Wednesday, 6th December-- 5

Deep Chemical Mixing in Soft Clays

Contents

Deep mixing and Southeast Queensland clays

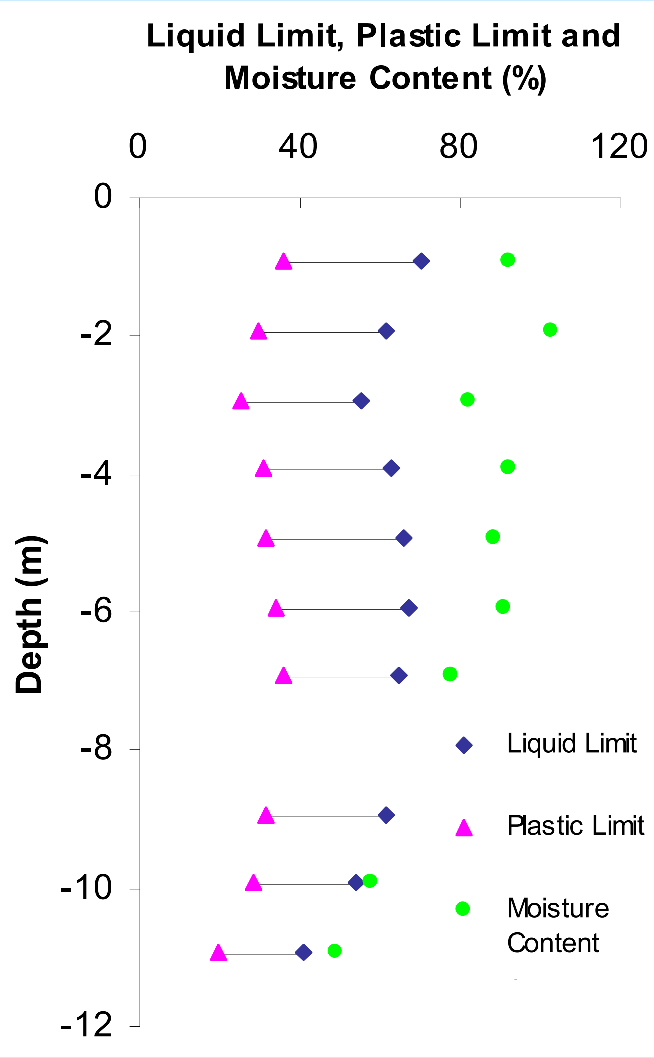


Figure 3.1: Liquid limit, moisture content and plastic limit profile (Gold Coast Highway)

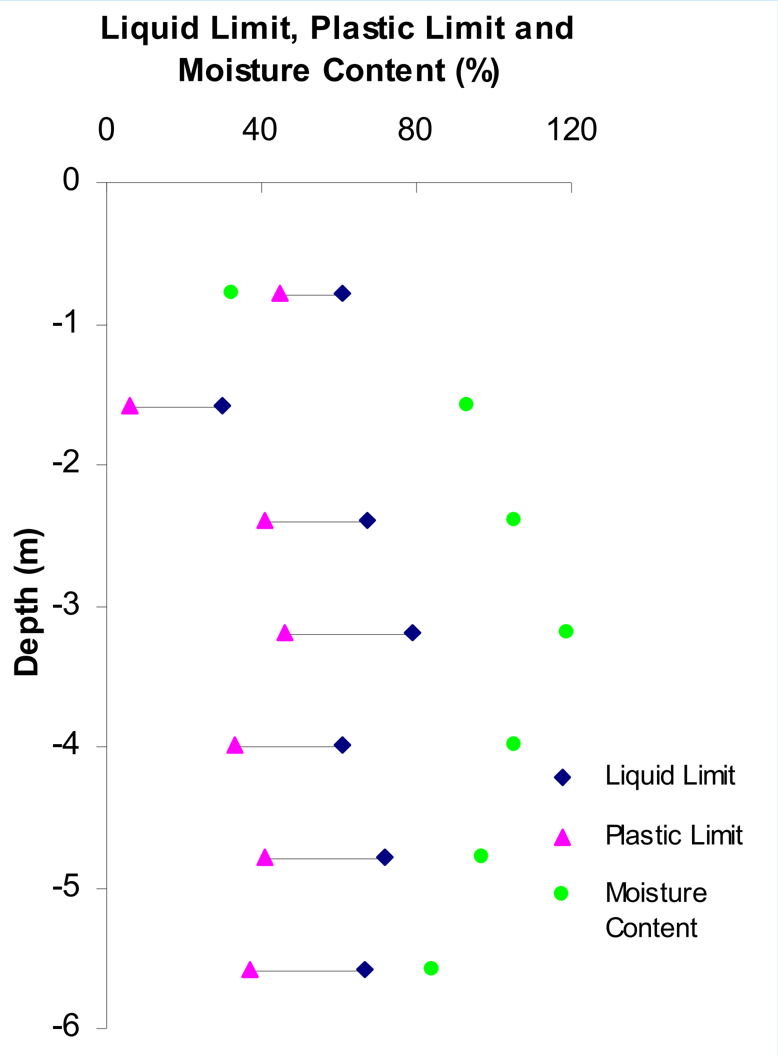


Figure 3.2: Liquid limit, moisture content and plastic limit profile (Sunshine Coast Motorway)

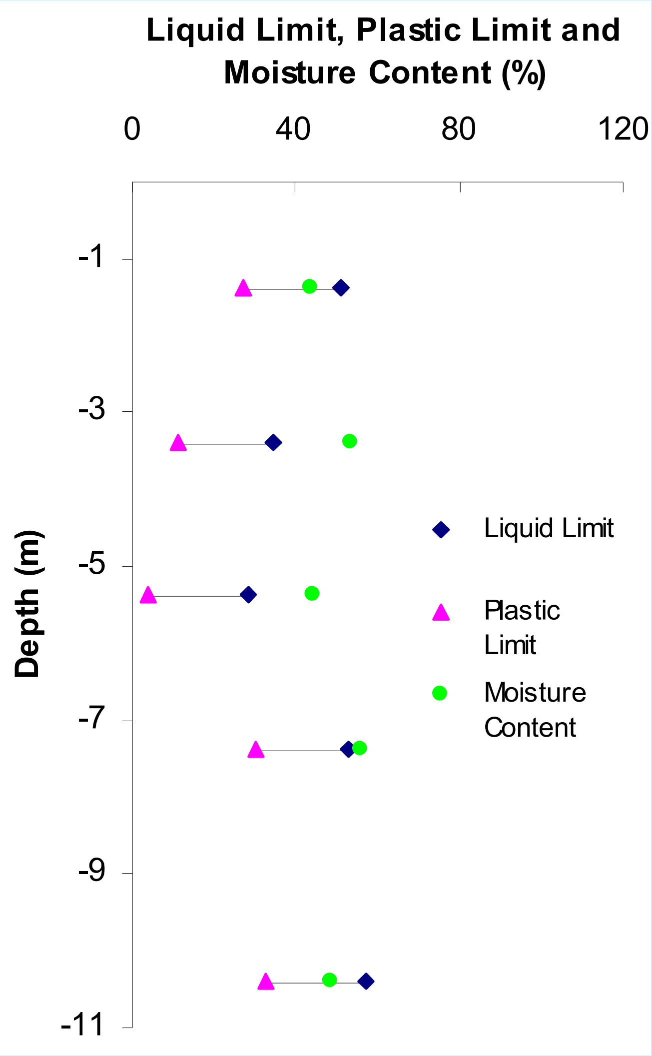


Figure 3.3: Liquid limit, moisture content and plastic limit profile (POB Motorway)

Sills, G. C. & Hird, C. C. (2005). *Géotechnique* **55**, No. 8, 597–602

Coefficient of consolidation from piezocone measurements

G. C. SILLS* and C. C. HIRD†

Pore pressure dissipation tests were carried out employing two miniature piezocones, with areas of 1 cm^2 and 5 cm^2, in a bed of reconstituted kaolin. By using independently determined values of the coefficient of consolidation, the results were interpreted to derive appropriate values of rigidity index for use with the theory of Teh & Houlsby. In accordance with the theory, different filter positions on a piezocone (tip, face and shoulder) were not found to require different values of rigidity index. However, the importance of allowing for initial load relaxation at the commencement of the dissipation test was demonstrated, and there appeared to be a systematic effect of piezocone size.

KEYWORDS: clays; consolidation; *in situ* testing; site investigation

On a effectué des essais de dissipation de la pression des pores en employant deux piézocônes miniatures, avec une surface comprise entre 1 cm^2 et 5 cm^2, dans une couche de kaolin reconstitué. En employant des valeurs, établies indépendamment, du coefficient de consolidation, on a interprété les résultats pour en dériver des valeurs approximatives de l'indice de rigidité pouvant être utilisées avec la théorie de Teh et Houlsby. D'après cette théorie, différentes positions du filtre, sur un piézocône (bout, face et épaulement) ne nécessiteraient pas des valeurs diverses de l'indice de rigidité. Toutefois, on a démontré l'importance de la prévision de la relaxation initiale de la charge au début de l'essai de dissipation, et il semble qu'il existe un effet systématique de la taille du piézocône.

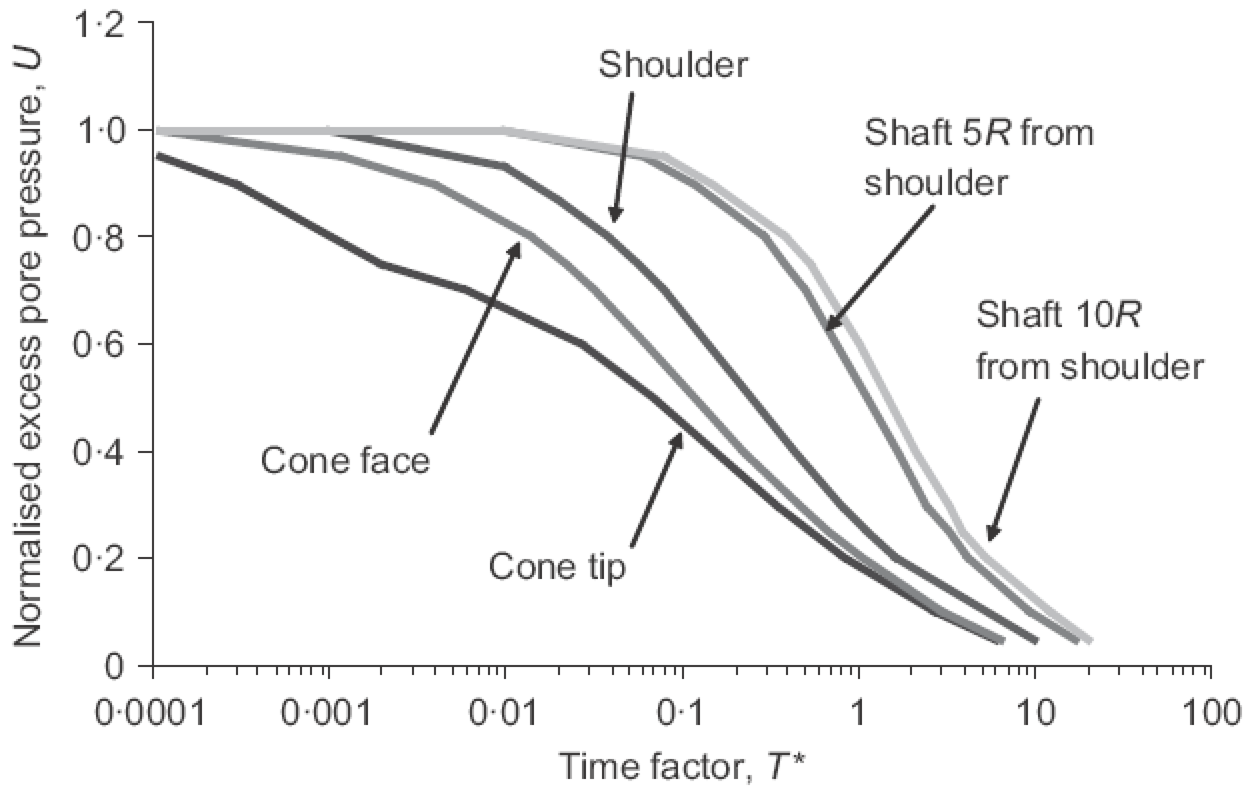


Fig. 1. Normalised excess pore pressure dissipation (after Teh & Houlsby, 1991)

- **Organic Soils and Peat**
  - **Low specific gravity   1.1 to 2.5**
  - **Voids ratio   2 – 25**

Historical Developments of DMM (Probaha, 1998)

1954	Intrusion Prepakt Co. (United States) develops the Mixed in Place (MIP) Piling Technique (single auger), which sees only sporadic use in the United States.
1961	MIP already used under license for more than 300,000 lineal meters of piles in Japan for excavation support and groundwater control. Continued until early 1970s by the Seiko Kogyo Company, to be succeeded by diaphragm walls and DMM (SMW) technologies.
1967	The Port and Harbor Research Institute (PHRI, Ministry of Transportation, Japan) begins laboratory tests, using granular or powdered lime for treating soft marine soils (DLM). Research continues by Okumura, Terashi et al. through early 1970s to: (1) investigate lime-marine clay reaction, and (2) develop appropriate mixing equipment. Unconfined compressive strength (UCS) of 0.1 to 1 MPa achieved. Early equipment (Mark I-IV) used on first marine trial near Hameda Airport (10 m below water surface).
1967	Laboratory and field research begins on Swedish Lime Column method for treating soft clays under embankments using unslaked lime (Kjeld Paus, Linden – Alimak AB, in cooperation with Swedish Geotechnical Institute (SGI), Euroc AB, and BPA Byggproduktion AB). This follows observations by Paus on fluid lime column installations in the United States.
Late 1960s	China reported to be considering implementing DLM concepts from Japan.
1972	Seiko Kogyo Co. of Osaka, Japan begins development of Soil Mixed Wall (SMW) method for soil retaining walls, using overlapping multiple augers (to improve lateral treatment continuity and homogeneity/quality of treated soil).
1974	PHRI reports that the Deep Lime Mixing (DLM) method has commenced full-scale application in Japan. First applications in reclaimed soft clay at Chiba (June) with a Mark IV machine developed by Fudo Construction Co., Ltd.

Historical Developments of DMM (Probaha, 1998)

	Applications elsewhere in Southeast Asia follow the same year. (Continues to be popular until 1978 – 21 jobs, including two marine applications – when CDM and Dry Jet Mixing (DJM) overtake.)
1974	Intensive trials conducted with Lime Columns at Skå Edeby Airport, Sweden: basic tests and assessment of drainage action (columns 15 m long and 0.5 m in diameter).
1974	First detailed description of Lime Column method by Arrason et al. (Linden Alimaik AB).
1974	First similar trial embankment using Swedish Lime Column method in soft clay in Finland (6 m high, 8 m long; using 500-mm-diameter lime cement columns, in soft clay).
1975	Swedish paper on lime columns (Broms and Boman), and Japanese paper on DLM (Okumura and Terashi) presented at same conference in Bangalore, India. Both countries had proceeded independently to this point. Limited technical exchanges occur thereafter.
1975	Following their research from 1973 to 1974, PHRI develops the forerunner of the Cement Deep Mixing (CDM) method using fluid cement grout and employing it for the first time in large-scale projects in soft marine soils offshore. (Originally similar methods include DCM, CMC (still in use from 1974), closely followed by DCCM, DECOM, DEMIC, etc., over the next five years).
1975	First commercial use of Lime Column method in Sweden for support of excavation, embankment stabilization, and shallow foundations near Stockholm (by Linden Alimak AB, as contractor and SGI as consultant/researcher).
1976	Public Works Research Institute (PWRI) Ministry of Construction, Japan, in conjunction with Japanese Construction Machine Research Institute begins research on the DJM method using dry powdered cement (or less commonly, quick-lime); first practical stage completed in late 1980. Representatives of PHRI also participate.
1976	SMW (Soil Mixed Wall) method used commercially for first time in Japan by Seiko Kogyo Co.
1977	CDM (Cement Deep Mixing) Association established in Japan to coordinate technological development via a collaboration of industrial and research institutes. (Now has about 50 members.)

Historical Developments of DMM (Probaha, 1998)

1977	First design handbook on lime columns (Broms and Boman) published by Swedish Geotechnical Institute (describes unslaked lime applications only).
1977	First practical use of CDM in Japan (marine and land uses).
1977	China commences research into CDM, with first field application in Shanghai using its own land-based equipment in 1978.
1979	Tenox Company develops Soil Cement Column (Teno Column) system in Japan: subsequently introduced into the United States in 1992.
1980	First commercial use in Japan of DJM, which quickly supersedes DLM thereafter (land-use only).
1981	Prof. Jim Mitchell presents general report at ICSMFE (Stockholm) on lime and lime cement columns for treating plastic, cohesive soils, increasing international awareness.
Early 1980s	DJM Association established in Japan. (Now with more than 20 members.)
1983	Eggestad publishes state-of-the-art report in Helsinki dealing with new stabilizing agents for Lime Column method.
1984	SWING method developed in Japan, followed by various related jet-assisted (W-R-J) methods in 1986, 1988, and 1991.
1985	First commercial use of Lime Cement Column method in Finland.
1985	SGI (Sweden) publishes 10-year progress review (Åhnberg and Holm).
Mid 1980s	First application of lime cement columns in Norway (under Swedish guidance).
1986	SMW Seiko Inc. commences operations in the United States under license from Japanese parent Seiko Kogyo Co. and thus introduces contemporary DMM to U.S. market.
1987	The Bachy Company in France develops "Colmix" in which mixing and compacting the cemented soil is achieved by reverse rotation of the multiple augers during withdrawal. Developed as a result of research sponsored by French national highways and railroads. Appears to be first European development outside Scandinavia.
1987 – 1989	SMW method used in massive, landmark ground treatment program for seismic retrofit at Jackson Lake Dam, WY.

Historical Developments of DMM (Probaha, 1998)

1987	Cementation Ltd. reports on use of their single auger deep mixing system in U.K. (developed in early-mid 1980s).
1987	First experimental use of CDM for ground treatment (involving the Takenaka Company) in China (Xingong Port, Taijin).
1987	First use of DMM for excavation support in Shanghai, China.
1987 – 1988	Development by Geo-Con, Inc. (United States) of DSM (Deep Soil Mixing – 1987) and SSM (Shallow Soil Mixing – 1988) techniques.
1989	The Trevisani and Rodio Companies in Italy develop their own DMM version, starting with dry mix injection, but also developing a wet mix method.
1989	Geo-Con uses SSM technique for gravity wall at Columbus, GA.
1989	DMM technology included in Superfund Innovative Technology Evaluation Program of the U.S. Environmental Protection Agency for demonstration as a technology for in situ solidification/stabilization of contaminated soils or sludges. Subsequently used in practice.
1989	Start of exponential growth in use of lime cement columns in Sweden.
1989	The Tenox Company reports more than 1000 projects completed with SCC method in Japan, prior to major growth thereafter (9000 projects to end of 1997, with a $100 to 200 million/year revenue in Japan and elsewhere in Southeast Asia).
1990	New mixing equipment developed in Finland using cement and lime (supplied and mixed separately): capable of creating columns greater than 20 m deep, 800 mm in diameter, through denser, surficial layers.
1990	Dr. Terashi, involved in development of DLM, CDM, and DJM since 1970 at Port and Harbor Research Institute, Japan, gives November lectures in Finland. Introduces more than 30 binders commercially available in Japan, some of which contain slag and gypsum as well as cement. Possibly leads to development of "secret reagents" in Nordic Countries thereafter.
1991	Low Displacement Jet Column Method (LDis) developed in Japan.
1991	Bulgarian Academy of Sciences reports results of local soil-cement research.
1991	Geotechnical Department of City of Helsinki, Finland, and contractor YIT introduce block stabilization of very soft clays to depths of 5 m using a variety of different binders.

Historical Developments of DMM (Probaha, 1998)

Early 1990s	First marine application of CDM at Tiajin Port, China: designed by Japanese consultants (OCDI) and constructed by Japanese contractor with his own equipment (Takenaka Doboku).
1992 – 1994	SMW method used for massive earth retention and ground treatment project at Logan Airport, Boston, MA.
1992	Chinese Government (First Navigational Engineering Bureau of Ministry of Communications) builds first offshore CDM equipment "fleet", using Japanese technology used for first time (1993) at Yantai Port. (Reportedly the first wholly Chinese Design-Build DMM project.)
1992	Jet and Churning System Management (JACSMAN) developed by Fudo Company and Chemical Grout Company in Japan.
1992	New design guide (STO-91) produced in Finland based on experience in 1980s and research by Kujala and Lahtinen (involving 3000 samples from 29 sites).
1992 – 1993	First SCC installation in United States (Richmond, CA).
1993	First DMM activities of Millgard Corporation (United States), largely for environmental work.
1993	DJM Association Research Institute publishes updated Design and Construction Manuals (in Japanese).
1993	CDM Association claims 23.6 million m^3 of soil treated since 1977.
1994	SMW claims 4000 projects completed worldwide since 1976, comprising 12.5 million m^2 (7 million m^3).
1994	SMW used for 19,000 m^2 of soil retention on Los Angeles Metro (Hollywood Boulevard), CA.
1994	CDM Association manual revised and reissued (in Japanese).
1994	First commercial application of original Geojet system in the United States (Texas) following several years of development by Brown and Root Company.
1994	DJM Association claims 1820 projects completed up to year's end (total volume of 12.6 million m^3).
Mid 1990s	First use of lime cement columns in Poland (Stabilator Company).

Historical Developments of DMM (Probaha, 1998)

1995	Finnish researchers Kukko and Ruohomäki report on intense laboratory research program to analyze factors affecting hardening reactions in stabilized clays. Discusses use of new binders (e.g., slag, pulverized flyash, etc.).
1995	Swedish government sets up new Swedish Deep Stabilization Research Center at SGI (1995 to 2000: $8 to 10 million budget): Svensk Djupstabilisering. Consortium includes owners, government, contractors, universities, consultants, and research organizations co-coordinated by Holm of SGI and Broms as "scientific leader." Research planned: creating an experience database; properties of stabilized soil; modeling of treated soil structures; quality assurance; and work performance. Results to be published in a series of reports.
1995	Finnish government sets up similar new research consortium until 2001 for the ongoing Road Structures Research Programme (TPPT) to improve overall performance of road structures (similar to Swedish program members and scope).
1995	From 1977 to 1995, more than 26 million m^3 of CDM treatment reported in Japan.
1995	Swedish Geotechnical Society publishes new design guide for lime and lime cement columns (P. Carlsten) focusing on soft and semi-hard columns. English version released in 1996.
1995	From 1980 to 1996, about 15 million m^3 of DJM treatment reported in Japan.
1995 – 1996	SMW method used for massive soil retention scheme at Cypress Freeway, Oakland, CA.
1996	Report on use in Japan of FGC-DM (Flyash-Gypsum-Cement) method (a form of CDM).
1996	SGI (Sweden) publishes 21-year experience review.
1996	First commercial use of lime cement columns in the United States (Stabilator Company in Queens, NY).
1996	More than 5 million lineal meters of lime and lime cement columns reportedly installed in Sweden since 1975. Annual production in Sweden and Finland now averages about the same output. Sweden's market is 2 to 4 times larger than Finland's, which in turn far exceeds Norway's.
1996 – 1997	Hayward Baker, Inc. installs 1.2- to 1.8-m diameter DMM columns for foundations, earth retention, and ground improvement in various U.S. sites.

Historical Developments of DMM (Probaha, 1998)

1997 – to date	SMW method used for massive ground treatment project at Fort Point Channel, Boston, MA (largest DMM project to date in North America), and other adjacent projects. Input at design stage to U.S. consultants by Dr. Terashi (Japan).
1997	First commercial use in the United States of modified Geojet system (Condon Johnson and Associates at San Francisco Airport, CA).
1997	Major lime cement column application for settlement reduction at I-15, Salt Lake City, UT (proposed by Stabilator USA, Inc.).
1997	Geo-Con, Inc. uses DMM (with concrete facing) for permanent excavation support, Milwaukee, WI.
1997 – 1998	Master Builders Technologies develop families of dispersants for soil (and grout) to aid DMM penetration and mixing efficiency.
1998	First application by Trevi-ICOS Corporation of their DMM in Boston, MA.
1998	Raito, Inc. establishes office in California, offering various DMM technologies under license from Japan (including DJM, CDM, and Raito Soil Mixed Wall), and wins first project in California in early 1999.
1998	Geo-Con, Inc. conduct full-scale demonstration of VERTwall DMM concept in Texas.
1998	First Deep Mixing Short Course presented in the United States (University of Wisconsin – Milwaukee, August).
1998	Formation of Deep Mixing Subcommittee of Deep Foundations Institute during annual meeting in Seattle, WA, October.

Laboratory studies on Bangkok clays

Physical Properties of the Base Clay

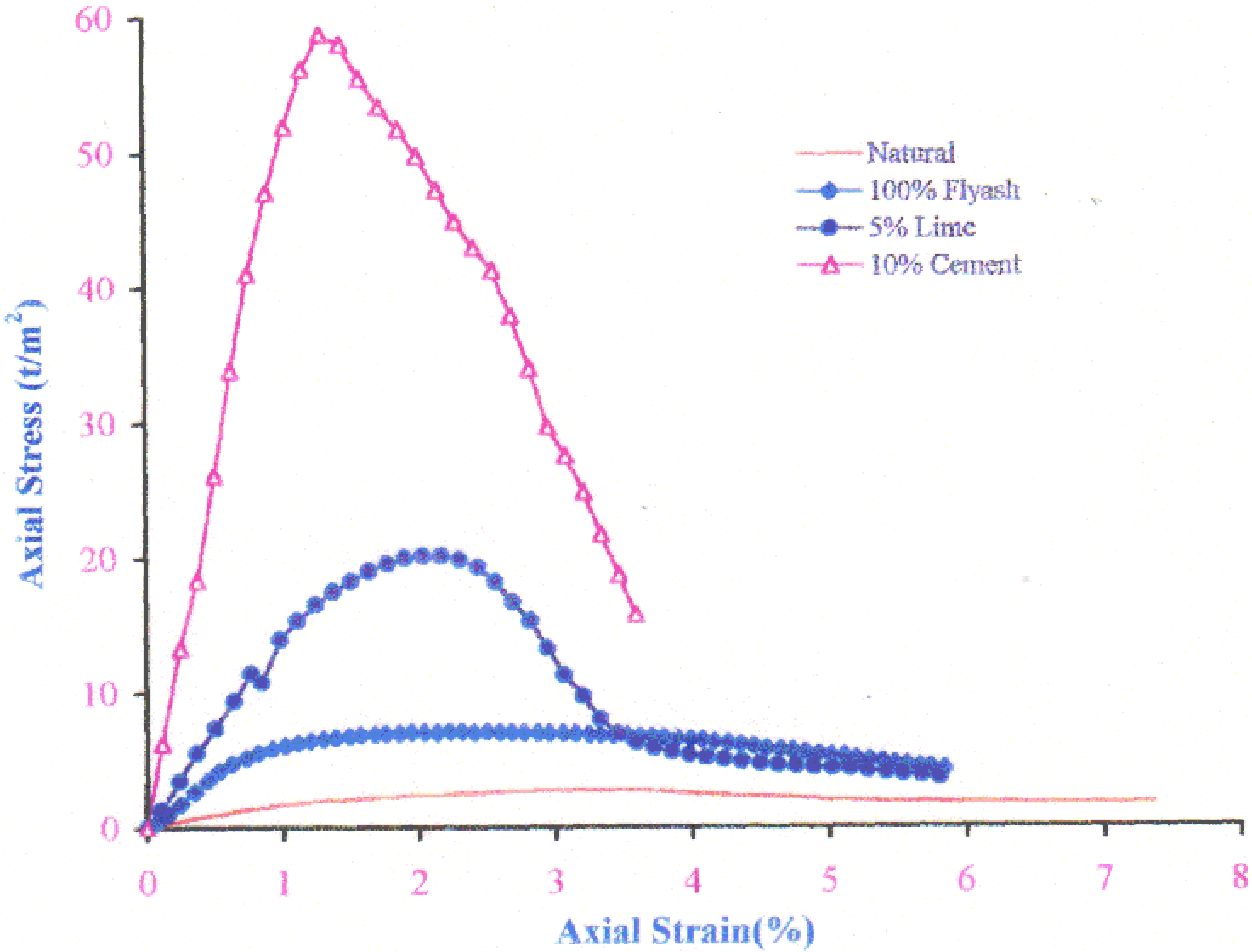
Liquid Limit LL, (%)	98- 108
Plastic Limit PL, (%)	28-31
Plasticity Index PI, (%)	70-77
Water Content (%)	90-96
Grain Size Distribution:	
• Clay (%)	75
• Silt (%)	22
• Sand (%)	3
Total Unit weight, γ_t (t/m^3)	1.41-1.46
Dry Unit weight, γ_d(t/m^3)	0.73- 0.75
Initial Void ratio, e_0	2.66-2.68
Specific Gravity	2.69
Color	Dark Gray

