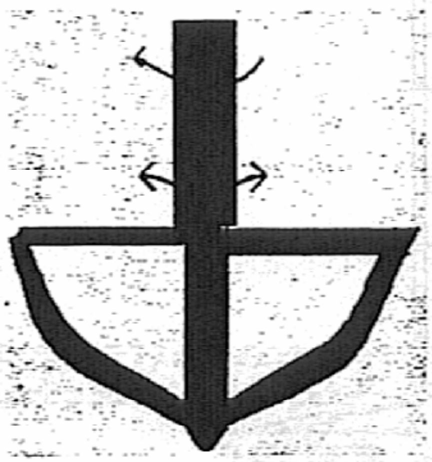


Figure 110. Lime-cement column self-contained rig and holding tank (Stabilator, 1992).

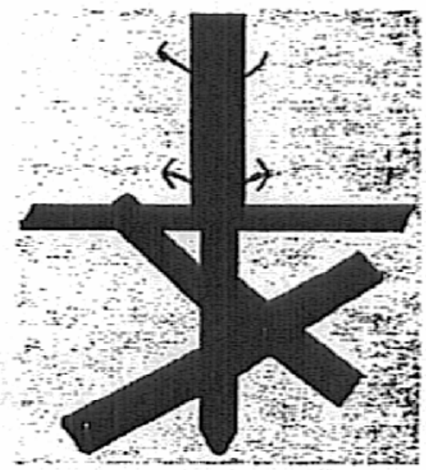






Traditional mixing tool

Good for sands.
Also lime and lime-cement.
To mix and compact.



Mixing tool for cement

Cement in organic soils.
Poorly penetrates harder soils.
(Needs more mixing).

Figure 111. Lime-cement column cutting tools (Stabilator, 1992).

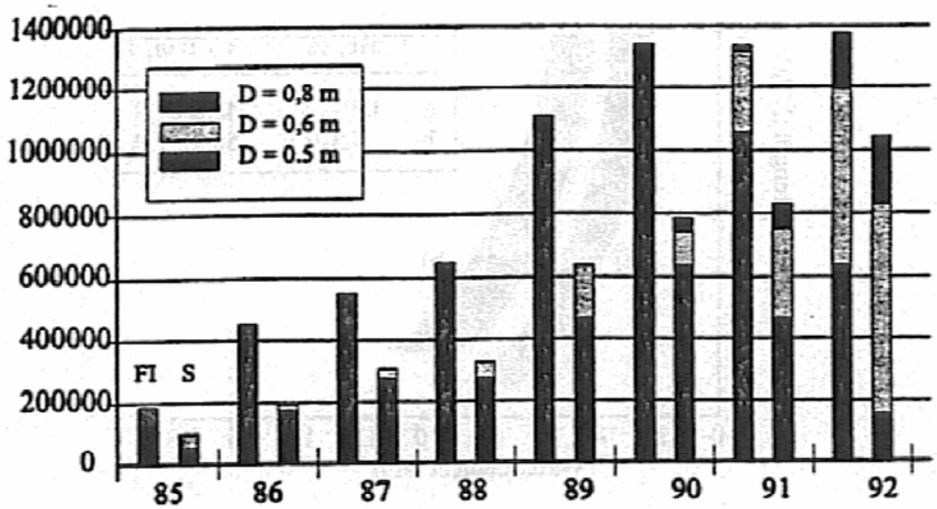
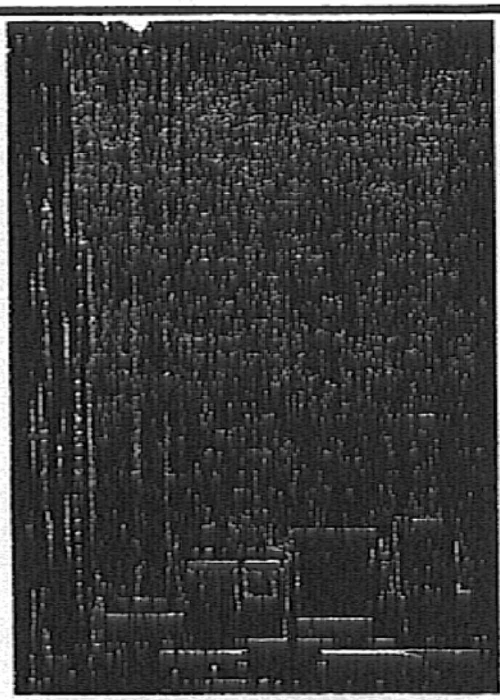


Figure 112. Volume of deep mixing treatment (lin. m) in Sweden and Finland (Rathmeyer, 1996).



- **Transportation length 16 m, crawler length 4.8 m**
- **Transportation height 4.1 m**
- **Transportation width 3.1 m**
- **Compressor 5 bar (8 bar)** (Available)
- **Rotation speed 200 rev/min, torque 1.1 tm** (Typically 170 rpm)
- **Ground pressure 37 kPa**
- **Max inclination 45^0 over the machine**
- **Max production length 25 m**
- **Max column diameter 800 mm**

Figure 113. QA/QC record (Stabilator, 1996).

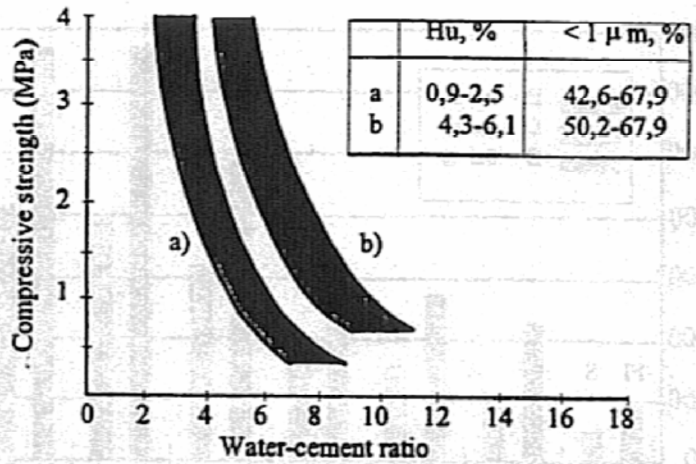


Figure 114. Compressive strength (at 20°C and 28 days) versus w/c ratio (21 soil types) (Rathmeyer, 1996).

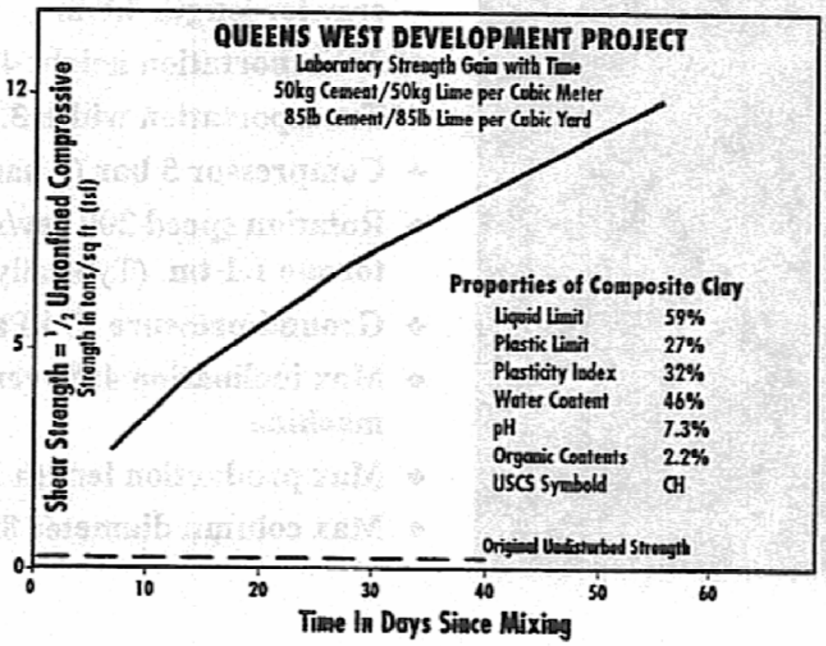


Figure 115. Shear strength versus time (days) since mixing (Stabilator, 1997).

Peat type and degree of decomposition	Binder	Binder content	Deformation parameter m	Deformation parameter β	Permeability k (m/s)
S H2	P40/28	400 kg/m^3	122,4	0,954	$10^{-5,8}$
C H3	P40/28+ CaO 1:1	"	14,3	0,649	$10^{-9,6}$
CS H3	P40/28	"	150,2	0,639	$10^{-6,1}$
BC H 2-3	P40/28+ CaO 1:1	"	15,7	0,429	$10^{-6,3}$

Figure 116a. Deformation parameters and permeabilities of the stabilized peat samples (Huttunen and Kujala, 1996).

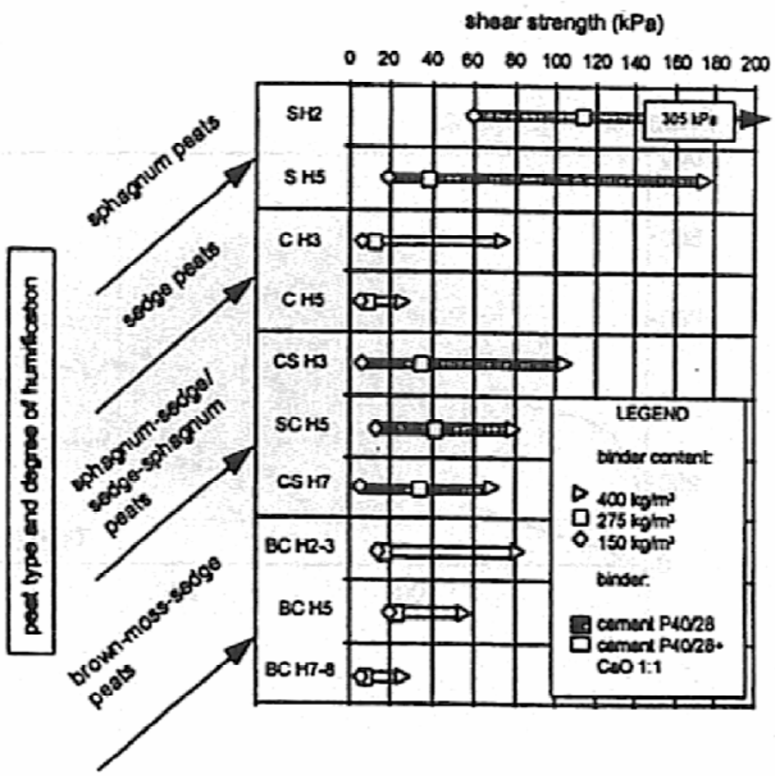


Figure 116b. Shear strengths of stabilized peat with different binder contents after 180 days of curing (Huttunen and Kujala, 1996).

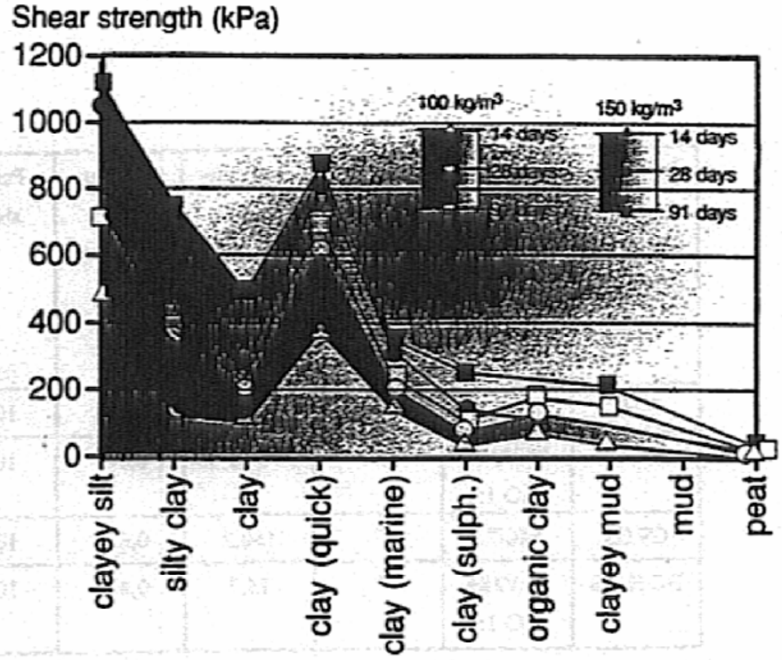


Figure 117a. Shear strength versus soil type stabilized with cement (Åhnberg et al., 1995).

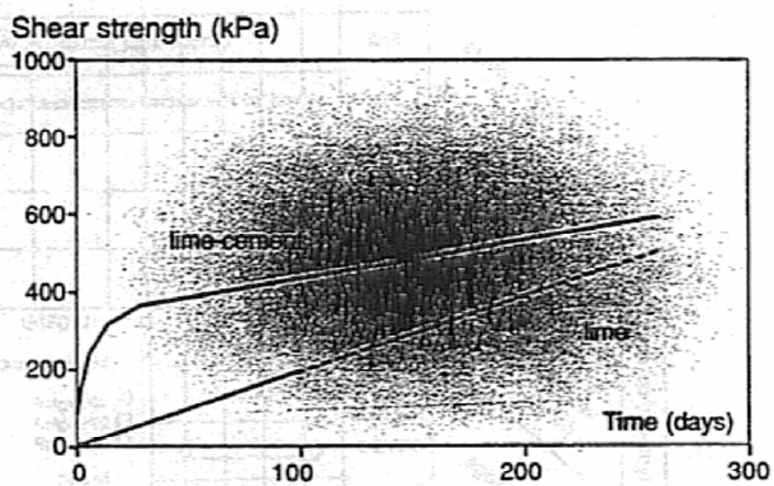


Figure 117b. Comparison of strength development with time after mixing, for lime and lime cement stabilized soil (Åhnberg et al., 1995).

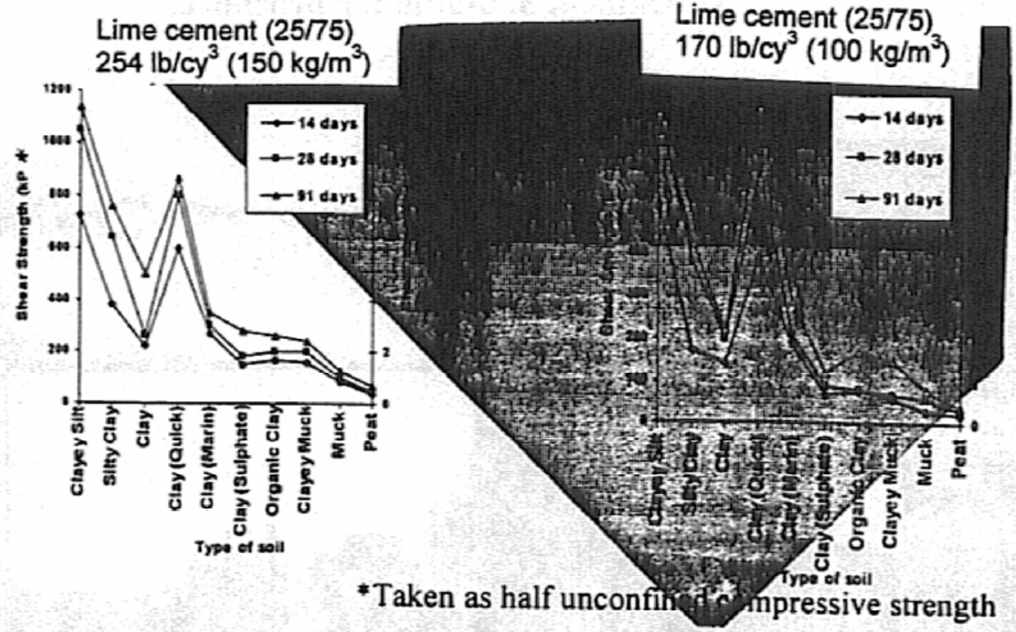


Figure 118. Shear strength of different treated soils (Esrig, 1999b).

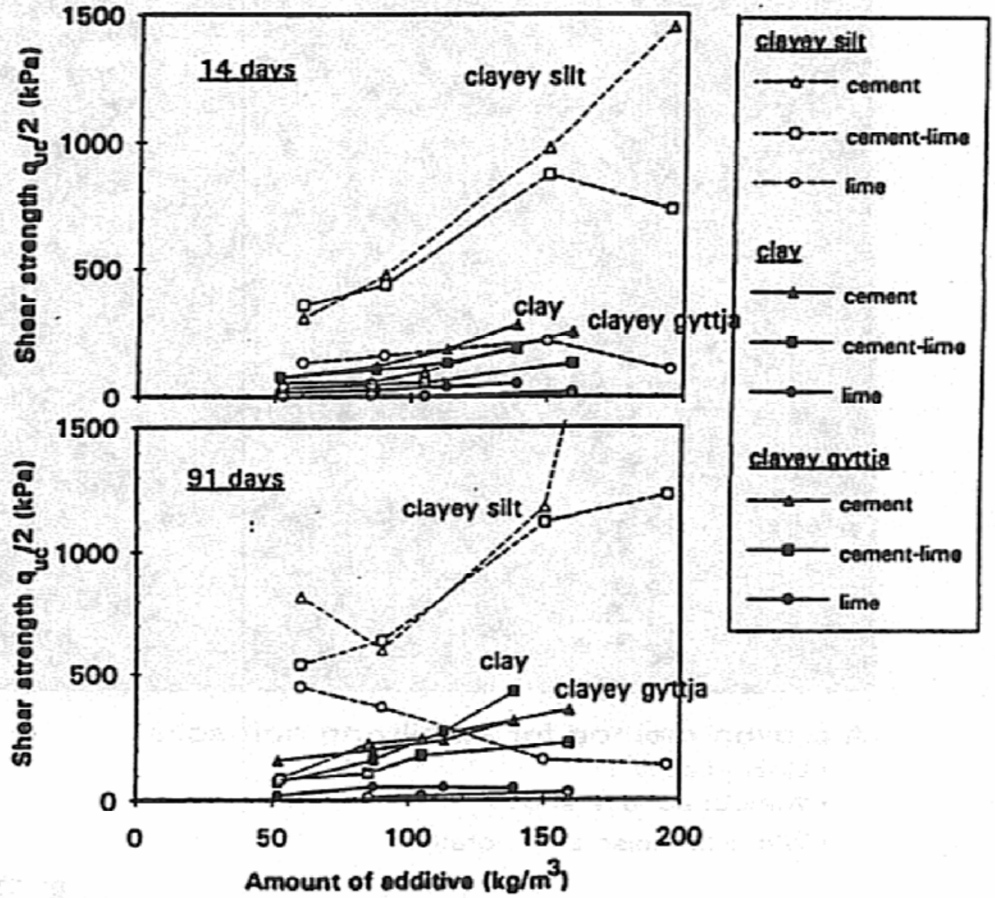
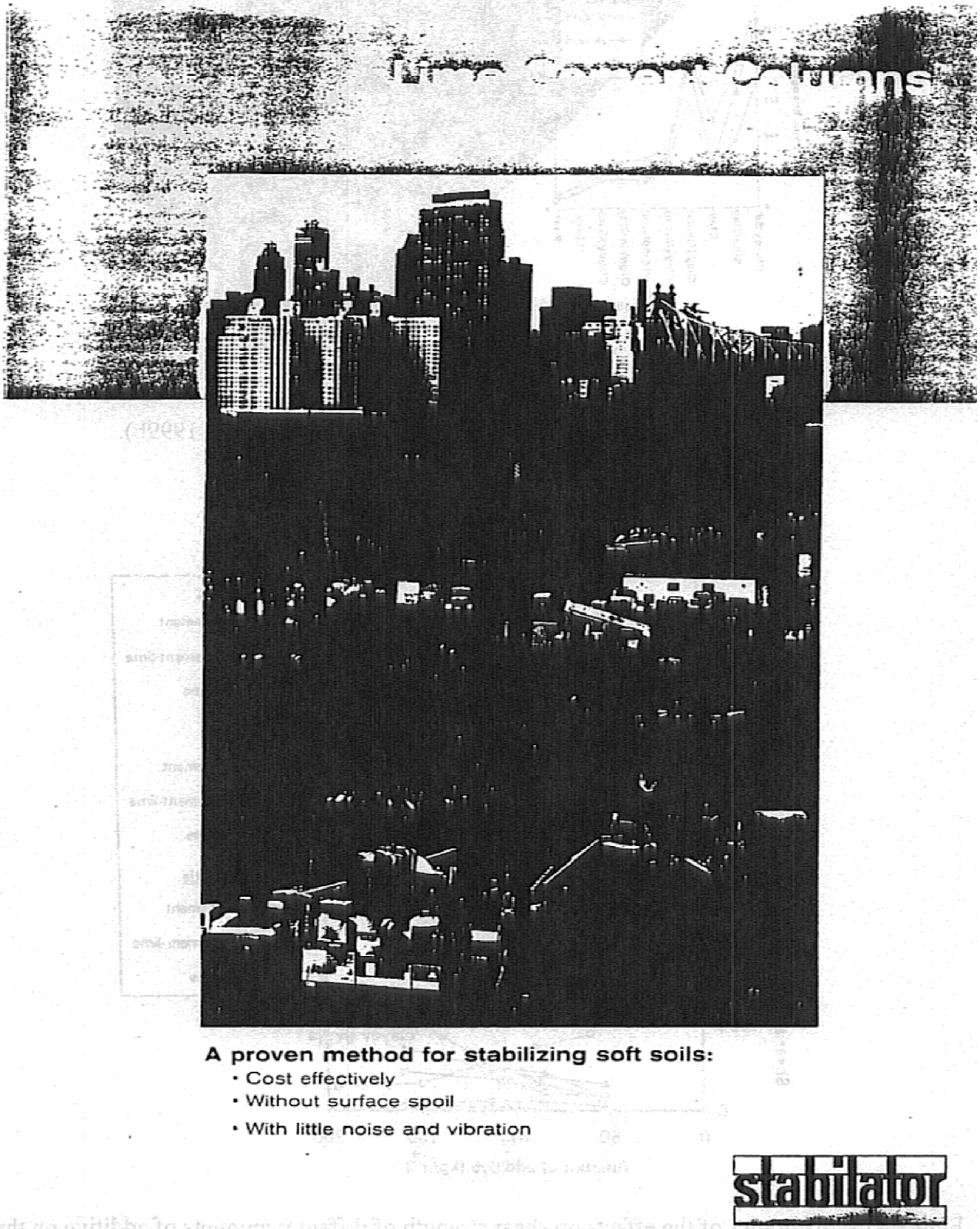


Figure 119. Examples of the effects on shear strength of different amounts of additive on three soils stabilized in the laboratory (Åhnberg et al., 1994).

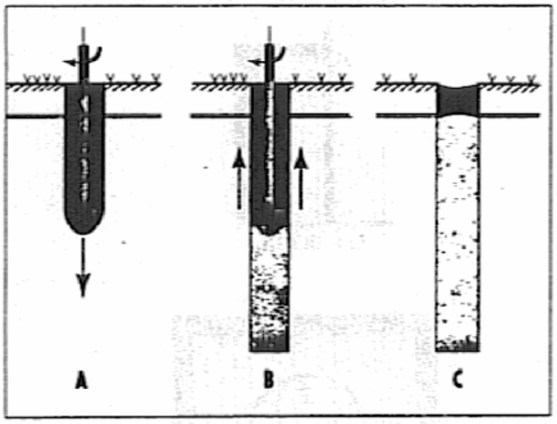
Attachment 8. Stabilator brochure.



The Process

Lime Cement (LC) Columns™ have been used in Europe for over 25 years to stabilize soft soils. The LC process produces a composite material of moderate strength at lower cost than alternative stabilization methods without creating spoil on the surface. The installation process is practically noise and vibration free.

Mixing tool for constructing Lime Cement Columns™.



(A) Mixing tool is inserted to prepare the soil. (B) Lime and cement are injected and mixed as tool is rotated and raised. (C) Depths of completed columns are predetermined and controlled by on-board computer.

An LC Column is constructed by injecting, under air pressure, a combination of dry quick (unslaked) lime and cement into soil, and mixing the soil, lime and cement with a kelly-bar-mounted tool as it is rotated and raised to the surface.

The lightweight, crawler-mounted Stabilator LC machine is computer controlled and includes the mixing tool, sealed lime and cement storage containers, a mixing tank, and an air compressor. The self-contained machine is mobilized rapidly with leads in place, requiring one person for normal operation.

Technical Information

Diameter: 20" (500 mm) to 40" (1000 mm)

Depth: To 82' (25 meters)

As compared to untreated ground:

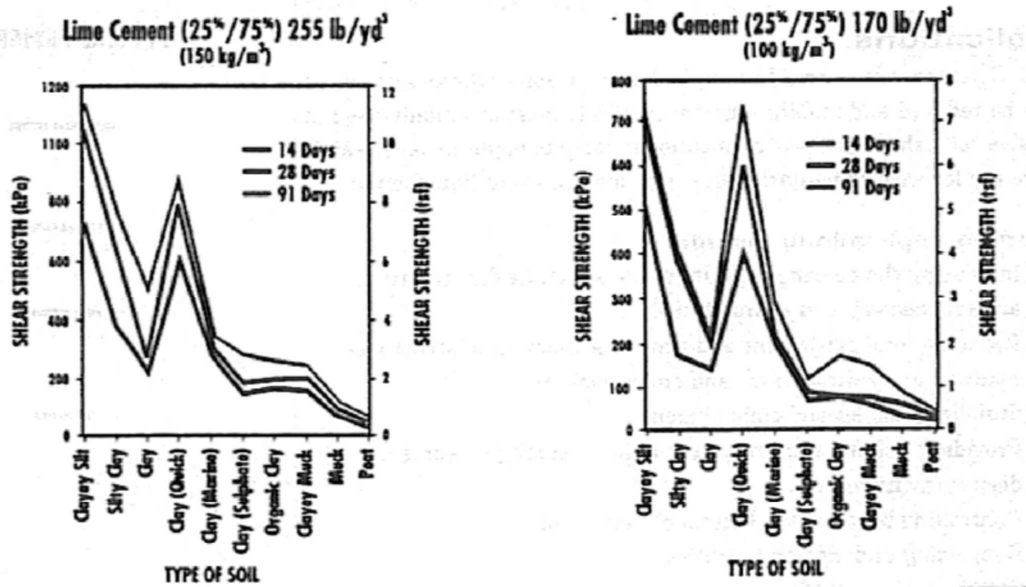
- Total settlement is reduced by 2/3 or more.
- Time for complete settlement is reduced by a factor of four.
- Secondary compression is insignificant.

Strength and compressibility varies with:

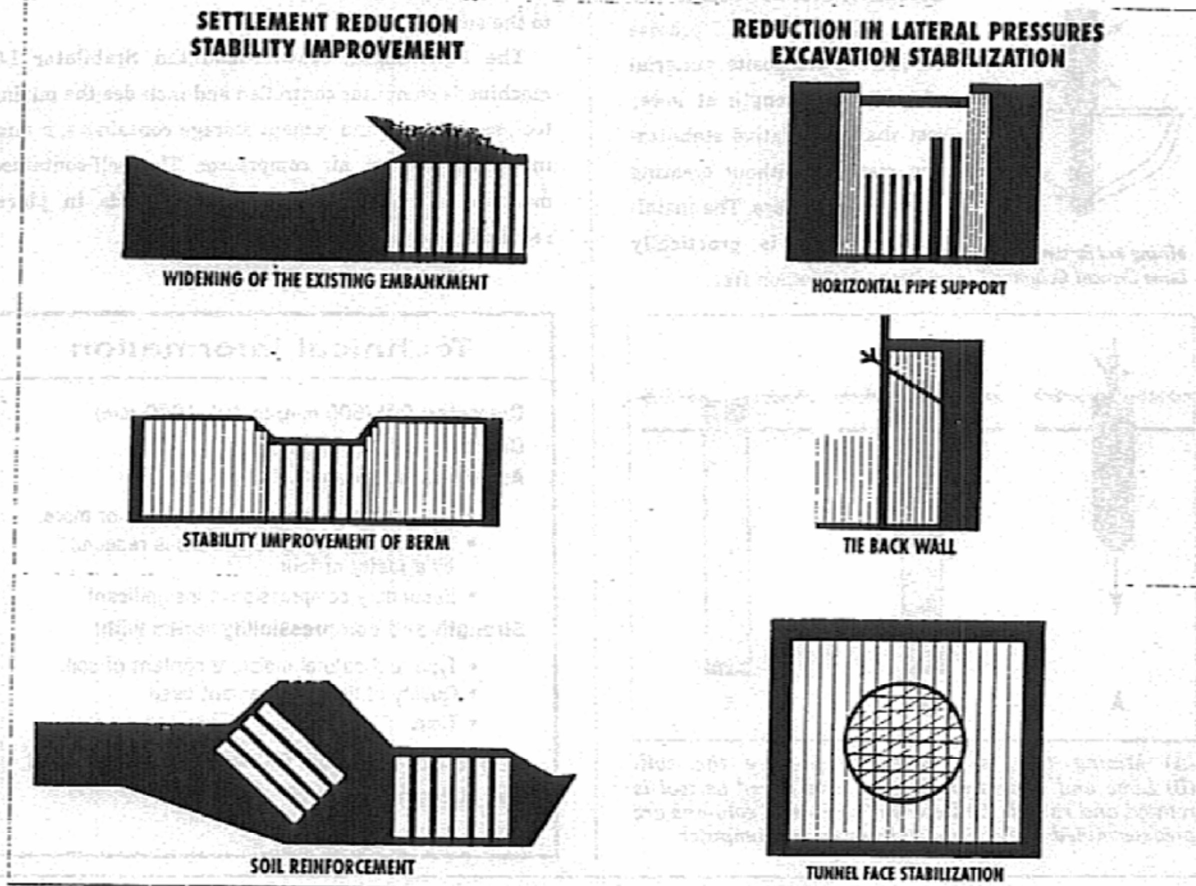
- Type and natural moisture content of soil.
- Quality of lime and cement used
- Time

Field results show that LC Columns have maintained their strength for over 25 years.

SHEAR STRENGTH IN DIFFERENT SOIL TYPES



APPLICATION EXAMPLES: STABILATOR LC METHOD



Applications

LC Columns are normally installed in soft soils where settlement must be reduced and stability increased. While most commonly used in cohesive soils, they also have application in loose to medium dense sands where the low-cost cementation they provide can avoid liquefaction.

Common applications include:

- Increasing the bearing capacity of the subgrade for structures and for roadway and railroad fills.
- Reducing total settlement and time of settlement of structures, roadway and railroad fills, and embankments.
- Stabilizing slopes and embankments.
- Providing lateral restraint and/or reduced earth pressures in deep excavations.
- Controlling heave of the bottom of excavations
- Supporting underground utilities.
- Stabilizing tunnel faces.

TYPICAL PATTERNS

RECTANGULAR PATTERN

TRIANGULAR PATTERN

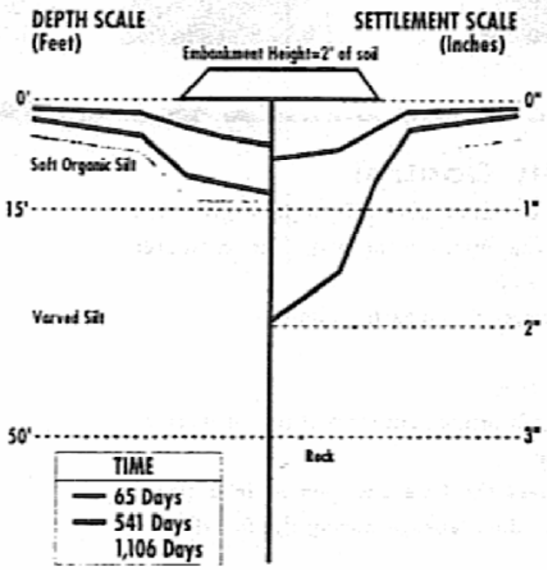
PANEL PATTERN

CELL PATTERN

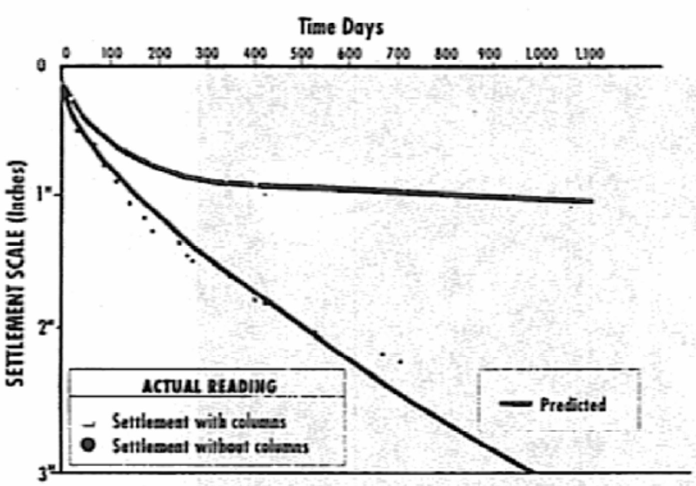
BLOCK PATTERN

Typical Results

Approximately four million linear meters of LC Columns are installed in Scandinavia alone each year. They have also been used for significant projects in Southeast Asia and Europe. Typical results with and without LC treatment are shown below:



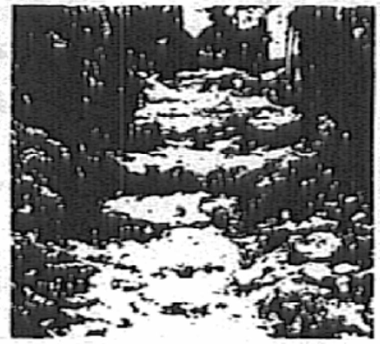
PARTIALLY PENETRATING COLUMNS



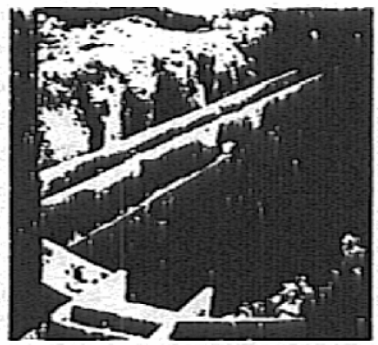
SETTLEMENT OF EMBANKMENT ON SOFT ORGANIC SILT

Comparison with columns and without columns

LC Columns reduce total settlement and increase rate of settlement.



(A) LC Columns installed in a trench to support a sewer.



(B) LC Columns installed to avoid "bottom" instability.

(C) LC Columns installed to support a railroad embankment.

stabilator

Quality Control

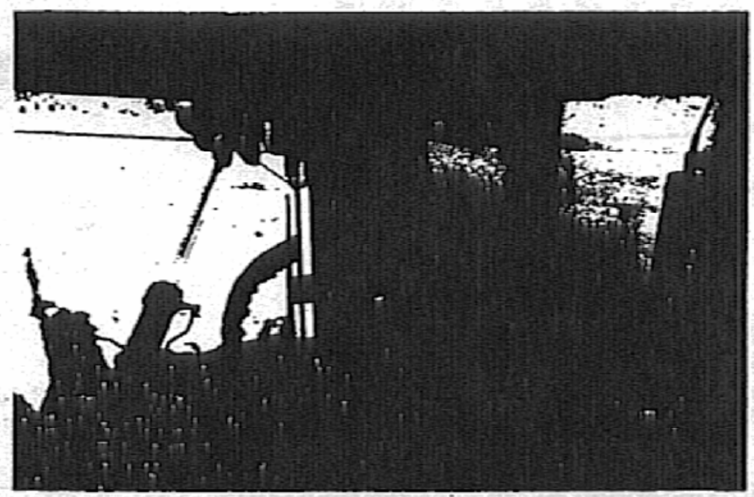
A computer in the cab of the Stabilator LC machine gives the operator precise control of the injection process. The computer also maintains complete records of:

- The quantity of material injected into each column.
- The rate of injection.
- Speed of tool rotation and rise.

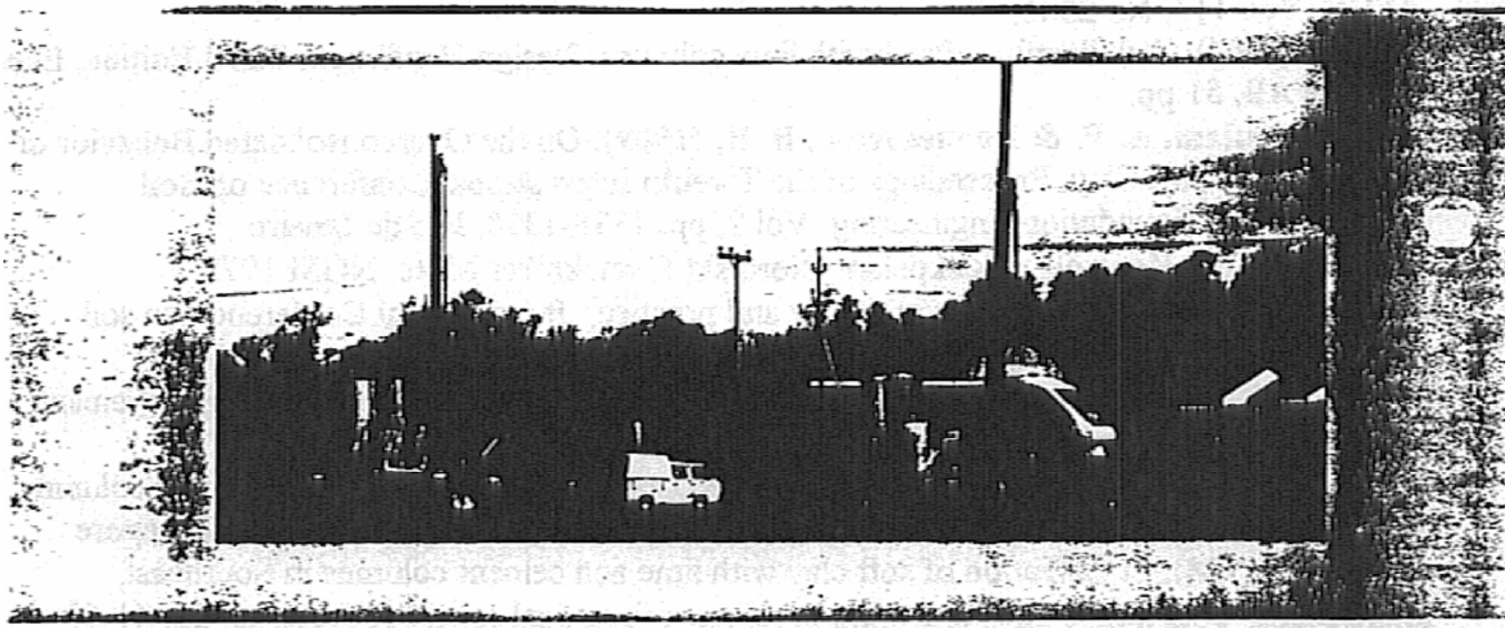
The records can be displayed or printed out for real-time inspection and for quality assurance records.

The Stabilator machine mixes the lime and cement in a closed system, eliminating the risk of dust leakage during the installation process.

Under ISO 9000, the Stabilator Lime and Cement Column process has been certified as incorporating QA/QC procedures to assure quality of work.



stabilator



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TREVIMIX (24)

1. INTRODUCTION

The method is classified as DRE. It was developed in Italy by TREVI S.p.A. of Cesena, Italy, in the late 1980s and was first used to stabilize lignite quarry dump materials at the ENEL power station at Pietrafitta in 1988. Rodio has also conducted a limited number of projects using the Trevi equipment (including Pietrafitta), under an agreement whereby a royalty was paid to Trevi for a period. The WRS (Wet Rotary Shaft) version (Multimix) began development in 1991. General data on Trevimix are provided in Attachment 1.

2. GENERAL PROCESS

The general principle is shown in Figures 120a and 120b. The soil structure is disintegrated during drilling (at constant penetration rate and rpm: about 20 rpm preset based on the type of soils to be treated). In particularly tough conditions, a little water can be added. Water is also mixed in drier soils to ensure subsequent efficient cement hydration. The goal of this preconditioning is to get the soil as close as possible to its liquid limit. The augers are then raised at about 30 rpm. with reverse rotation at preset constant rotation and lift rates, while dry materials are injected via nozzles in the shaft, below the mixing paddles. The special shapes of the mixing tools create voids in the soil into which the compressed air "drops" the binder, which is then blended. The shape of the blades also promote a uniform blending of the dry material injected, and provides recompacting of the mixed soil. Also, the geometry of the blades and kelly and the use of "a protection bell," ensure that only air is expelled (and intercepted) from each column location and not errant cementious materials (Figure 121). Such bell(s) over the auger(s) collect and channel the air away. One or two columns can be created simultaneously, typically 1 m in diameter. to depths of 30 m. The binder is injected by low-pressure air via nozzles located below the mixing blades. The addition of binder can be varied as desired during drilling, during drilling and uplift at any ratio, or during uplift only

With respect to the use of slurry, or dry binder, Pagliacci and Pagotto (1994) note:

- Better "mechanical characteristics" are obtained by dry binders especially in cohesive soil. Grout injection leads to increased water content in the system and "characteristics" 30% to 50% lower.
- The use of sand with wet methods helps only slightly and only in cohesive soils (UCS upto 9 MPa possible).
- Wet mixing is mechanically simpler (equipment and QA/QC controls) and thus is preferable in "difficult" geographic areas.
- The use of dry methods (in appropriate soils, i.e., moisture content 60% to 145%) produces minimal spoil or heave.

Originally, this system was designed to treat very soft to soft cohesive soils (undrained cohesion < 25 kPa), or very loose to loose cohesionless soils (N < 4 to 6). However, more recent works

(Pagliacci and Pagotto, 1994) claim that cohesive soils with cohesion values of up to 200 kPa, and cohesionless soils with N-values up to 25 can be treated.

3. EQUIPMENT (Figure 122)

Base — An appropriate crawler-mounted crane is used (Soilmech EC or Linkbelt LS 38/318 is common on Trevi projects). The protection bell at the ground surface prevents expulsion of binder. Mast is 33 m, stroke is 25 m, hoist is 80 kN, and thrust is 80 kN. (Most recently, 30-m depth capacity has been claimed.)

Shafts — One, or more commonly, two augers are used, each independently hydraulically rotated (40 to 60 kN-m at 10 to 40 rpm/shaft), operating off a power pack of 250 kW. The shafts appear to be mounted on fixed leads. (Alternatively, square rods rotated by a rotary turntable can be used.) The shafts give 800- or 1,000-mm-diameter columns (more common) and are separated by a fixed (but variable) distance of 1.5 to 3.5 m, depending on the design. The augers may have separate internal lines (water; air/binder). Tool type depends on soil and an "idling bar" can be added to help mixing efficiency.

Grout Plant — Typical silos and compressors are illustrated in Figure 122. Significant problems noted in the maintenance of the injection plant include the high level of abrasion, the effects of humidity on the dry materials, and the drifting calibration of the QA/QC equipment.

Control — Typically, computer control and recording of injection and withdrawal parameters are conducted. Tests of product include coring, exposure, sampling of large blocks, and extraction.

Production — At the Livorno Italy site, (highly compressible clays of water contents up to 60%), the average industrial production is reported to have reached 139 m per 8-h shift (average 108 m). Instantaneous penetration rates are around 0.4 m/min and withdrawal rates are about 0.6 m/min (Pietrafitta data).

4. MIX CHARACTERISTICS

Grout — Dry cement is most common now, as opposed to lime since cement is used for all soil types, whereas lime is restricted to soft cohesives only; cement has a shorter setting time, gives higher strength and lower deformability, is easier to work with, and gives more constant results.

Typically, cement factors are 150 to 250 kg/m^3, but can be higher, depending on soil and design requirements. UCS varies from 2.1 to 6.3 MPa. Cement-sand mixes have also been experimented with Other agents, e.g., quicklime (either powered or granular of size 5 mm in size) can be used, depending on soil type and the purpose of treatment.

Treated Soil In general, the dry cement binder absorbs water from the soil, releases part of the calcium compounds (lime) and forms hydrated cement and hydrated lime. The hydrated cement hardens around the soil particles. The hydrated lime releases calcium ions that combine with the silica and alumina present in clayey soils to produce a reaction similar to the one that leads, in nature, to the formation of pozzolan. Figure 123 shows the relationship between the content and type of various binders and UCS (Catalano, 1999). Dry methods apparently produce higher strengths than the equivalent wet methods, with cement producing the highest. At Pietrafitta, the soil moisture content was 60 to 145% and its shear strength was 24 kPa. Type I cement was injected at 180 to 210 kg/m of column (1 m diameter) to depths of 20 to 30 m. This increased UCS by 15 to 20 times, E-value by 10 to 50 times (undrained) or 30 to 100 times (drained).

At Livorno in early 1990, the soft, highly compressible clays had water content up to 60% and undrained shear strengths as low as 30 kPa to greater than 20m depth. Type I-II cement as introduced at 230 kg/m of column (290 kg/m^3 soil), gave an average UCS of 2.5 MPa (range 1.8 to 4.2) (Figure 124), and E = 1 to 2.66 x 10^3 MPa (up to 3.125 x 10^3 MPa in more sandy horizons).

5. PATENTED/PROTECTED FEATURES

The system is very similar to comparable Japanese methods except for allowing for the possibility of injecting water during penetration. This is a patented feature held by TREVI.

6. PARTICULAR ADVANTAGES

Binder can be easily varied and optimized, together with the injection parameters, to produce homogeneous, economically mixed soil. No spoil or waste is generated, and the method is environmentally safe since the air outflow is trapped and cleaned. Mixed soils are of uniform consistency, even in clays up to 200 kPa shear as a result of the special design of "mixer" tool. Quantity of binder injected is automatically controlled in real time. The cost (1992) was about $50/m, which was claimed to be higher than the corresponding wet method (Multimix). The method is only applicable in softer unobstructed soils, especially saturated cohesives.

7. OPERATING COMPANIES

The system is patented by TREVI and is also used under license by Rodio. Both companies are headquartered in Italy and have offices in the United States (Trevisani since May 1997). TREVI has used this method in Thailand.

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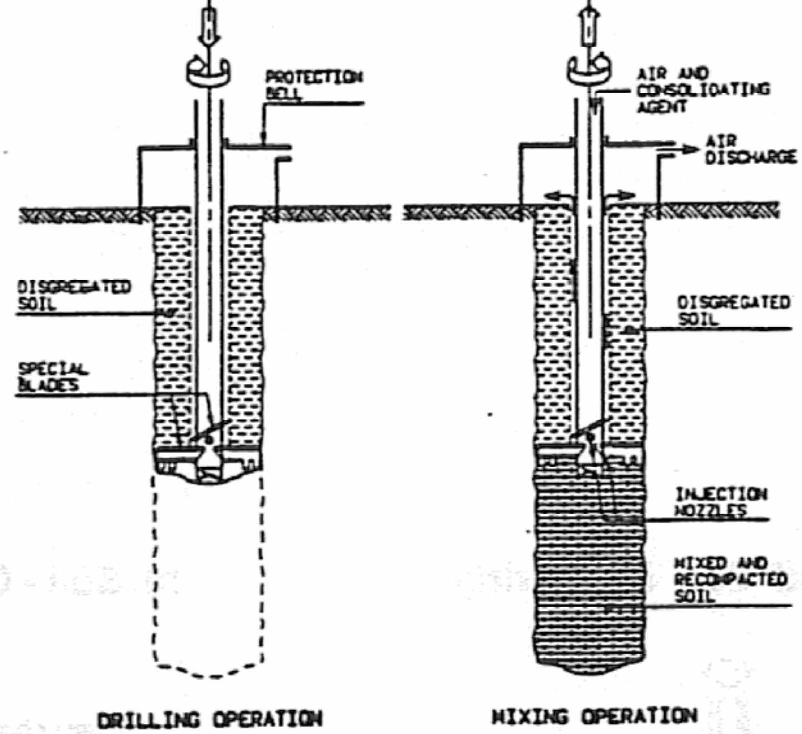


Figure 120a. Scheme of Trevimix method (Pavianni and Pagotto, 1991).