Chemical Properties of the Base Clay

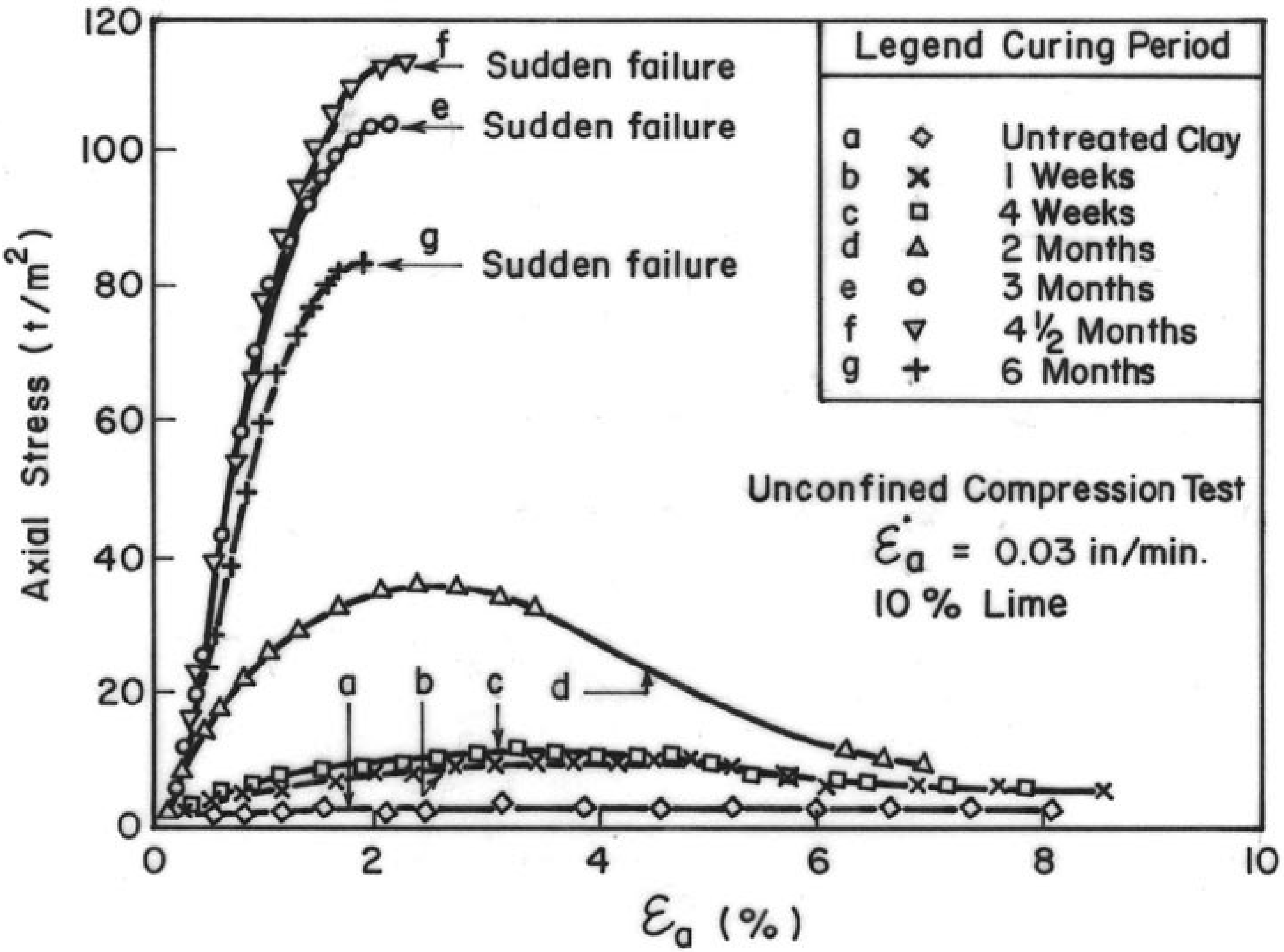
Organic Matter ; (%)	2.46
p^H (Soil : water =1:1)	6.50
Cation Exchange capacity (meq/ 100 g)	47.55
Soluble Salt (mg/100g)	
Chloride, Cl^-	247.00
Sulphate, SO_4^{2-}	288.00
Total soluble salt content	535.00
Exchangeable Cations (mg/100 g)	
• Calcium, Ca^{2+}	309.42
• Magnesium, Mg^{2+}	56.63
• Sodium, Na^+	43.40
• Potassium, K^+	15.20

Properties of Cement and Flyash

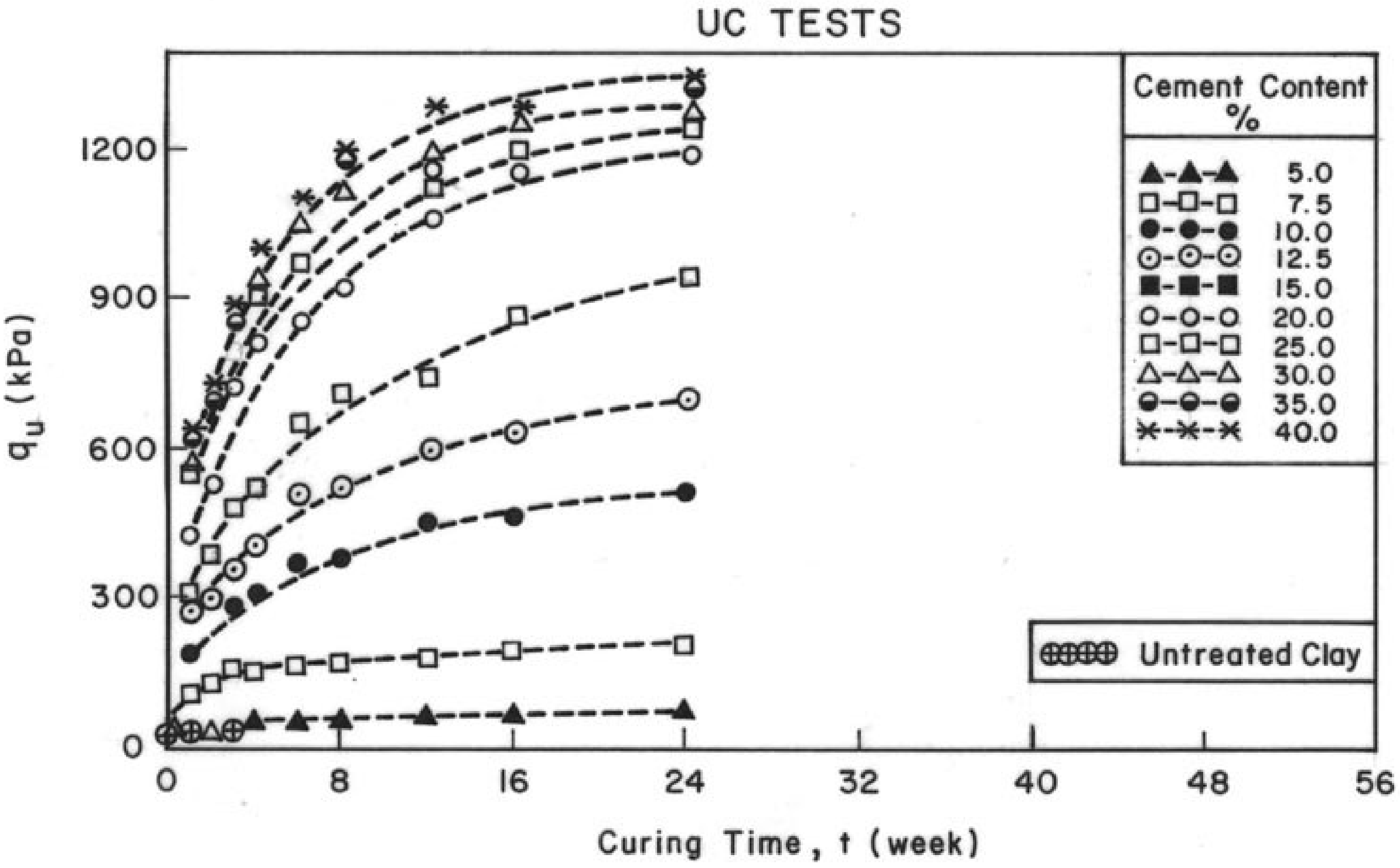
Physical Properties	Portland Cement	Mae-Moh Flyash
Specific Gravity	3.12	1.89
Bulk Density (gm/cm^3)	1.02	0.98
Fineness		
- % Retaining 45 µm, max.	-	58.18
- Blanie Fineness (cm^2/mg)	3350	1770
Moisture content, max.	0.11	0.14
Chemical Properties		
Silicon dioxide (SiO_2)	20.67	46.14
Aluminum Oxide (Al_2O_3)	6.21	26.75
Ferric Oxide (Fe_2O_3)	3.06	10.07
Calcium Oxide (CaO)	64.89	8.33
Magnesium Oxide (MgO)	0.82	2.46
Potassium Oxide (K_2O)	0.53	2.67
Sodium Oxide (Na_2O)	0.06	0.77
Sulpher Trioxide (SO_3)	2.71	1.12
Titanium dioxide (TiO_2)	-	0.63
Phosphorus Pentaoxide (P_2O_5)	-	0.17
Dicalcium Silicate (C_2S)	53.26	-
Tricalcium Silicate (C_3S)	19.05	-
Tricalcium Aluminate (C_3A)	11.28	-
Gypsum content	5.64	-
Insoluble residue	0.20	-
Free lime	0.91	0.12
Loss on ignition, max.	0.86	0.59



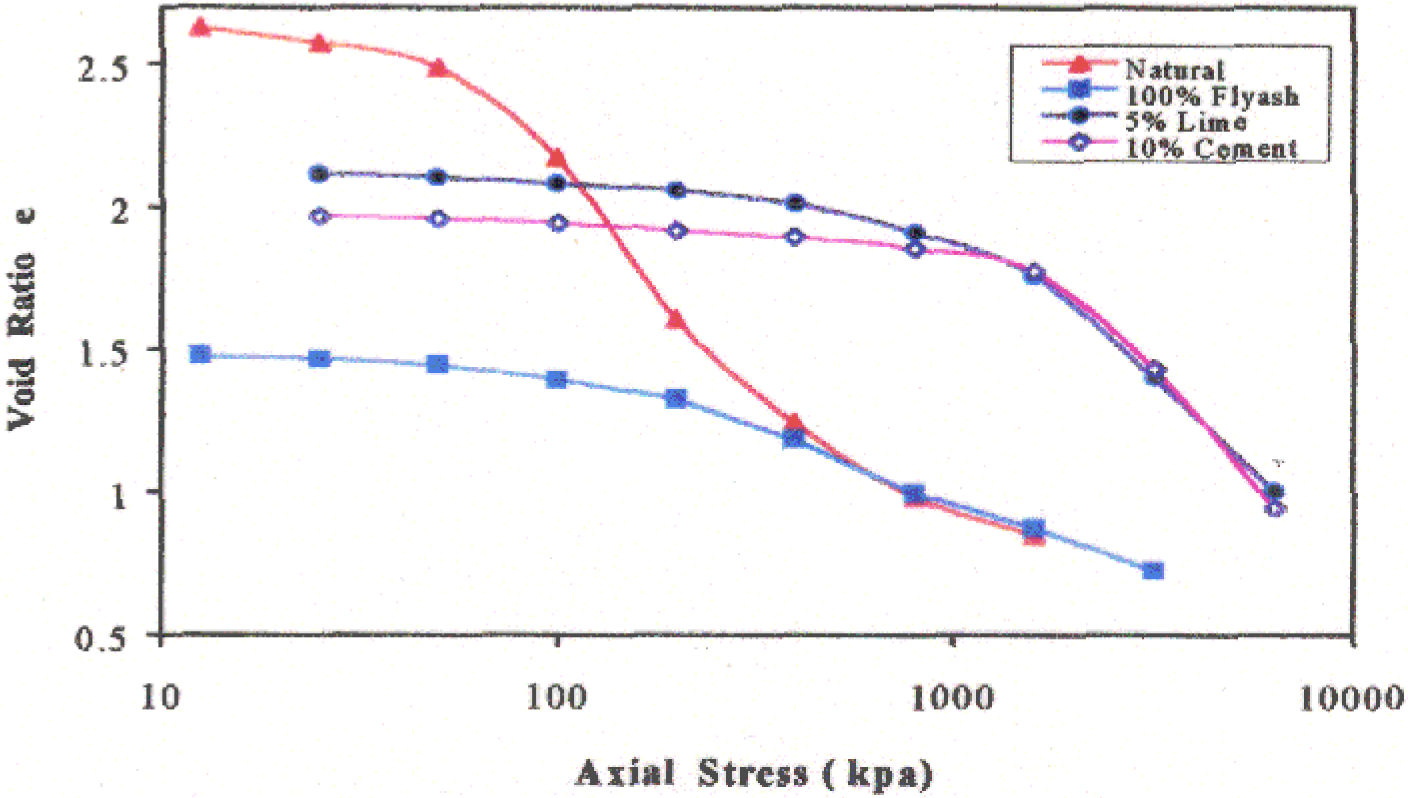
Unconfined compression tests on treated and untreated samples



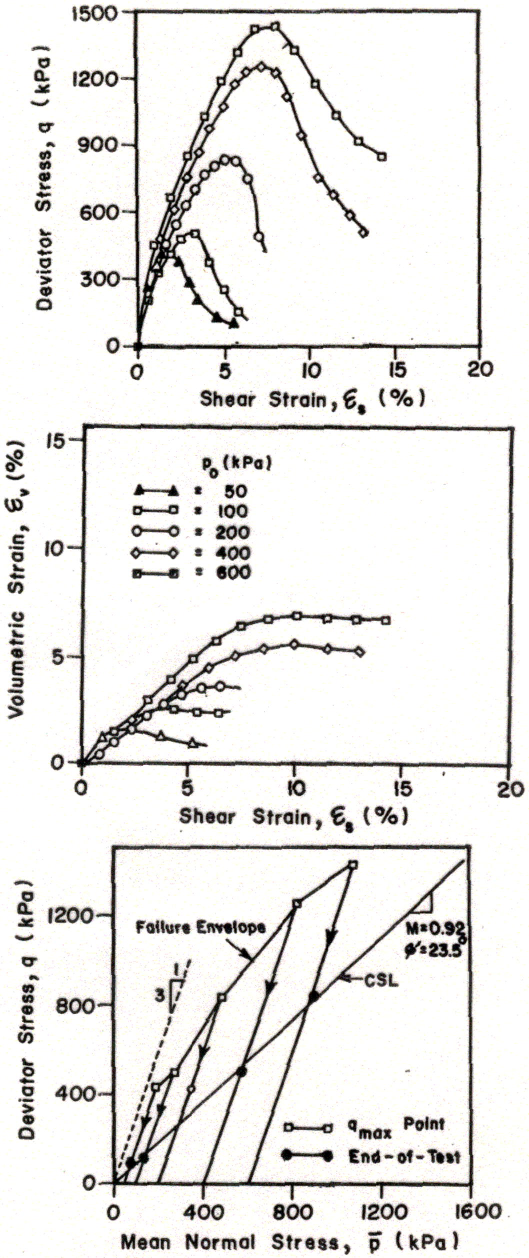
Typical Stress-Strain Curves from Unconfined Compression Tests (Lime Treated Clay)



Unconfined Compressive Strength with Curing Time (Cement Treated Clay)



(e, log $\bar{\sigma}$v) relations in high pressure Oedometer test



Behavior of treated samples in triaxial Drained test

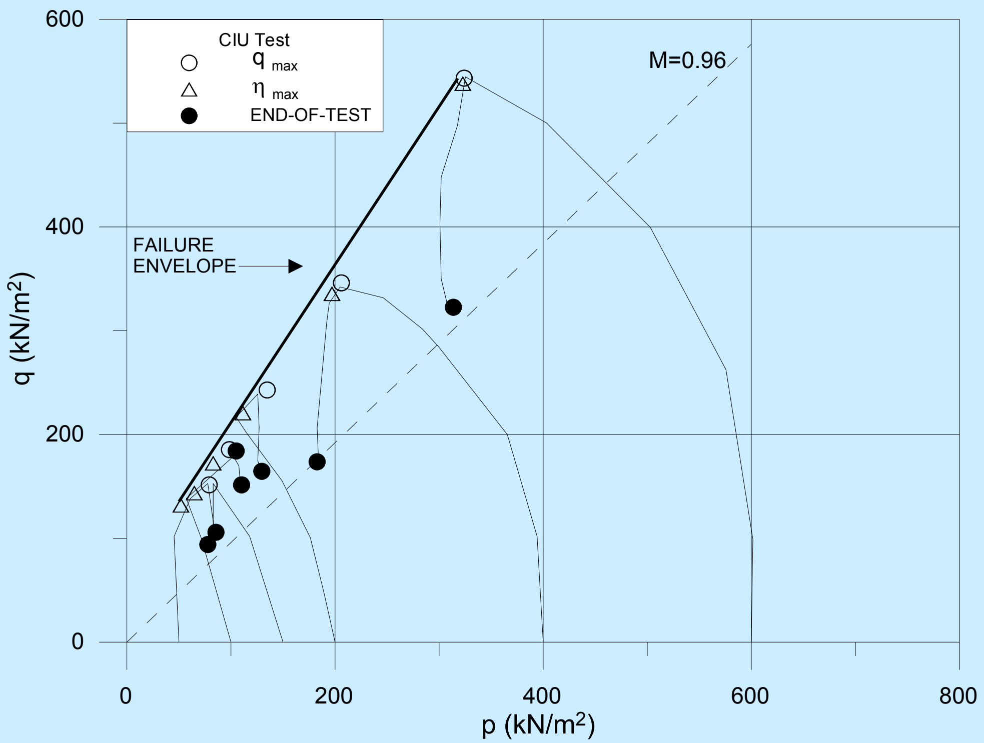


Figure 19b Effective stress paths for lime treated clay (10% lime content, 1 month curing)

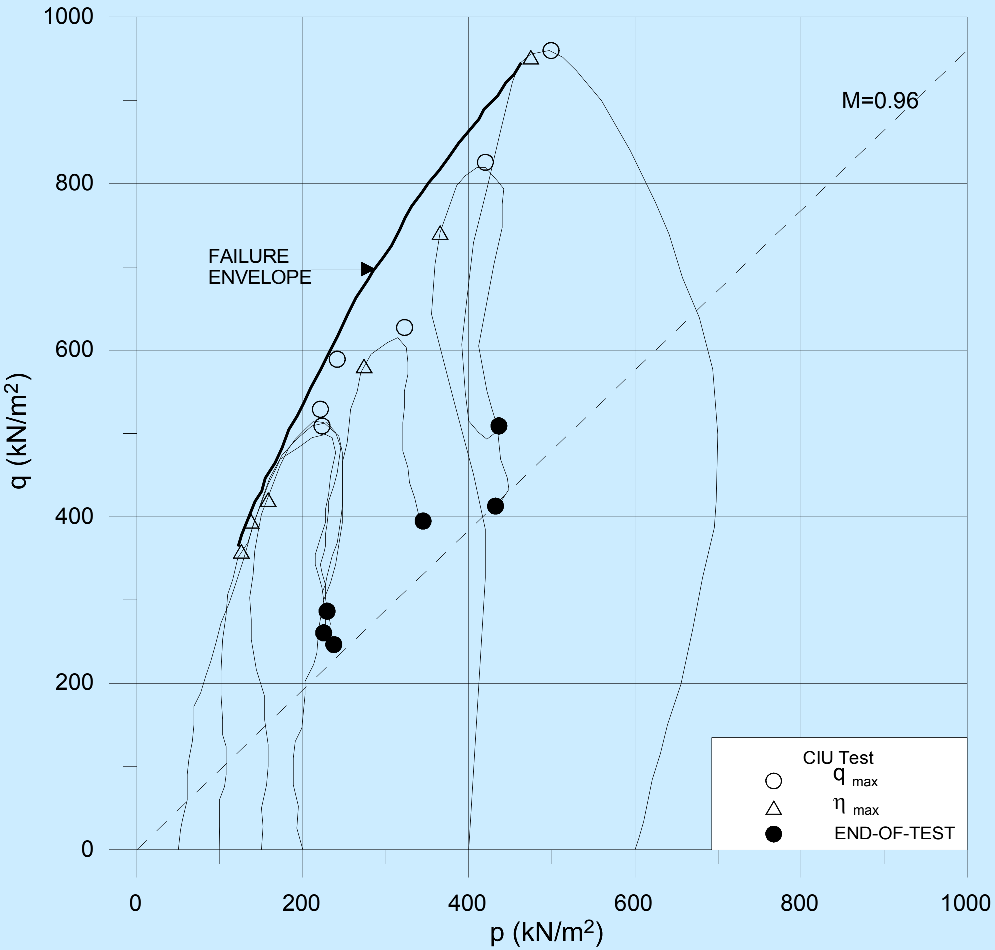
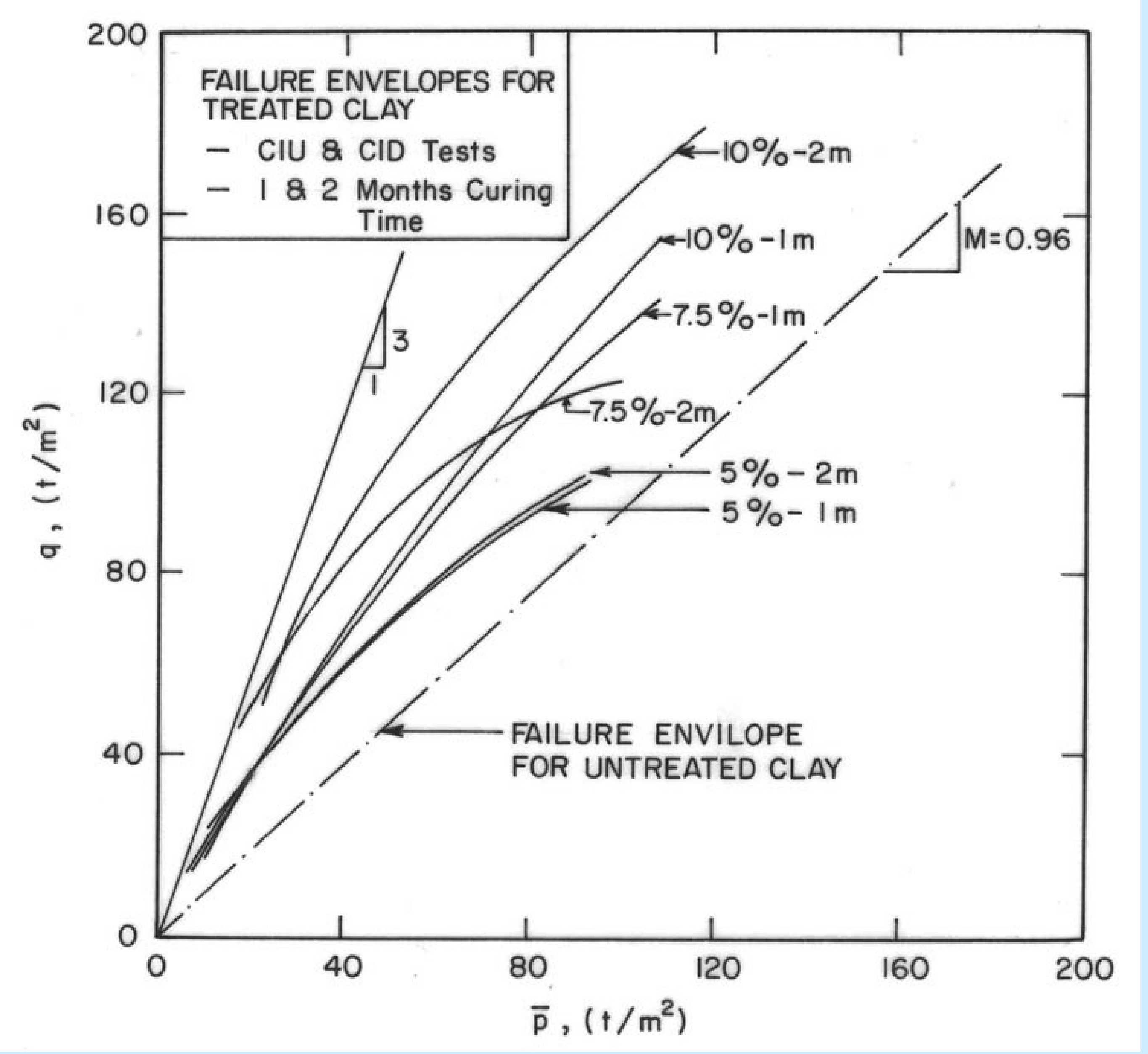
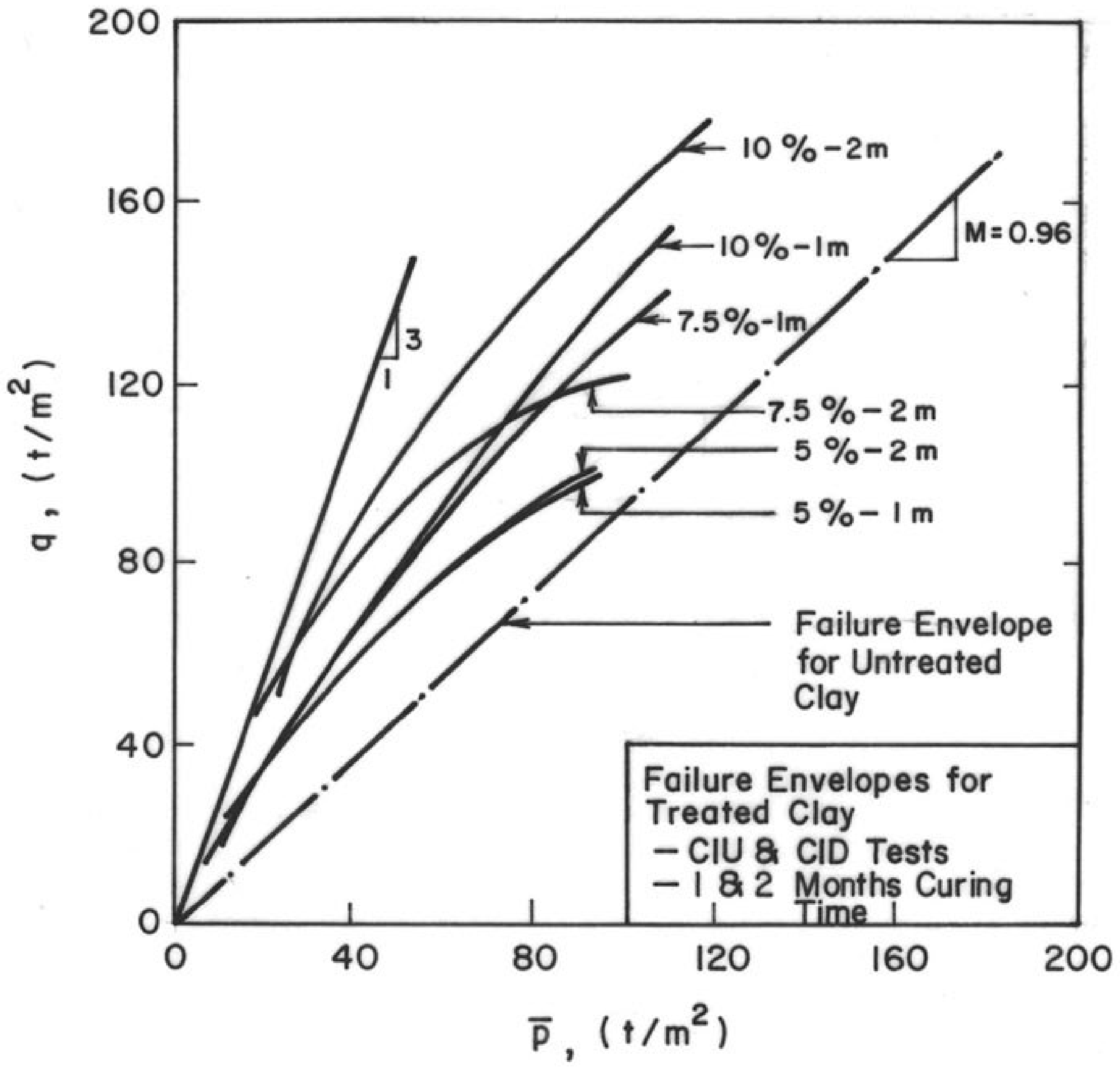