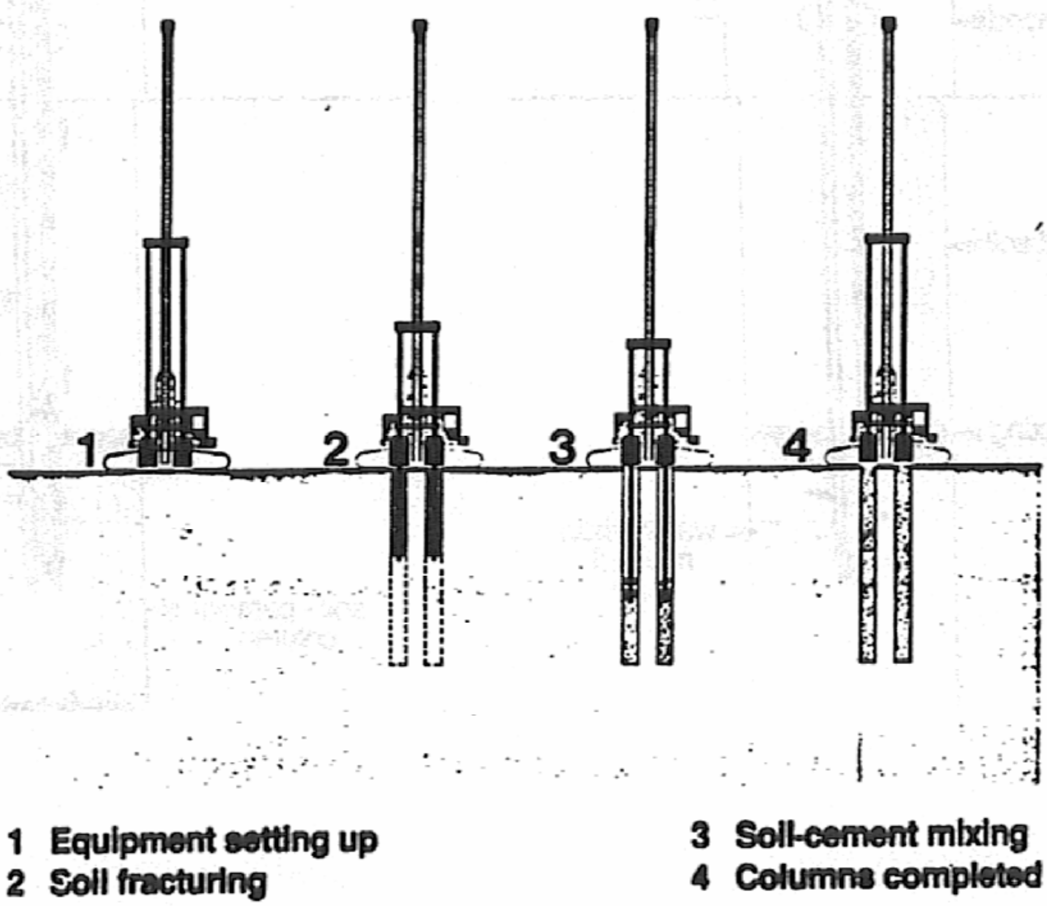


Figure 120b. Schematic of the installation process (Rodio, 1990).

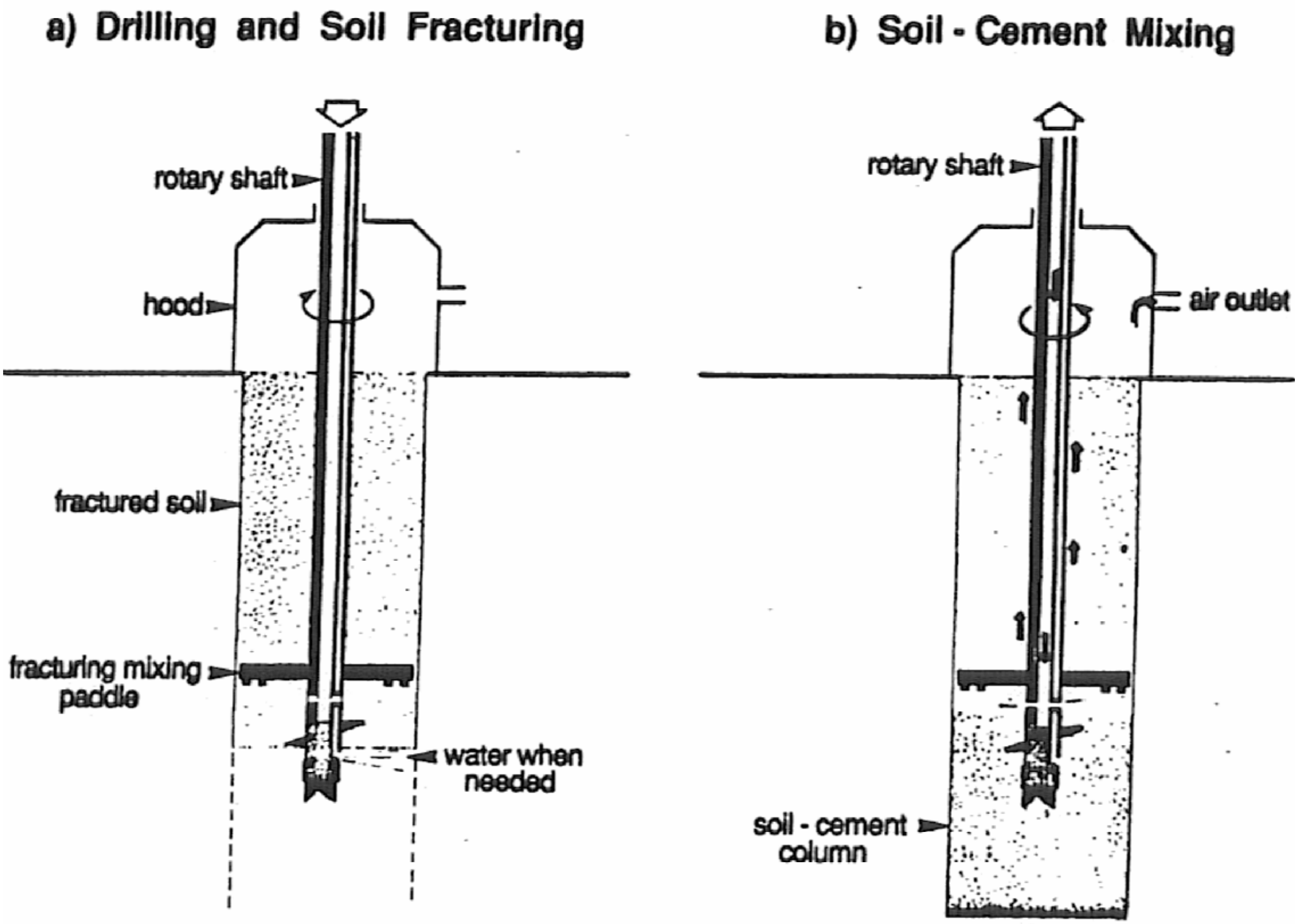


Figure 121. Excavation and mixing phases of column installation (Rodio, 1990).

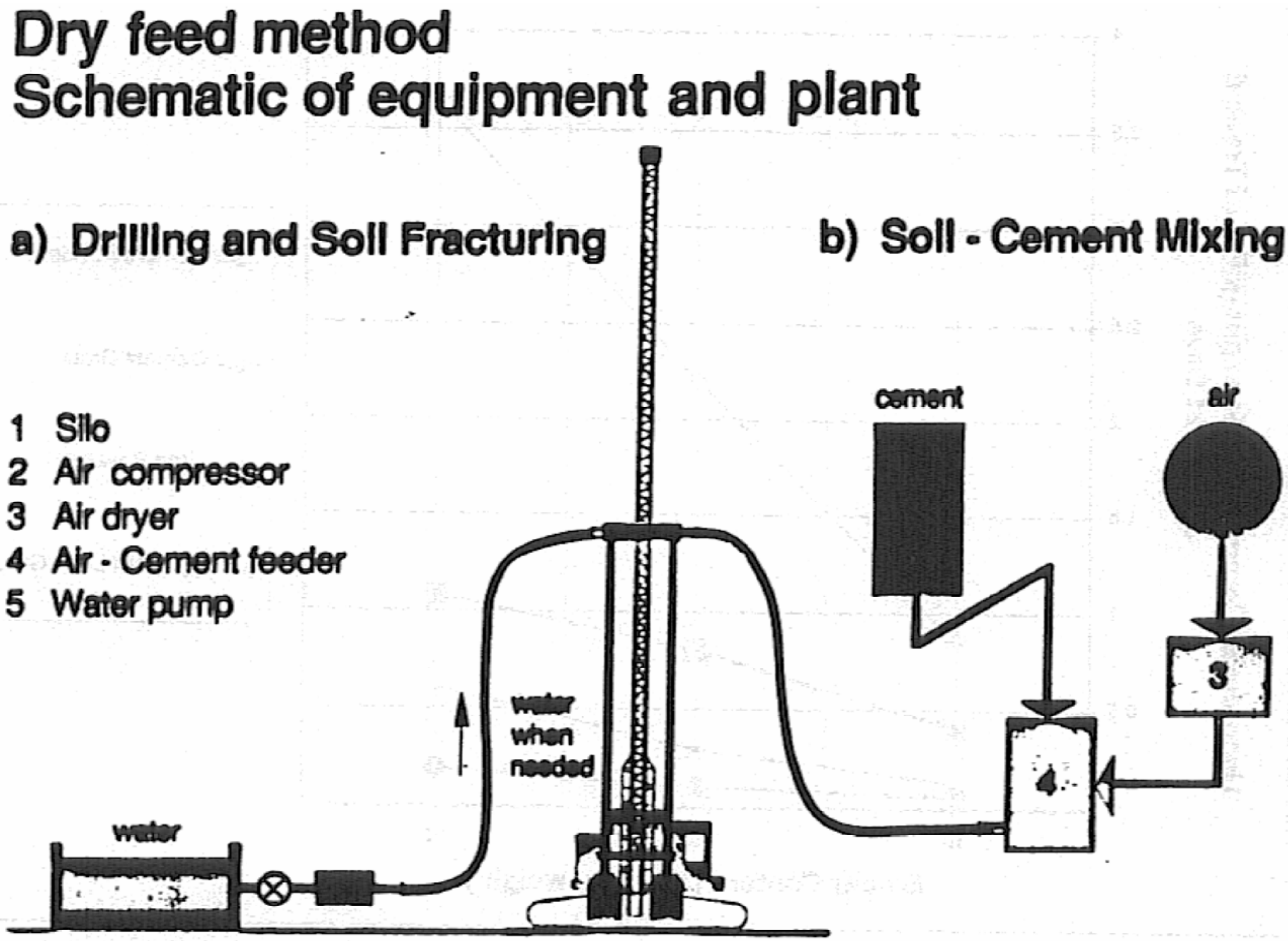


Figure 122. General layout of the equipment (Rodio, 1990).

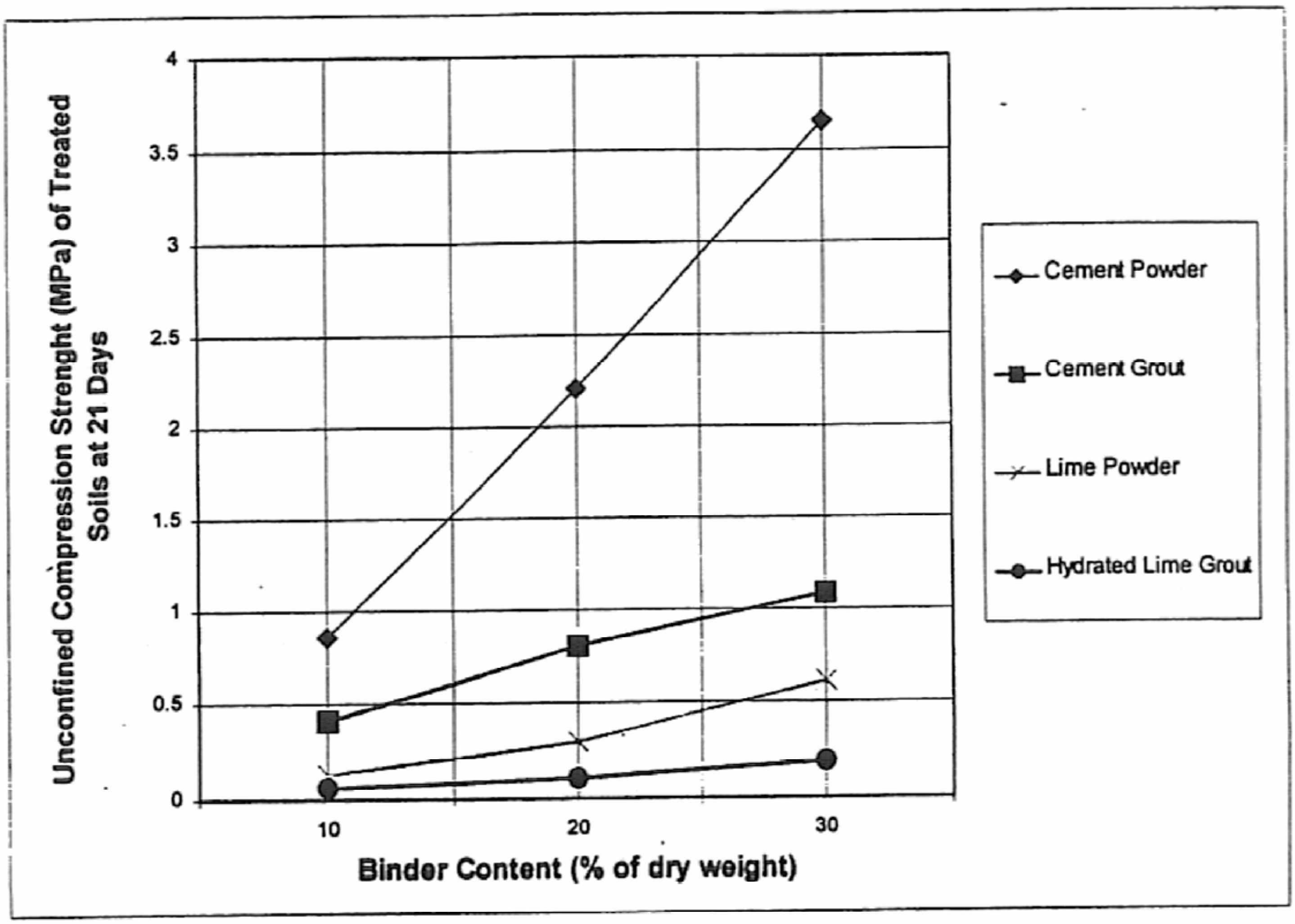


Figure 123. Unconfined compressive strength vs. binder content (Catalano, 1990).

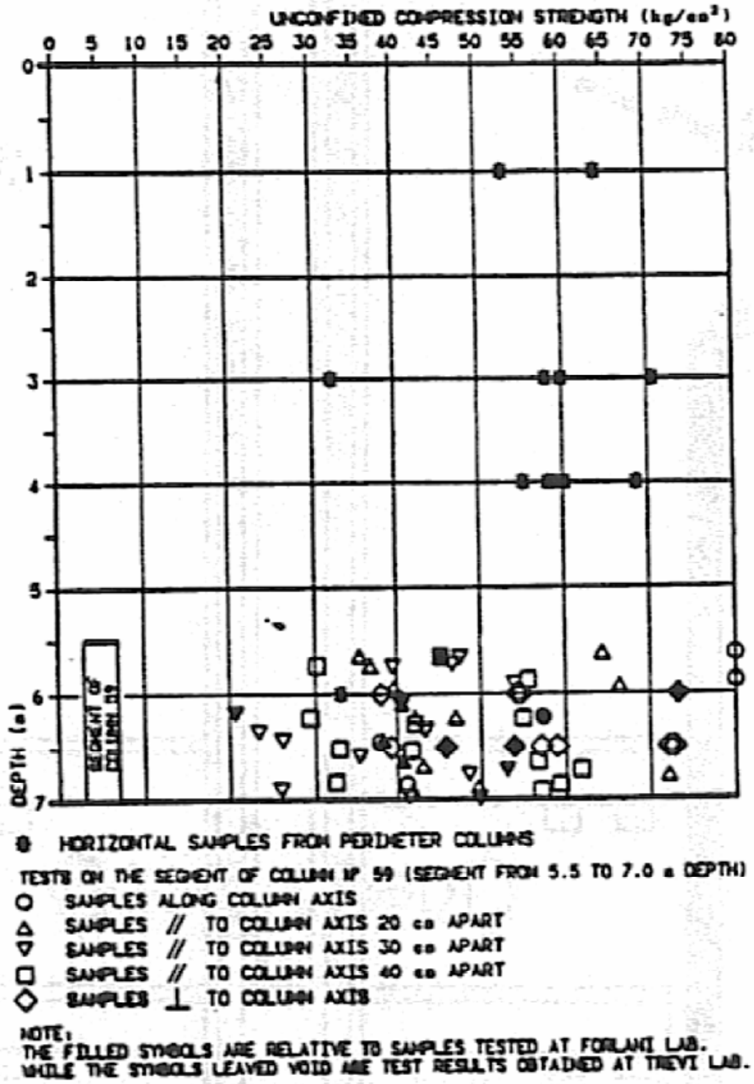


Figure 124. Strength characteristics from laboratory tests on samples recovered in directions parallel and perpendicular to the axes of the columns (Paviani and Pagotto, 1991).

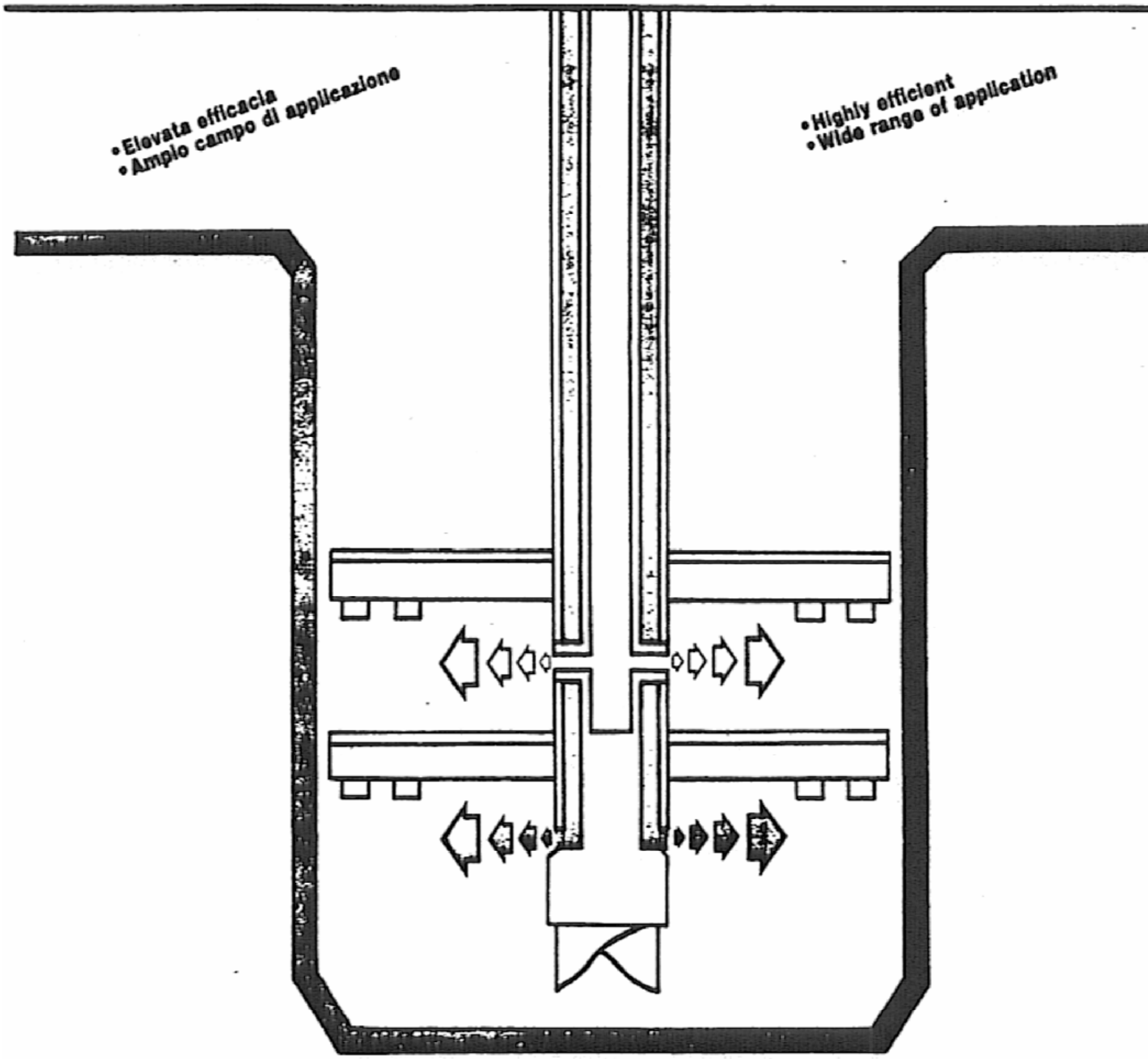
TREVIMIX

Una tecnologia avanzata

per il consolidamento dei terreni mediante miscelazione in sito di agente consolidante in polvere.

An advanced technology

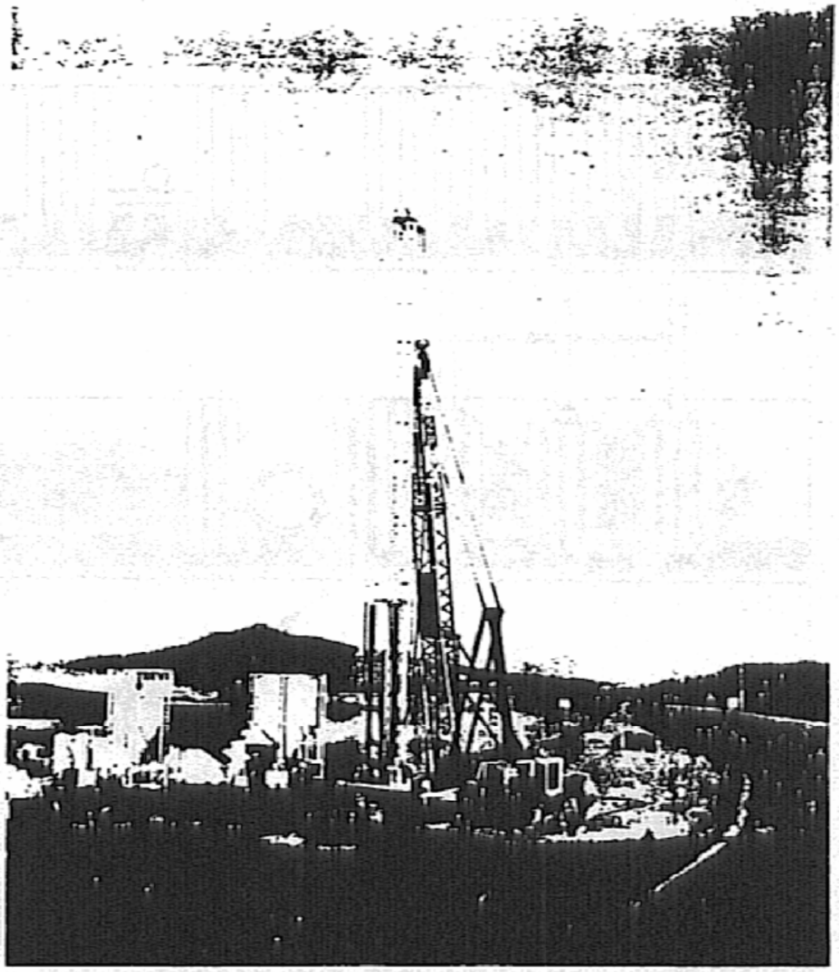
for soil consolidation by mixing in situ of stabilizing powder agent.