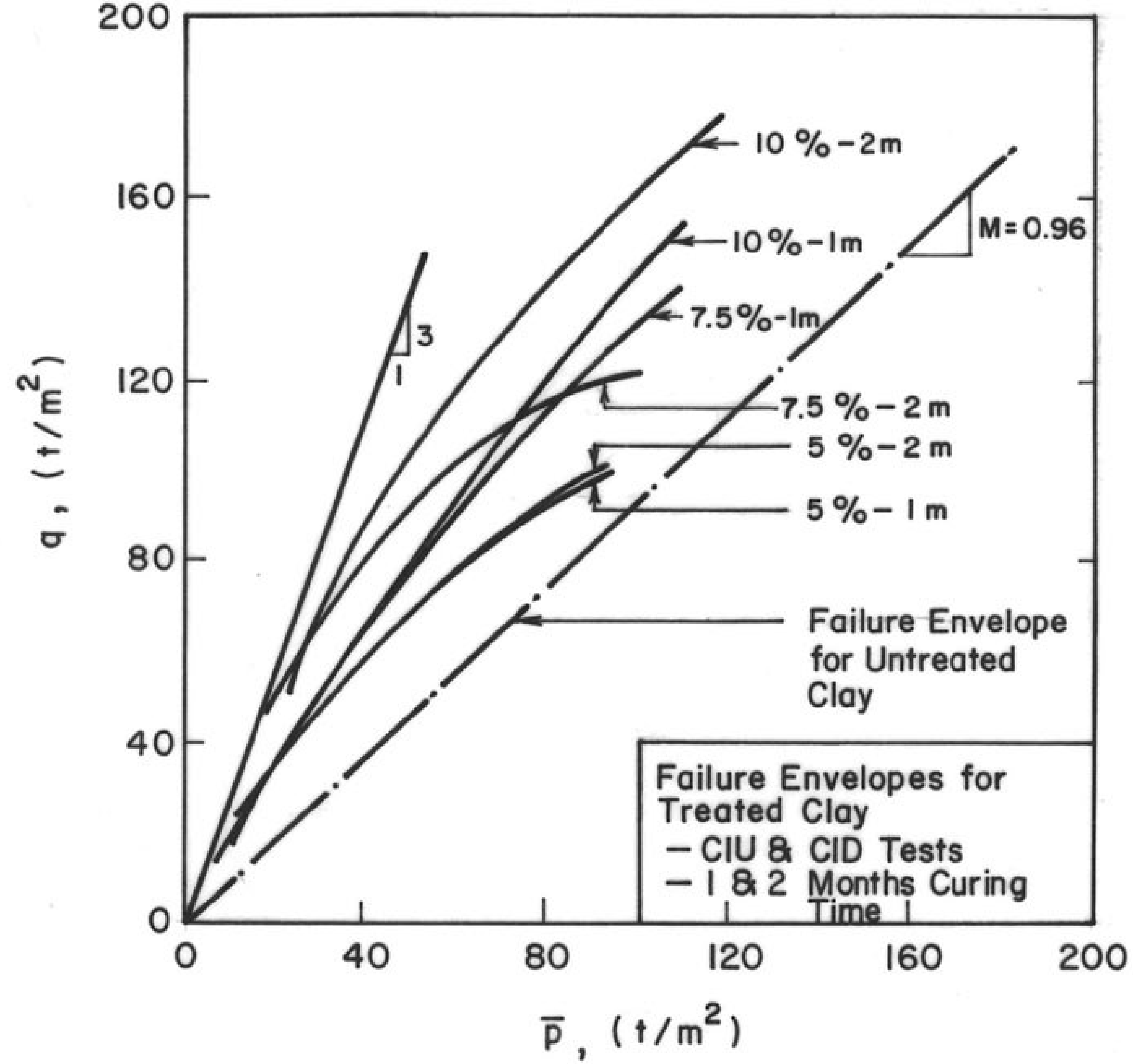
Figure 20b Effective stress paths for lime treated clay (10% lime content, 2 months curing)



FAILURE ENVELOPES FOR TREATED CLAY
— CIU & CID Tests
— 1 & 2 Months Curing Time
10%-2m
10%-1m
7.5%-1m
7.5%-2m
5%-2m
5%-1m
M=0.96
3
1
FAILURE ENVILOPE FOR UNTREATED CLAY
q, (t/m²)
p̄, (t/m²)
0
40
80
120
160
200

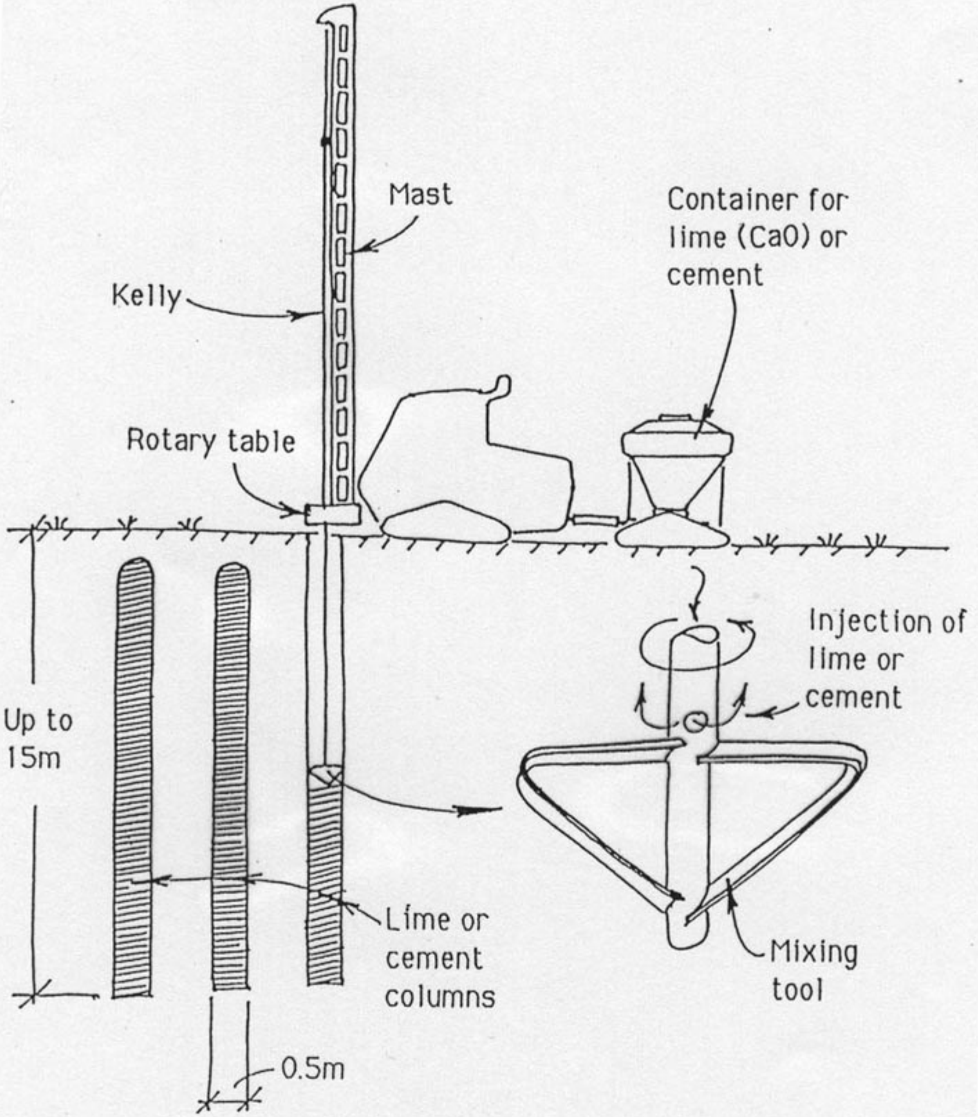


Failure Envelopes in $(q, \bar{p})$ Plot Lime Treated Clay



Failure Envelopes in (q , $\overline{p}$) Plot Lime Treated Clay

Applications of deep mixing



The lime or cement column method

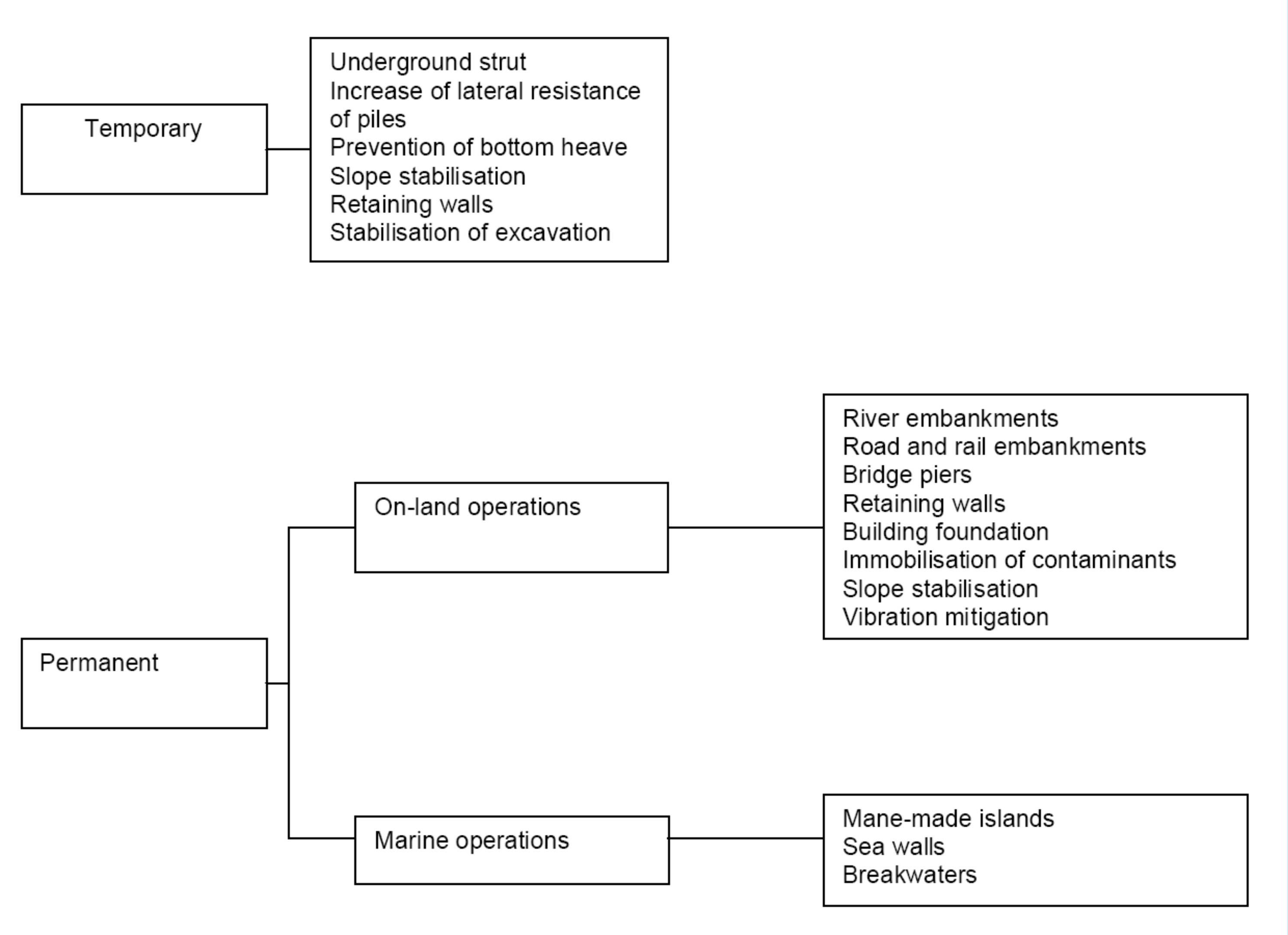


Figure 3. Applications of deep mixing for various purposes.

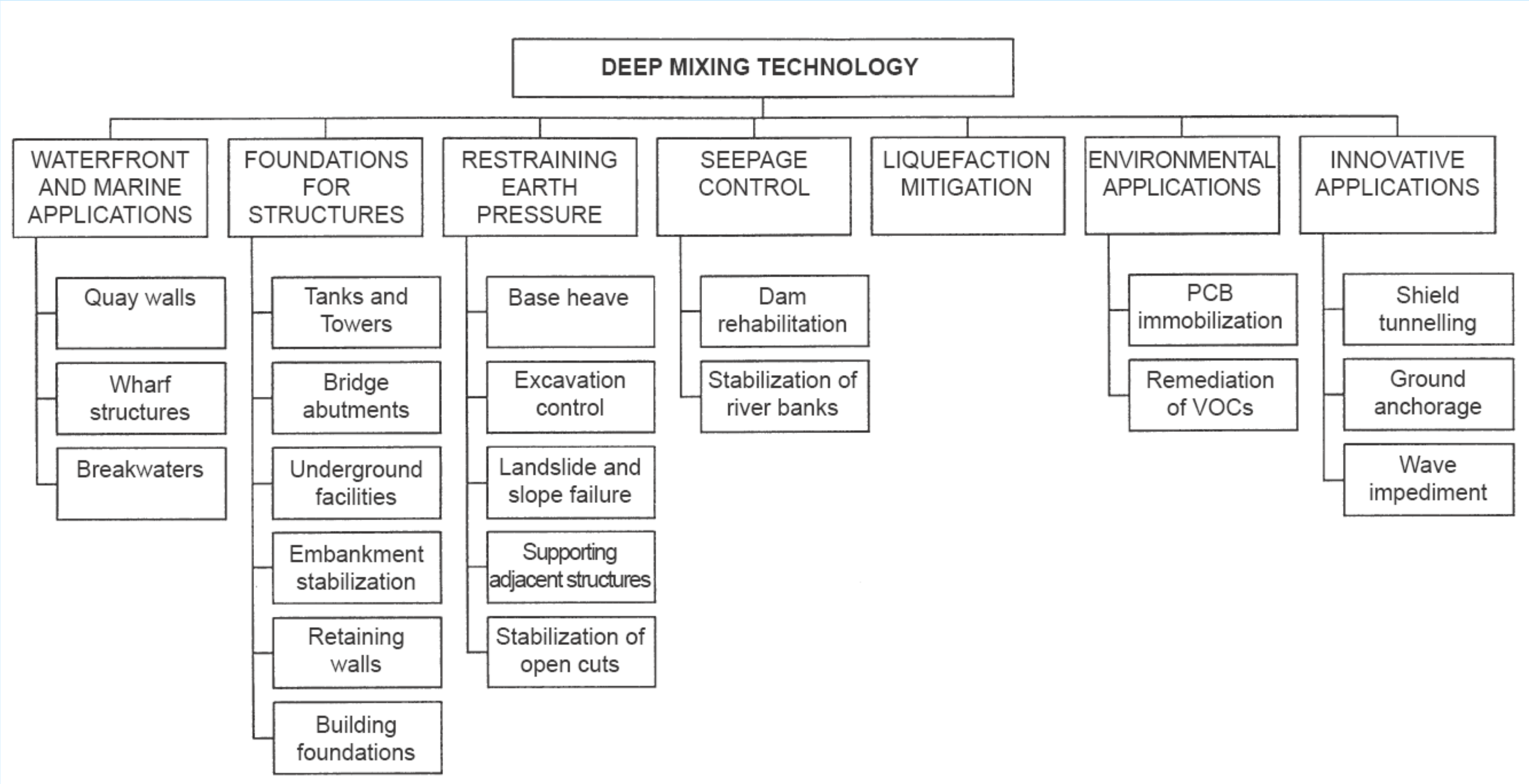


Figure: Flowchart of various applications of deep mixing technology

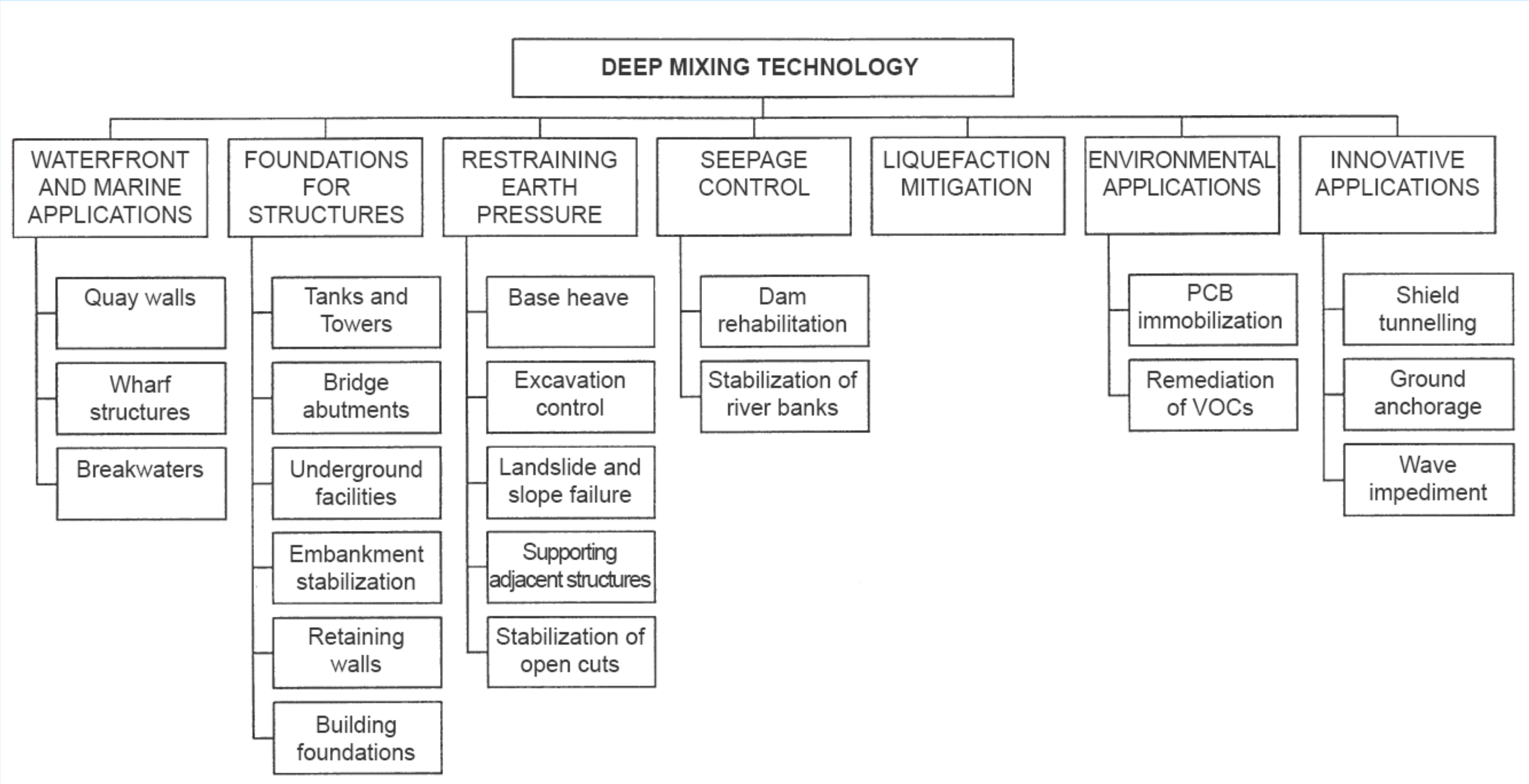


Figure: Flowchart of various applications of deep mixing technology

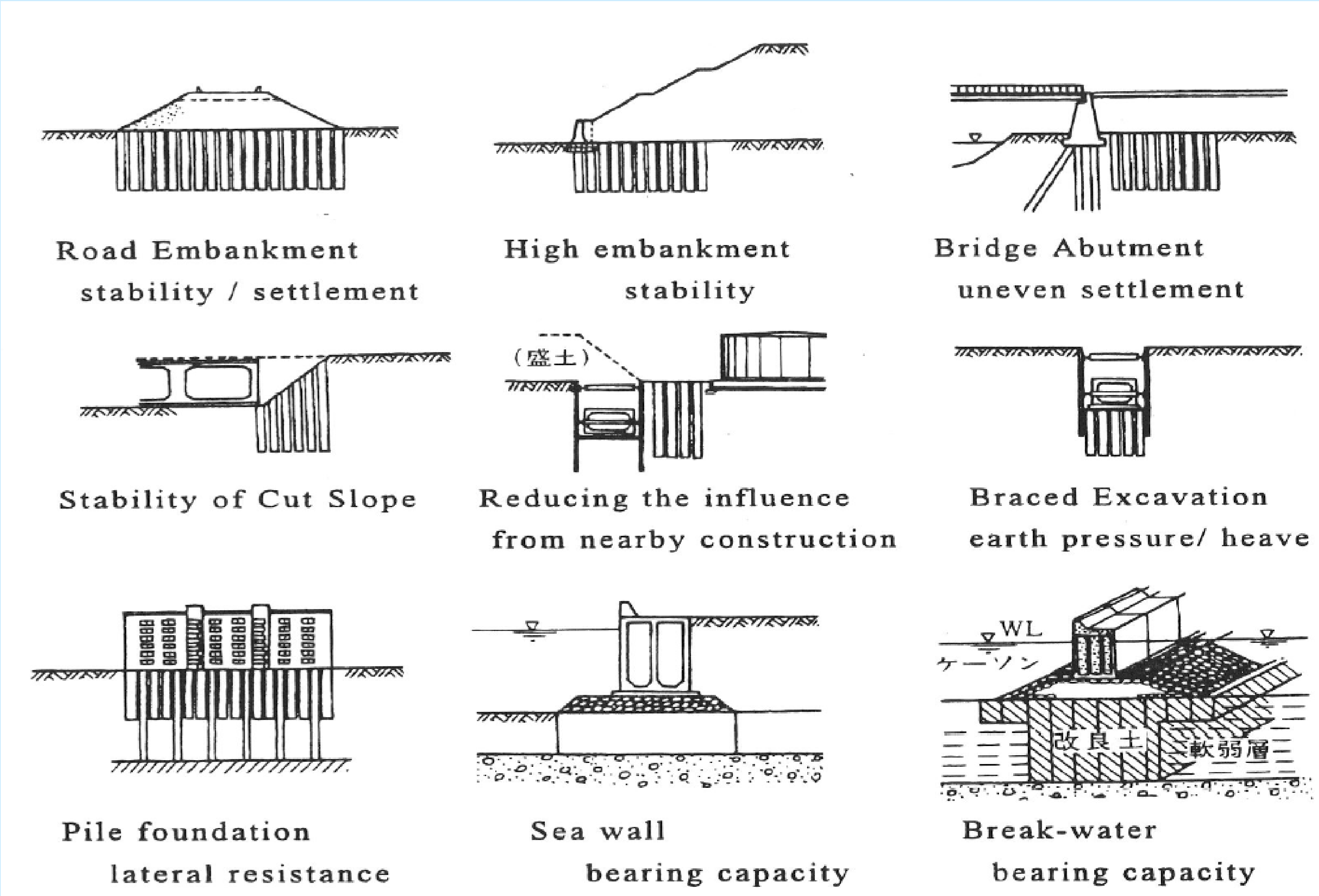


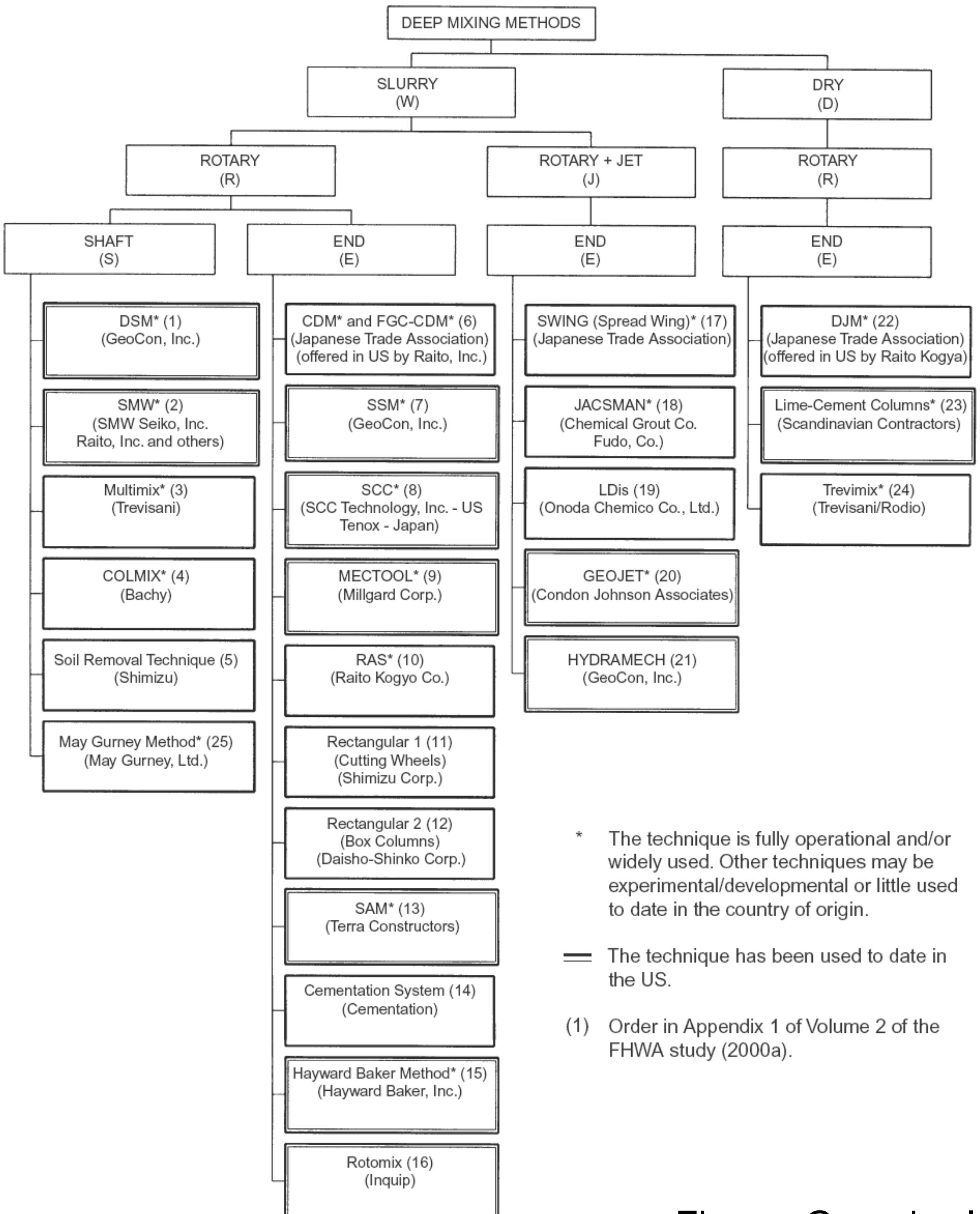
Figure 2 A variety of deep mixing applications after CDM Association (Terashi, 1997)

a) Dry mixing

b) Wet mixing

Terminology of the DM family

· DCM: deep chemical mixing
· CDM: cement deep mixing
· DMM: deep mixing method
· CMC: clay mixing consolidation method
· CCP: chemical churning pile
· DCCM: deep cement continuous method
· DJM: dry jet mixing
· DLM: deep lime mixing
· SWING: spreadable WING method
· RM: rectangular mixing method
· JACSMAN: jet and churning system management
· DeMIC: deep mixing improvement by cement stabilizer
· Mixed-in-place piles
· In situ soil mixing
· Lime±cement columns
· Soil±cement columns
· SMW: soil mix wall
· DSM: deep soil mixing.



* The technique is fully operational and/or widely used. Other techniques may be experimental/developmental or little used to date in the country of origin.

═ The technique has been used to date in the US.

(1) Order in Appendix 1 of Volume 2 of the FHWA study (2000a).

Figure: Generic classification of DMM techniques

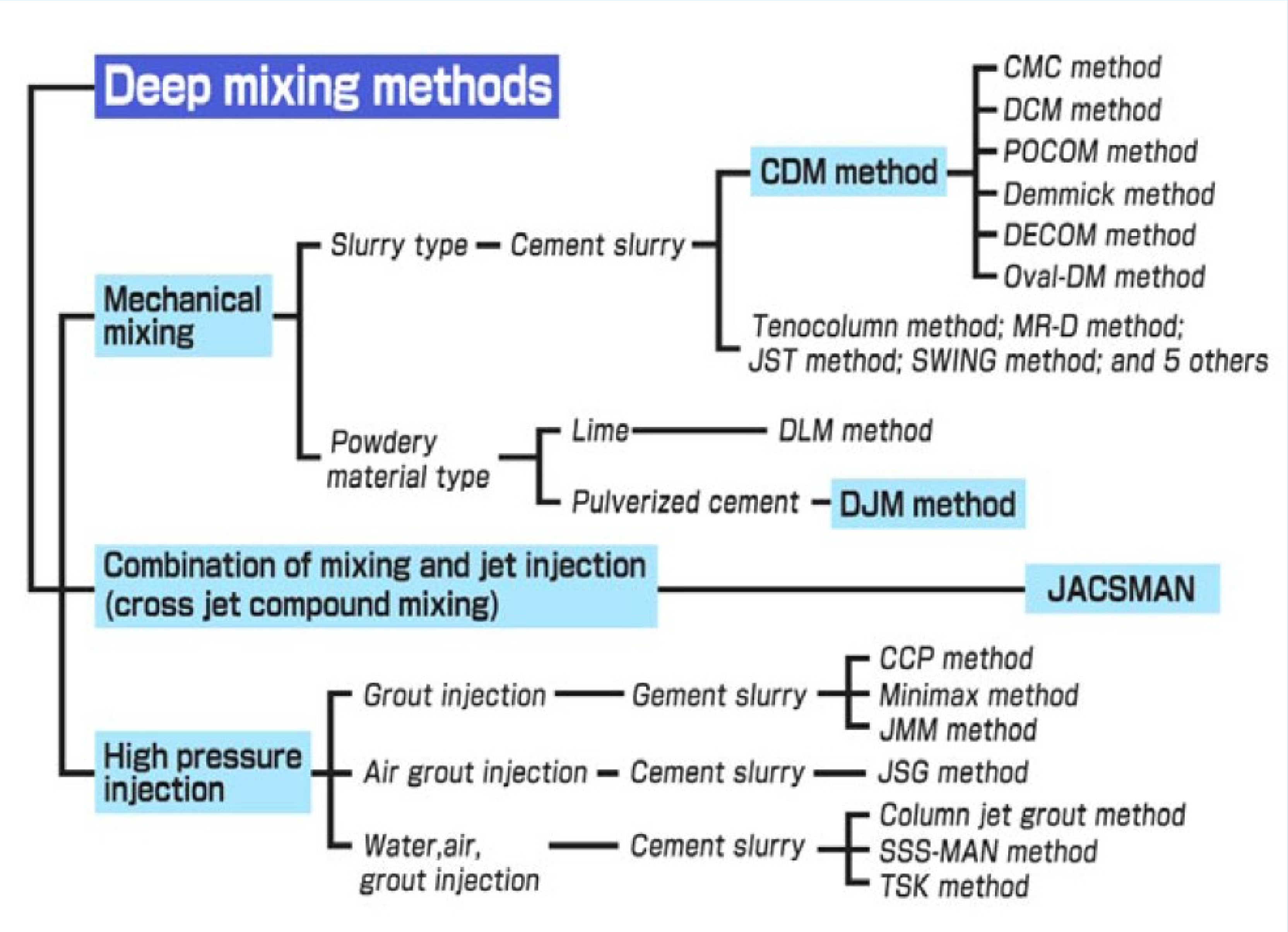


Figure 2.1 Clarification of Deep Mixing methods

Dry Mixing:

Japan, cumulative quantity 1980 - 2004: 26,243,000 m^3 (Japan DJM data)

Sweden, 2003 annual volume: 587,000 m^3 (SGI)

United States, cumulative from 1996 to present: No data. <500,000 m^3 (estimated by authors)

Wet Mixing:

Japan, cumulative through 2004: 55,000,000 m^3 (from CDM, Japan)

United States, cumulative through 2004: < 3,500,000 m^3 (DFI, 2004)

Nations	Type of Mixing	Diameter (m)	Maximum depth	Main purpose and Construction records
Japan	Wet	1.0-1.6	50m (-70m, from sea level, off-shore)	Many kinds of purposes, such as port structure (quay-wall, breakwater) foundation, Self standing retaining wall, building foundation, anti-liquefaction with lattice type pile arrangement, and so on
	Dry	1.0-1.3	33m	Road embankment and river dike foundation for increasing stability and reducing settlement. It is difficult for Dry method to be applied in the sandy layer with low natural water content, less than 30%.
Thailand	Wet,Dry	0.6	20m	Road embankment foundation for increasing stability and reducing settlement. Application for self standing retaining wall is now considering for some projects.
Korea	Wet	1.0		Not so many cases
Singapore	Wet	1.0-1.3	20m or less	self standing retaining wall for excavation work for building foundation, Not so many cases
Vietnam	Wet	0.6-1.3	30m or less	Road embankment and river dike foundation for increasing stability and reducing settlement

Table 5.1 General application of Deep Mixing for each Asian countries

Table 1.1 Soil Properties in Asia (after Tanaka, 2001)

	Ip	Wn (%)	Density (g/m^3)	Su (kPa)	Su/p	cv (cm^2/day)	pH
Japan-Ariake	28-116	42-200	2.62	8-40	0.25-0.45	50- 200	6.5 - 7.5
Japan-Yokohama	54-77	74-100	2.68	130-160			
Japan-Hachirogata	75-150	78-207	-	20-60			
Korea-Pusan New port marine clay	30-47	46-65	2.73	22-38	0.2 - 0.3		
Hong Kong-Lantau island marine clay		48-64		8-30		Cv=80 Ch=35	
Vietnam-Mekong Delta	35-64	65-95	2.67-2.78	25		10- 60	5.4 - 5.8
Thailand-Bangkok	41-73	41-120	2.74	10-40			
Singapore	42-57	50-60	2.76	17-90	0.2-0.32		

Installation Patterns

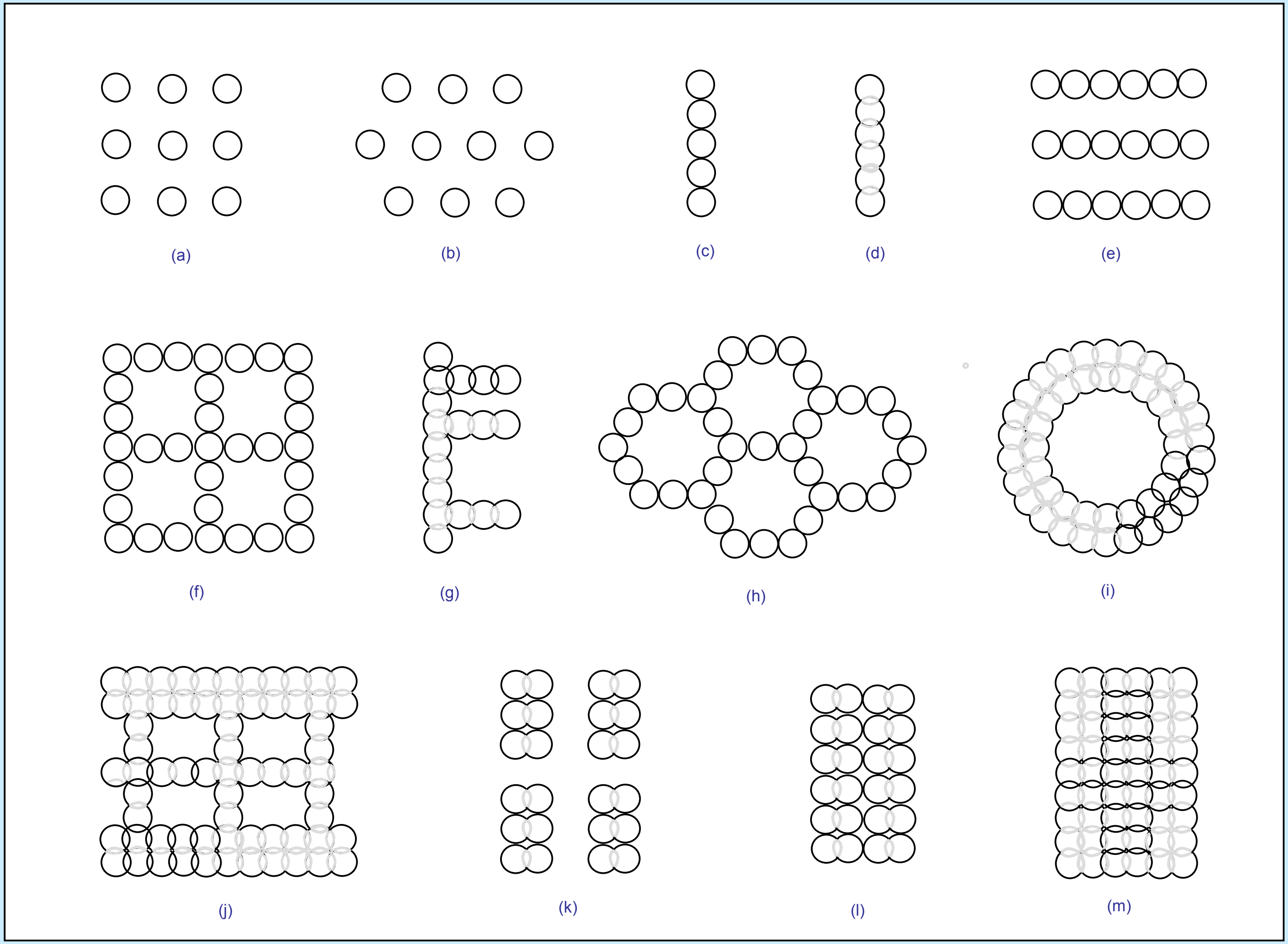


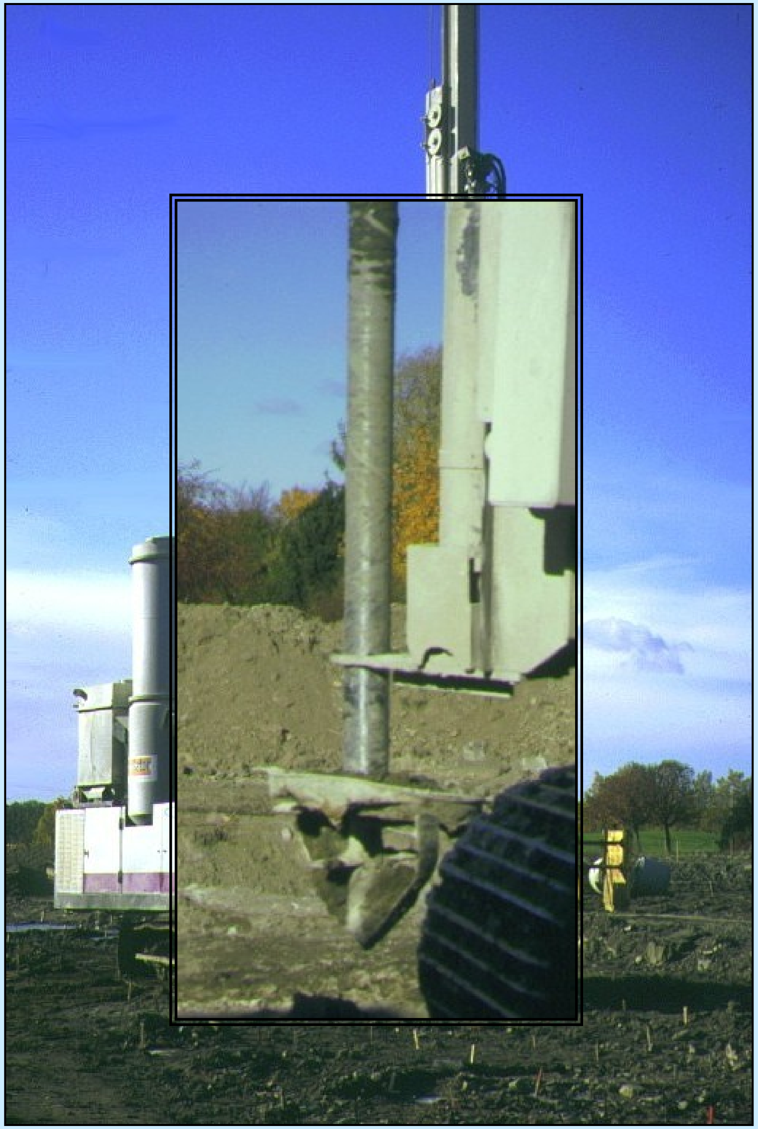
Figure 6.9 Long rod type deep mixing machines

Figure 7.3 Dry type machine for two rods type

Figure 6.11 Photograph of Self-standing retaining wall in Haneda airport

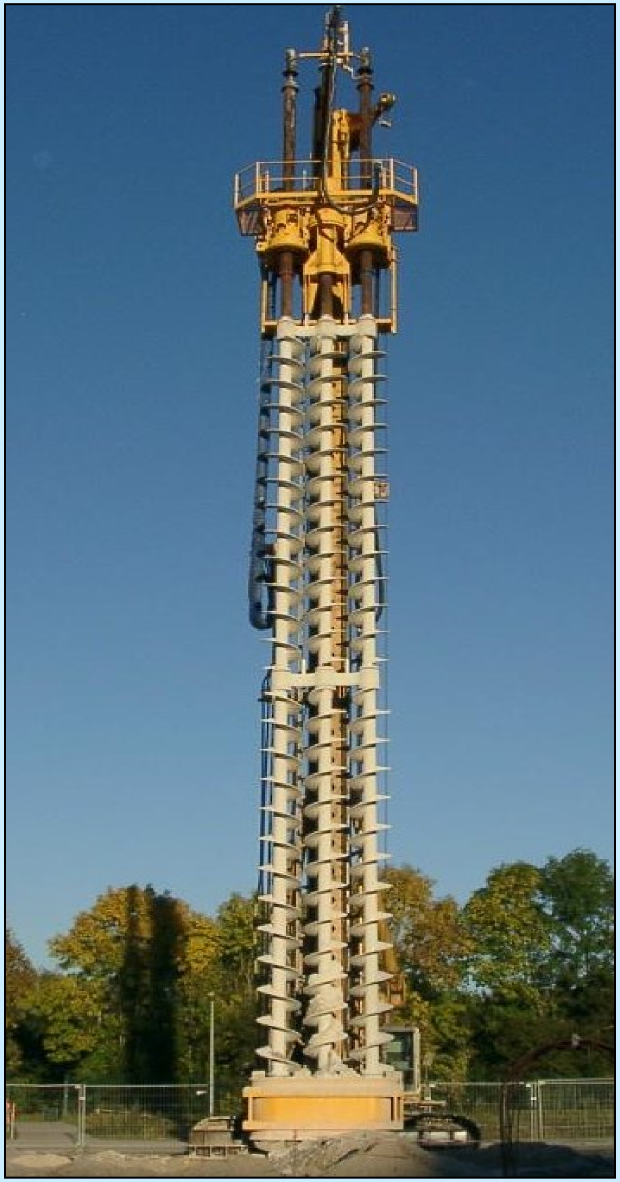
Figure 6.13 are the photograph of DMM machine for Self-standing retaining wall in Singapore

Soil Mixing Methods

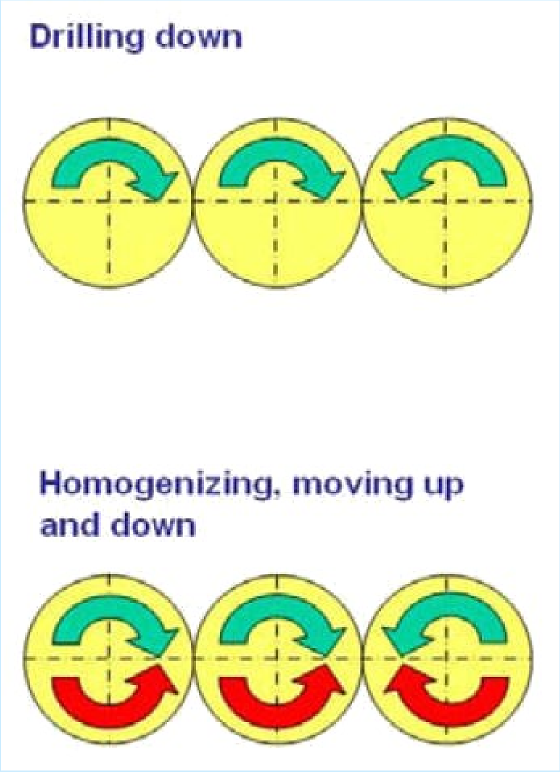


Dry Mixing – Nordic Method

Soil Mixing Methods



Wet Mixing – Central European Methods



Soil Mixing Methods

Recently developed wet Mixing Methods

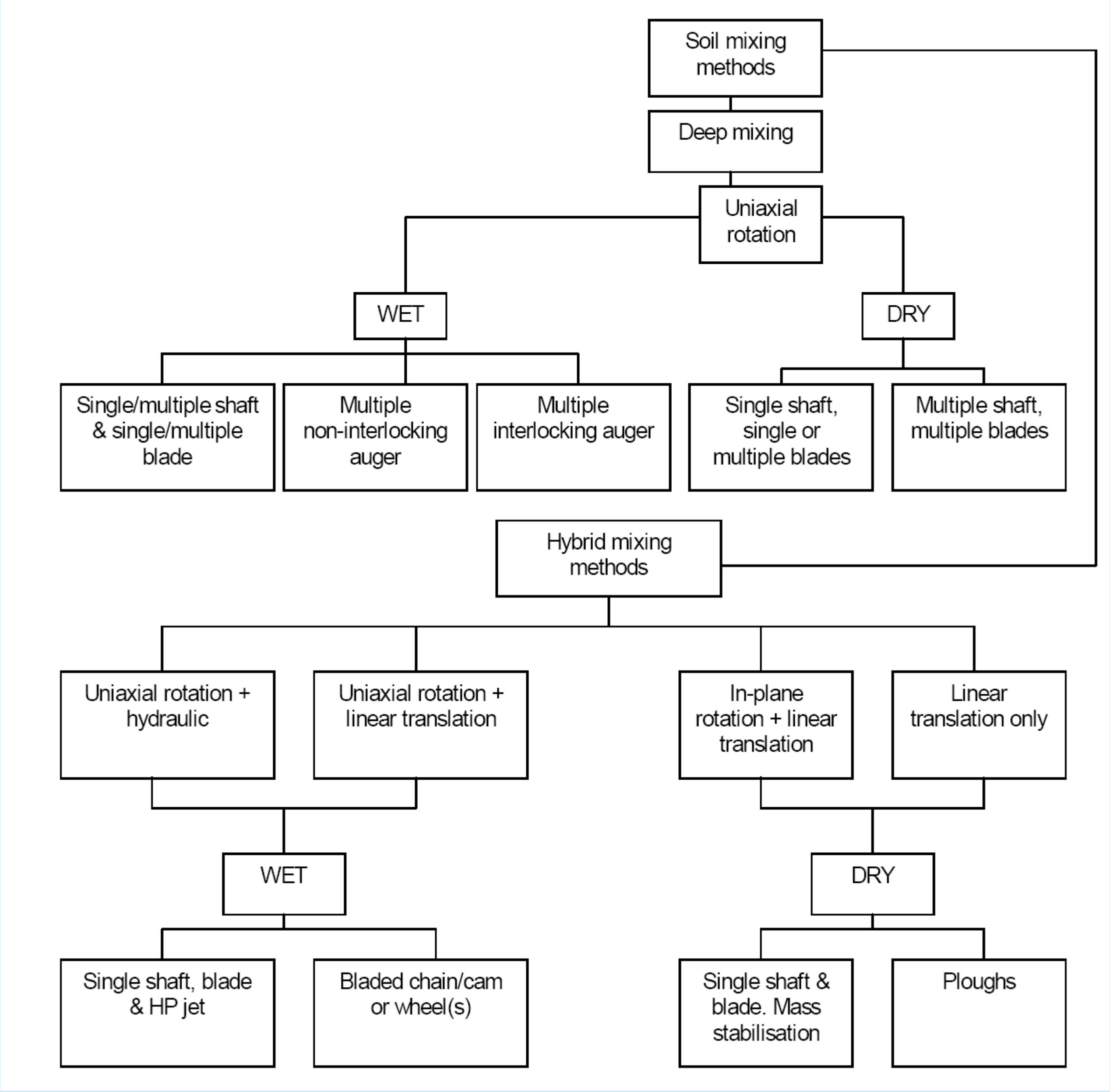
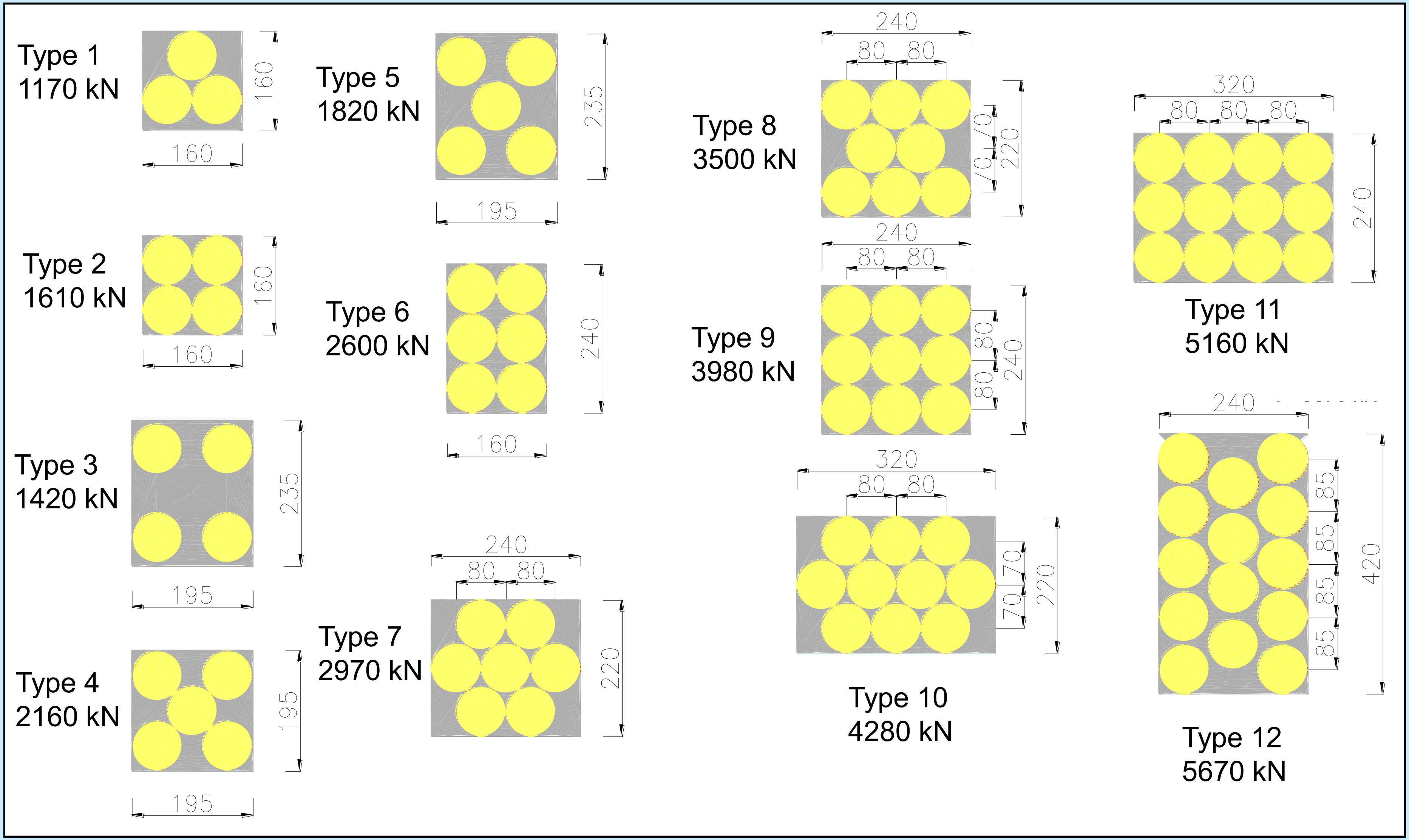


Figure 2. General classification of equipment used by the deep mixing methods included in the Code and by hybrid mixing methods not included.

Figure 7.7 Mixed column with Dry mixing

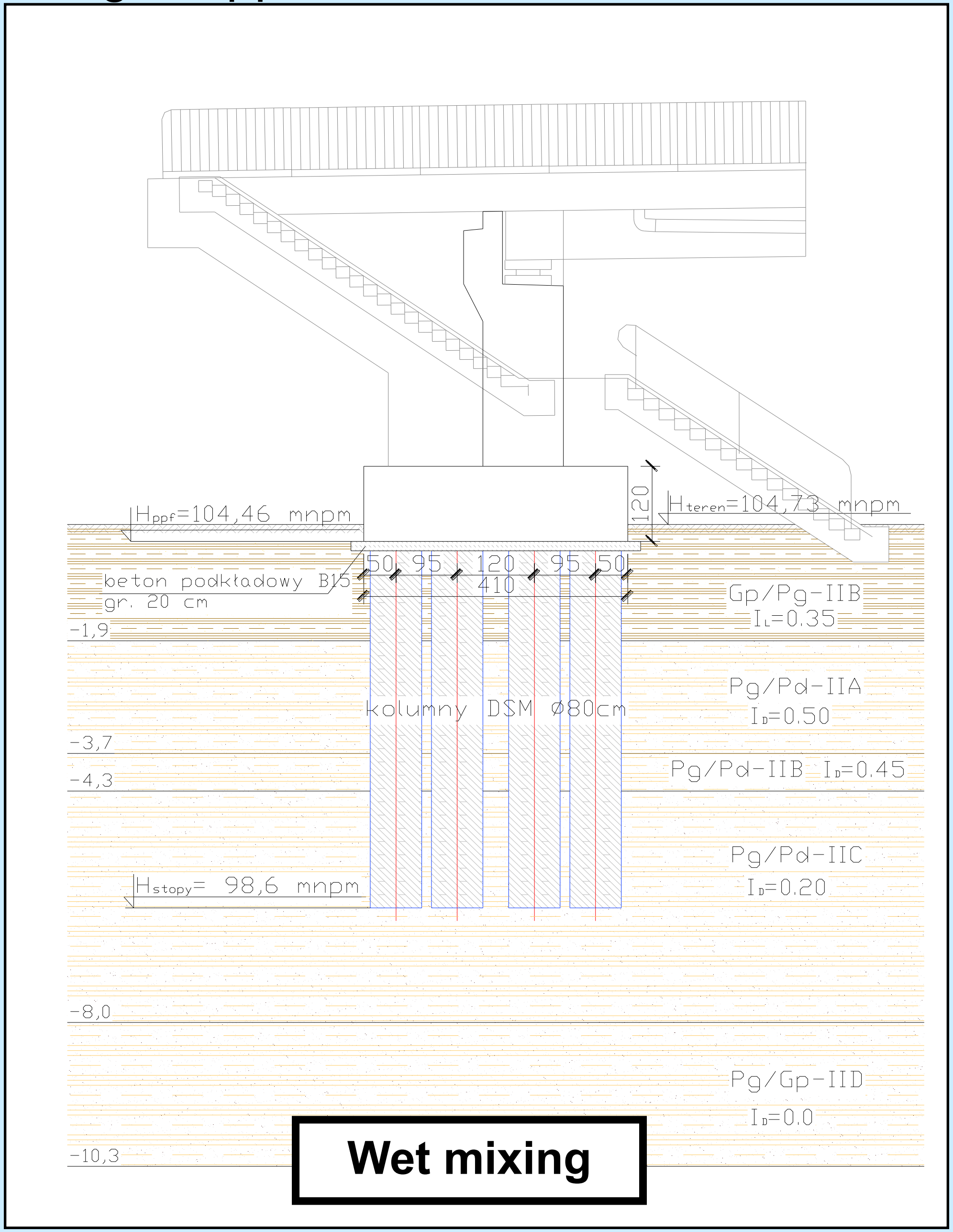
Wet mixing

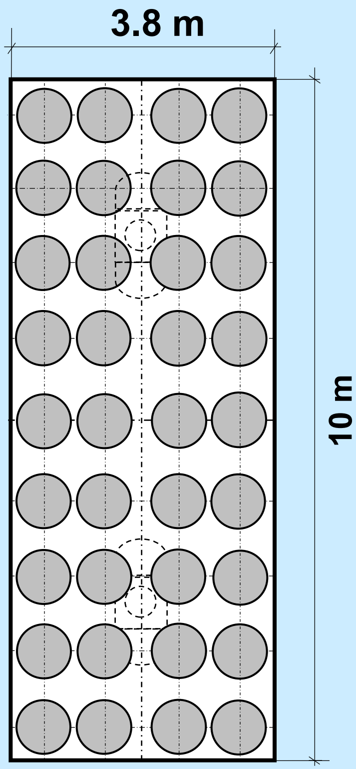
MEGAPLEX, Poland



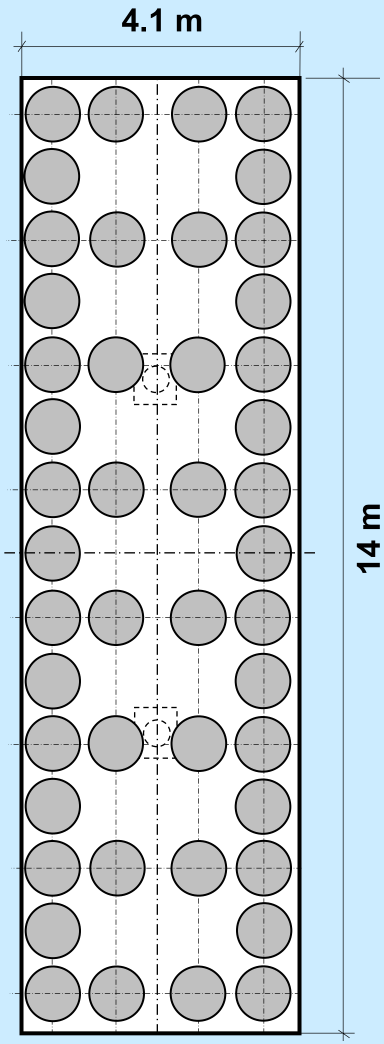
Courtesy of Keller Polska

Bridge supports on DM columns – A2, Poland (ca 80 bridges)





Supports:
P2, P3, P4,
on 36 columns



Supports:
P1, P5,
on 46 columns

Courtesy of Keller Polska

Figure 1. Deep mixing installation to reduce vibrations at high speed trains (Holm et al, 2002)