TREVI

TREVIMIX

La tecnologia TREVIMIX rappresenta un importante sviluppo nel settore del consolidamento del terreno mediante apporto, con miscelazione meccanica in sito, di idonei agenti stabilizzanti.
La peculiarità del TREVIMIX è quella di utilizzare, come agente stabilizzante, un prodotto in polvere e/o granulare (solitamente cemento o miscela cemento/sabbia) immesso nel terreno, preventivamente disgregato da uno speciale "mixer" rotante, per mezzo di un flusso di aria compressa a bassa pressione (trasporto eolico).
L'agente consolidante utilizzato può essere, oltre al cemento, la calce viva o altro materiale in polvere e/o granulare (sino ad un diametro massimo di 5 mm), in funzione delle caratteristiche del terreno e delle finalità del consolidamento.
La tecnologia TREVIMIX consente di aumentare la resistenza dei terreni trattati grazie alla reazione chimica che si innesca tra l'agente consolidante ed il terreno.
Il terreno e l'agente consolidante, miscelati tra loro in presenza di acqua, formano in breve tempo un ammasso rinforzato stabile a seguito di una reazione pozzolanica (idratazione).
La particolarità del TREVIMIX consiste in un sistema brevettato, utilizzato in fase di perforazione, per umidificare eventuali livelli aridi di terreno con il quantitativo di acqua necessaria alla reazione di idratazione terreno/agente consolidante.
La tecnologia TREVIMIX permette di ottenere colonne di terreno consolidato di diametro 800-1000 mm, per profondità superiori ai 25 metri.



ECONOMICITÀ E RAPIDITÀ

Il dosaggio [illegible] dell'agente consolidante in funzione dei terreni da consolidare, la ridotta dispersione dei valori finali di resistenza e la rapidità del raggiungimento degli stessi, la costanza dei diametri e delle profondità trattati, la sicurezza e pulizia del metodo, rendono il TREVIMIX particolarmente concorrenziale rispetto ai tradizionali sistemi di consolidamento dei terreni.

CONTROLLO DEL TRATTAMENTO

Il trattamento viene controllato mediante una centrale automatica che registra in continuo la quantità di agente consolidante immesso nel terreno. Tale registrazione, unitamente al controllo dei parametri di perforazione e di miscelazione, fornisce tutti i dati necessari alla valutazione delle corrette procedure operative.

EFFICIENZA ELEVATA DELLA MISCELAZIONE

La particolare forma del "mixer" con[illegible] una notevole rapidità di disgregazione e miscelazione del terreno, assicurando una distribuzione uniforme del consolidante su tutta la sezione interessata dalla rotazione del "mixer" stesso.
La possibilità di inviare acqua, in fase di perforazione, in quantità necessaria ad umidificare i livelli di terreno arido attraversati, permette di applicare tale tipo di consolidamento anche a terreni altrimenti non trattabili.

EFF[illegible]MENTO

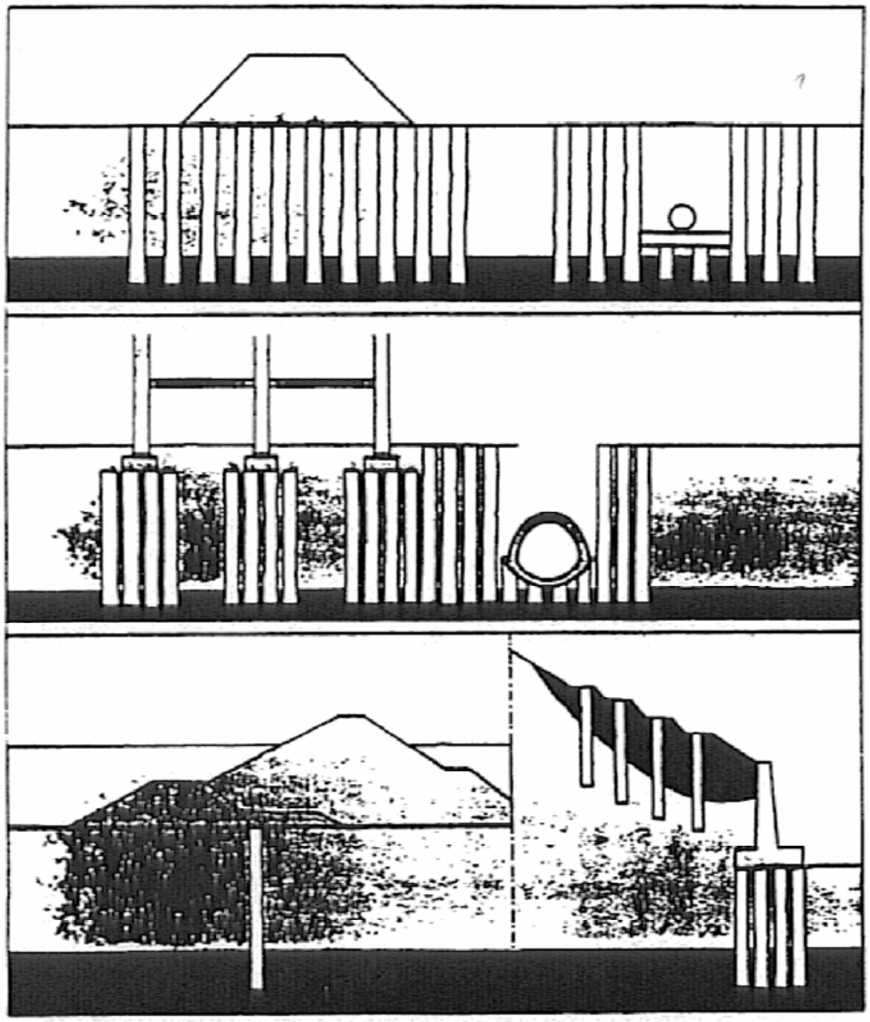
La p[illegible] utilizzando [illegible] nel terreno, per cui a parità di dosaggio si ottiene una maggiore resistenza finale del trattamento.
L'impiego di agente consolidante in polvere comporta un volume inferiore di materiale immesso nel terreno, rispetto a quello iniettato con miscele tradizionali, con conseguente minore rischio di sollevamento del piano lavoro.

POSSIBILITÀ DI STABILIRE IL GRADO DI CONSOLIDAMENTO NECESSARIO

Il risultato del consolidamento può variare da resistenze minime (pochi kg/cm²) sino a valori elevati (alcune decine di kg/cm²), semplicemente variando il quantitativo di agente in polvere immesso nel tereno.

TECNOLOGIA NON INQUINANTE

I materiali polverulenti utilizzati ve[illegible] messi nel terreno attraverso un sistema a tenuta stagna e lo spurgo consiste essenzialmente nella aria compressa necessaria al trasporto. Un trattenitore di polvere posto a bocca foro impedisce la dispersione dell'aria nella atmosfera.
L'affidabilità della tecnologia è garantita dalla semplicità di esecuzione del trattamento e dalla uniformità di diametro delle colonne realizzate, indipendente, al contrario dei sistemi jet grouting, dalla natura del terreno in sito.



The TREVIMIX technology represents a great step ahead in the soil consolidation field by the introduction of the mixing in situ with stabilizing agents. The peculiarity of the system lies in the use of a powder or granular agent (usually cement or cement/sand mix) that is pneumatically fed into the soil previously disgregated by a special rotating "mixer", by means of a compressed air flow at low pressure (eolic driving).
Other than cement, the agent can be quicklime powder or other powdered or granular material (max. size grain 5 mm), depending on nature of soil and purpose of consolidation.
The TREVIMIX method allows to increase the resistance of the treated soils, due to the chemical reaction resulting from mixing the soil with the stabilizing agent.
When the agent and the soil are mixed together in presence of water, a reinforced and stable mass shortly develops, due to the pozzolanic reaction involved by the process (hydration).
The feature of the TREVIMIX consists in a pantented method, used during the drilling stage, that provides moisturizing of dry layers of ground by addition of water in adequate quantity to produce the soil/agent hydration.
The system permits to obtain columns of stabilized soil, with diameters ranging from 800 to 1000 mm to over 25 m of depth.

FAST AND CHEAP PROCESS

The TREVIMIX is highly competitive in respect of other systems for soil consolidation, as much it permits to optimize the amount of agent, depending on requirements, to reduce scattering of the final resistance values and reach them quickly, to achieve uniformity of treatment, as far as diameters and depths are concerned; finally, to work in safe and clean conditions.

CONTROL OF TREATMENT

Treatment is controlled by an automatic station that provides a non-stop reading of the quantity of agent fed into the ground, other than recording of the drilling and mixing parameters as well as of the full data needed to evaluate the correct operational processes.

EFFICIENT MIXING SYSTEM

The special shape of the "mixer" allows to perform rapidly the disgregation and mixing of the soil, assuring an even distribution of the stabilizing agent over the whole area covered by the mixing blades.
Water can be added during drilling to moisture dry layers of soil that may be encountered, hence this type of consolidation can be extended to formations which could not be otherwise treated.

EFFICIENT CONSOLIDATION

The setting process of the agent makes use of the water existing in the ground, therefore, for an equal quantity of stabilizing agent, the final resistance of the treatment will be higher.
If the powder agent is used, less volume of material is fed into the ground in comparison with normal grouting fillings, this resulting in a reduced risk of rising the work level.

SELECTION OF DEGREE OF STABILIZATION

The degree of consolidation can be varied from minimum values (a few kg/cm²) to maximum ones (more than kg/cm²), by merely varying the amount of powdered agent fed into the soil.

NON-POLLUTING PROCESS

The powdered materials are fed into the soil through a tight system and the out flow essentially consists of the air needed to drive them.
A dust collector fitted at the inlet of the hole, prevents fines from exhausting into the atmosphere.
The reliability of the method is guaranteed by the simplicity of the treatment method that, unlike the jet grouting systems, permits to obtain columns of uniform diameter, regardless of the nature of the soil.

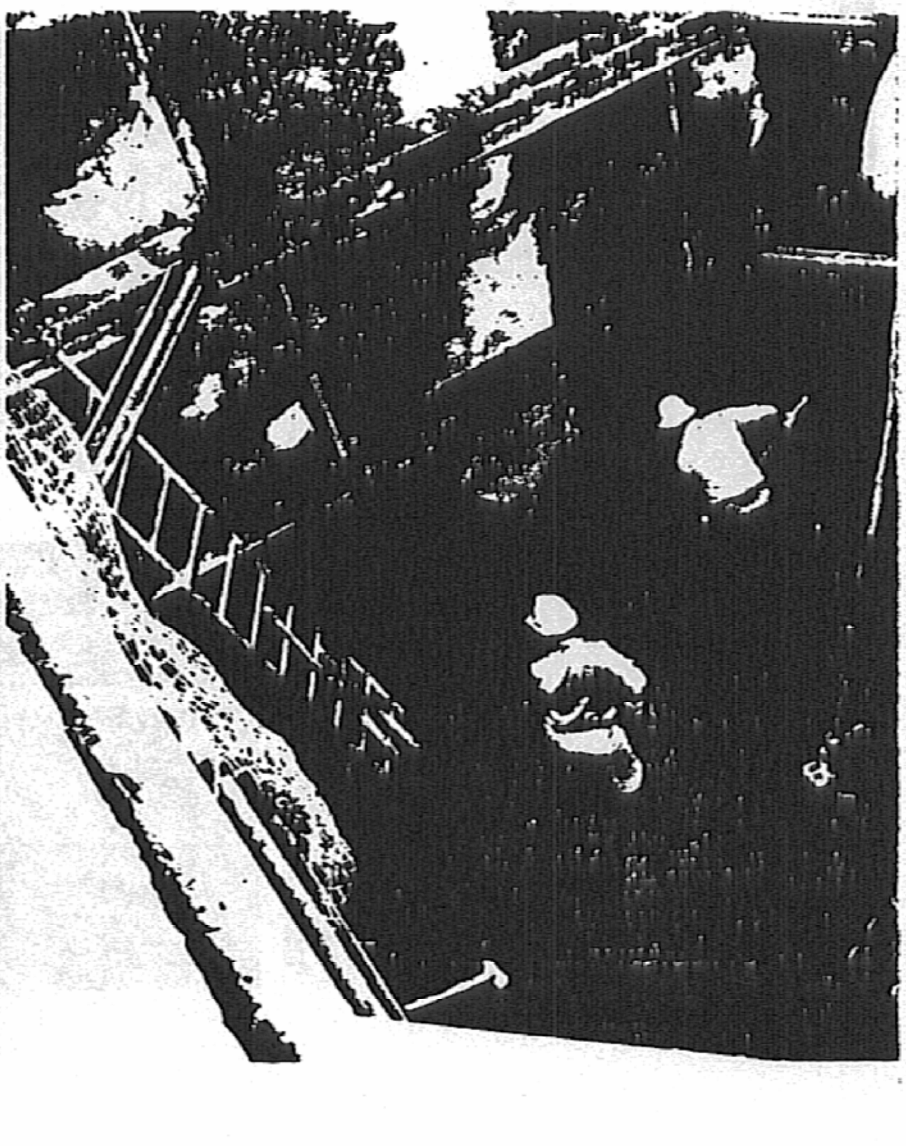
Applicazioni del metodo
Fields of applications

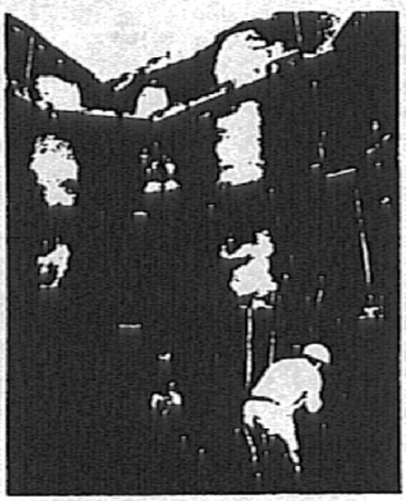
La tecnologia TREVIMIX si adatta, grazie alle sue peculiarità, a svariati impieghi, sostituendo con efficacia le tecniche di consolidamento adottate sino ad ora.
In figura 1, 2, e 3 sono rispettivamente riportati:
- i campi di applicazione, in funzione della natura dei terreni, di alcune tecniche di consolidamento raffrontate alla tecnologia TREVIMIX;
- i risultati ottenuti con le suddette tecniche, in termini di resistenza alla compressione;
- il tempo necessario ad ottenere tali risultati.

Due to its peculiarity, the use of the TREVIMIX can be extended to a variety of applications, by effectively replacing the stabilization techniques so far adopted.
Fig. 1, 2, and 3 report respectively:
- the application fields in different soil conditions of some systems of consolidation in comparaison with the TREVIMIX.
- The results obtained with such systems, in terms of compressive strength.
- The time needed to get such results.

METODO *METHOD*	TIPO DI TERRENO *TYPE OF SOIL*				OSSERVAZIONI *REMARKS*
	ORGANICO *ORGANIC*	ARGILLOSO *CLAYEY*	LIMOSO *SILTY*	SABBIOSO *SANDY*	
TREVI-MIX *TREVI-MIX*					EFFICACE ANCHE NEI TERRENI ORGANICI *EFFECTIVE EVEN IN ORGANIC SOILS*
DRENI VERTICALI *VERTICAL DRAINS*					
PALI DI COMPATTAZIONE IN SABBIA *SAND COMPACTION PILES*					
COLONNE DI CALCE *QUICK LIME COLUMN*					POCO EFFICACE NEGLI STRATI INTERPOSTI TRA STRATI DI SABBIA *POORLY EFFECTIVE THROUGH LAYERS INTERBEDDINGS SANDY STRATA*
INIEZIONE DI MISCELE LIQUIDE *GROUTING*					

Fig. 1





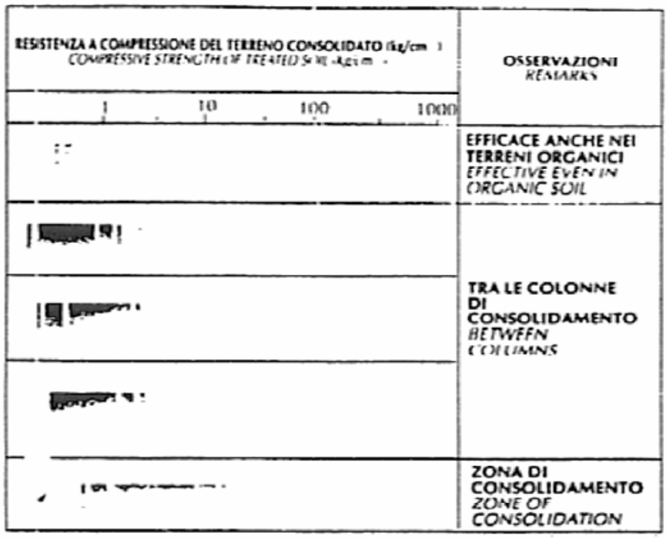

RESISTENZA A COMPRESSIONE DEL TERRENO CONSOLIDATO (kg/cm)
OSSERVAZIONI
REMARKS
1
10
100
1000
EFFICACE ANCHE NEI TERRENI ORGANICI
EFFECTIVE EVEN IN ORGANIC SOIL
TRA LE COLONNE DI CONSOLIDAMENTO
BETWEEN COLUMNS
ZONA DI CONSOLIDAMENTO
ZONE OF CONSOLIDATION

Fig. 2

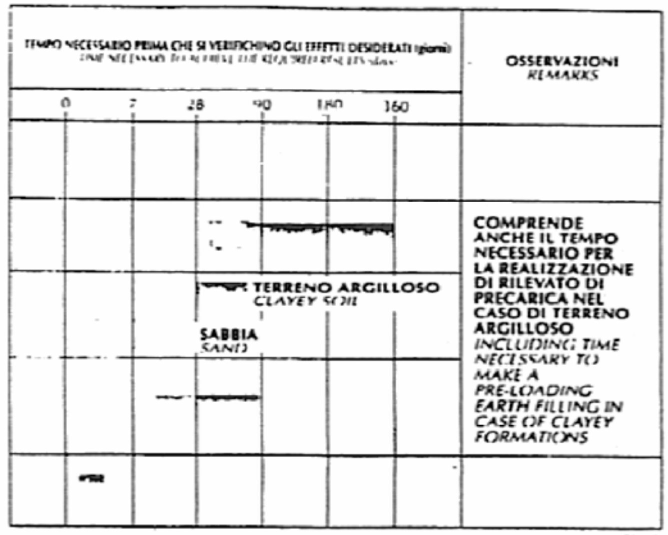
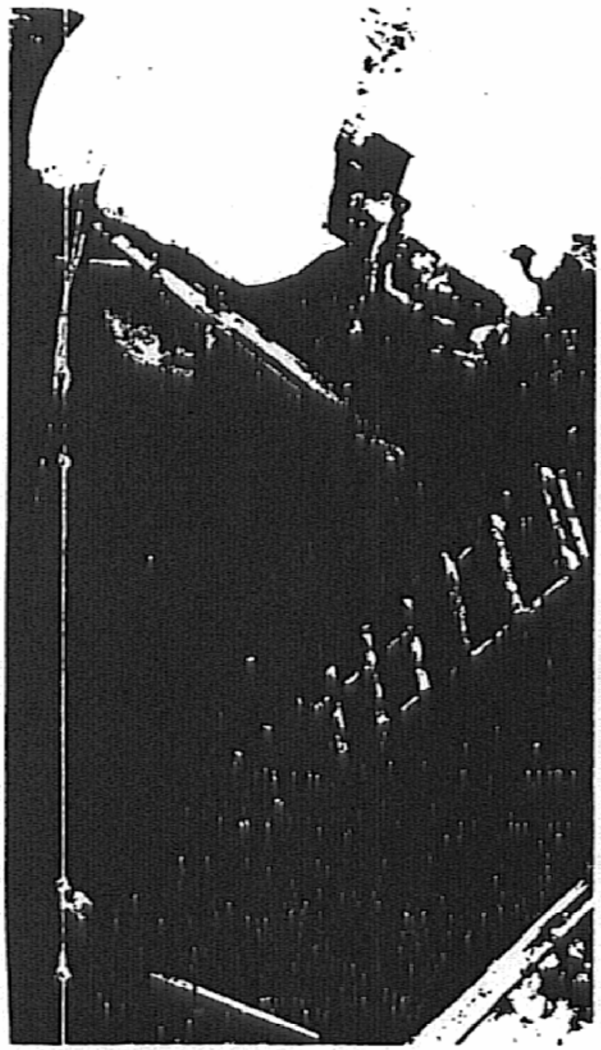
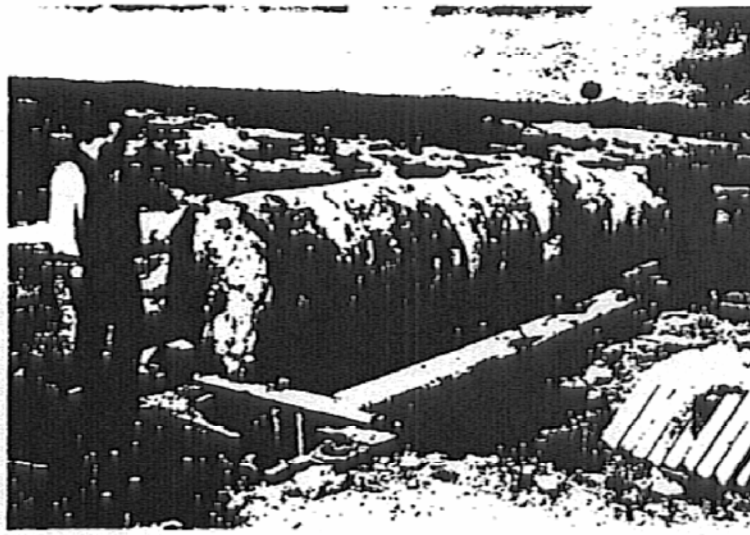
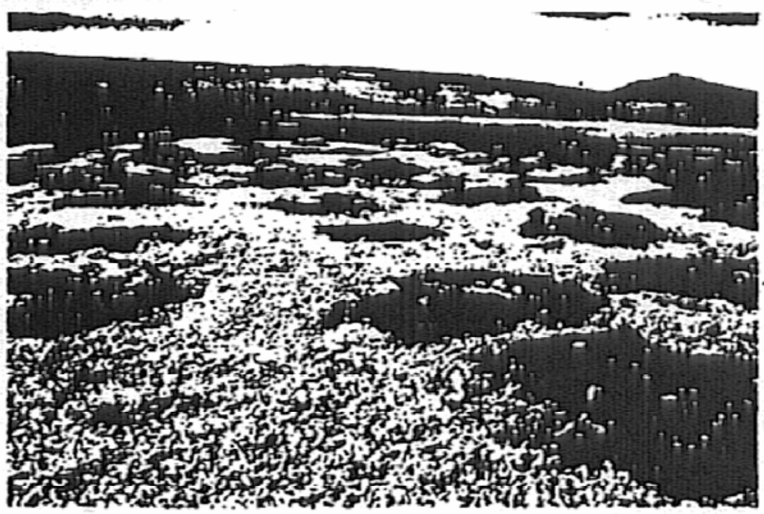

TEMPO NECESSARIO PRIMA CHE SI VERIFICHINO GLI EFFETTI DESIDERATI (giorni)
OSSERVAZIONI
REMARKS
0
7
28
90
180
160
TERRENO ARGILLOSO
CLAYEY SOIL
SABBIA
SAND
COMPRENDE ANCHE IL TEMPO NECESSARIO PER LA REALIZZAZIONE DI RILEVATO DI PRECARICA NEL CASO DI TERRENO ARGILLOSO
INCLUDING TIME NECESSARY TO MAKE A PRE-LOADING EARTH FILLING IN CASE OF CLAYEY FORMATIONS

Fig. 3







Caratteristiche operative
Operations features

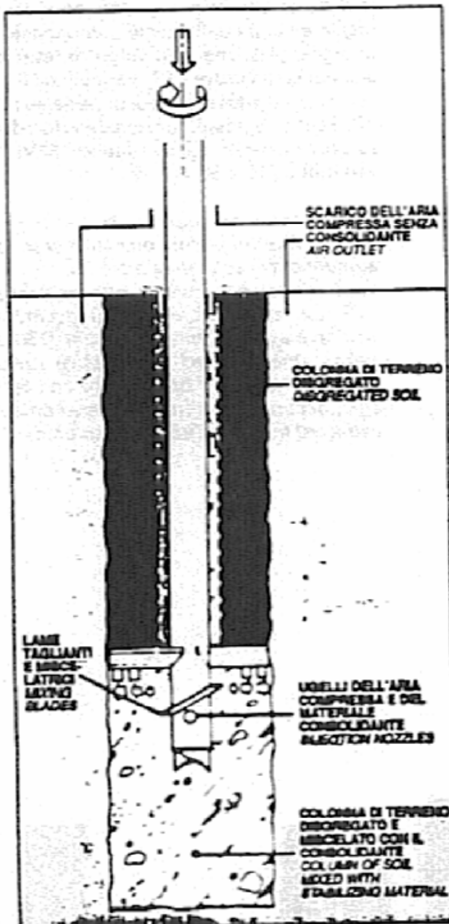
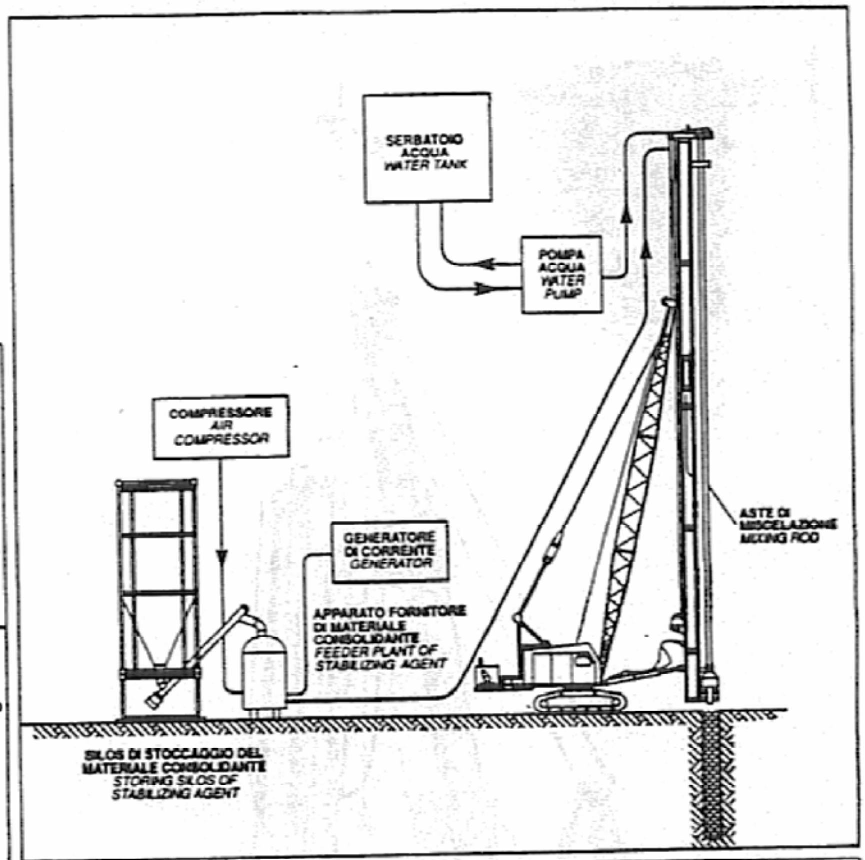


Fig. 4



ATTREZZATURA TIPO *EQUIPMENT MODEL*	-	MONOTESTA *SINGLE HEAD*	BITESTA *TWIN HEAD*
DIAMETRO MIXER *MIXER DIAM.*	mm	800-1000	800-1000
NUMERO MIXER *NUMBER OF MIXERS*	-	1	2
INTERASSE MIXER *MIXER CENTER DISTANCE*	mm	-	800-3000
VELOCITA' DI ROTAZIONE DEL MIXER *MIXER ROTATION SPEED*	rpm	5-50	5-50
COPPIA MASSIMA *TORQUE MAX*	kgm	4000	4000
PROFONDITA' MASSIMA *DEPTH MAX*	m	30	22
VELOCITA' DI AVANZAMENTO E DI RISALITA *DRIVING AND RAISING SPEED*	m/min	0.5-3.0	0.5-3.0

Il materiale stabilizzante trasportato dall'aria viene proiettato attraverso opportuni ugelli posti in prossimità delle lame facenti parte del "mixer", verso i vuoti prodotti nel terreno dalla rotazione delle lame opportunamente sagomate a tale scopo.

Quando l'agente consolidante e l'aria entrano negli spazi vuoti, la pressione si riduce rispetto a quella presente all'interno delle aste e la conseguente diminuzione della velocità del flusso comporta l'impossibilità di ulteriore trasporto del consolidante. Questo ultimo si deposita pertanto negli spazi vuoti delle lame.

L'agente consolidante viene a questo punto mescolato al terreno grazie all'azione delle lame.

Il materiale stabilizzante risulta in tal modo distribuito e miscelato uniformemente su tutto il campo di rotazione del "mixer".

L'aria, esaurito il compito di trasporto, si libera verso la superficie del terreno attraverso gli spazi vuoti esistenti tra la batteria di aste ed il terreno (Fig. 4).

La batteria di aste utilizzata è attrezzata con un sistema di invio dell'acqua, da utilizzarsi in tutti quei casi in cui si debbano attraversare livelli di terreno asciutti. In tali casi l'acqua ha la funzione di fornire al terreno l'umidità necessaria alla reazione di presa dell'agente stabilizzante con il terreno.

L'agente consolidante viene inviato alla attrezzatura di perforazione e trattamento per mezzo di una centrale automatica di stoccaggio e fornitura.

The air driven stabilizing material is ejected to the voids left in the soil by the rotation of the especially-shaped blades of the "mixer", through nozzles fitted close to such blades. When the agent with the air fill the voids, the pressure drops in respect of that existing inside the rods, and the consequent reduction of the flow speed prevents that additional amounts of agent are transferred into the soil. The agent settles in the voids and then rotation of the blades provides mixing with the soil.

The stabilizing material is thereby spread and evenly mixed all over the zone covered by the rotation of the mixer.

The air, having completed its driving function, freely flows out to the surface through the annular space between the rod string and the soil (Fig. 4).

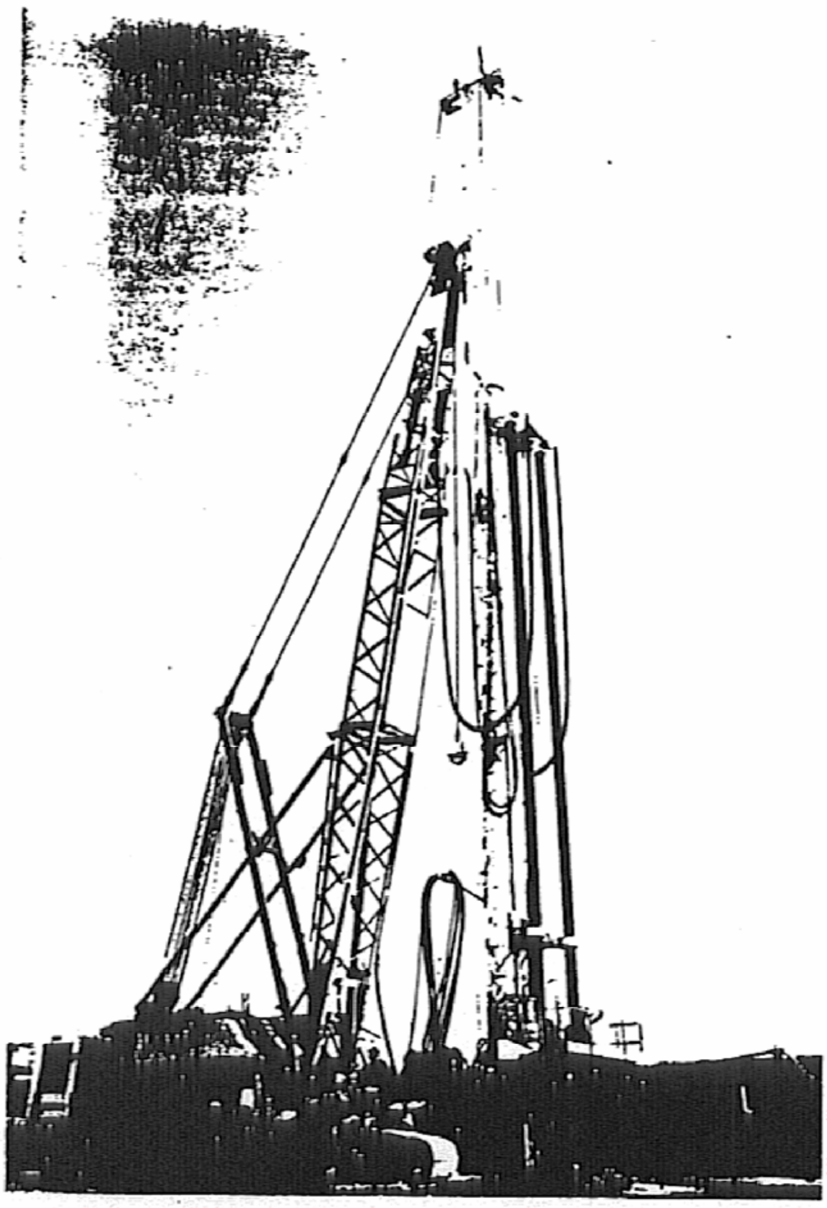
The rod equipment is provided with a water circulation system which is used when dry layers of ground have to be penetrated. In such cases, the water is the mosturizing mean that provides the setting reaction of the agent with the soil.

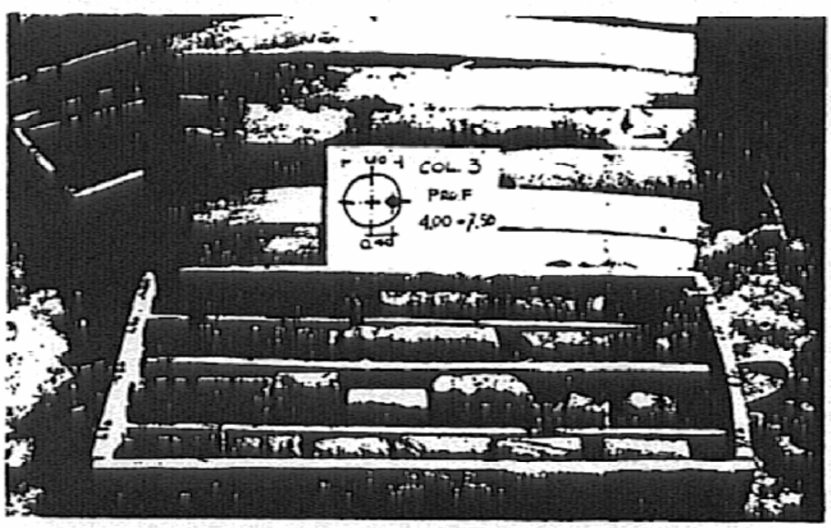
The agent is conveyed to the drilling and treatment equipment from an automatic storing and feeder plant.

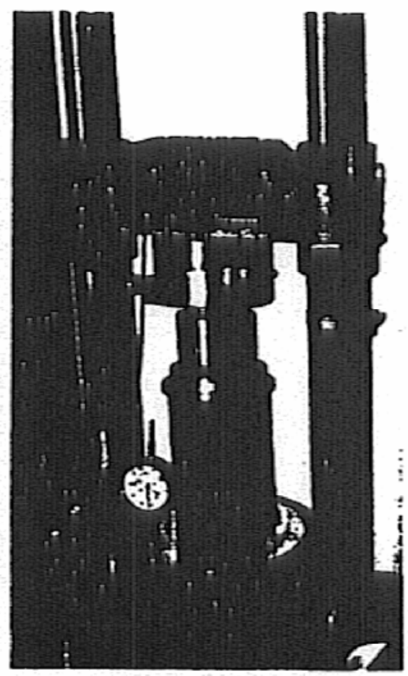
Caratteristiche del terreno trattato
Treated soil specification

La resistenza a compressione ad espansione laterale libera (E.L.L.) dipende principalmente dalle caratteristiche del terreno e dal dosaggio e natura dell'agente consolidante.
In argille plastiche, con valori di resistenza alla punta, da prove CPT, variabili da 5 a 10 kg/cm², e con dosaggi medi di cemento (150-250 kg/mc), è possibile ottenere valori di qu, su provini estratti dalle colonne TREVIMIX, variabili da 10 a 50 kg/cm².

The unconfined expansion compressive strength mostly depends on nature of soil and amount of consolidating material.
In plastic clays, showing point resistance at CPT test ranging from.5 to 10 kg/cm2 and with average contents of cement (150-250 kg/m3), the reported compressive strength "qu" values, varied between 10 and 50 kg/cm2, according to tests performed on cores extracted from the TREVIMIX columns.







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APPENDIX 2. OBSERVATIONS ON SCANDINAVIAN PRACTICES FROM VISIT TO FINLAND AND SWEDEN, MAY 1997

Lime-Cement Column Method in Finland

A site visit was conducted on Tuesday, May 20, 1997, to a large lime-cement column project near Helsinki, Finland. The following general and specific data were provided by Jouni Happonen, Project Manager for YIT Corporation (Contractors), and Pentti Salo, Geotechnical Services Manager, Finnish National Road Administration.

Details of Project Visited

The work was being conducted to improve very soft clays to permit construction of Ring Road 2 with minimal settlement. Clay thickness varied from 5 to 21 m, and treatment was being conducted over a total length of 1400 m and a width of 30 m. A total of 50 mm of settlement is permitted within 1 year. Columns are 600 mm diameter at 1-m centers, generally on a triangular grid, reduced to 800-mm centers near a sewer. A total of 20,000 columns, for a total of 340,000 lin. meters, are being installed. The price is about $200,000 mobilization/demobilization (for 3 rigs), plus $6 to $7/m for columns. (This is regarded as being below the industry average, but given the large scale of the job, it is understandable.) Most jobs are less than $500,000 in value. This project is about 40% complete, and a good day's production is 1000 lineal m/10-h shift per machine. Details of YIT's system are provided in Attachment 11.

Three machines were in use:

- One large machine with a 120-mm-square Kelly and bottom drive, 100 rpm, and 21-m depth capacity at 600 mm diameter (up to 1 m is currently possible). This machine is associated with a crawler-mounted two-tank unit of 8 tonnes capacity. This machine weighs about 25 tonnes.
- Two slightly smaller rigs, each self-contained, with a top rotary head, 100-mm rods, 15-m depth potential, and 150 rpm.

Rate of advance is 150 mm/rotation going down (variable), and 15 mm/rotation on the way up (constant). Air is introduced going down to break up the clay and keep the port open: 35 kg/m of powder is blown in at 0.7 MPa on the way up. All is computer-controlled and recorded. Air escapes easier with square rods. There was very little surface spoil.

- 1.2 m is considered to be the largest practical diameter (depending on depth and soil).
- Material is 50:50 lime to cement ratio, pre-blended on site as appropriate.
- Shear strength of column is 100 to 120 kPa (50% UCS).
- Contractor is responsible for QA/QC, but he subcontracted this to a geotechnical testing lab (Viatek). Test program included CPT (also in 0.2% columns), and column exposure and extraction.

Typical routine data sheets and the official job description are attached as Attachment 2.

Lime-Cement Column Method in Sweden
(Meeting With G. Holm, SGI)

Around 1967, Kjeld Paus, a Norwegian contractor living in Sweden, began to conduct research, together with his personal contracts at SGI and Bengt Broms. This followed a visit to the United States where he observed Hayward Baker, Inc. installing lime-cement slurry columns. Test columns were installed at the famous SGI test facility outside Stockholm in very soft clays, using only quicklime. These were excavated and tested. Further laboratory tests followed, including testing of soils from other sites with various "binder" additions. Lime was used initially since surface soil stabilization with lime was common. The lime also gave continuing improvements with time (pozzolanic, ion exchange, drainage, etc.). More field testing was carried out at test embankments from 1972 to 1974.

SGI had an excellent link with an engineer from the Municipal Authority of a Stockholm suburb. A solution was designed in 1974 and implemented in 1975. This was for excavation support and ground reinforcement for a pipeline. The firm Linden-Alimak (L-A) had bought the patent from Paus and installed the columns. The project was very successful. L-A continued until the mid 1980s when the patent expired and new ownership took the company in new directions.

SGI had published the 1974 papers on the test work, without any contact with Japan, and had continued with minimal technical exchange since then. Initial columns were 500 mm diameter by 10 m deep (for most Swedish applications). Now 1.0 or 1.2 m to 30-m of depth (Göteborg), is possible, although most are 600 mm, and 800 mm is also a popular choice. This graph also illustrates a slow, but steady, growth until about 1989 after which growth has been very rapid, despite a relatively flat general economic situation. This has been due to:

- Great demand by road and railway authorities.
- Greater awareness and acceptance (fostered by SGI) among owners and consultants.

Output is currently around 3 to 4 million meters/year (1994 was similar to 1995 and 1996), probably peaked when compared to a total Scandinavian and Southeast Asian output of 6 million lineal meters. Columns are used in place of piles, lightweight fills, and drains. Most projects have more than 30,000 lineal meters to be installed. Typical production rates are 400 to 1000 lineal meters/8-h shift (depending on the amount of additive, diameter, penetration rates, and lifting rate).

Research continues into:

- Their use in even poorer ground (organics).
- New materials (gypsum, flyash, different cements).
- Mixing tools.
- Design methods.
- QA/QC.
- Use of sand in organic soils (now stopped by Japanese due to accelerated equipment wear, but apparently still pursued by Trevisani).

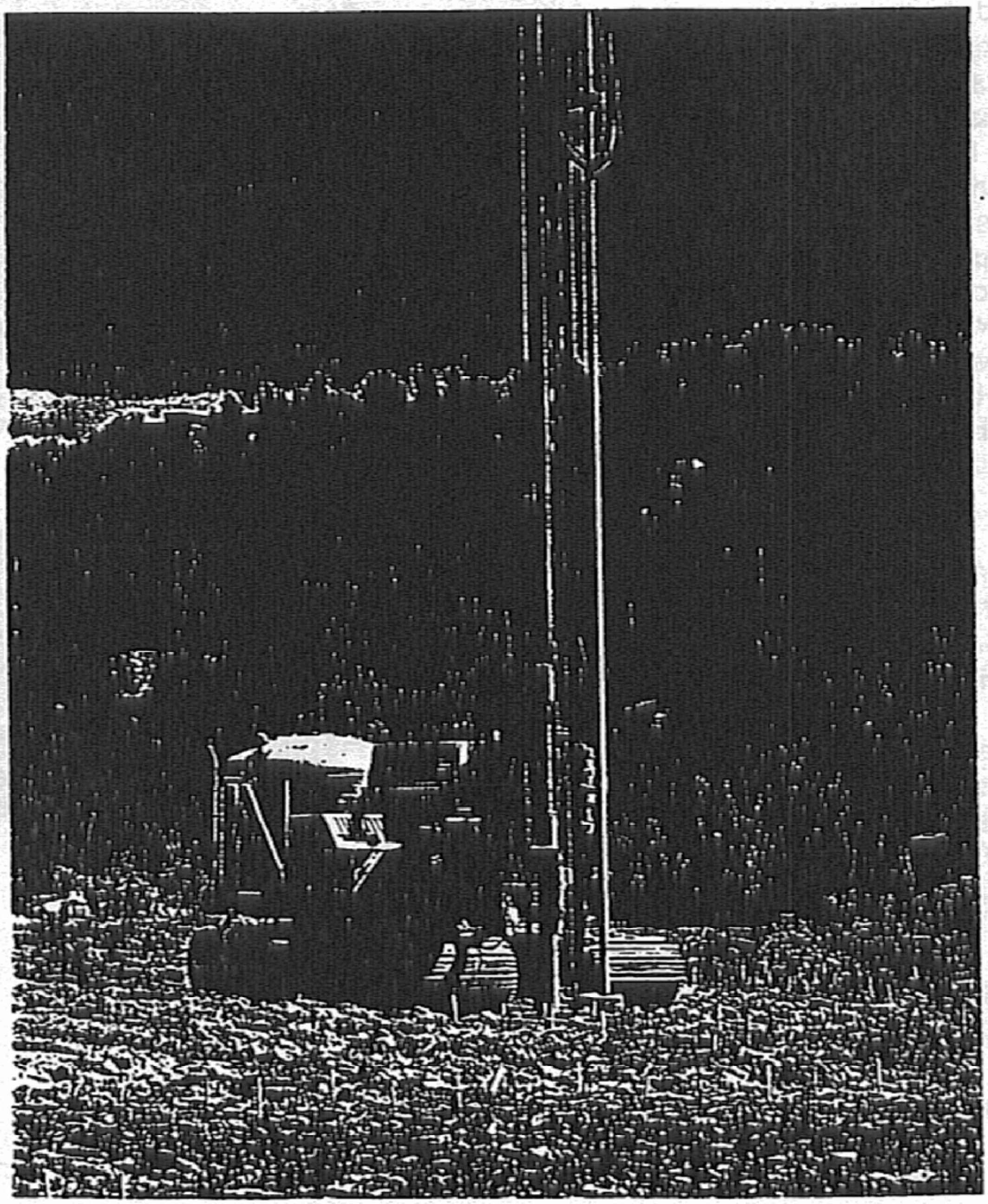
Various data confirm the almost exclusive use of lime-cement materials in current practice.

Other key dates:

- 1985 – 10-year review of research and experience to date (SGI: Åhnberg and Holm).
- 1995 - Swedish Deep Stabilization Research Center consortium formed for 5-year, $4-million research plan (under Holm).
- 1995 - Swedish Geotechnical Society issues specifications for use.
- 1996 – 21-year update published.

(Most recently, an additional European research program has been funded, focusing on infrastructure enhancements, e.g., high-speed rail lines.)