Factors influencing strength increase

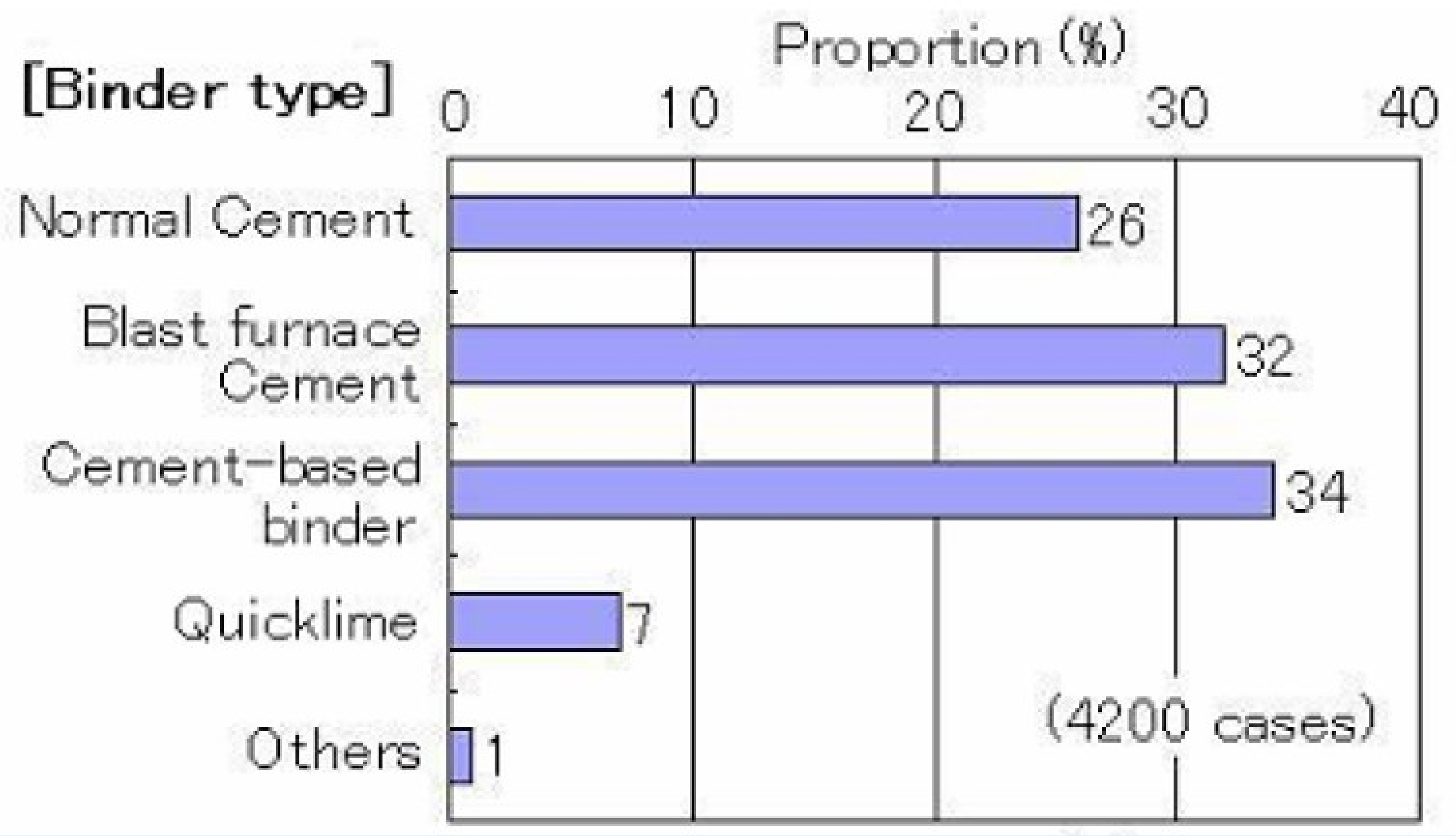
I	Characteristics of binder	
	1	type of binder
	2	quality of binder
	3	mixing water and secondary additives
II	Characteristics and conditions of Soil	
	1	physical, chemical and mineralogical properties of Soil
	2	organic content
	3	pH of pore water
	4	water content
III	Mixing conditions	
	1	degree of mixing
	2	timing of mixing/ re-mixing
	3	quantity of binder
IV	Curing conditions	
	1	temperature
	2	curing time
	3	humidity
	4	wetting and drying/ freezing and thawing

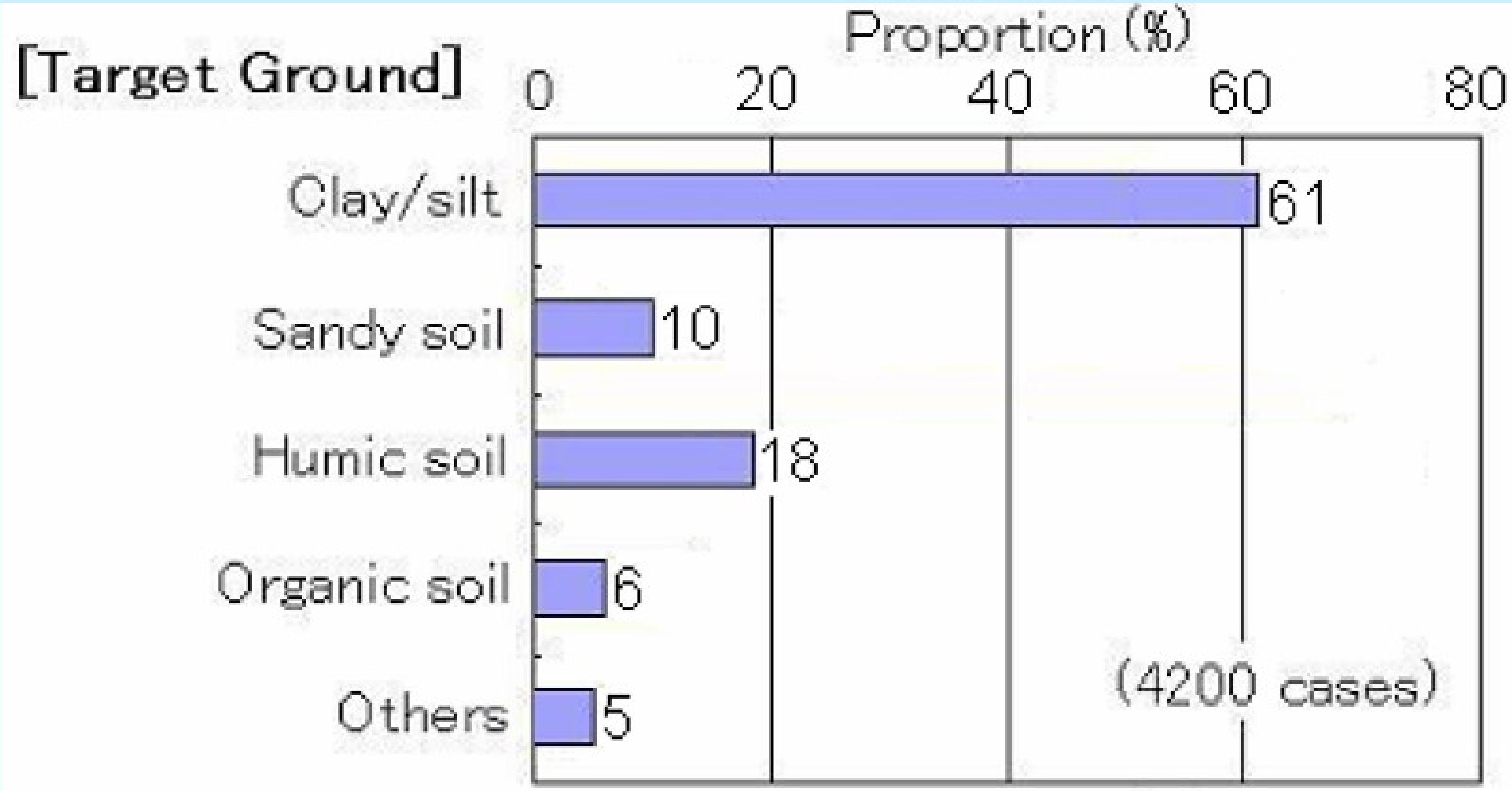
Table 1 Factors affecting the strength increase (Terashi, 1997)

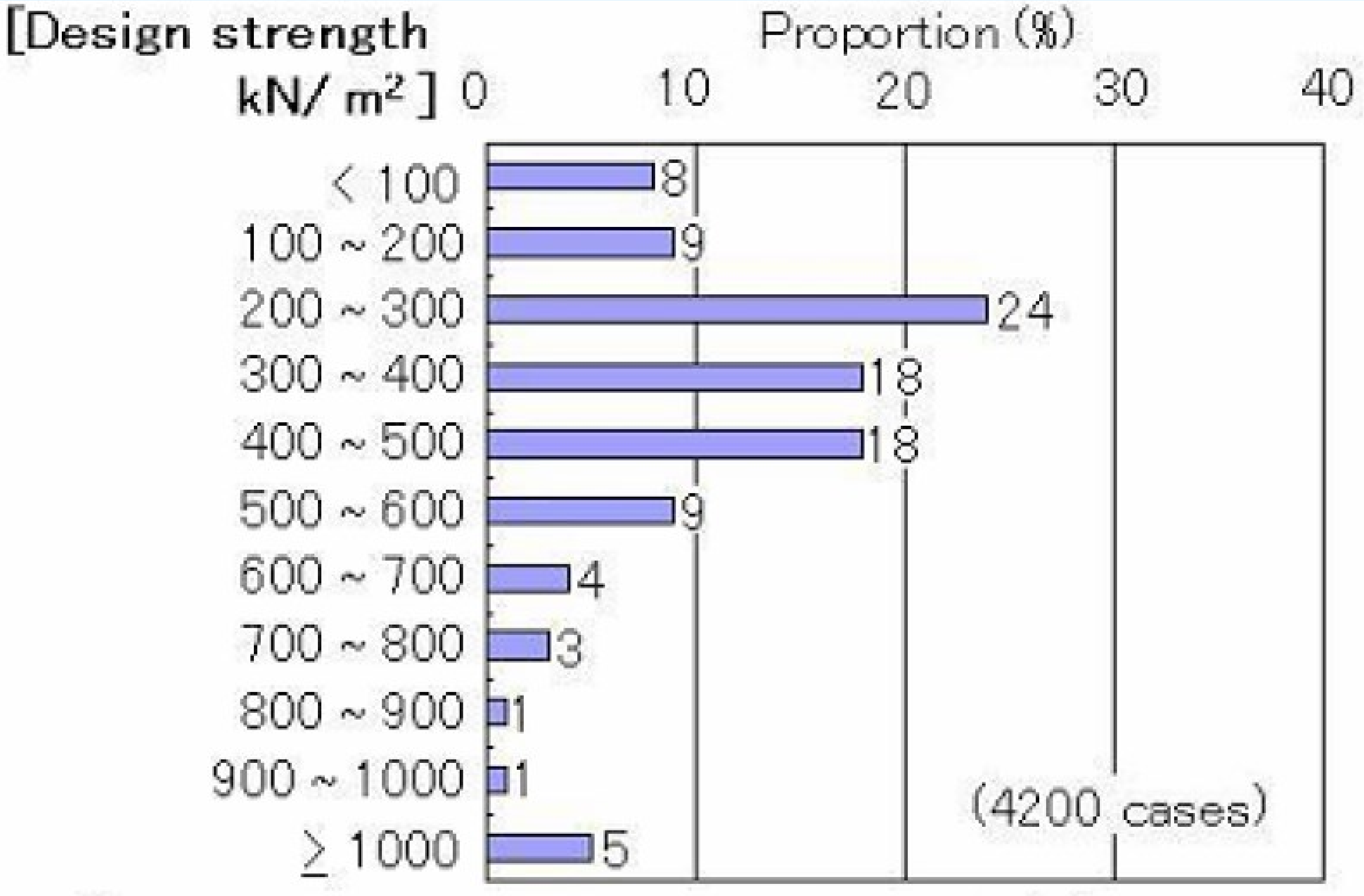
Binder	Silt Organic content 0-2%	Clay Organic content 0-2%	Organic Soils, e.g. Gyttja Organic Clay Organic content 2-30%	Peat Organic content 50-100%
Cement	xx	x	x	xx
Cement + gypsum	x	x	xx	xx
Cement +furnace slag	xx	xx	xx	xxx
Lime + cement	xx	xx	x	-
Lime + gypsum	xx	xx	xx	-
Lime + slag	x	x	x	-
Lime +gypsum + slag	xx	xx	xx	-
Lime +gypsum + cement	xx	xx	xx	-
Lime	-	xx	-	-

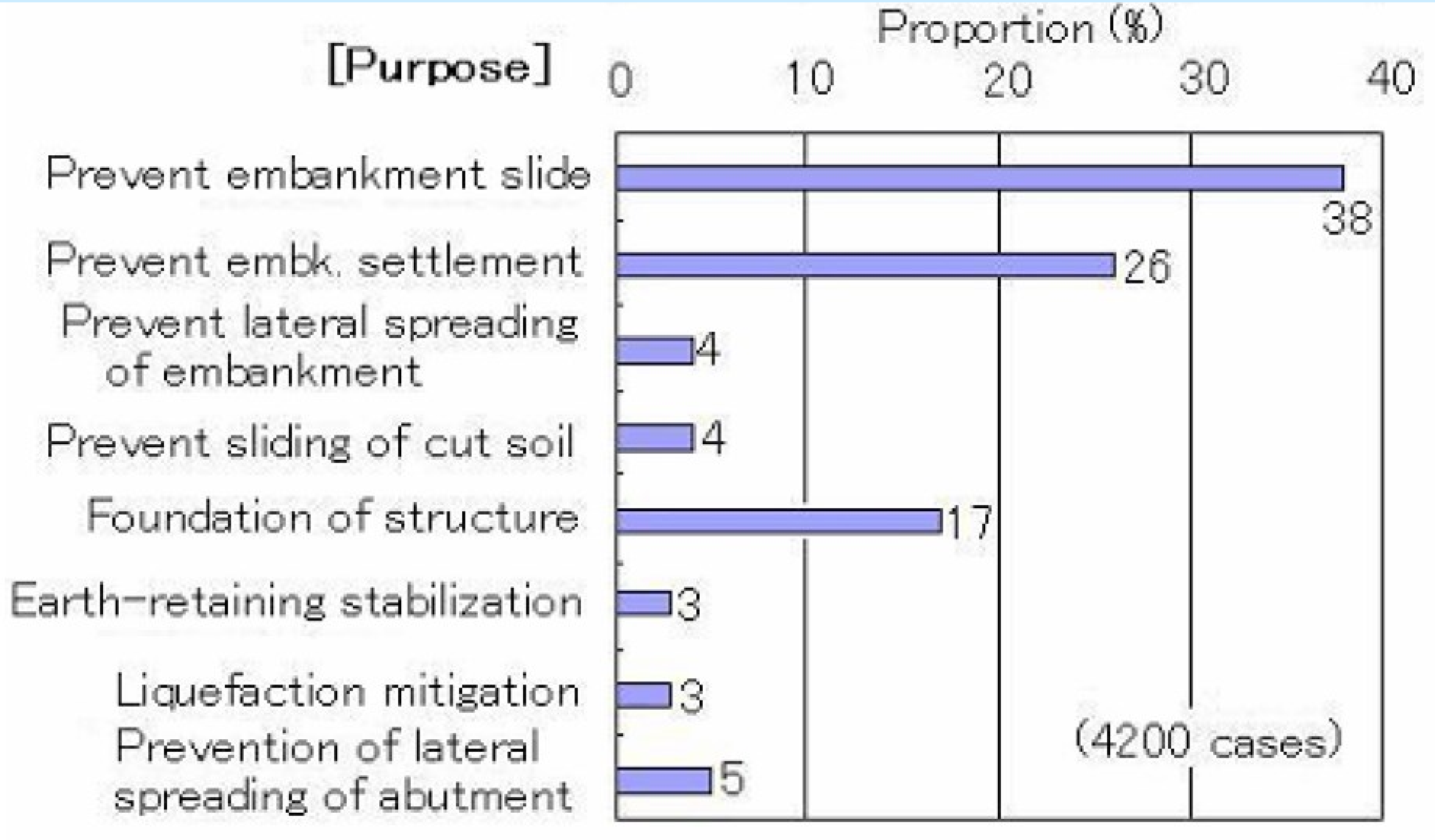
xxx very good binder in many cases
xx good in many cases
x good in some cases
- not suitable

Figure 12. Relative strength increase based on laboratory tests on European soils.


[Binder type]
Proportion (%)
0
10
20
30
40
Normal Cement
26
Blast furnace Cement
32
Cement-based binder
34
Quicklime
7
Others
1
(4200 cases)


[Target Ground]
Proportion (%)
0
20
40
60
80
Clay/silt
61
Sandy soil
10
Humic soil
18
Organic soil
6
Others
5
(4200 cases)


[Design strength
kN/ m²]
Proportion (%)
0
10
20
30
40
< 100
100 ~ 200
200 ~ 300
300 ~ 400
400 ~ 500
500 ~ 600
600 ~ 700
700 ~ 800
800 ~ 900
900 ~ 1000
≥ 1000
8
9
24
18
18
9
4
3
1
1
5
(4200 cases)


Proportion (%)
[Purpose]
0
10
20
30
40
Prevent embankment slide
38
Prevent embk. settlement
26
Prevent lateral spreading of embankment
4
Prevent sliding of cut soil
4
Foundation of structure
17
Earth-retaining stabilization
3
Liquefaction mitigation
3
Prevention of lateral spreading of abutment
5
(4200 cases)

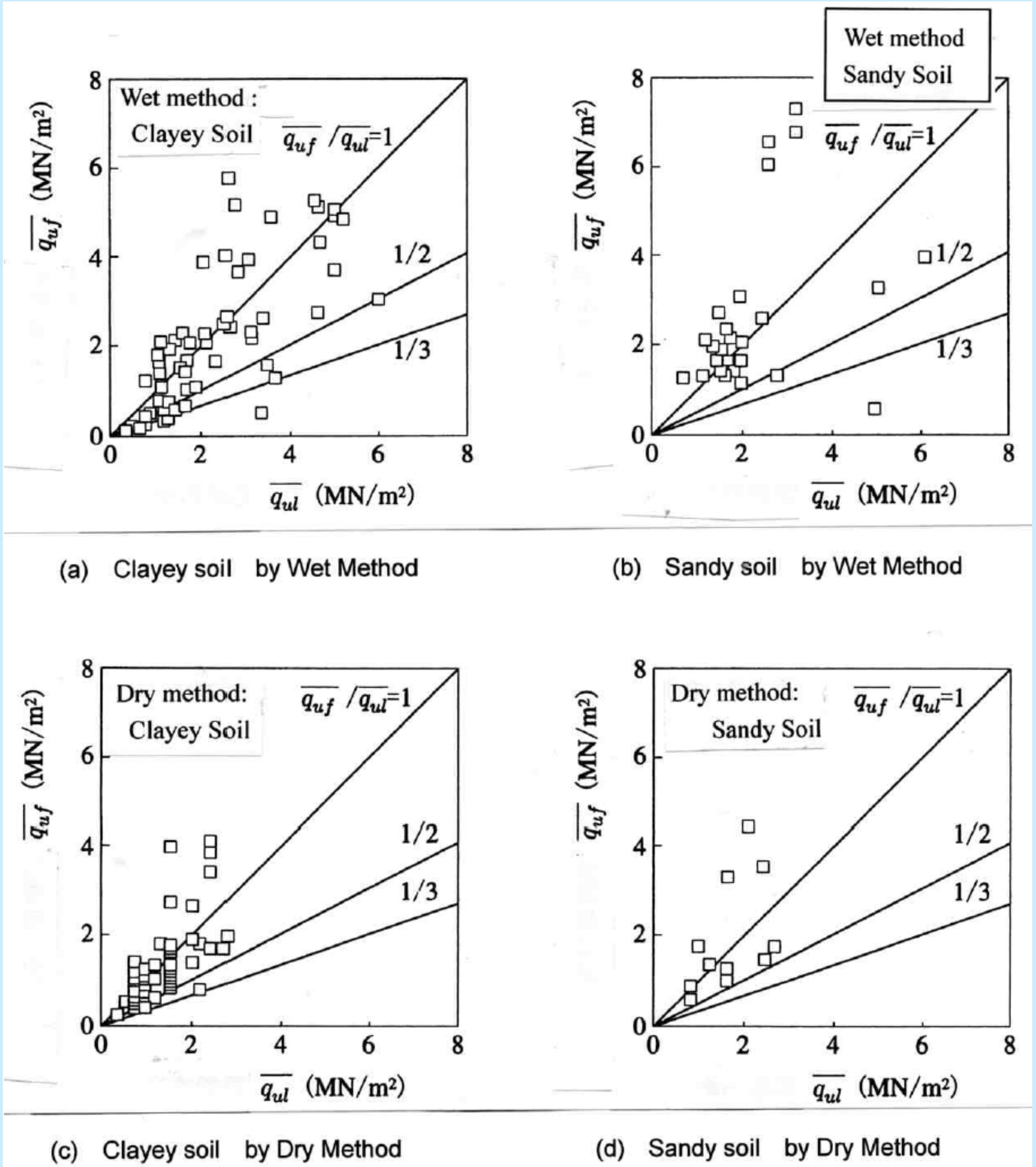


Figure 5 Relation between average field strength q_{uf} and laboratory strength q_{ul} for on-land works (Public Works Research Center, 1999)