DEEP STABILIZATION with lime and cement column method

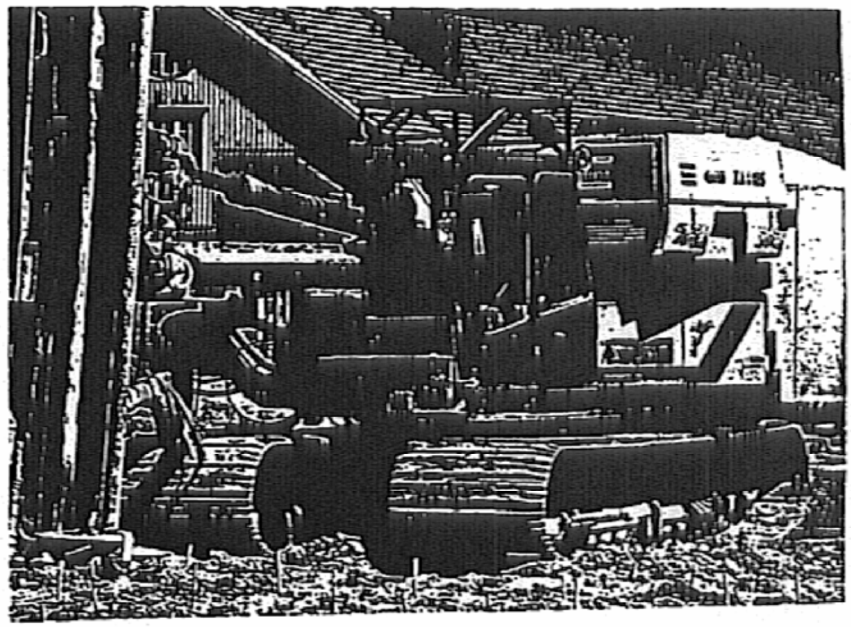


DEEP STABILIZATION

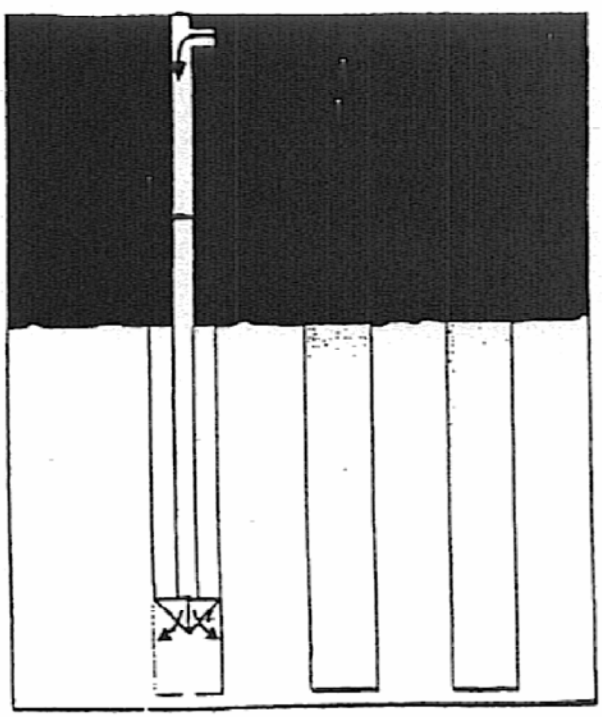
with lime and cement column method

The deep stabilization by lime or cement columns is a method that helps to cut down expenses of foundation comparing to piling. The savings in costs are not achieved only by columns, but also the upper structure has effect on the costs of the whole structure.

Deep stabilization is carried out by drilling into clay or silt with a mixing machine which has a mixing blade, diameter 0,5 m. When the planned depth has been reached, the mixing blade is raised up and the rotation direction is changed and the rotation speed of the mixing blade is increased at the same time. A powdery or granular agent is pneumatically fed into soft soil, improving the stability and strength of the soil. The stabilizing agent fed pneumatically is injected into the void created behind the mixing blades by their rotation and is distributed uniformly throughout the entire area traced by the blades.



The air separated from the stabilizing agent rises along the rotating shaft through the clearances between the shaft and the soil, and is released into the atmosphere.



As a result, there will be a column, diameter 0,5 m, which solidity is multiple compared to the soil. Stabilizing is happened as the lime binds water in the soil. From that follows an ion exchange in clay minerals, and in time this improves the solidity of stabilized ground.

A uniform strength is obtained in the surrounding stabilized soil.

The method has been used in Finland already twenty years. Experiences have always been positive.

Where to use deep stabilization

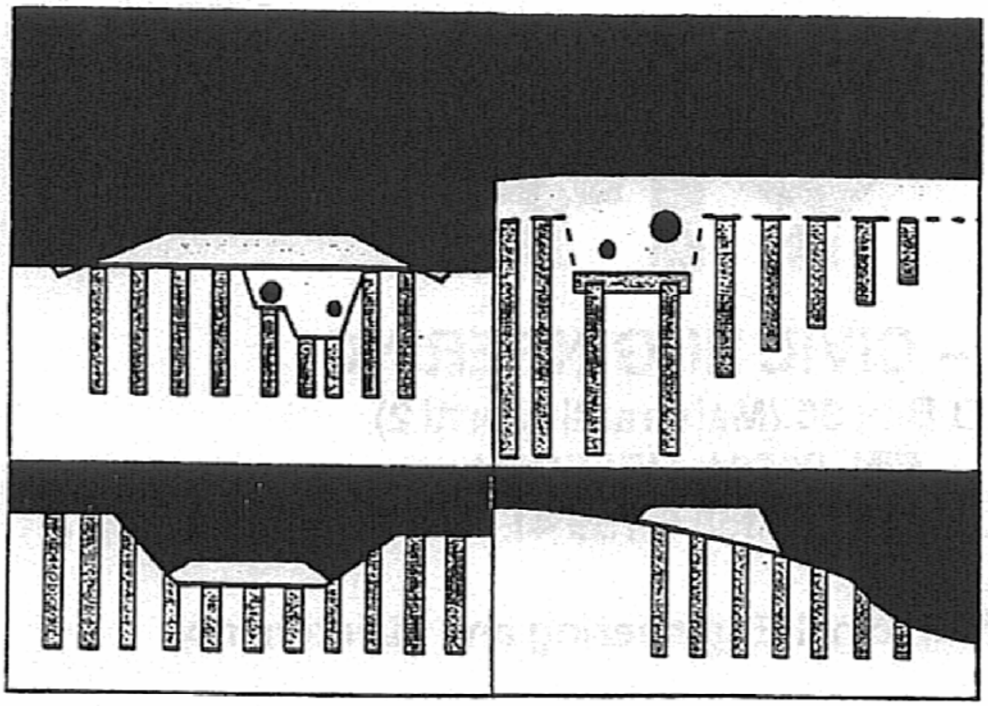
Lime and cement column stabilization is a perfect solution of foundation in large scale project areas. As a method for solidating ground, it is very competitive on large areas.

Streets, pipelines and the network of technical service
- *prevention of disadvantageous impressions*
- *improvement of the stability in building pit's excavations*
- *improvement of stability in banks*

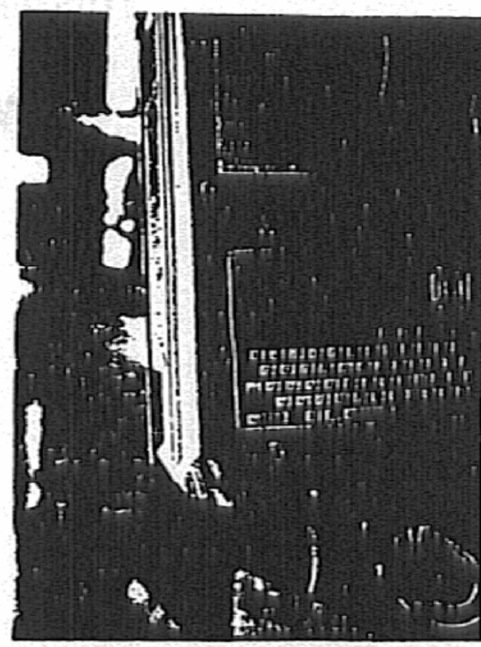
The construction in a slope or in a cutting
- *improvement of stability*

Different kinds of transfer constructions
- *evening of impressions*

Pipeline construction
- *exhaust of disadvantageous impressions*
- *improvement of street's stability*



Deep stabilization is carried out with modern methods and equipment.



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Attachment 12. Typical routine data sheets and official job description of project visited.

PIARC DEEP STABILIZATION IN FINLAND

The road embankment of ring road 2 of Helsinki, Espoo, Lystimäki-Turunväylä

THE PRIMARY FUNCTION OF THE STABILIZATION
The deep stabilization has been used to improve the stability and reduce the settlement of the road embankment.

The road embankment

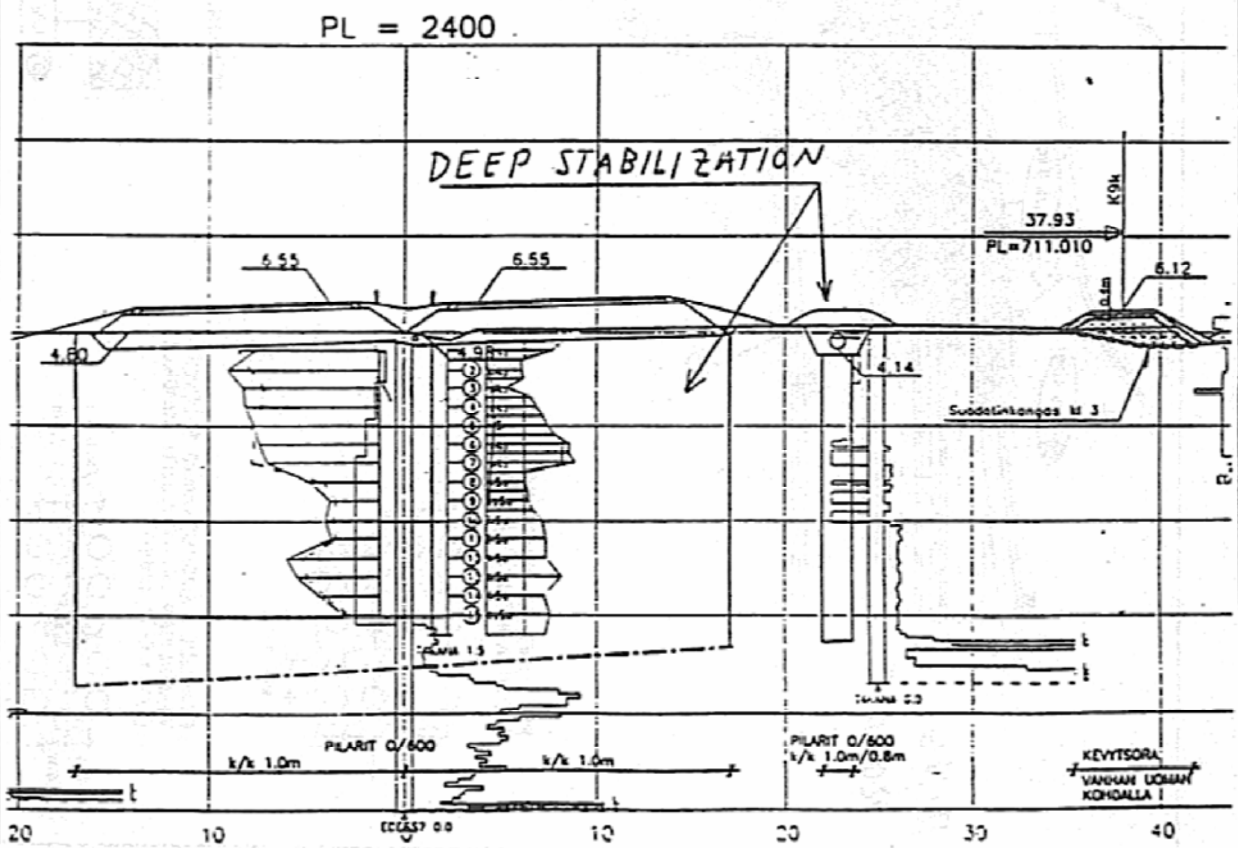
The deep stabilization has been made in winter 1996-97 and the work will be continued. The deep stabilization has been made with ϕ=600 mm columns. The height of the columns is 2...20 m and the distances of the columns are 0,8...1,1 m. The height of the road embankment is about 1...3,5 m. At this construction phase there are five separate stabilization areas. About 1440 m of road embankment will be constructed over deep stabilization.

The location of the trial embankment

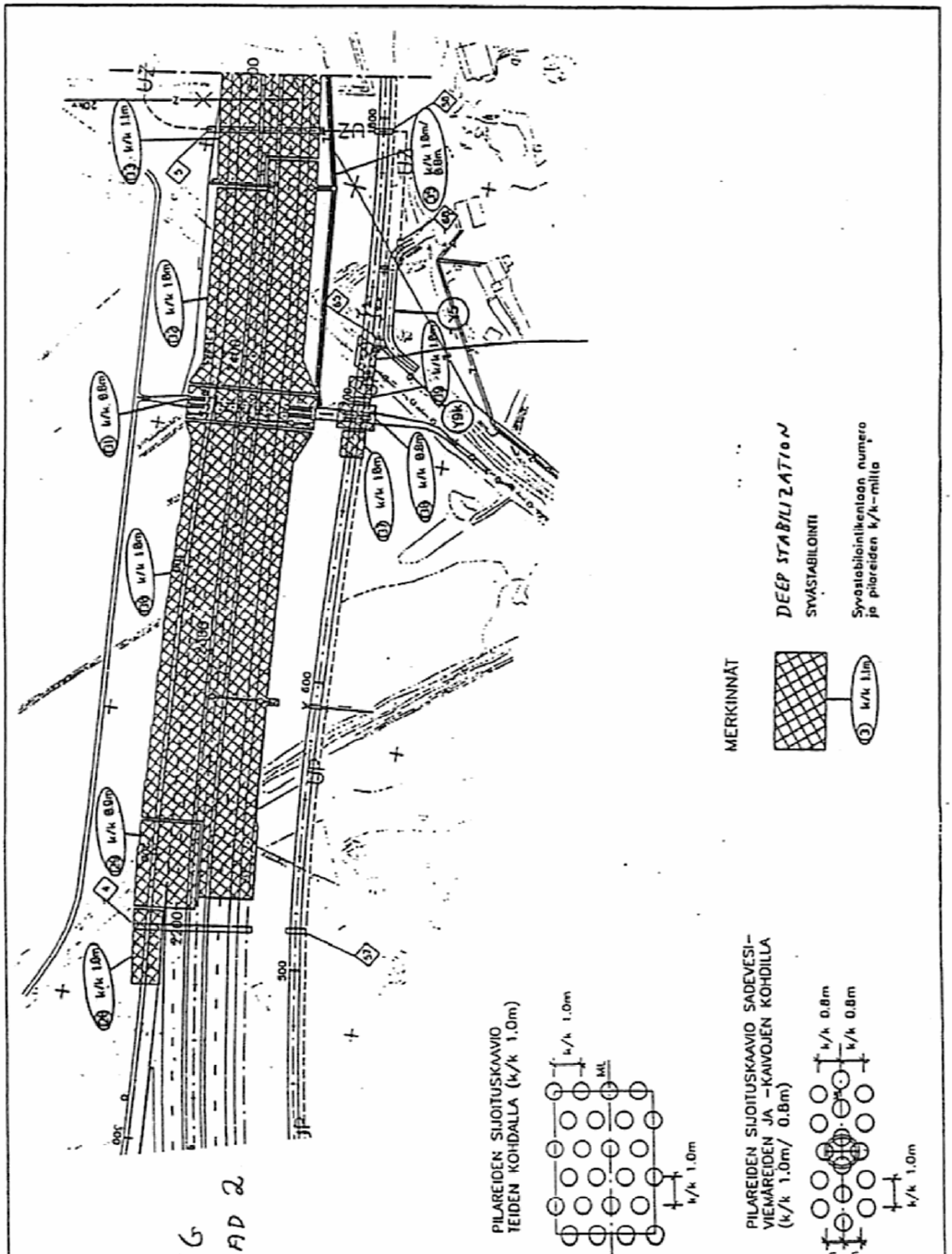
The ring road 2 of Helsinki will be constructed between ring roads 1 and 3 at Espoo about 15 km from Helsinki to north-west.

The properties of the ground

The uppermost layer of the ground, 0...1 m, is crust. Under the crust there is about 2...20 m layer of mud and soft clay (w=20...210 %, τ=5...15 kPa). Under the clay layer there is silt/sand and glacial till.



The road embankment of ring road 2 of Helsinki, Espoo, Lystimäki-Turunväylä



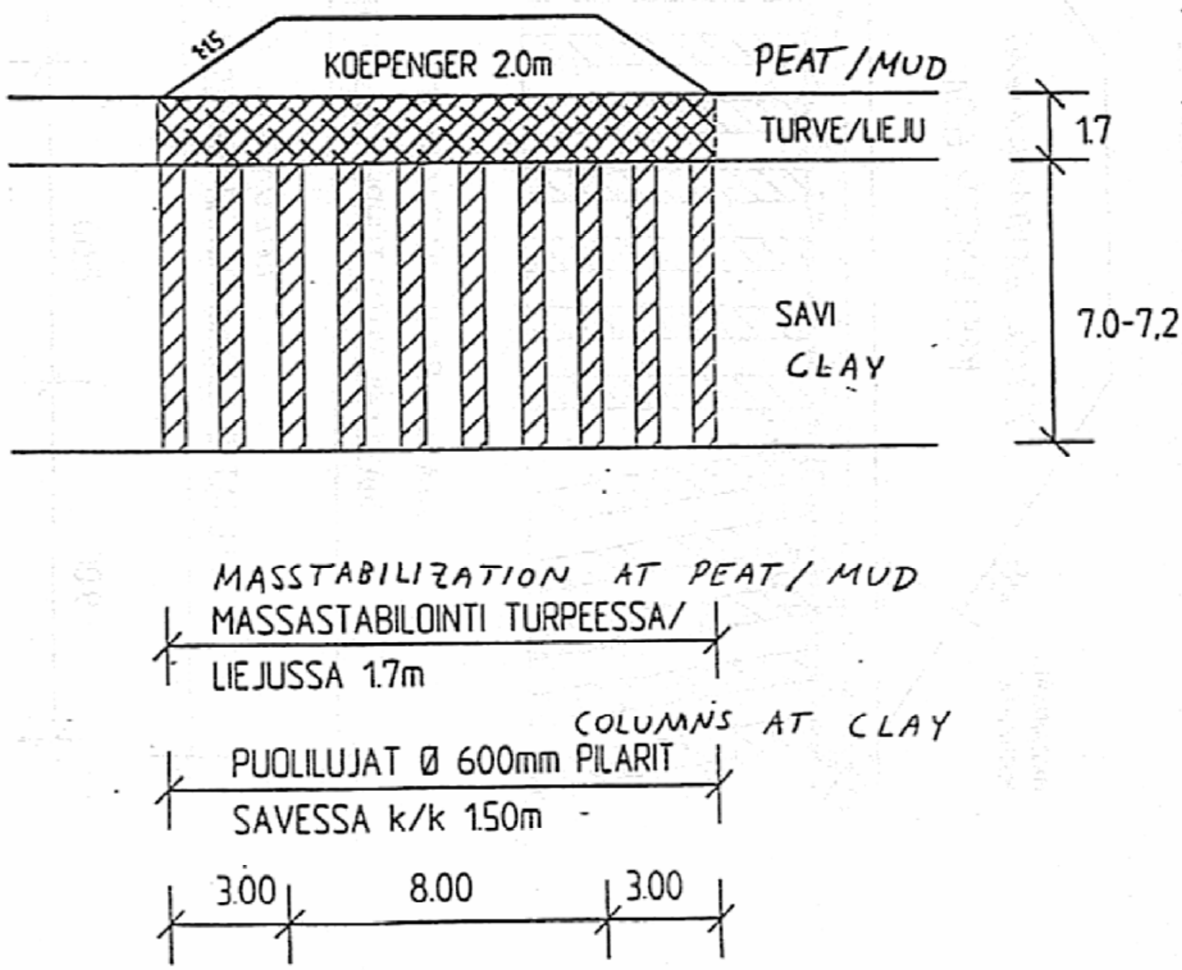
The trial embankment in Kirkkonummi, Tolsa, KT51

THE PRIMARY FUNCTION OF THE STABILIZATION
The deep stabilization and masstabilization has been used to improve the stability and reduce the settlement of the trial embankment.

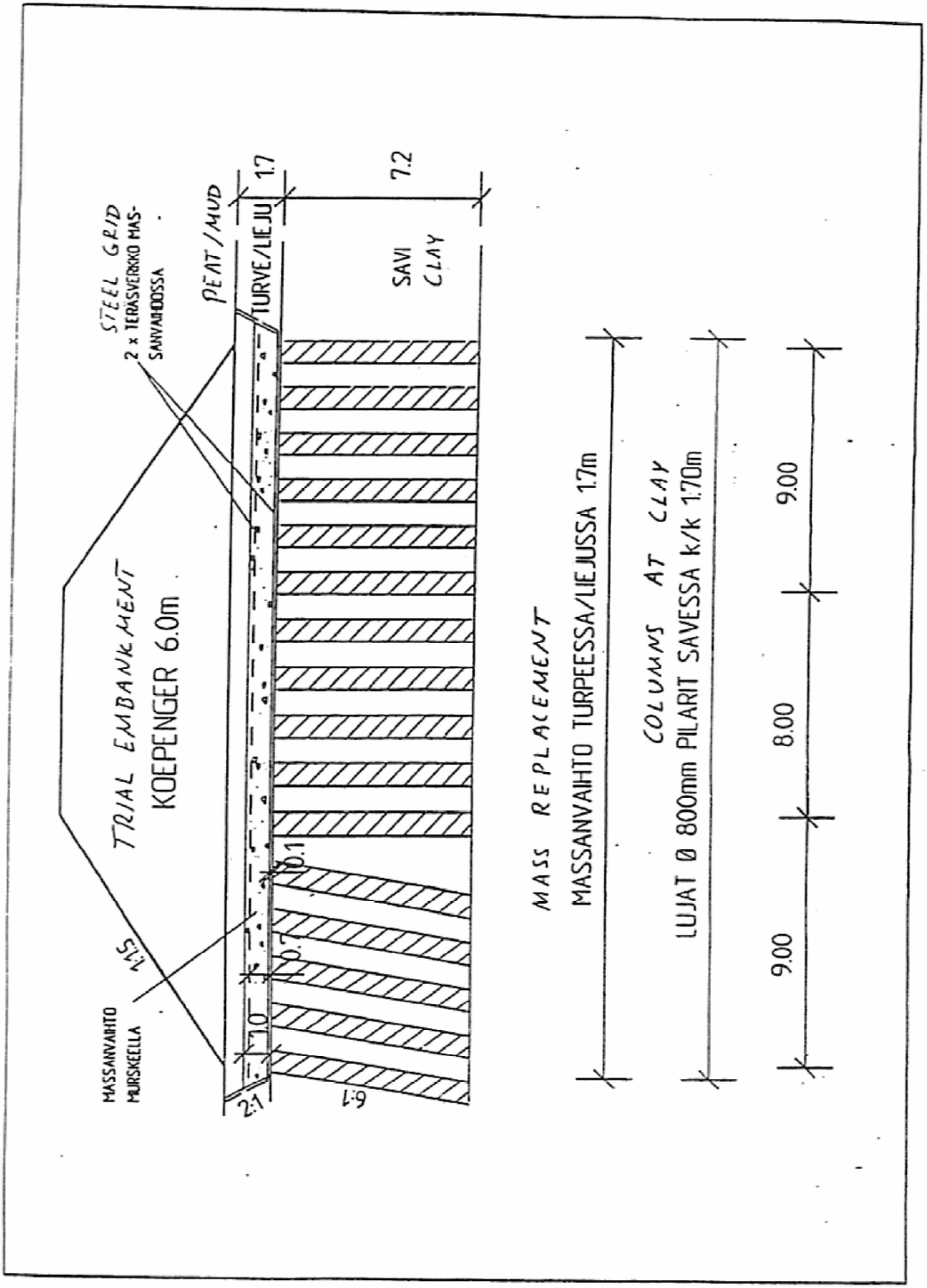
The trial embankment
The deep stabilization and masstabilization has been made in autumn 1996. The construction of the full scale trial embankment will be made in winter and spring 1997. The deep stabilization has been made with ϕ=600 mm columns under the 2 m embankment and with ϕ=800 mm under the 6 m embankment. The columns are at the depth 1,7...9 m. Under the 2 m embankment has been made masstabilization at the depth 0...1,7 m. Under the 6 m embankment has used mass replacement method with steel grids to reinforce the embankment.