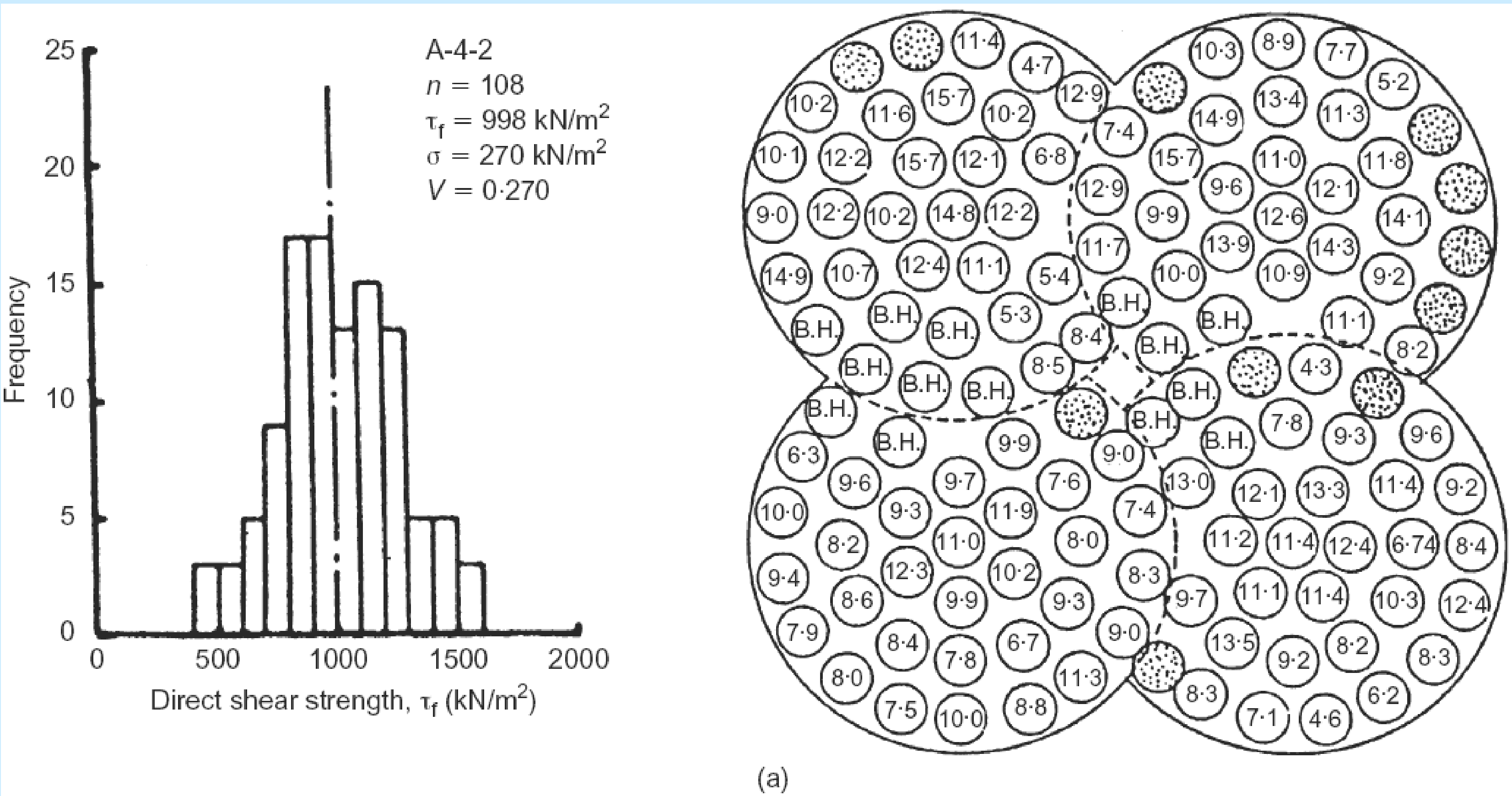


Figure: Distribution of shear strength in overlapped columns

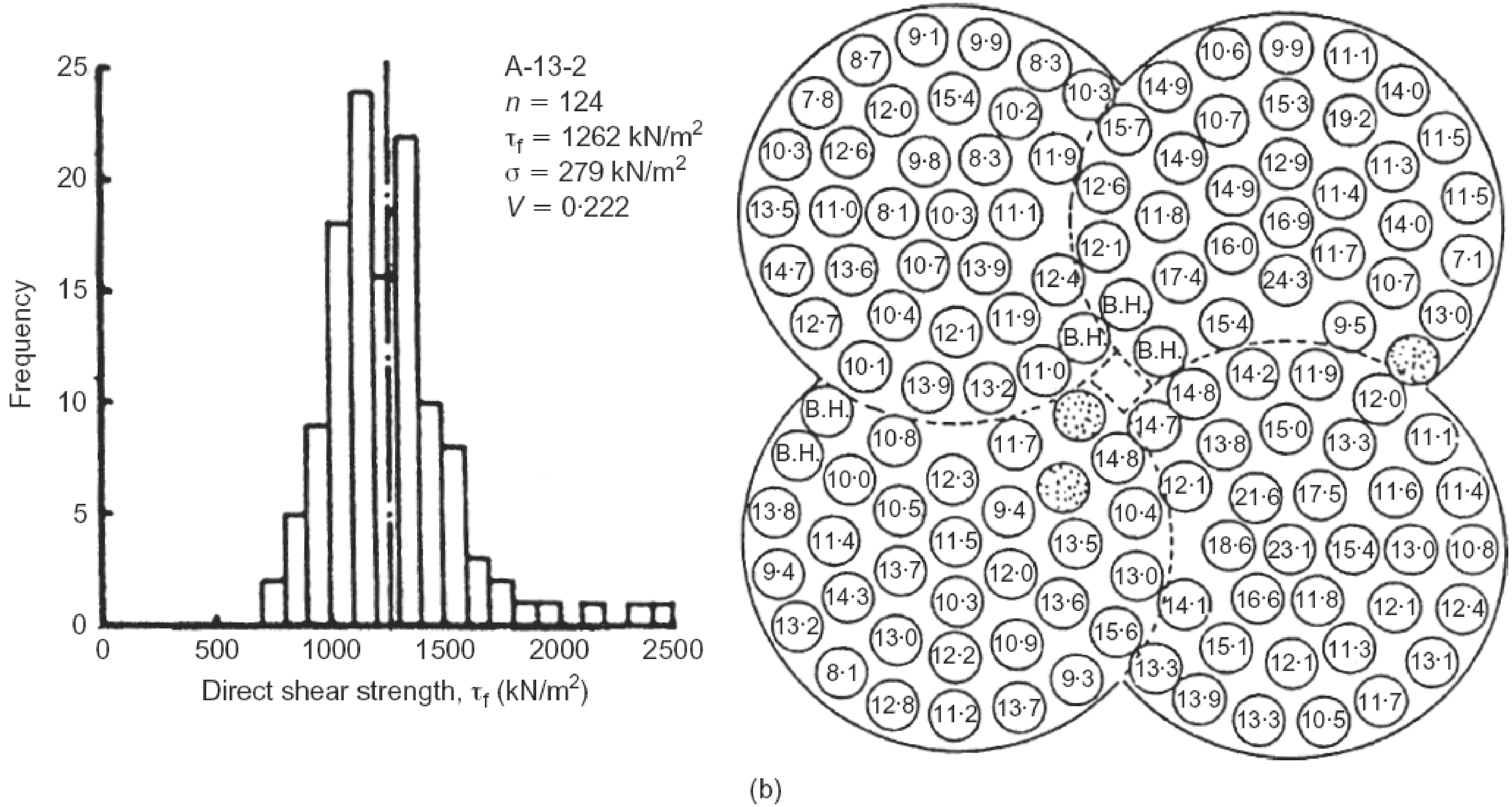


Figure: Distribution of shear strength in overlapped columns

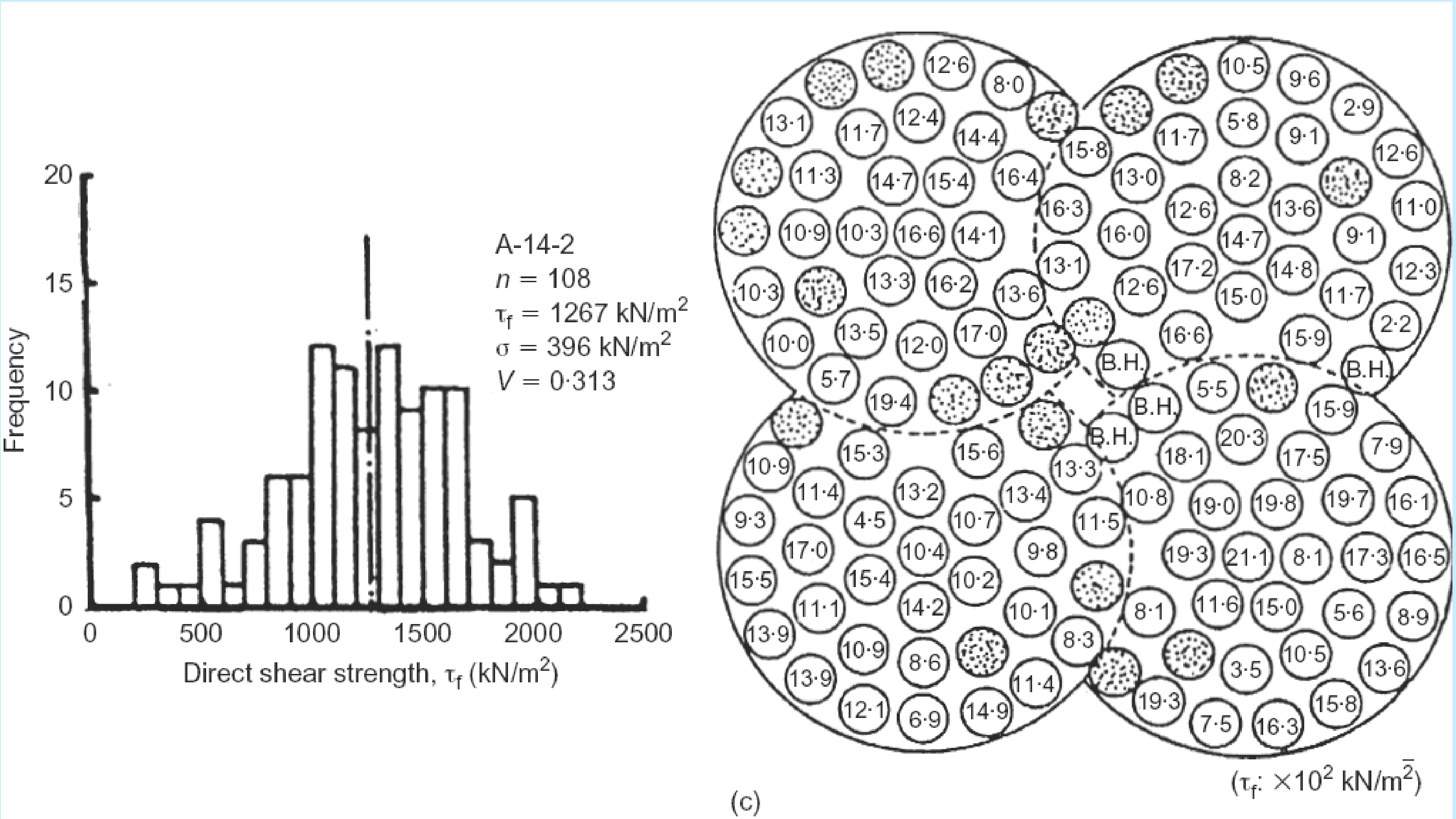


Figure: Distribution of shear strength in overlapped columns

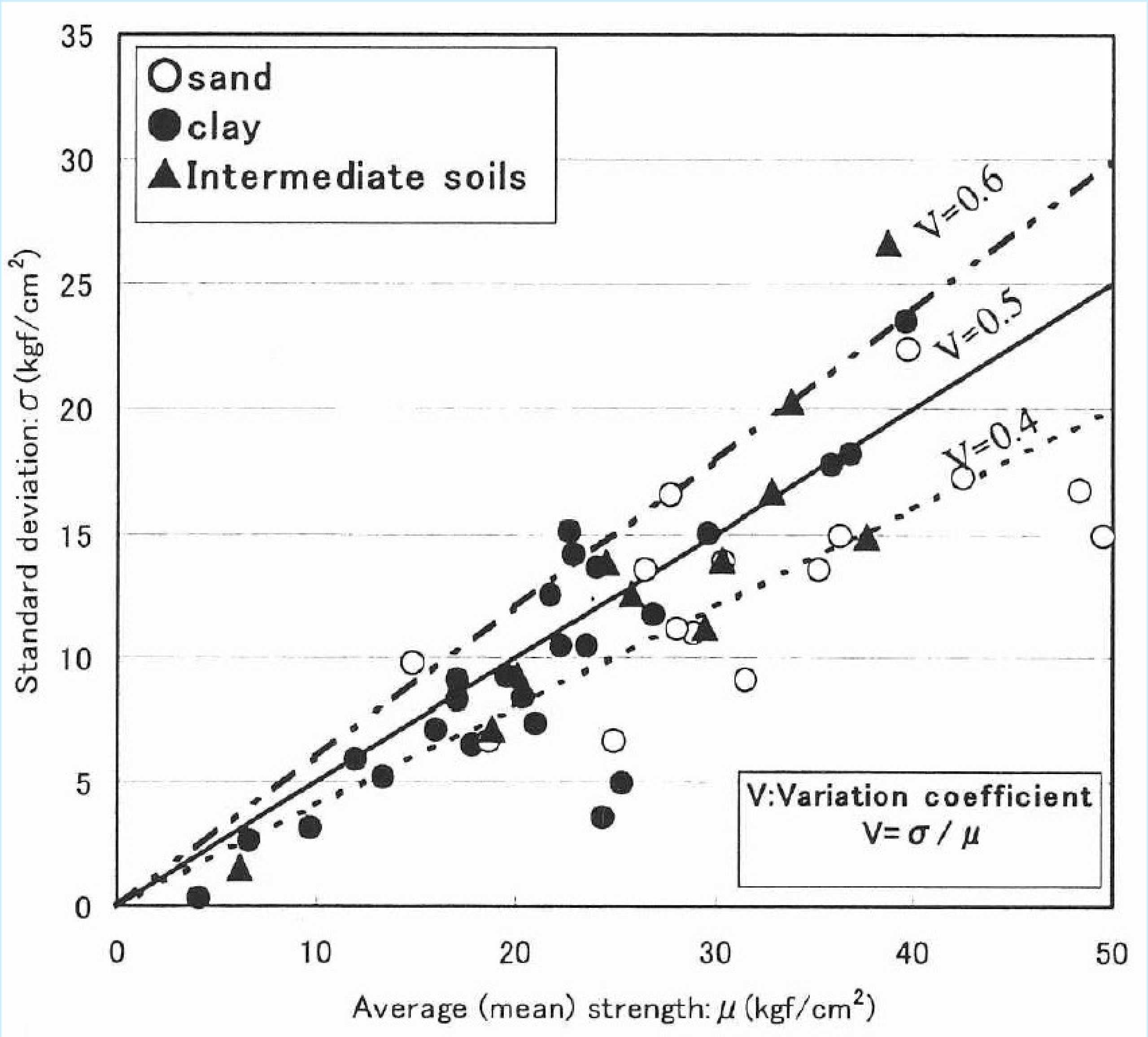


Figure 7 Relation between standard deviation and mean strength for on-land works (Matsuo, 2002)

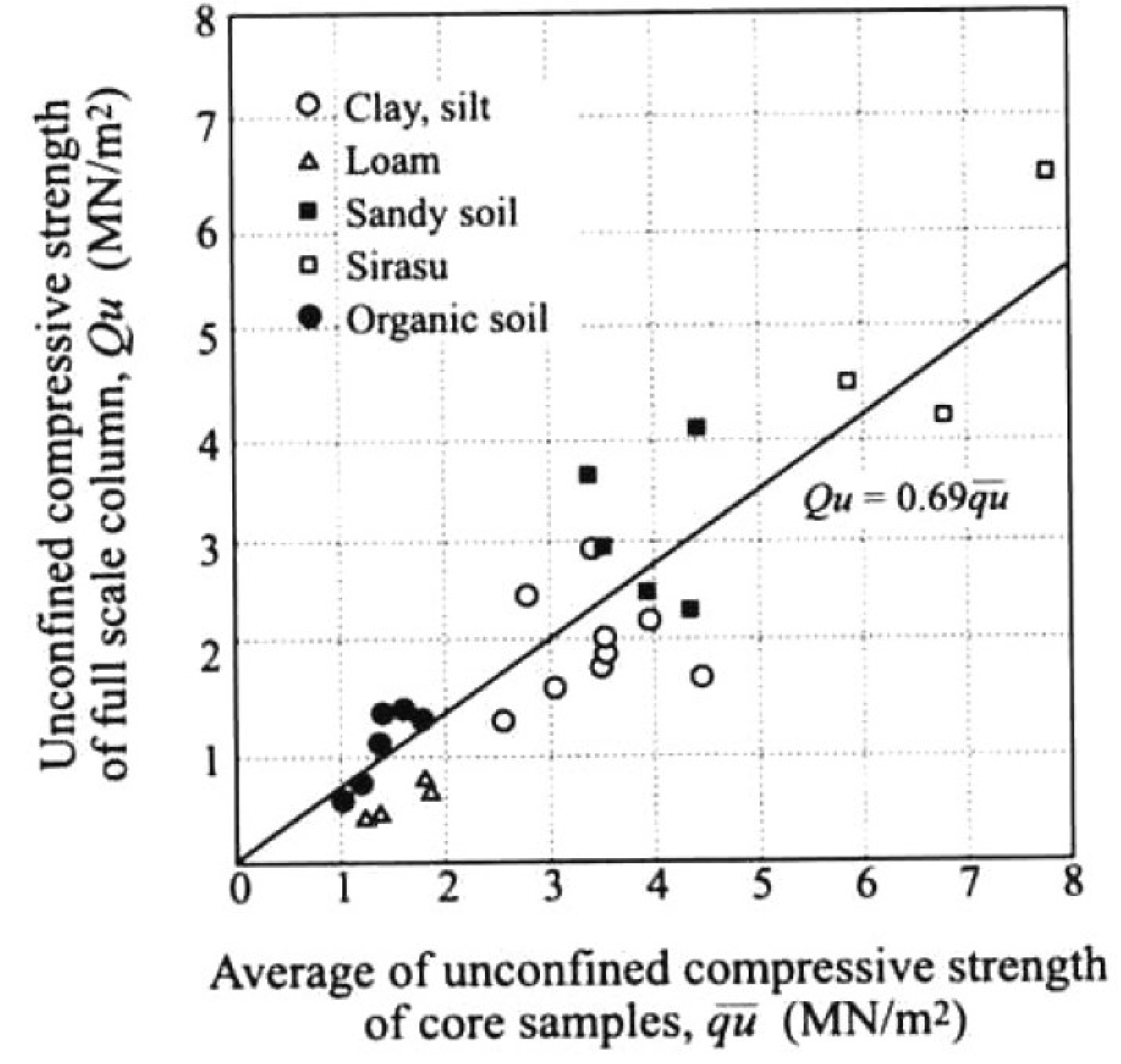


Figure 8 Comparison of failure load of full-scale columns and unconfined compressive strengths on core samples (BCJ, 1997)

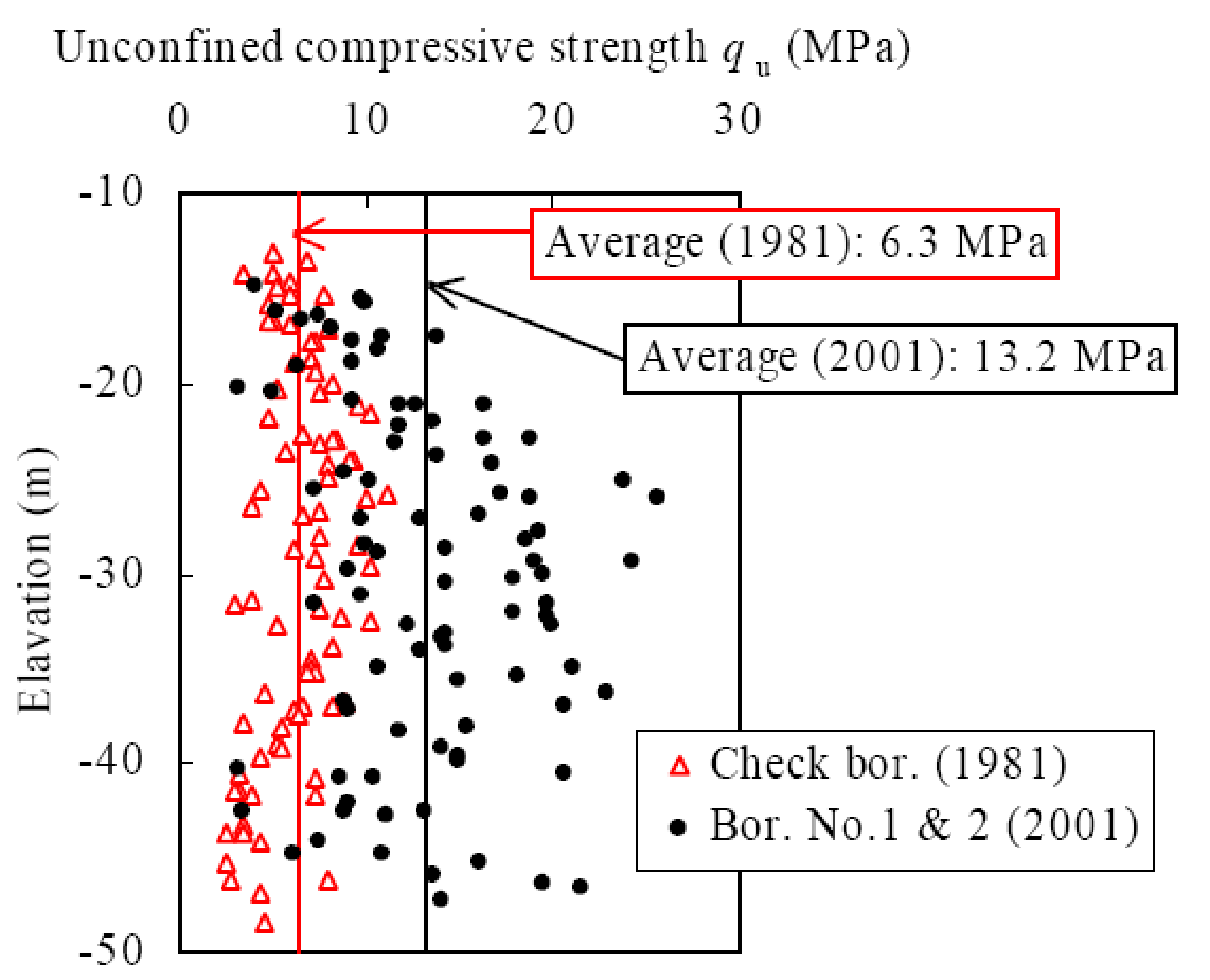


Figure 10 Profile of unconfined compressive strengths at 3 months and 20 years after the construction (Ikegami et al 2005)

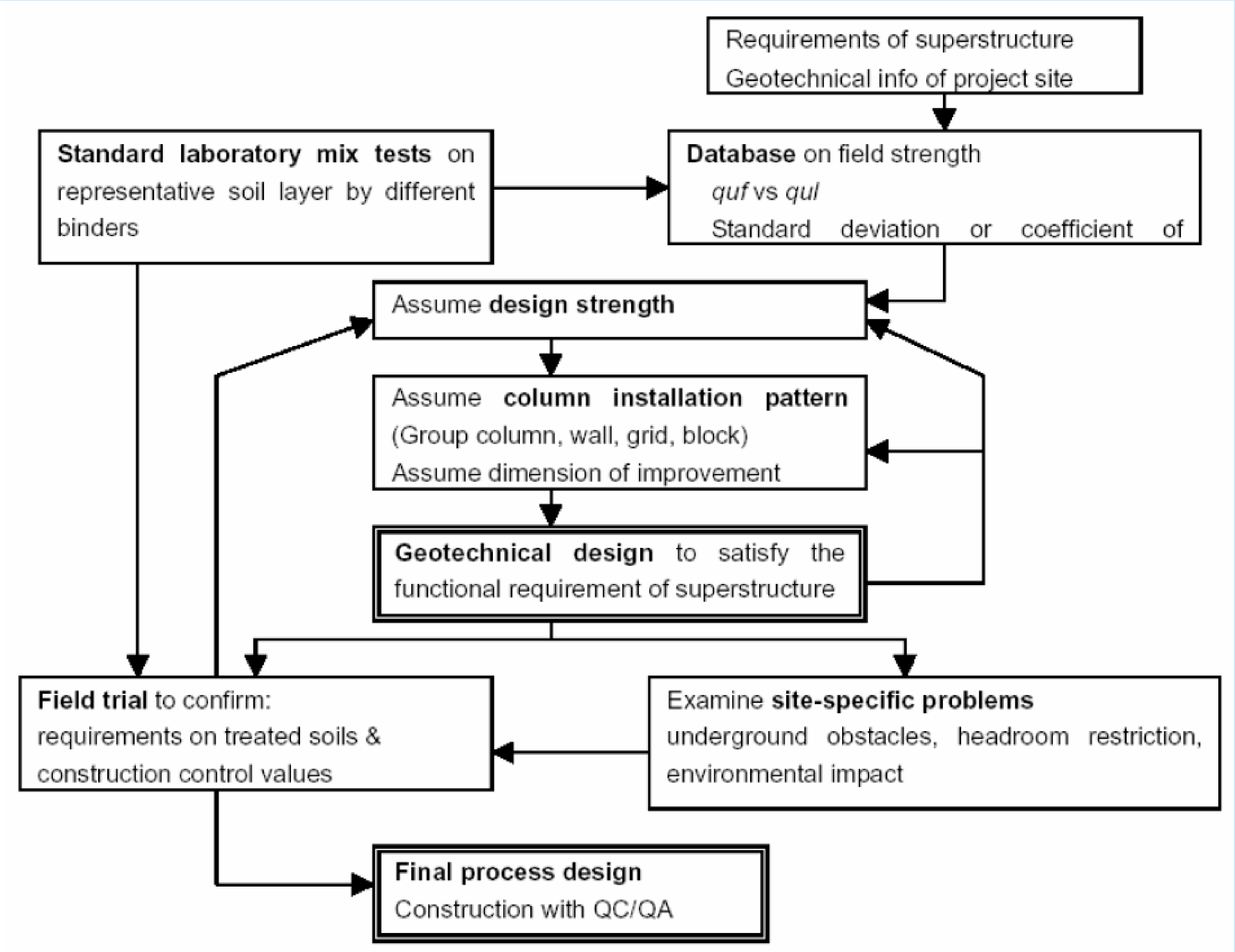


Figure 1 Work flow common to all the applications (Terashi, 2001)

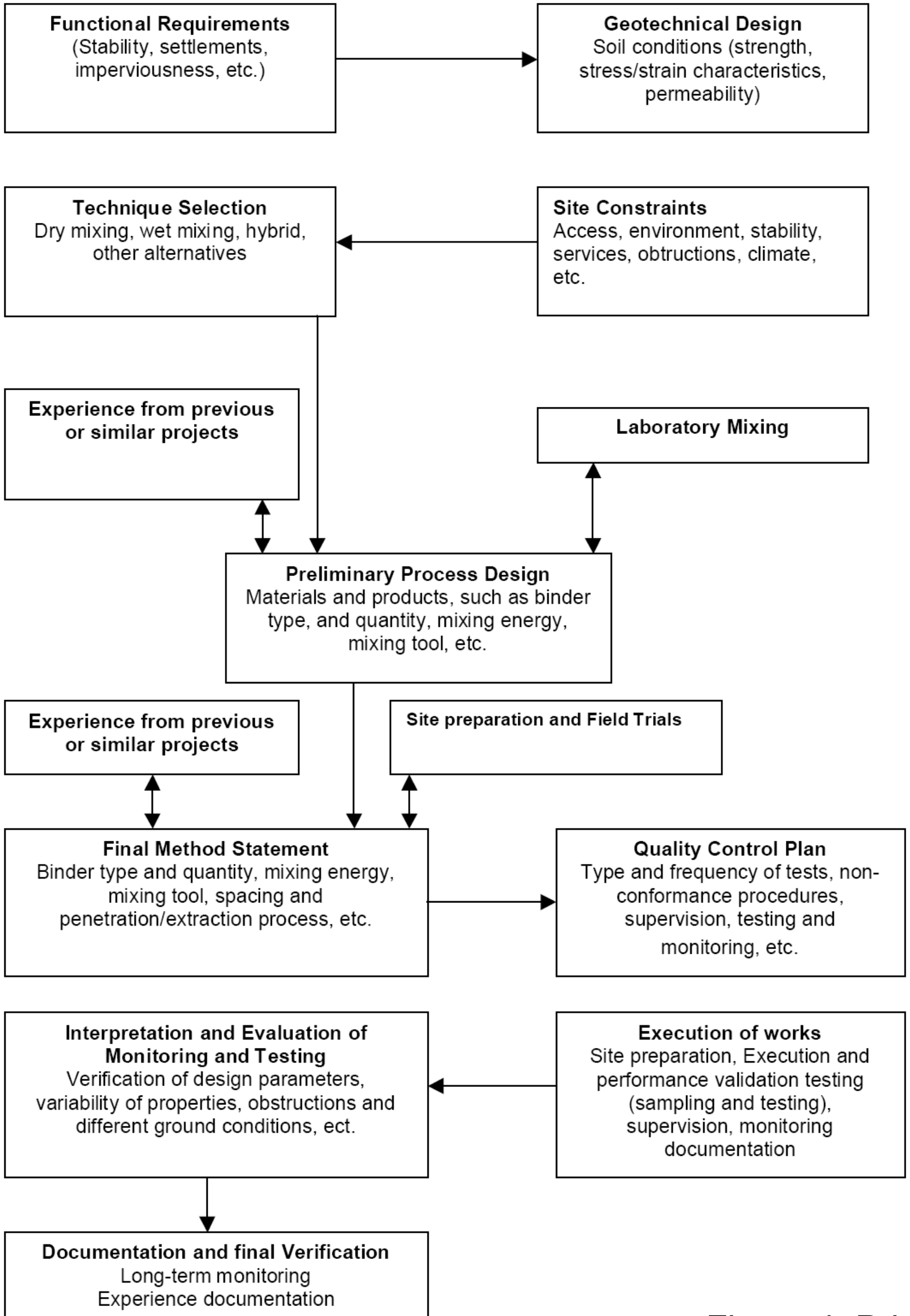


Figure 4. Principles of execution of deep mixing.

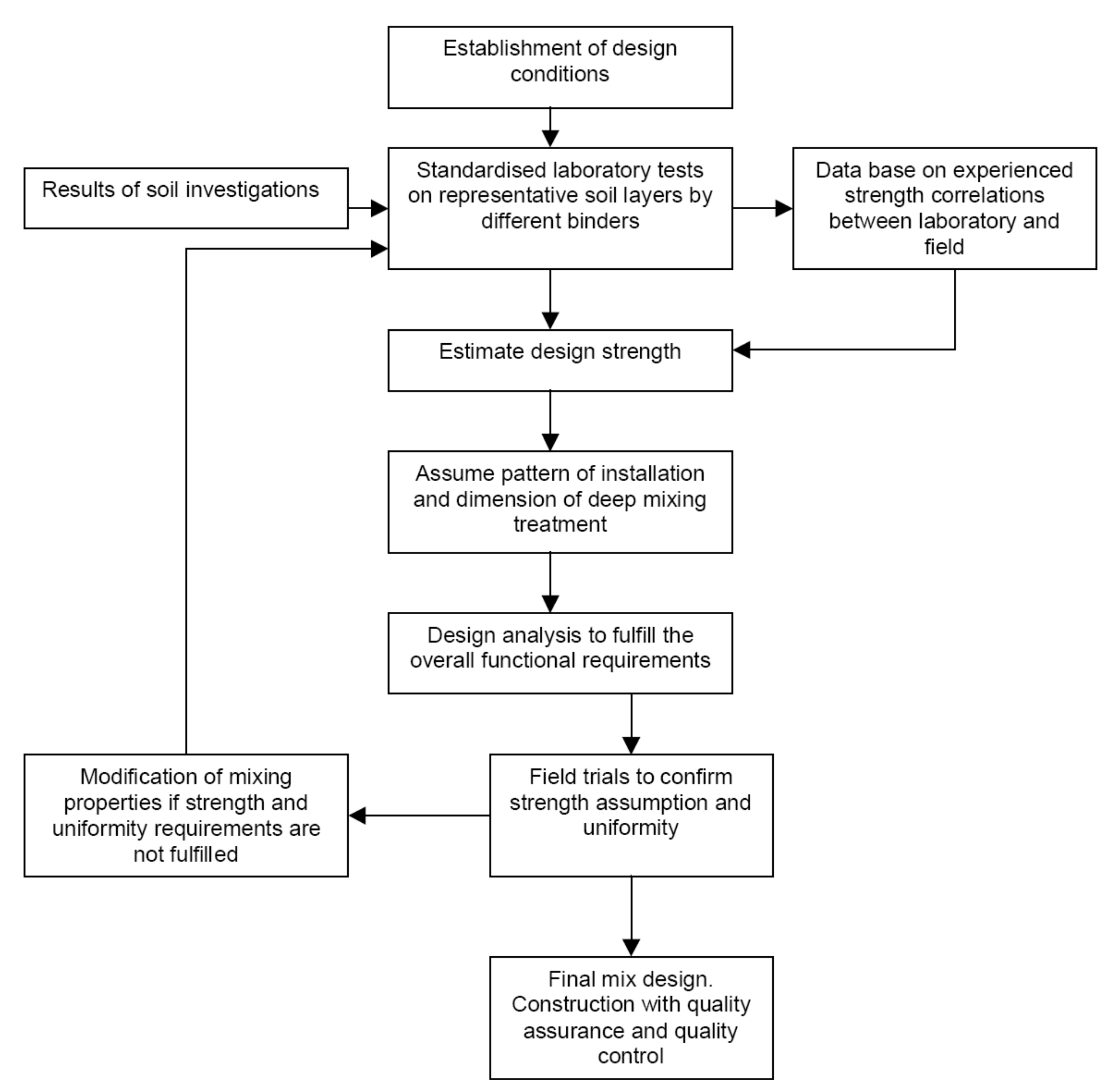


Figure 5. Iterative design process, including laboratory testing, functional design, field trials and process design.