The location of the trial embankment
The highway from Helsinki to Kirkkonummi may be extended in the future from Espoo to west. The trial embankment is constructed in the alignment of the highway about 25 km from Helsinki to west.

The properties of the ground
The uppermost layer of the ground, 0...0,8 m, is peat (w=200...600 %). Under the peat there is about 1 m layer of very soft mud (w=100...200 %). Under the mud layer there is about 7 m layer of clay (w=50...90 %, τ=8...15 kPa). Under the clay layer there is 6...8 m layer of silt/sand and glacial till.



The trial embankment in Kirkkonummi, Tolsa, KT51



The trial embankment in Veittoistensuo, Kausala, Vt 12

THE PRIMARY FUNCTION OF THE STABILIZATION

The deep stabilization and masstabilization has been used to improve the stability and reduce the settlement of the trial embankment.

The trial embankment

The deep stabilization and masstabilization has been made in spring 1993. The deep stabilization of the clay layers (3...18 m) has been made with ϕ=700 mm columns. The stabilization of the uppermost peat layer (0...3 m) has been done with masstabilization or column stabilization. This is the first time when the stabilization of peat has been used.

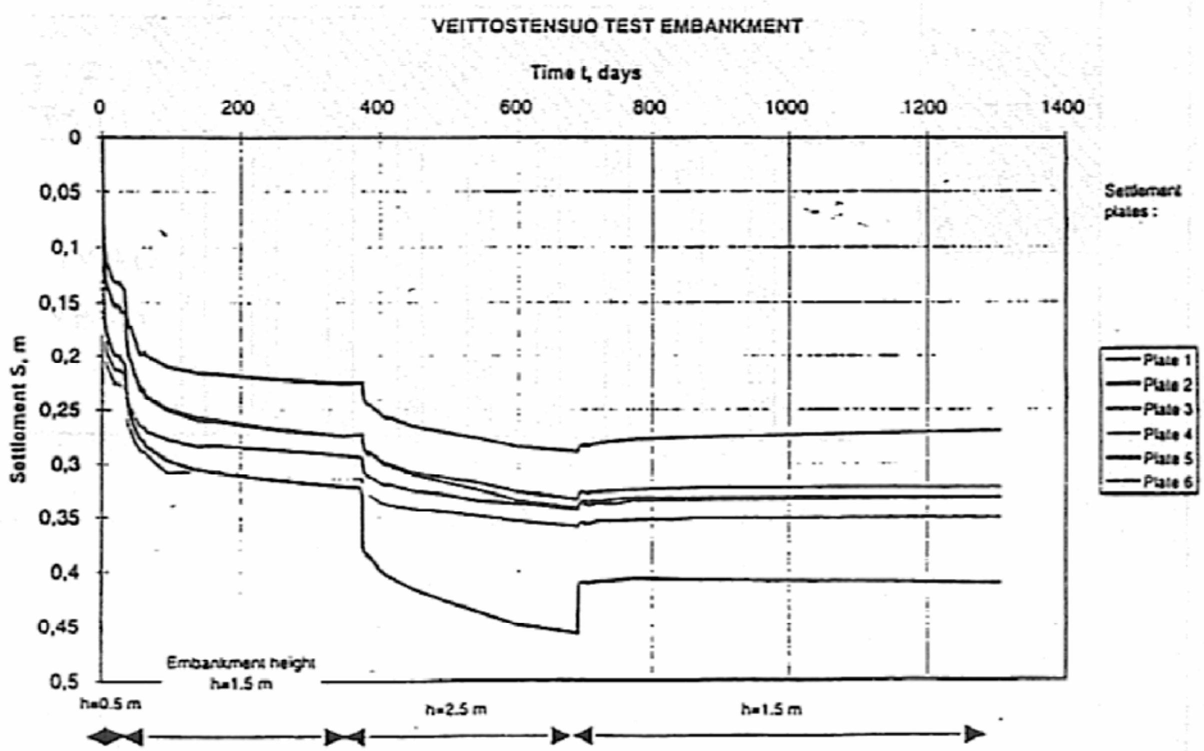
The height of the full scale trial embankment has been raised three times since construction (h=0.5, 1.5 and 2.5 m). After reducing the embankment height from 2,5 to 1,5 m (simulation of taking away preloading embankment) the settlement have practically stopped. Before the unloading the settlement of the test embankment have been 300...400 mm.

The location of the trial embankment

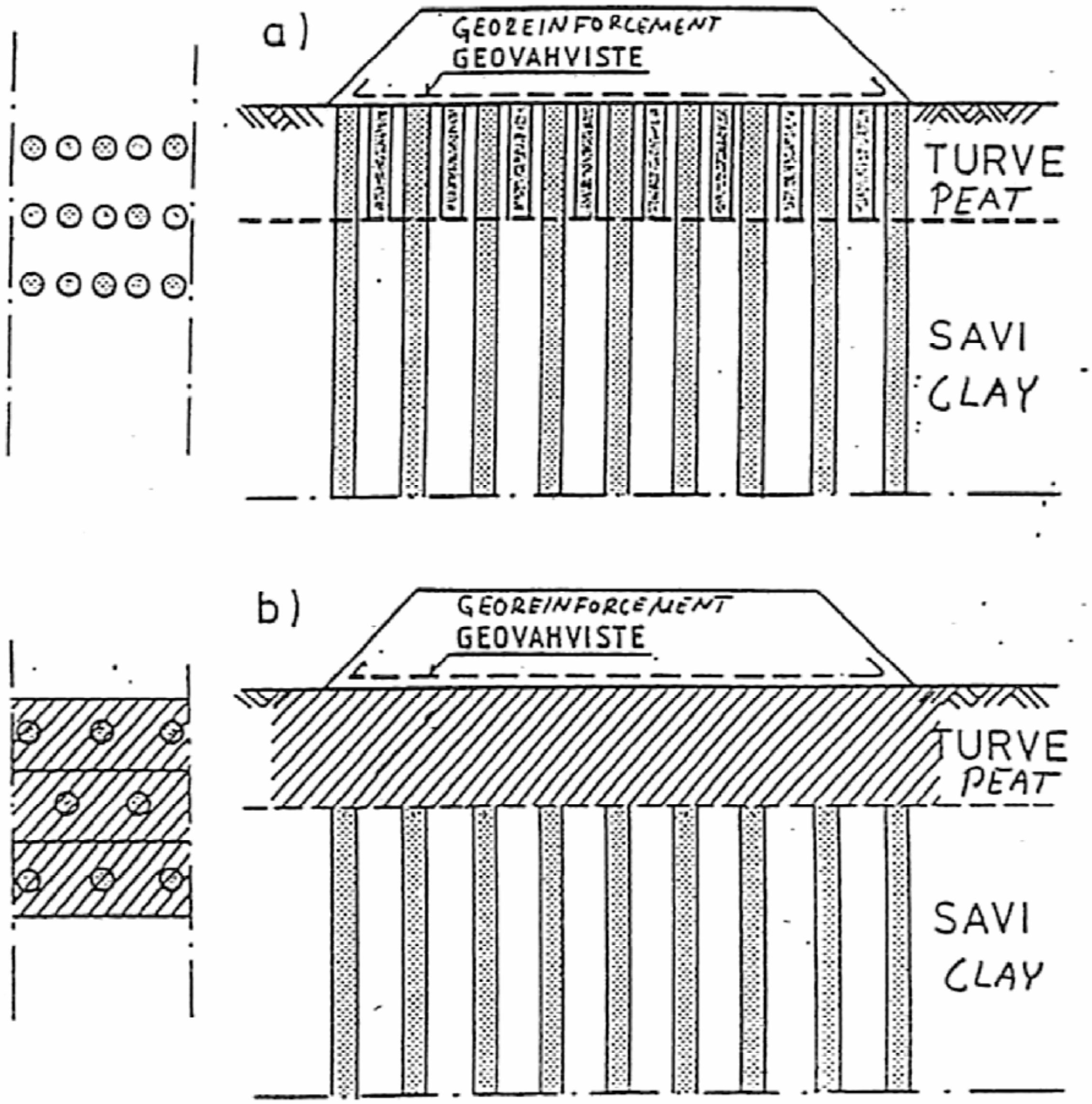
The trial embankment is at Veittoistensuo along highway 12 in south-east Finland.

The properties of the ground

The uppermost layer of the ground, 0...3 m, is peat (τ≈5...10 kPa). Under the peat there is about 15 m layer of clay (τ≈10...20 kPa). Under the clay layer there is silt and glacial till layers.



The trial embankment in Veittoistensuo, Kausala, Vt 12



The bridge embankments in Hertsby, Sipoo

THE PRIMARY FUNCTION OF THE STABILIZATION

The deep stabilization has been used to improve the stability of the bridge embankments.

<u>The bridge embankments</u>

A local road at Hertsby, Sipoo is under the repair and one new bridge over Sipoo river will be constructed. The bridge will be constructed on the cast-in-place piles in spring 1997. The deep stabilization under the bridge embankments has been made in winter 1996. The construction of the bridge embankments has been made in autumn and winter 1996-97.

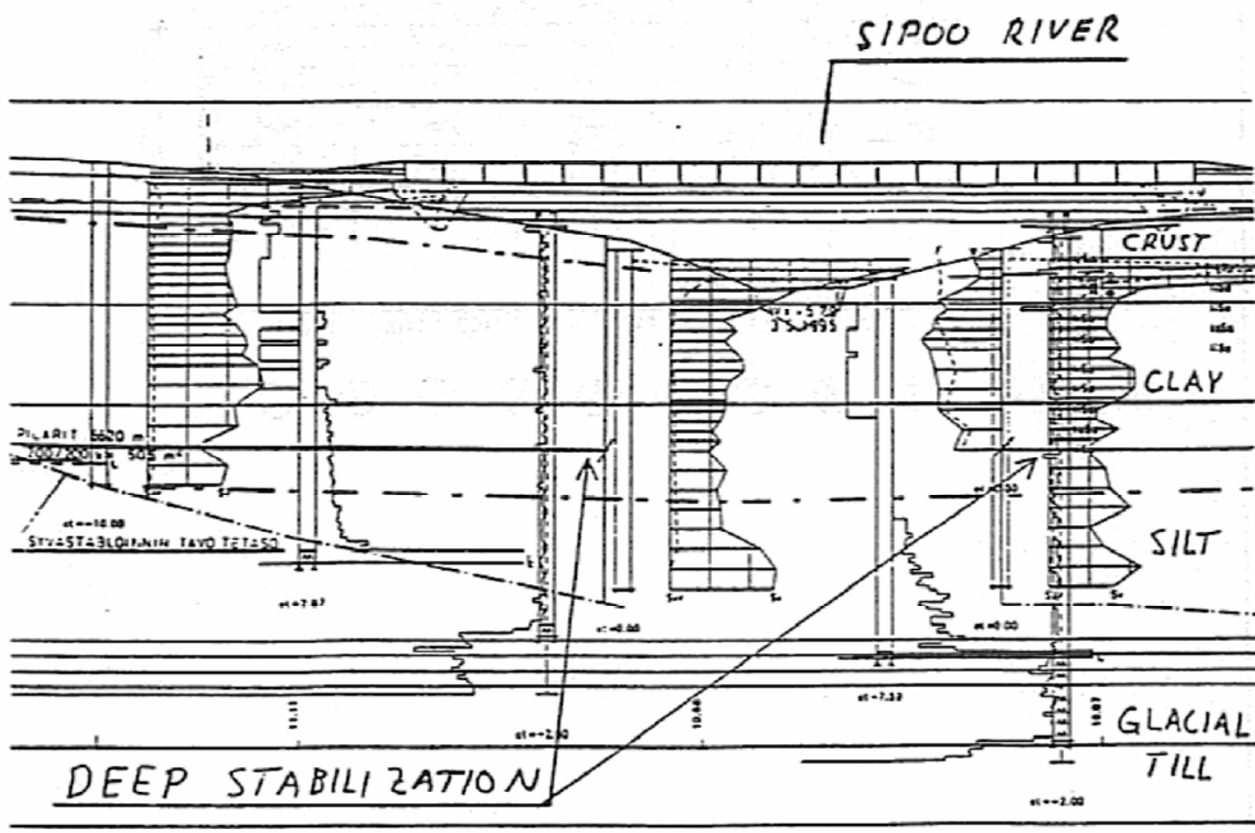
The deep stabilization has been made with ϕ=800 mm columns under the embankments. The length of the columns are 10...20 m. In the direction of the road are the columns located side by side. The height of the embankment is about 1,5...2,0 m. Over the columns is about 0,3 m sand layer and woven georeinforcement Stabilenka 200/200.

<u>The location of the bridge embankments</u>

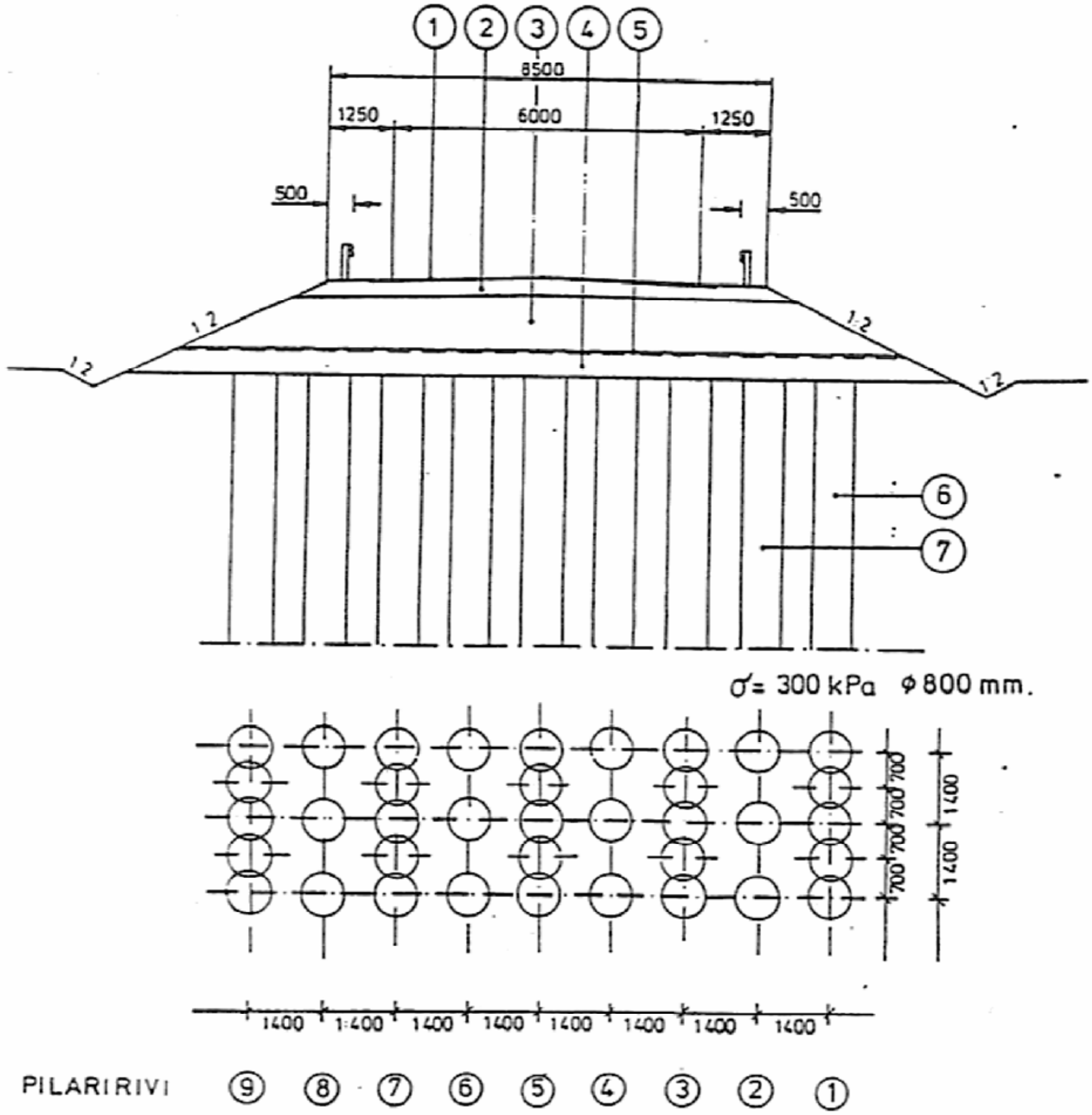
The site of the bridge embankments is about 30 km north-east of Helsinki.

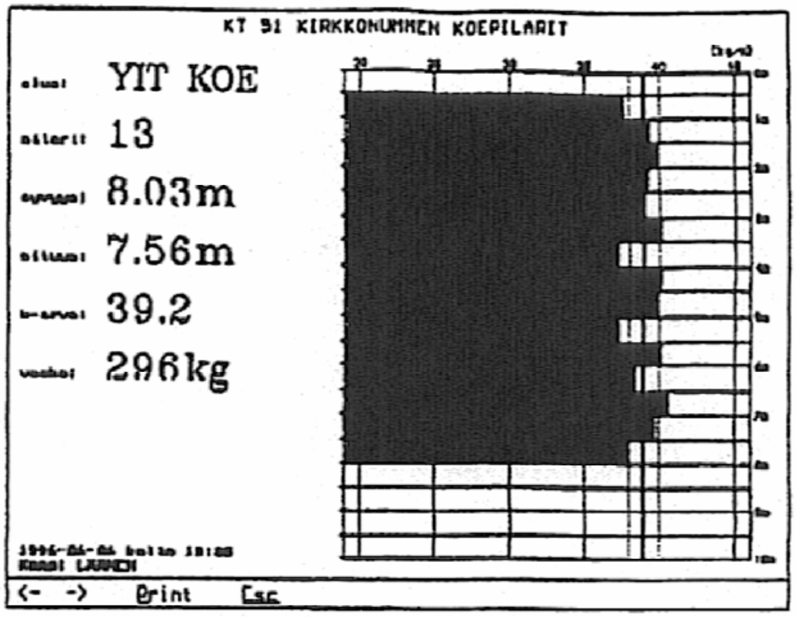
<u>The properties of the ground</u>

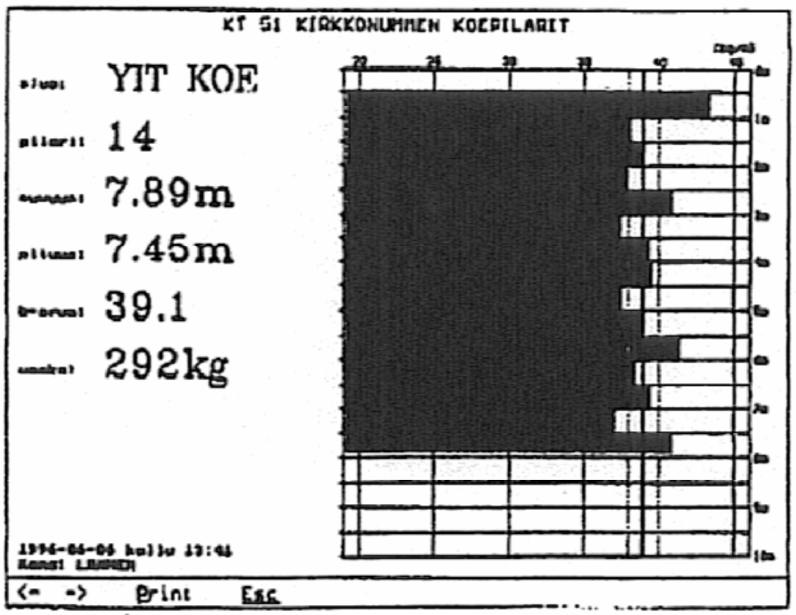
The thickness of the soft ground layers beside the Sipoo river is 10...20 m. The thickness of the crust is 1...1,5 m. Under the crust there is about 10...14 m layer of clay (τ=10...20 kPa). Under the clay layer there is about 0...6 m layer of silt. Under the silt layer there is about 1...5 m layer of glacial till.



The bridge embankments in Hertsby, Sipoo







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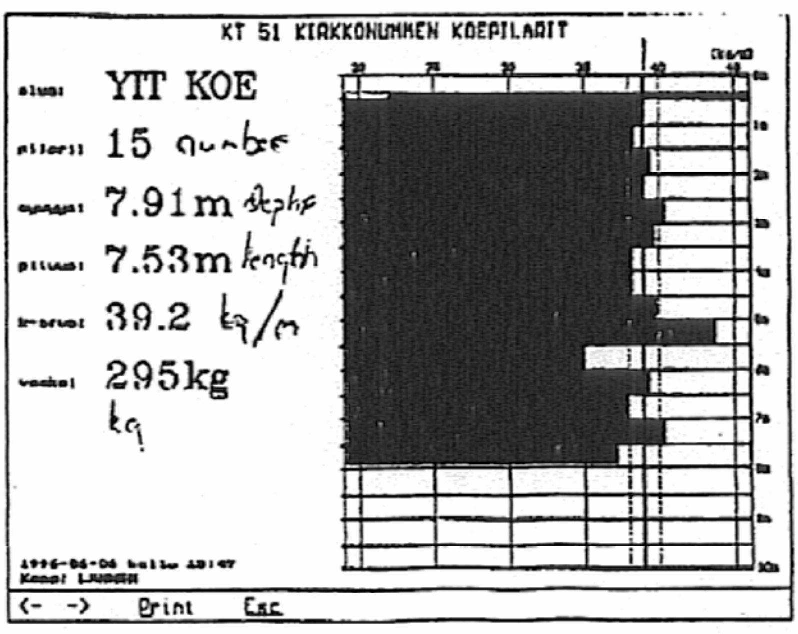


Completion time.

APPENDIX 3. NEW JOINT VENTURE FOR LIME COLUMN WORK IN THE UNITED KINGDOM
(*Ground Engineering*, 1998)

Twist of lime

A new joint venture between a UK contractor and a Swedish firm is hoping to revitalise interest in lime columns for ground improvement in the UK.

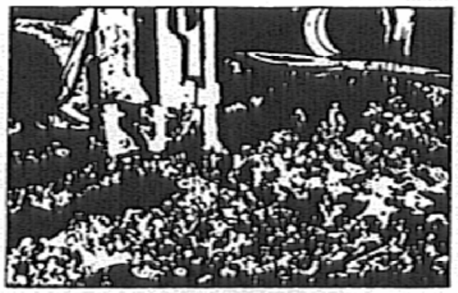
Lime columns are a tried and tested method of improving clays and silts, particularly in Sweden, although use in the UK to date is limited. The joint venture between UK's Stent Foundations and Swedish contractor Hercules Grundläggning hopes to revitalise interest in the use of the method in the UK.

The move draws on Stent's experience in the UK and Hercules' expertise in the use of dry lime and cement powder for improving soft clay and silt.

One of the reasons for this apparent lack of interest in lime columns is that use is limited to certain soil types, says Stent's Tom Schofield. "The method is largely restricted to soft estuarine clay, silt and organic rich soil, materials that are not as common in the UK as they are in Holland and Scandinavia, where lime columns are more widely used."

But lime stabilisation is not unheard of in the UK. Since 1987, Loughborough University's Geotechnical Engineering Research Group has been carrying out extensive research into lime stabilisation on clay soils. London Underground has used the technique to stabilise the failing cutting slopes and embankments throughout its network and has funded some of Loughborough's research, particularly in the application of lime columns, piles and nails.