Bangkok case history

Deep soil mixing used to reduce embankment settlement

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*Asian Institute of Technology, Bangkok, Thailand; †Bureau of Materials Research and Development, Department of Highways, Sri Ayuthaya Road, Bangkok, Thailand

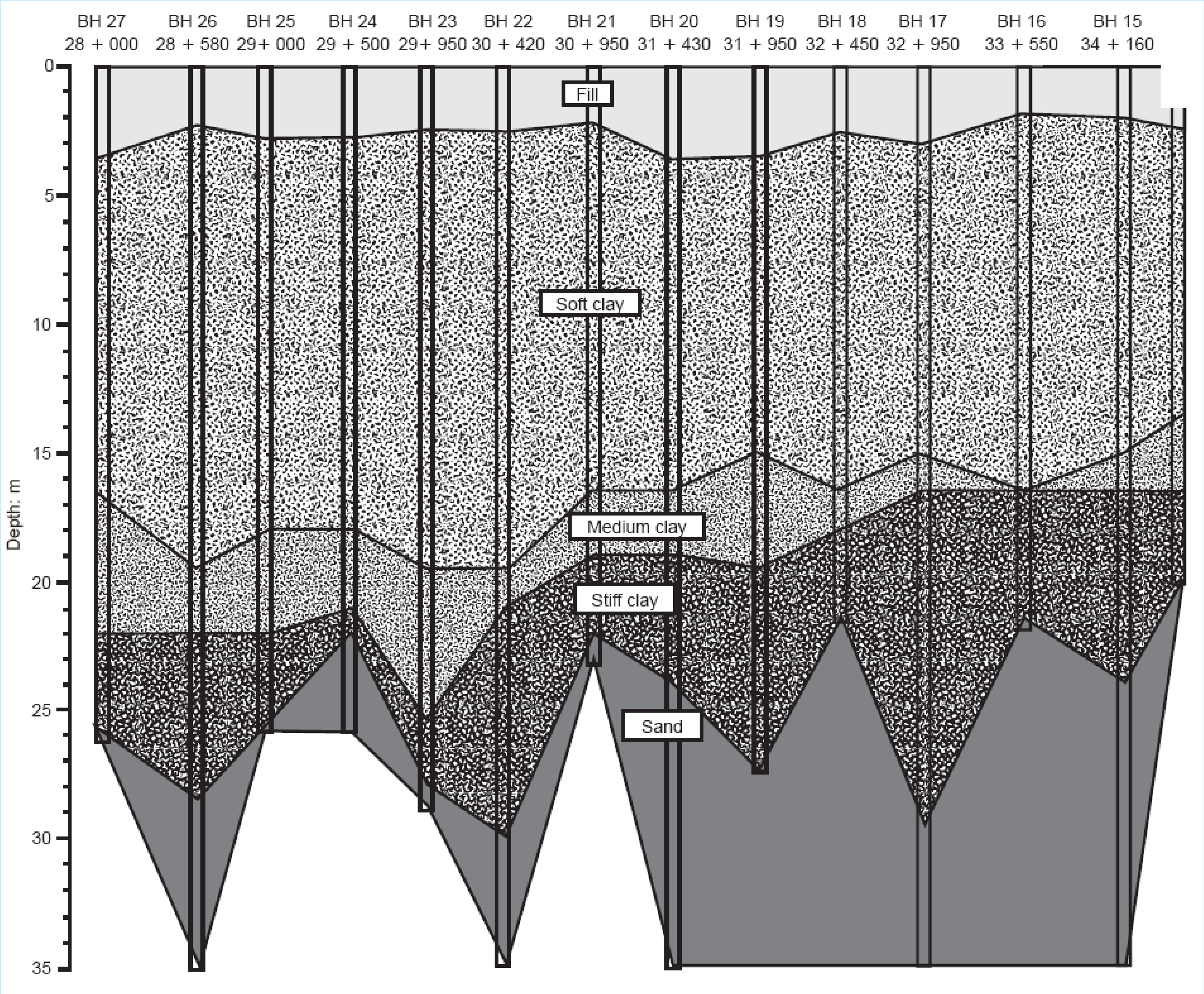


Fig. 2. Soil profile along station STA-28 . 000 to 34 . 500, Bangna-Bangpakong

Table 6.1 Specification of DMM in Bangkok

Application	Widening of Road	Column length	10-15m
Diameter	600mm	Improvement ratio	12.6%, 1.5m*1.5m, Square
Purpose of Improvement	Reduce settlement and Increase stability	Agent	Ordinary Portland Cement
Duration	1997-1999	Design strength	0.3MN/m^2

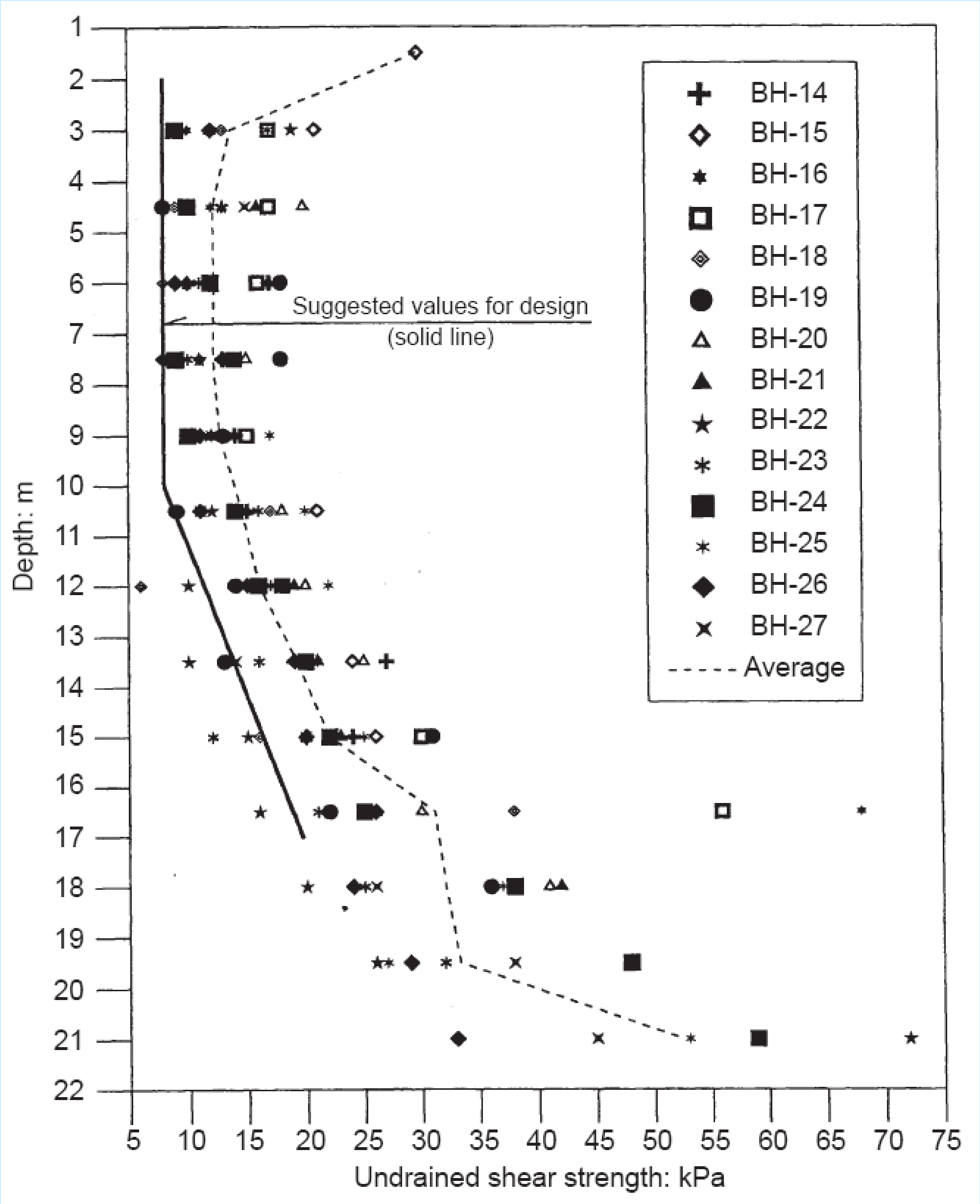
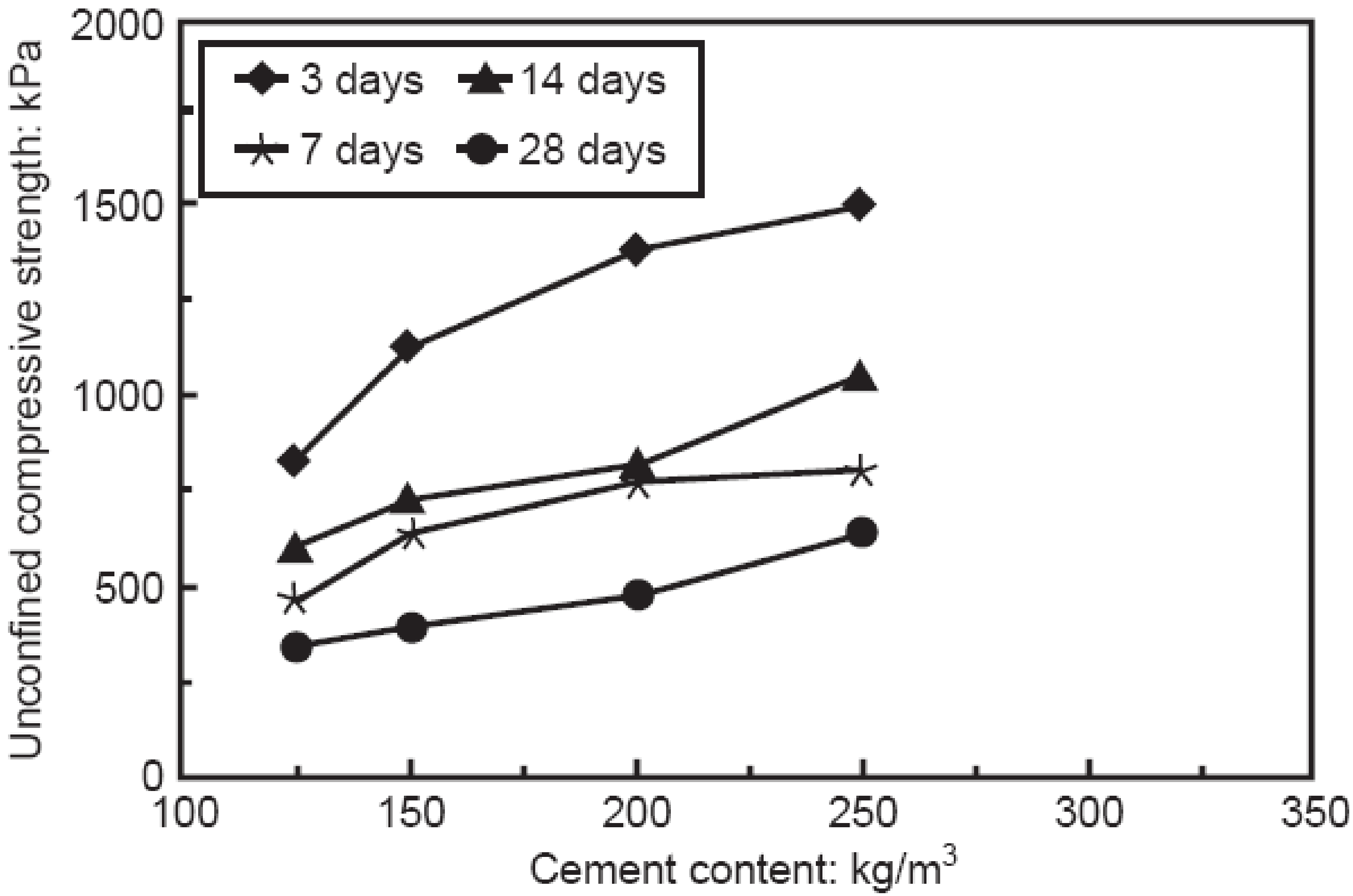
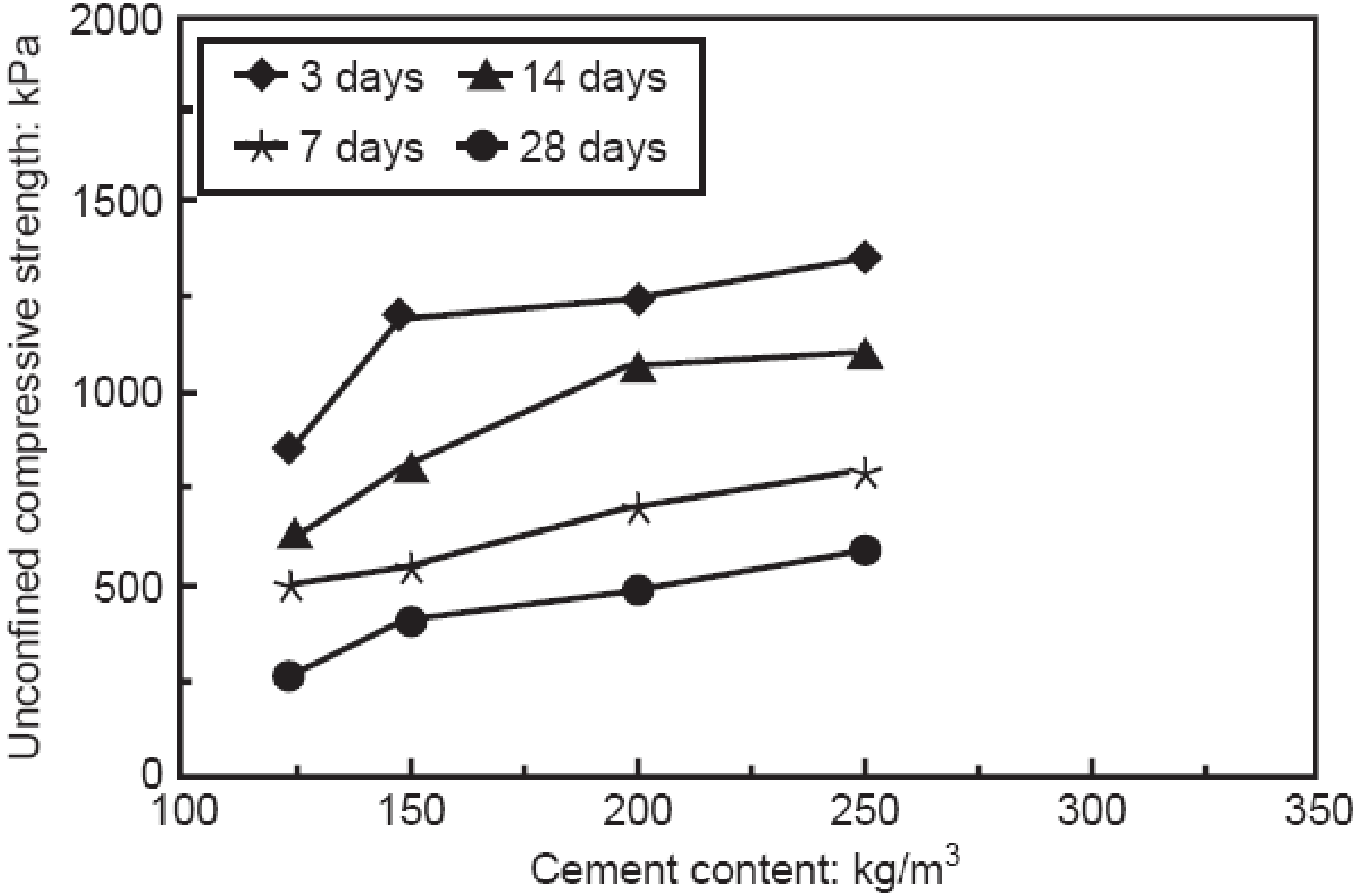


Fig. 3. Undrained shear strength from unconfined compression test in Section 3

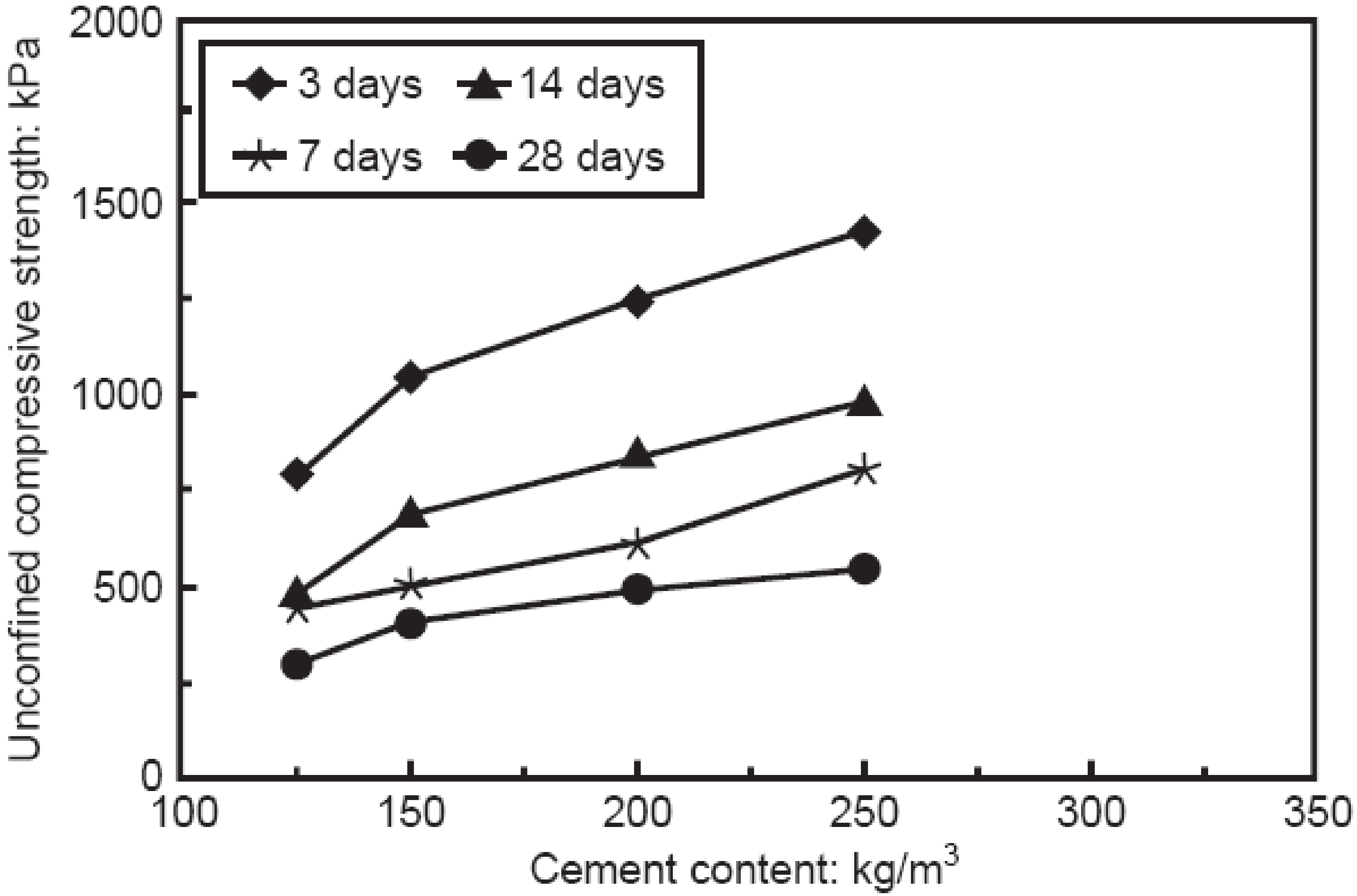


3 days
14 days
7 days
28 days
Unconfined compressive strength: kPa
2000
1500
1000
500
0
100
150
200
250
300
350
Cement content: kg/m3

(a)


3 days
14 days
7 days
28 days
Unconfined compressive strength: kPa
2000
1500
1000
500
0
100
150
200
250
300
350
Cement content: kg/m3

(b)



2000
1500
1000
500
0
100
150
200
250
300
350
Unconfined compressive strength: kPa
Cement content: kg/m3
3 days
14 days
7 days
28 days

(c)

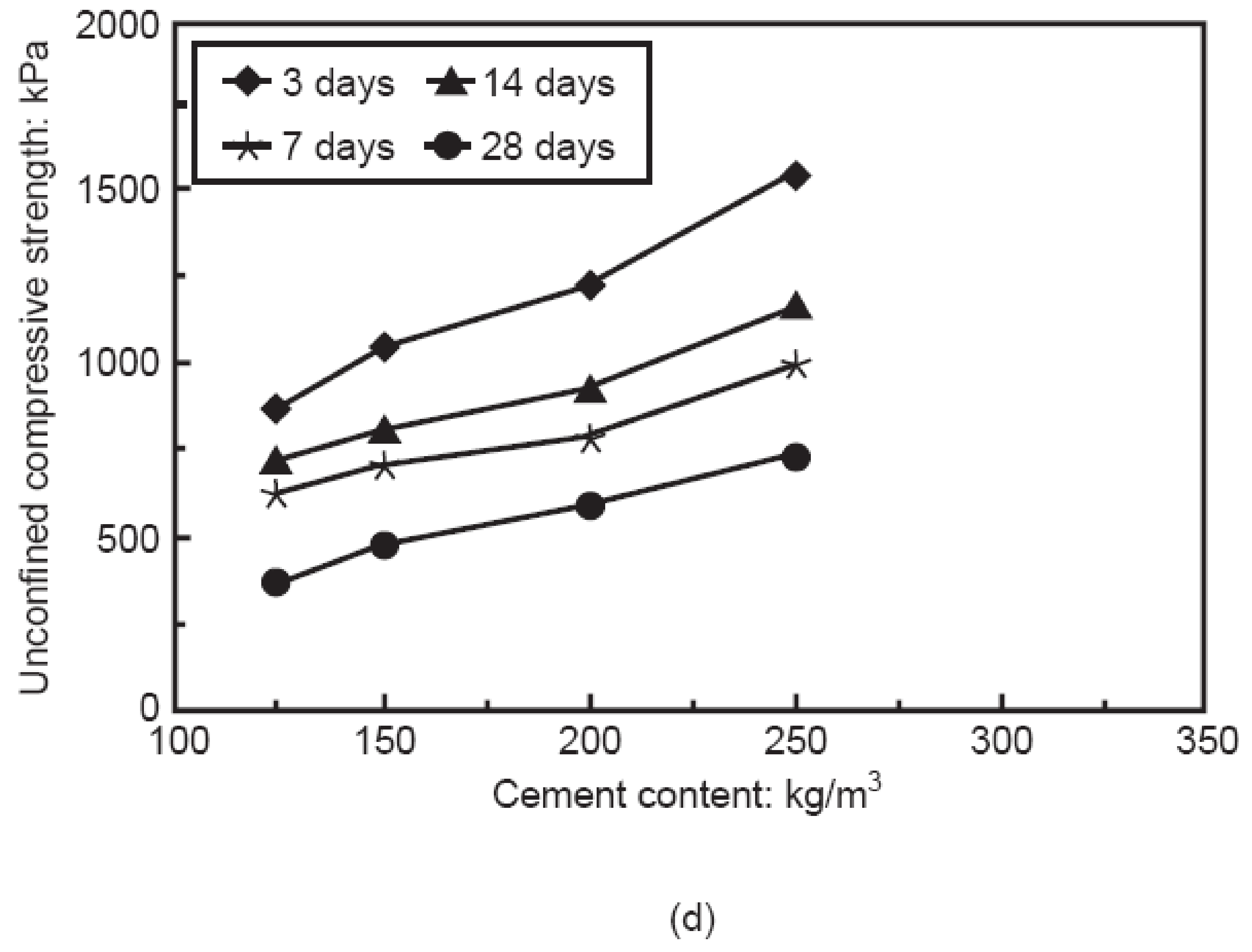


Fig. 4. Variation in strength of cement-treated clay with cement content, Bangna-Bangpakong Highway, km 29 . 500, at depths of (a) 3 m, (b) 6 m, (c) 12 m, (d) 15 m

Table 1. Parameters used for settlement analyses

Depth: m	γ: kN/m	σ_{vo}: kPa	σ_p: kPa	*RR*	*CR*	E_u: kPa	C_v: m^2/yr	C_h: m^2/yr
0–3	17·5	26·25	50	0·030	0·30	2600	2·5	5·0
3–9	14	49·5	50	0·045	0·45	1560	2·0	4·0
9–14	14·5	72·75	77	0·040	0·398	1820	2·0	4·0
14–16	14·5	88·5	95	0·035	0·35	2340	2·0	4·0
16–18	15·5	98·5	113	0·030	0·30	3250	2·5	5·0
18–19·5	16·5	108·88	125	0·025	0·25	4550	2·5	5·0

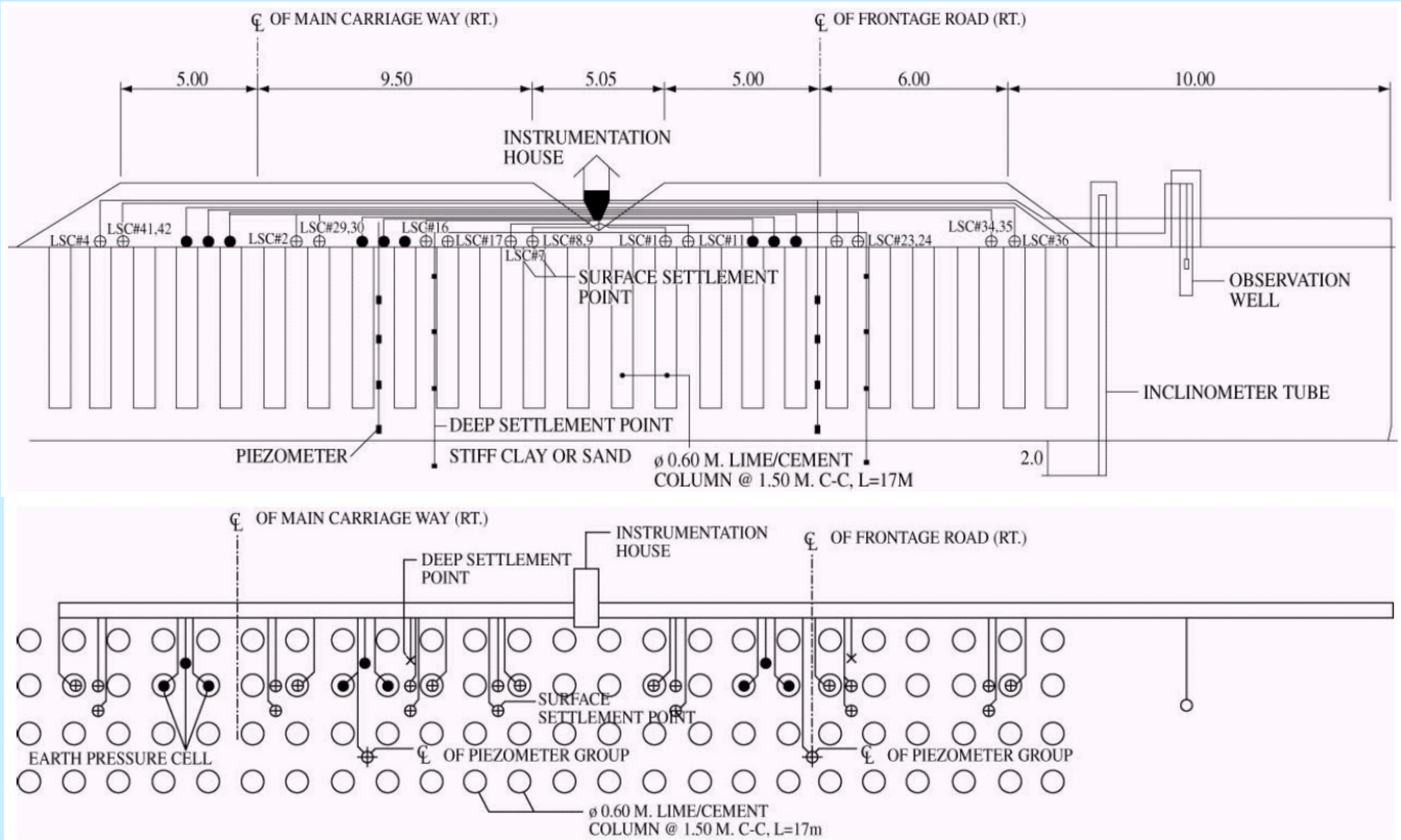


Figure 6.15 Monitoring section of Expressway widening project near Bangkok

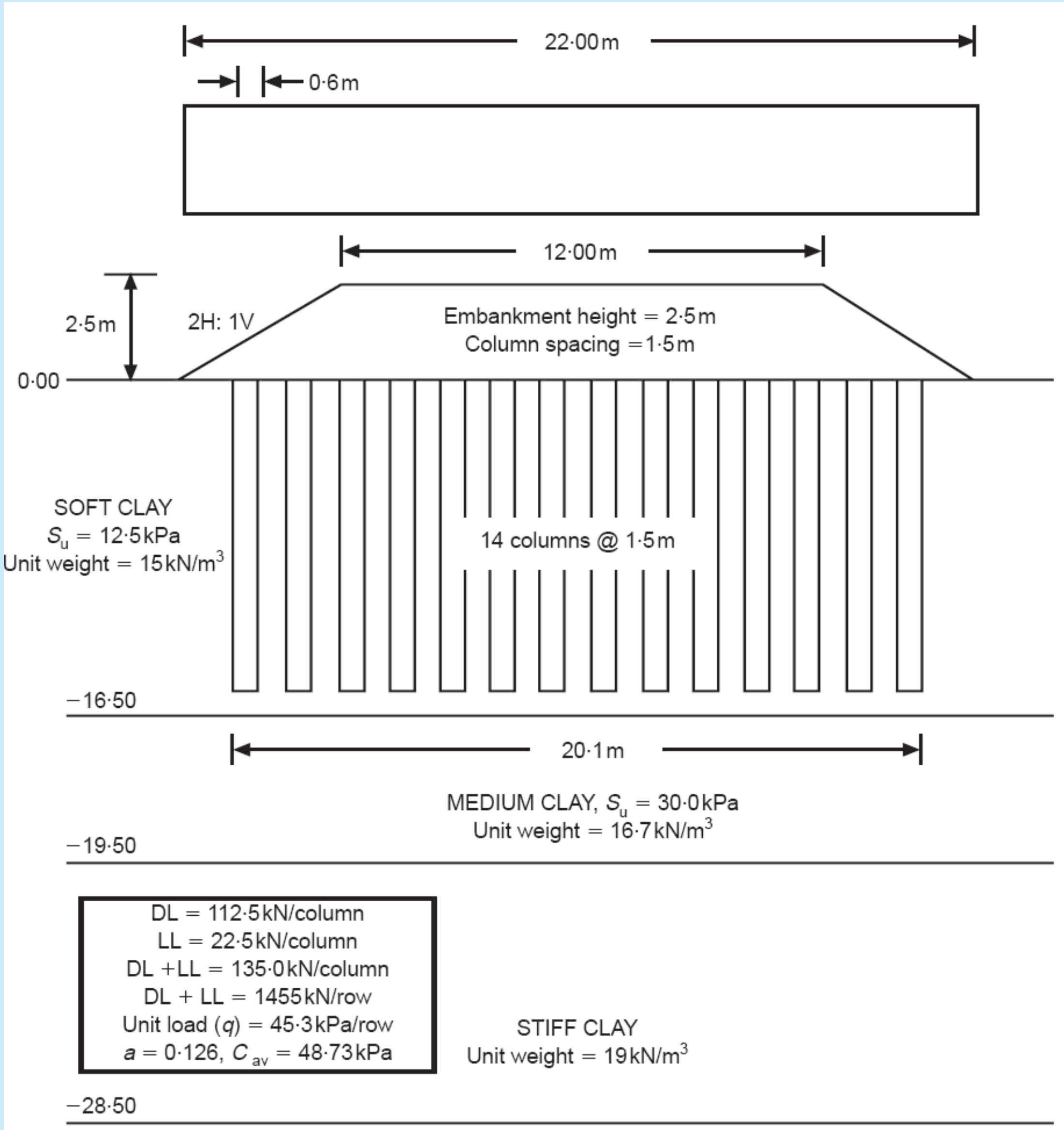


Fig. 1. Rehabilitation scheme for Bangna-Bangpakong Highway using DMM ground improvement