Stent has also carried out research into the lime pile treatment of clay slopes. The work involves field and laboratory studies on a London Clay embankment, investigating a range of different mixes of lime, cement and additives for stabilisation.



Installation is through a hollow stem auger.

Lime (used in combination with cement), when mixed insitu with soft clay, increases the soil's stiffness, permeability, erosion resistance and improves its volume stability against swelling and shrinkage.

There are a number of different mechanisms at work when lime is added. Initially, a dry lime powder will react with any moisture in the clay and hydrate. This results in an increase in effective stress, as the moisture content falls.

As hydration of the lime continues, it expands and its calcium ions bond with clay minerals, increasing the soil's plastic limit, lowering its liquid limit and forming a calcium silicate gel. There is an optimum amount of added lime that results in a maximum increase in the soil's plastic limit. Any more lime added past this "lime fixation point" is used in gel formation. The gel coats and binds other clay particles, increasing the stiffness of the clay. And along with these processes, the pore water pressure of the reworked clay reduces, causing consolidation and a further increase in the soil's shear strength.

The lime and cement mix is varied according to site requirements, calculated from strength measurements of samples from test columns. In general, a greater cement content offers higher strength, and less lime added reduces the amount of moisture removed from the soil. "The aim is to achieve a balance between the two," says Schofield.

Lime columns are formed using a hollow stem auger system. Once the required depth of column is reached, rotation is reversed, the auger is withdrawn and the lime and cement mix is injected by dry compressed air through the hollow stem. The retraction rate is slower to ensure the mix is fully incorporated with the reworked soil. It is possible to carry out mixing to 25m, although more commonly columns are formed between 10m and 15m, with rates of up to 50m/hour achievable.

The whole operation is computer controlled, which Schofield says ensures the columns are formed with an even distribution of lime and cement.

The method can be used to accelerate the settlement of wet, plastic clay. Typically, 600mm diameter columns are used, placed between 1m and 1.5m apart in a grid across the site. "The columns effectively increase the permeability of the ground by an order of up to 1,000, and consolidation therefore tends to be rapid, up to twice the rate of conventional wick drains," says Schofield. "Each column can perform as well as three wick drains and offers around 20% cost saving on other more conventional methods."

Lime columns are especially useful for embankment stabilisation. For temporary works, such as road cuttings, steeper cuts can be made if lime columns are used to stabilise the ground, reducing land take. And lime columns can be used to replace sheet piles as support for temporary excavations.

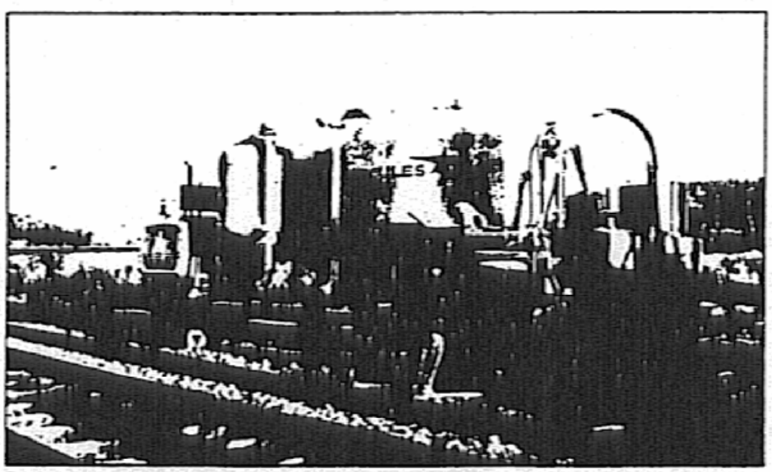
The method is used extensively in Sweden for foundations of rail and road pavements. "It is the most common foundation type for these structures in Sweden," says Schofield.

One of Hercules' current contracts is for a large road contract between Orebo and Arboga on the E18/E20, 160km west of Stockholm. Some 155,000, 600mm diameter columns (785,000m) and 1,000, 500mm diameter columns (9,000m) were installed in just 12 months for the main contractor NCC and the Swedish Road Authority.

Schofield adds that the method can also be considered for ground improvement below raft foundations for low-rise buildings, with loads of between 50kN/m² and 75kN/m². And the method is also effective for treating soils with high organic content. "In 95% of cases we can stabilise peat, although this is subject to an on-site trial using a mixture of additives."

For foundation design, the soil and lime columns are treated as a composite material with more and more of the applied load being carried by the columns with depth and the surrounding soil offering lateral support. "Design relies on the fact that the settlement of the soil must equal the settlement of the columns and is a factor of the strength, length and size of the columns," explains Schofield. The original designs are drawn up by Stent and then checked by Hercules, as the Swedish company has more experience of working to the accepted standards laid down by the Swedish Geotechnical Institute.

Schofield believes that demand for the technique will continue to grow as people realise the technical and economic benefits, helped partly he says by the increasing popularity of lime piles in the early 1990s.



The dry lime and cement mix is injected into the ground by compressed air.

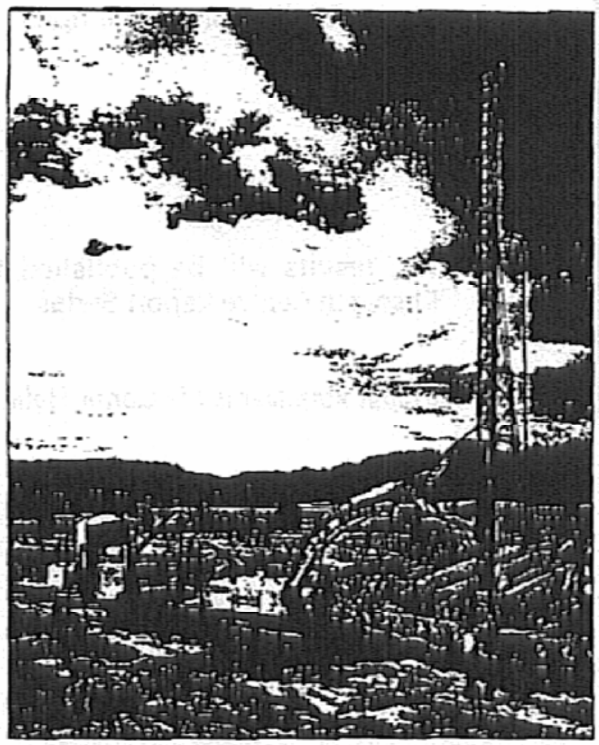
APPENDIX 4. INTRODUCTION TO THE SWEDISH DEEP STABILIZATION RESEARCH CENTER

Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

The Swedish Deep Stabilization Research Centre coordinates the research and developement activities concerning the lime-cement deep mixing technique as a high-technology method for the benefit of both the industry and the society.

Deep stabilization of soft soils with lime-cement columns

Deep stabilization of soft soils with lime-cement columns has been used in Sweden for 20 years. The method is primarily used for reduction of settlements and improvement of stability in connection with the construction of new roads and railroads. Lime-cement columns have also been used for the foundation of smaller buildings and bridges, the stabilization of trenches for pipes and the stabilization of natural slopes and also reduction of vibrations. The method is mainly used in soft clays but also in organic clays and clayey silts. The experience of the method is very favourable with respect to technological and economical aspects.



Example of equipment for lime-cement columns.

Joint Research Programme

During these past 20 years a great number of research projects have been performed. However, with respect to the large development potential of the method, a comprehensive research programme has been worked out to be performed in an extensive co-operation in 1995 to 2000. The research is coordinated and organized by the Swedish Deep Stabilization Research Centre. The members represent all different categories involved in the building process, authorities, contractors, lime and cement manufacturers, research institutes, universities, consultants and research councils. This cooperation enables research results to be communicated rapidly to the members of the center.

Objectives of the Research Programme

The objectives of the research programme are to

- expand the areas of application
- improve the cost-efficiency
- form a basis for export
- further improve the knowledge of the members

Research Activities

The research programme will deal with all aspects within the method as

- Properties of the stabilized soil
- Function of lime-cement stabilizations
- Installation of the columns
- Quality control methods

The results will be published in the Swedish Deep Stabilization Research Centre Report Series.

Project manager is Mr Göran Holm, Chief Engineer, M Sc Civ Eng

Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

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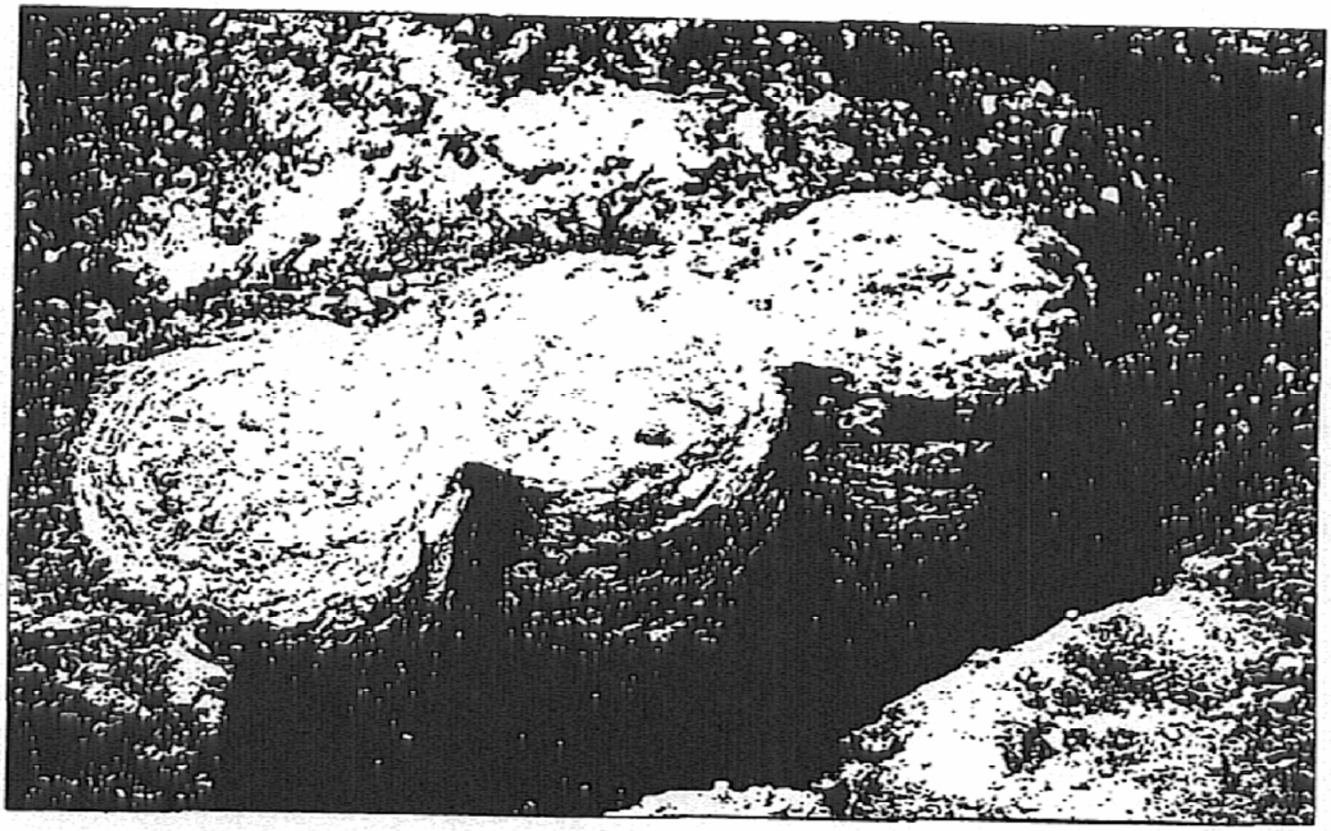

Deep stabilisation with lime/cement columns

Deep stabilisation improves stability and reduces settlements in embankment fills. In recent years, deep stabilisation has become the most commonly used strengthening method in Sweden, partly because it often has economic advantages over embankment piling and requires shorter construction times than vertical drainage. The Institute has developed a model for the design of deep stabilisation based on:

- Site investigations
- Laboratory tests
- Design
- Reports and construction documents
- Inspection
- Follow-up

The Svealand Rail Link

The SGI has been commissioned to design the lime-cement strengthening for the Svealand Rail Link. The depth of the clay in the area is up to 25 m. The columns have a diameter of 0.6 m and terminate at three different levels, 5, 10 and 15 m. The project is being followed up by measuring deformations, pore pressures and temperatures in order to study the mechanism of stepped lime-cement column strengthening and to determine whether the "Limeset" calculation model currently used is also suitable for lime-cement columns. A comparison has been made of the strength properties of the columns measured in the field and in the laboratory to determine differences between the methods and their influence on the calculation results. Columns have been extracted and triaxial tests carried out on 500 mm diameter samples. The SGI is conducting the follow-up jointly with with the National Rail Administration.

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APPENDIX 5. ABSTRACT FROM NEW FINNISH ROAD ADMINISTRATION SPECIFICATIONS FOR LIME-CEMENT COLUMNS

ABSTRACT

Deep stabilisation has become more common and there is a trend of applying stabilisation to more challenging tasks. This has increased the need for research and development. The production methods of stabilisation and the research of the binders used have recently been the main focus of development. The design methods need also to be developed in order to exploit the many possiblities of deep stabilisation.

Clay and silt layers can be strengthened by deep stabilisation and nowadays also mud and peat layers. The design strength is chosen depending on the soil, on the selected method of structural design and on the results of stabilisation tests. The goal has been to achieve same strengths in field conditions as in laboratory via improved production methods.

The design methods presented in this instruction are based on the classical soil mechanics. The deep stabilisated columns under embankments are devided in three groups: hard, semihard and soft columns. The hard columns act like piles and transmit all the load to the bearing stratum. When hard columns are used it is important to pay attention to the homogeneity of columns and arching. Particularly, the design methods for hard columns need development.

The semihard columns are assumed to act together with the subsoil so that part of the loading is transferred to the subsoil. Same settlements are to be expected. In Finland teh main experience has been of semihard columns and generally there has been no big surprises in their usage and design.

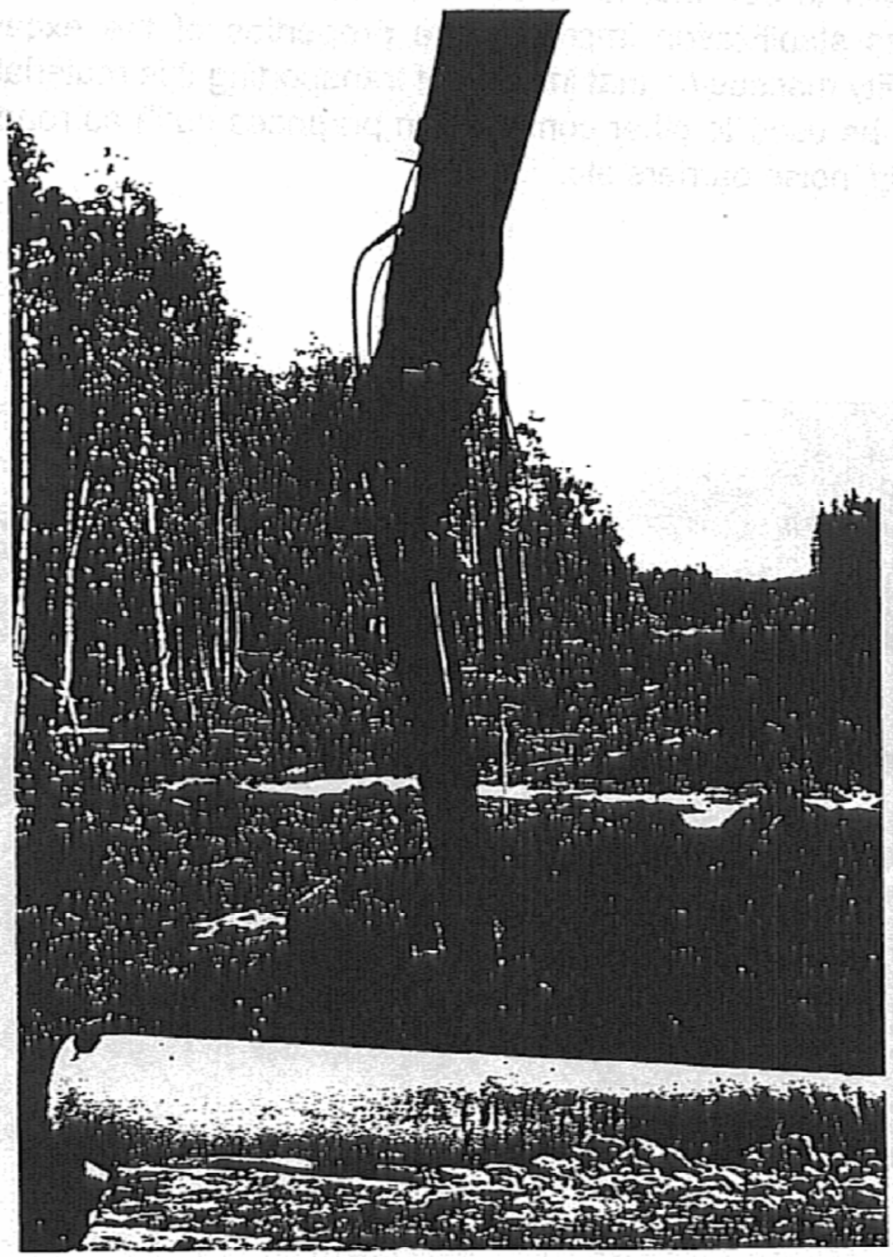
Columns designed so that their strength is exceeded are called soft columns. The soft columns can be assumed to act like vertical drains so that it is possible to speed up the settlement by over-loading. The soft columns are common in Sweden and there has been good experiences of them. Especially in the case of relatively high embankment, the designer needs to secure the stability.

Mass stabilisation is relatively new ground improvement method. The design and production methods of mass stabilisation still need a lot of research and development.

The most common mistakes related to stabilisation have become evident in stabilised slopes of cuts. The design of stabilisated cut is based on the natural stability. It is recommed to use either wall or block type stabilisation for this purpose.

APPENDIX 6. DETAILS OF "MASS STABILIZATION" METHOD OF YIT COMPANY

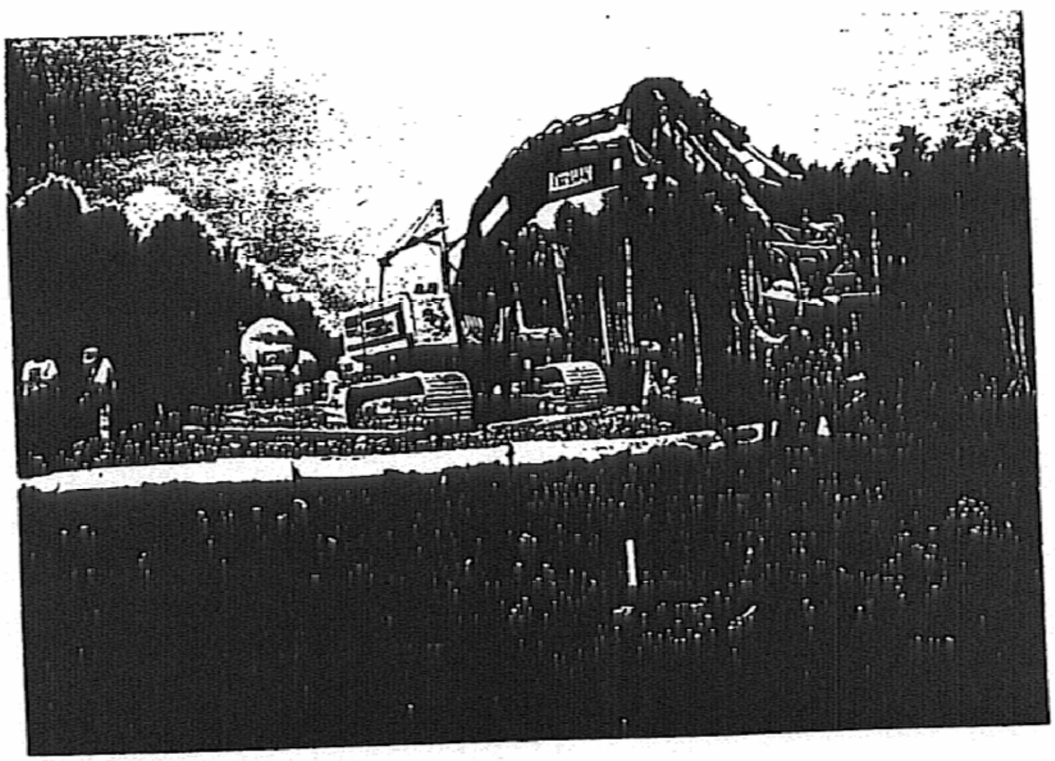
MASS STABILIZATION environmentally friendly technology



MASS STABILIZATION –
environmentally friendly technology

Mass stabilization is a new soil improvement method where stabilizer is mixed into soft clay, mud or peat. Mass stabilization is carried out by a mixing tool installed on an excavator machine. Mixing is done both in horizontal and vertical direction so that a homogenous enforced soil slab is formed due to effect of stabilizer. Without columns the whole mass is strengthened to a homogenous slab structure. Embankments can be founded on mass stabilized soil in the same way as on natural firm soil layers like moraine or gravel.

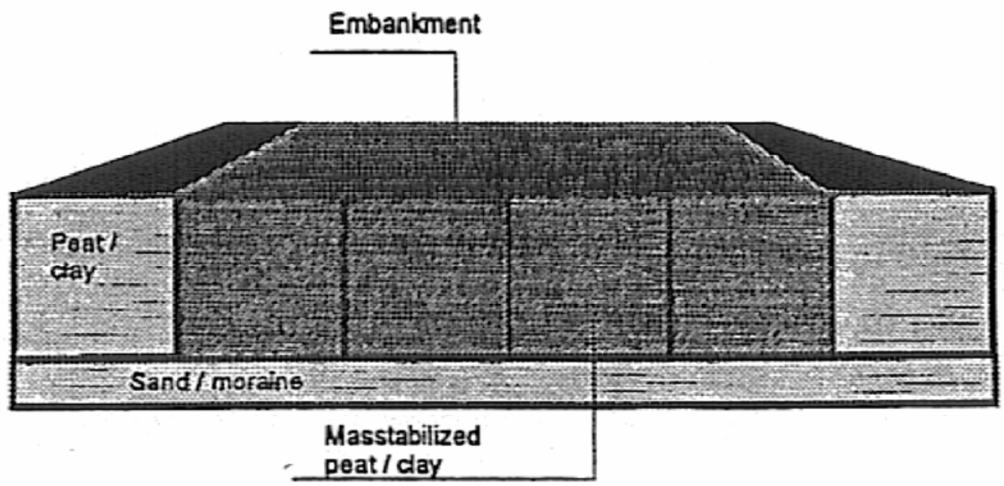
Mass stabilization can be implemented also by mixing stabilizer agents to soil that have been excavated and lifted to the ground. Mass stabilization improves the properties of the excavated, poor quality masses so that instead of transporting this material to landfill it can be used to other construction purposes such as road structures, filling, noise barriers etc.



New stabilizer agents, produced as by-products by industrial processes, can be used as stabilizers for deep- and mass stabilization instead of the traditionally used lime and lime-cement mixtures. In this way the stabilizer agent technology meets the principles of the environmentally friendly and sustainable development. Stabilizer agents as by-products are also much cheaper than the traditional lime-cement stabilizer agent.

Mass stabilization replaces conventional soil replacement method and so the need for natural stone- or crushed soil materials can significantly be decreased. Valuable gravel ridges and rock areas can be saved and load on soil dumps is reduced.

THE PRINCIPLE OF MASSTABILIZATION



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