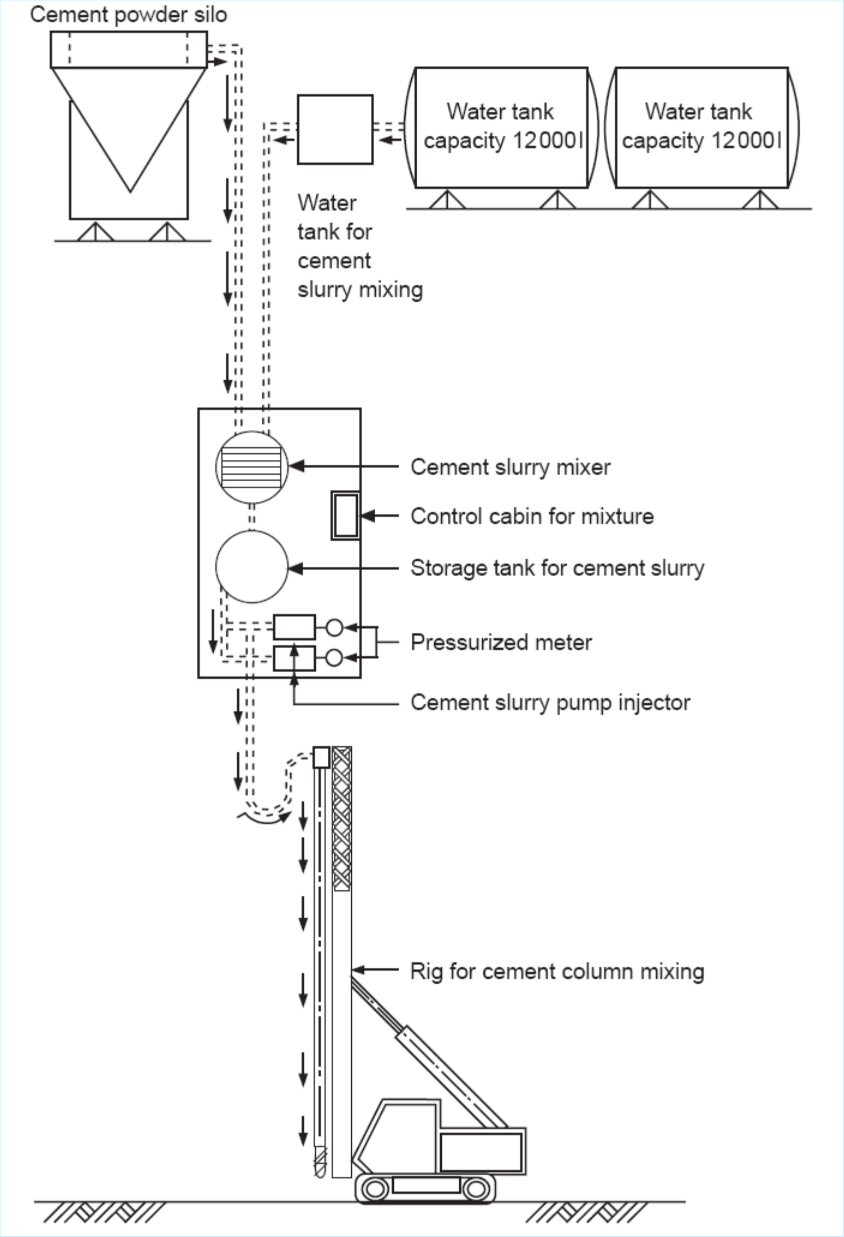
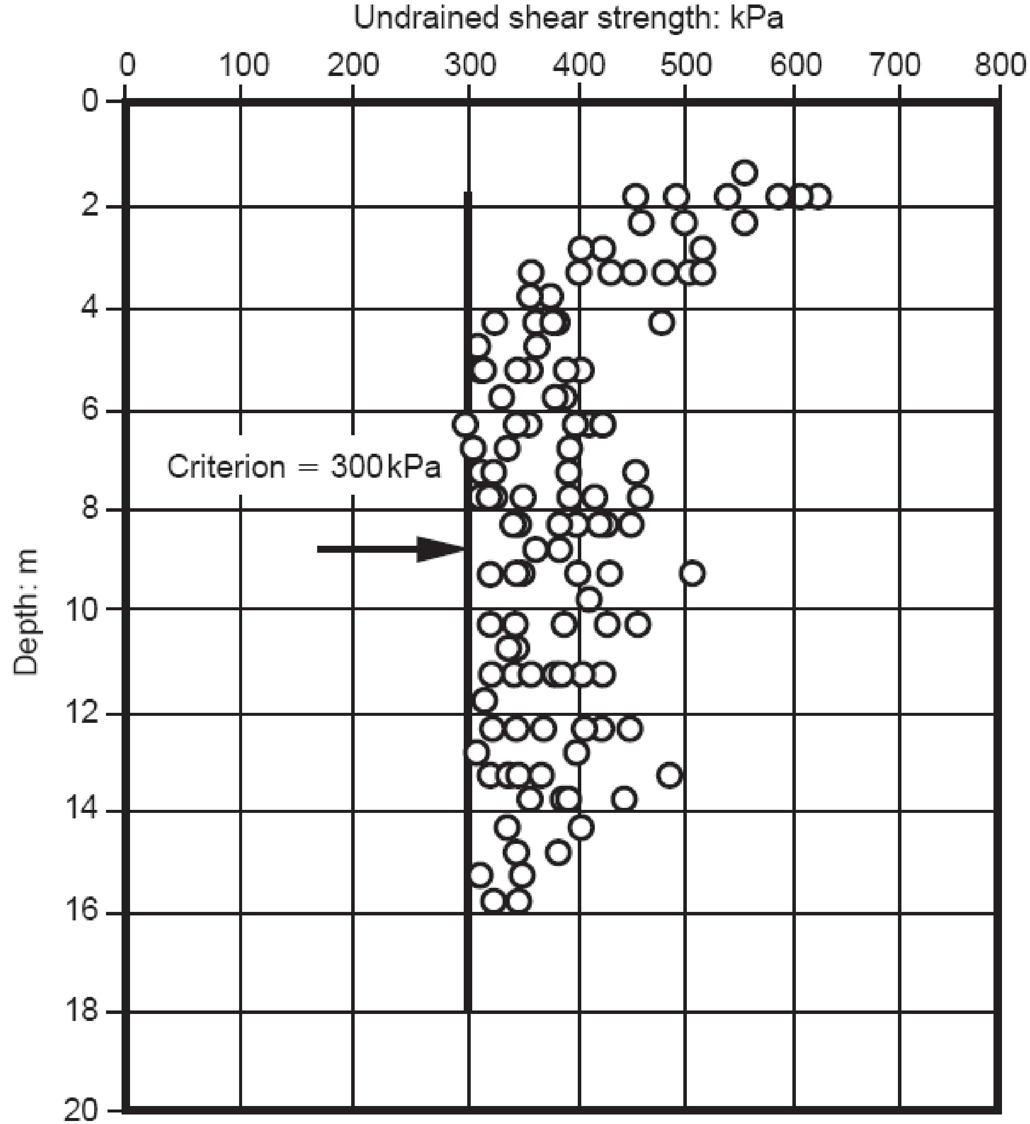
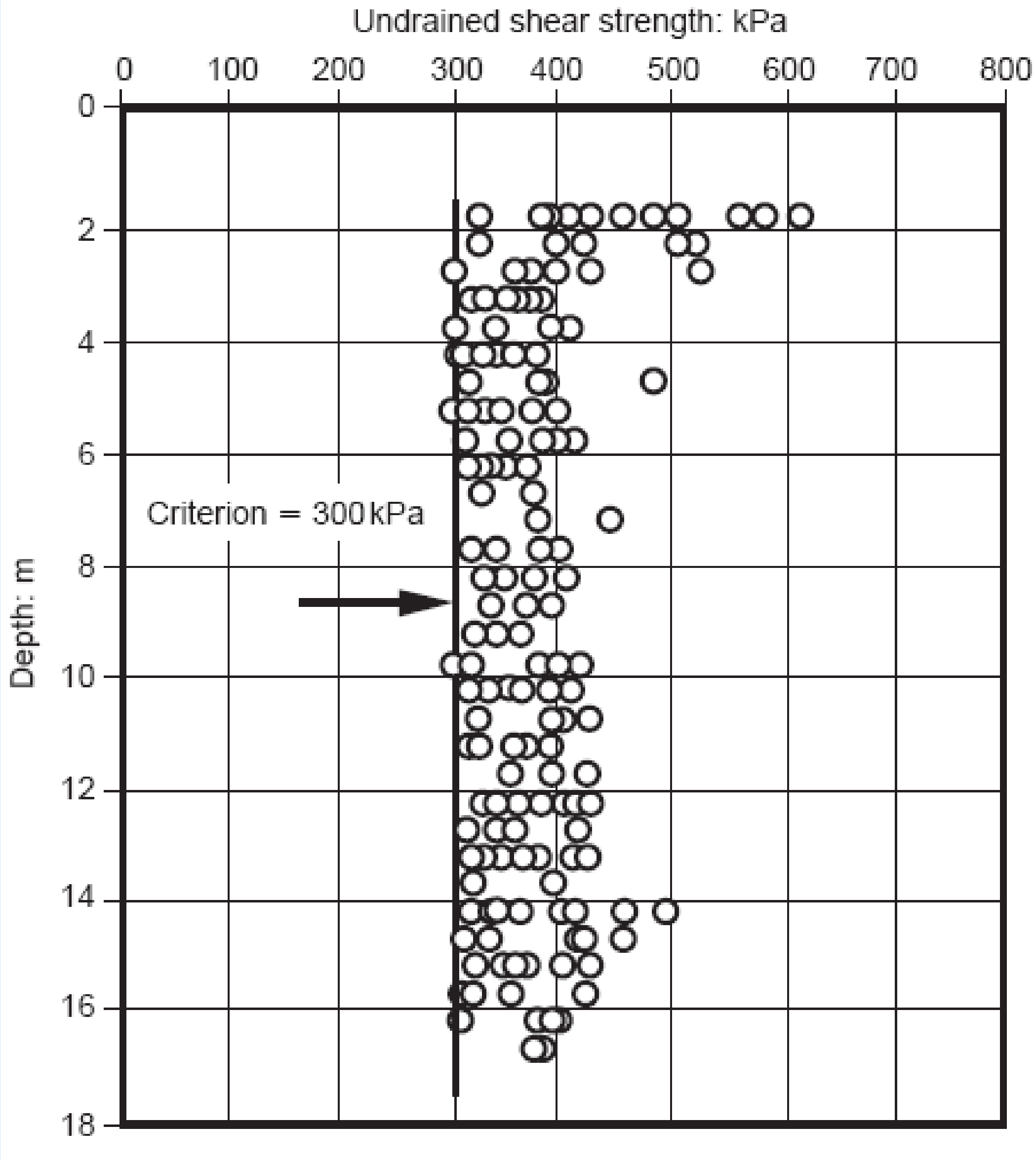


Fig. 5. System for manufacturing cement columns

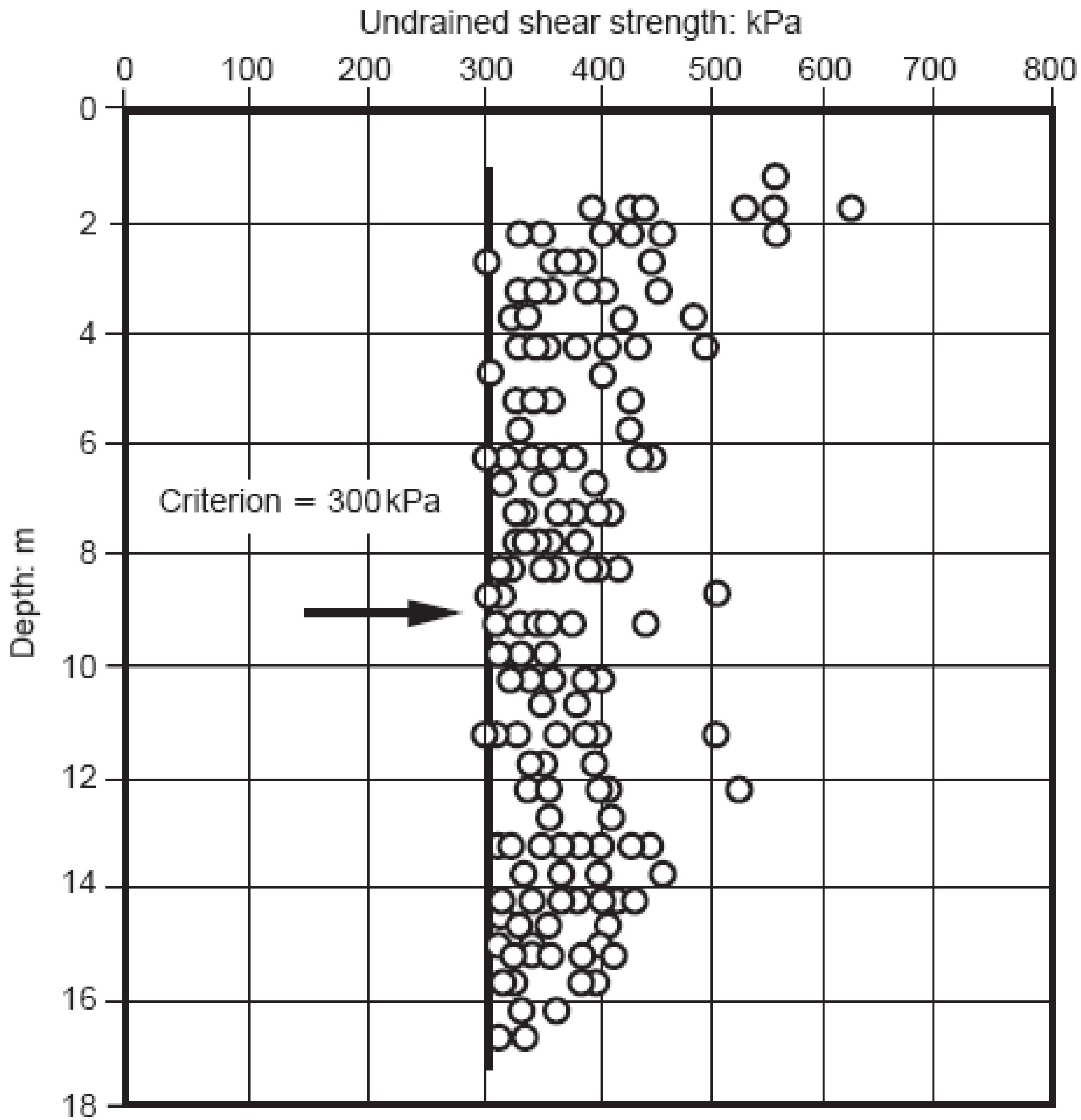
Fig. 6. (a) Mixing blades of DMM installation machine

Fig. 6. (b) installation of cement piles by DMM machine

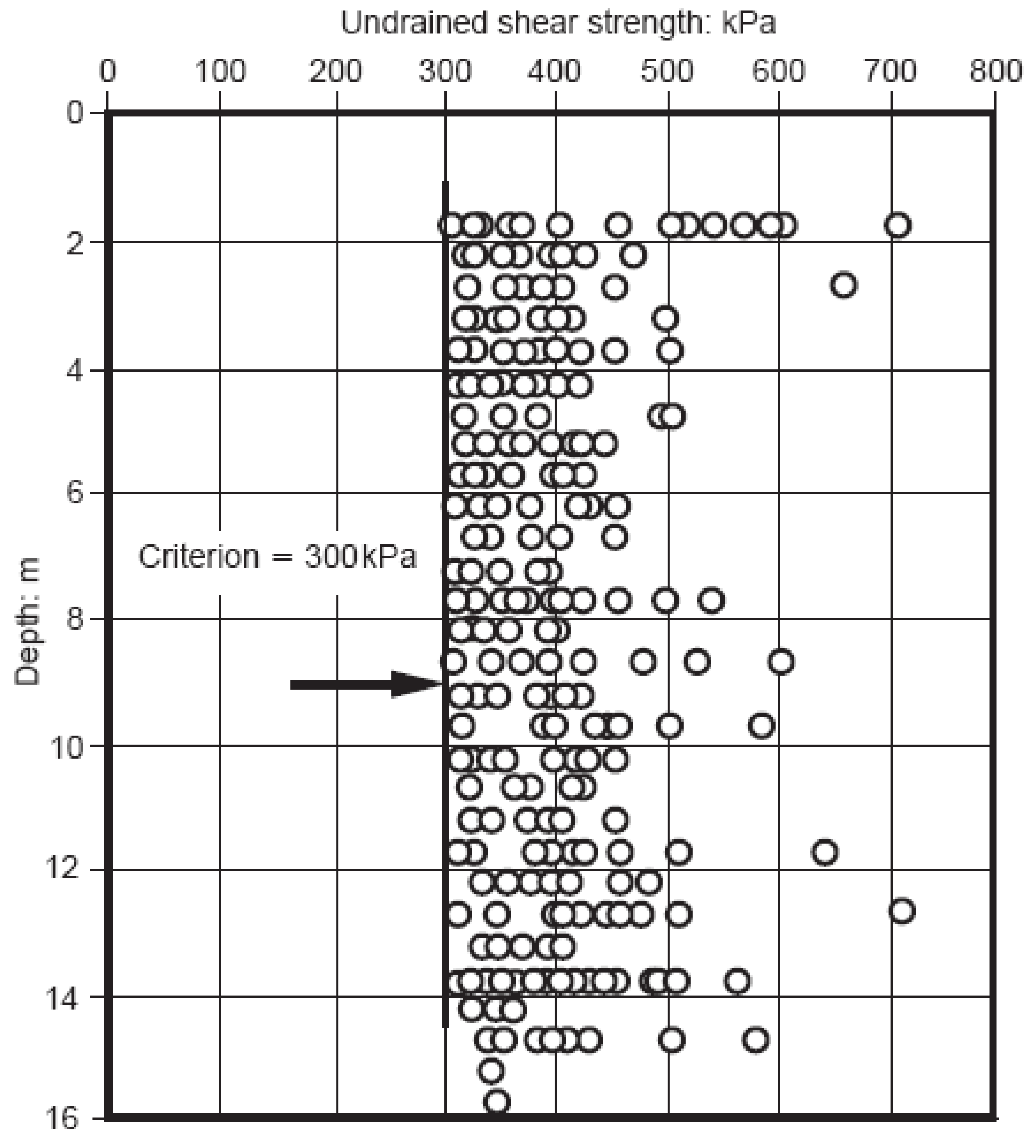

Undrained shear strength: kPa
0
100
200
300
400
500
600
700
800
Depth: m
0
2
4
6
8
10
12
14
16
18
20
Criterion = 300 kPa
(a)


Undrained shear strength: kPa
0
100
200
300
400
500
600
700
800
Depth: m
0
2
4
6
8
10
12
14
16
18
Criterion = 300 kPa

(b)


Undrained shear strength: kPa
0
100
200
300
400
500
600
700
800
0
2
4
6
8
10
12
14
16
18
Depth: m
Criterion = 300 kPa

(c)



Undrained shear strength: kPa
0
100
200
300
400
500
600
700
800
0
2
4
6
8
10
12
14
16
Depth: m
Criterion = 300kPa

(d)

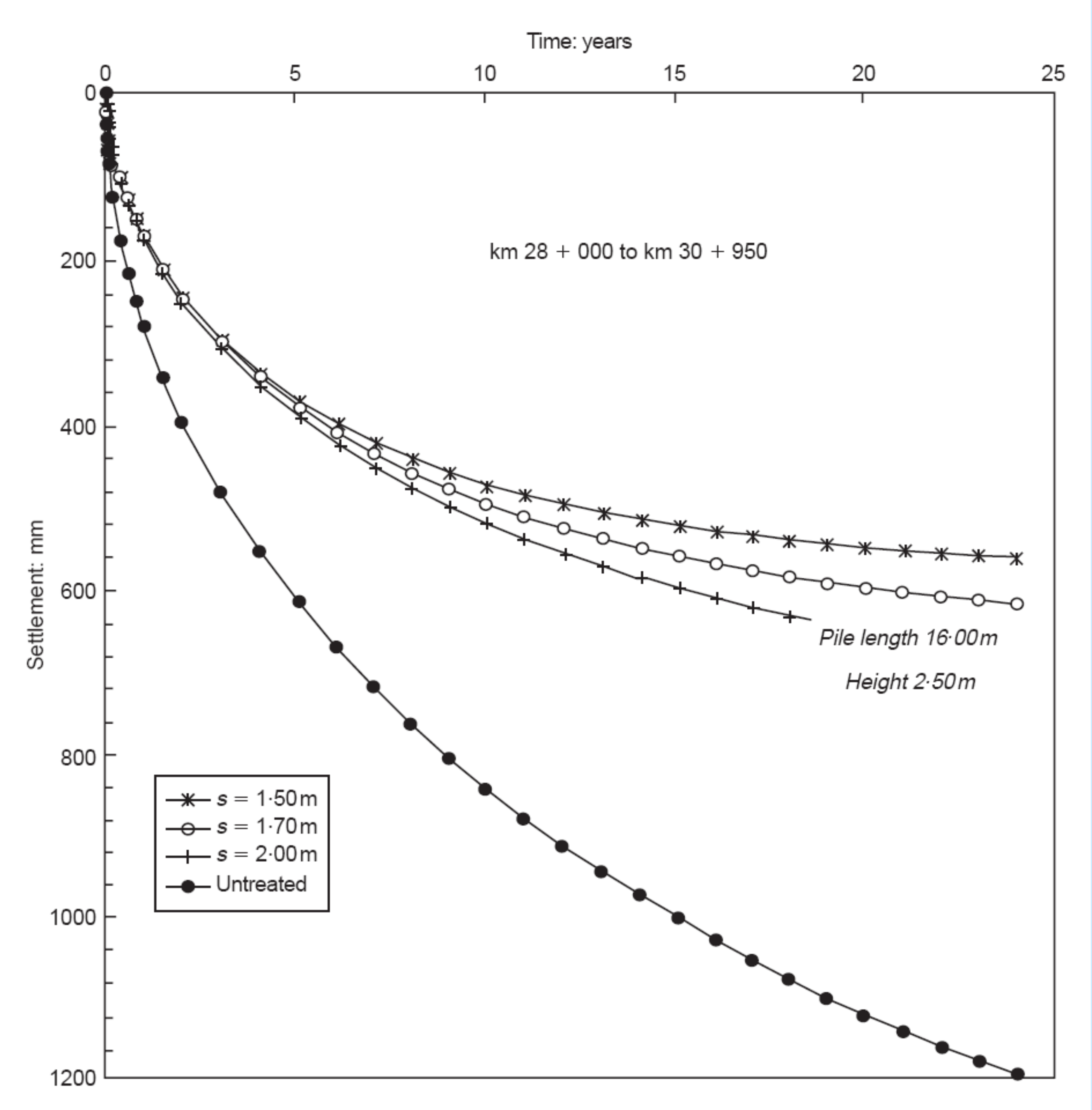


Fig. 8. Settlement-time relationship for pile tip at 16´00 m and embankment height 2´5 m with various column spacings

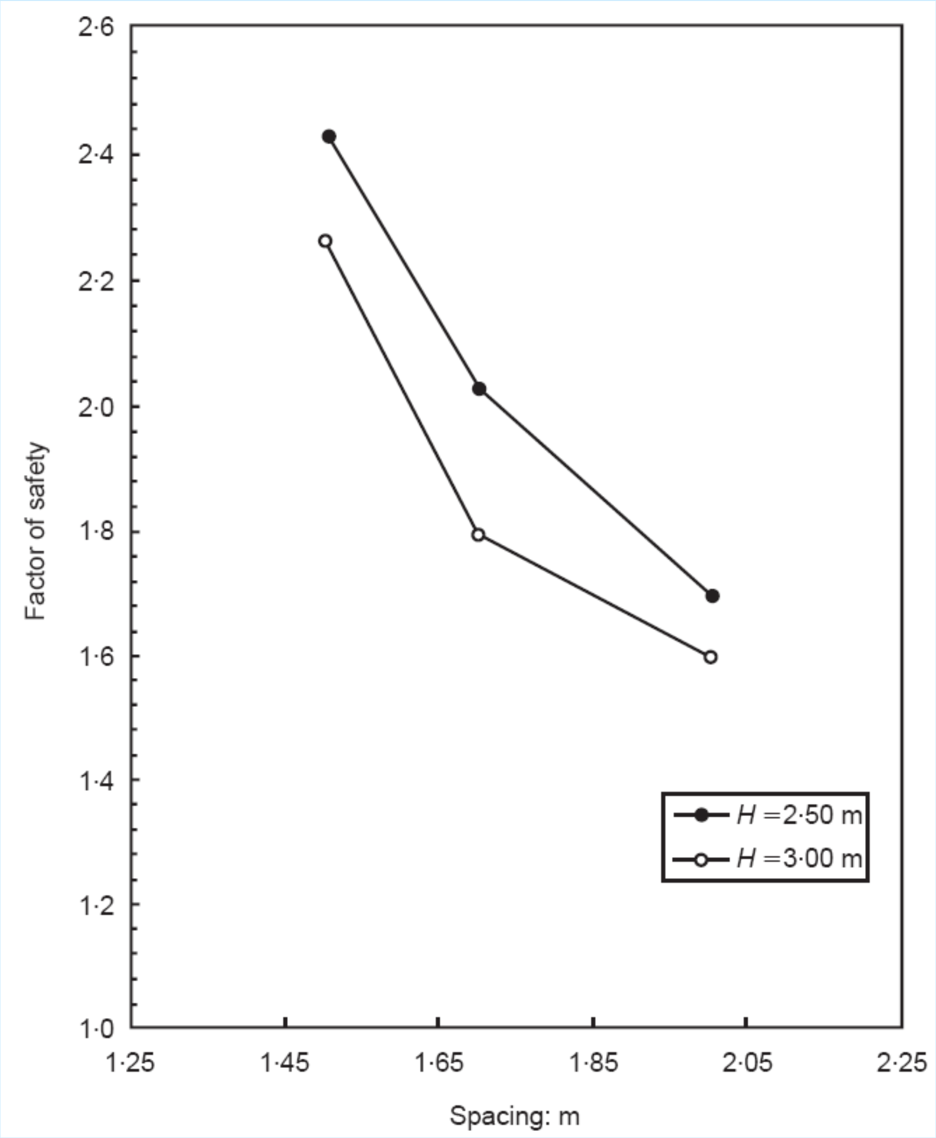


Fig. 9. Factors of safety for embankment heights of 2.5 and 3 m on cement-column-treated ground

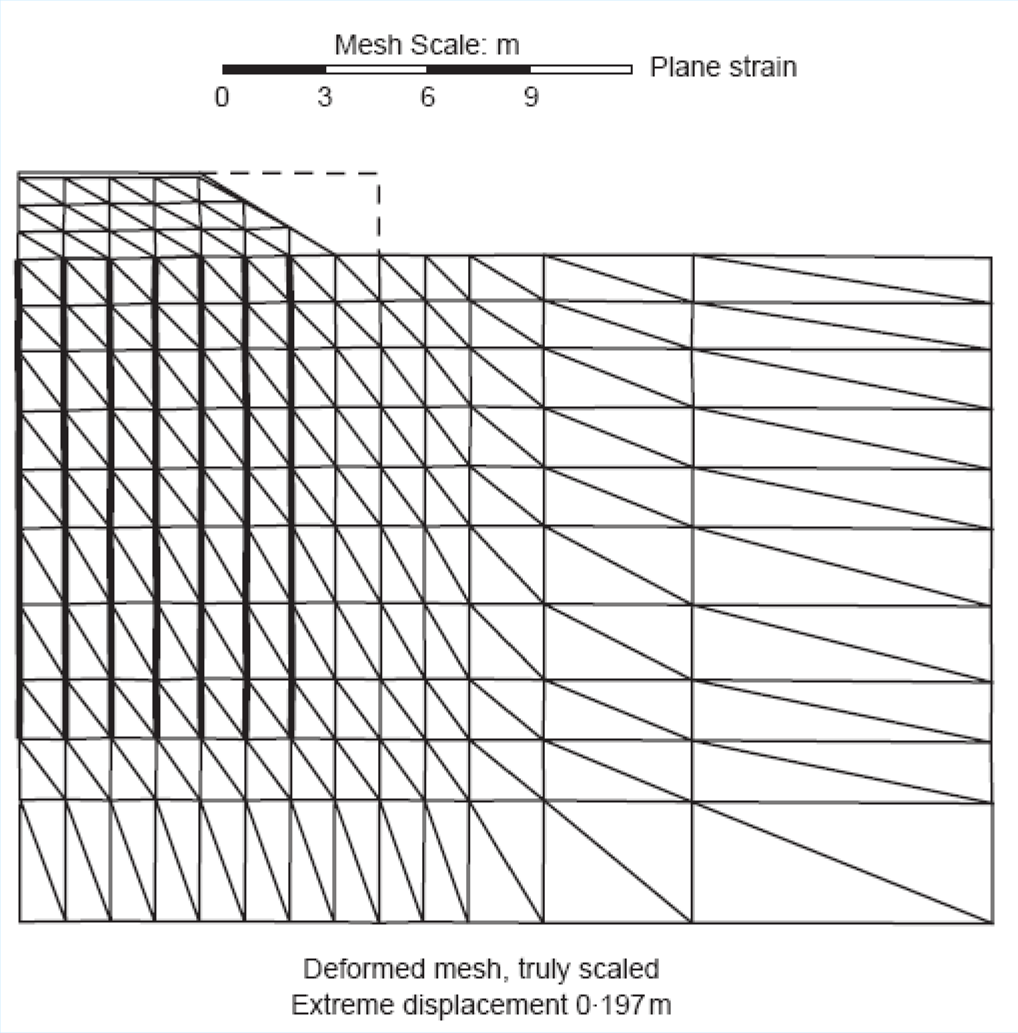


Fig. 10. Deformed mesh for 2´5 m high embankment on treated ground (undrained analysis)

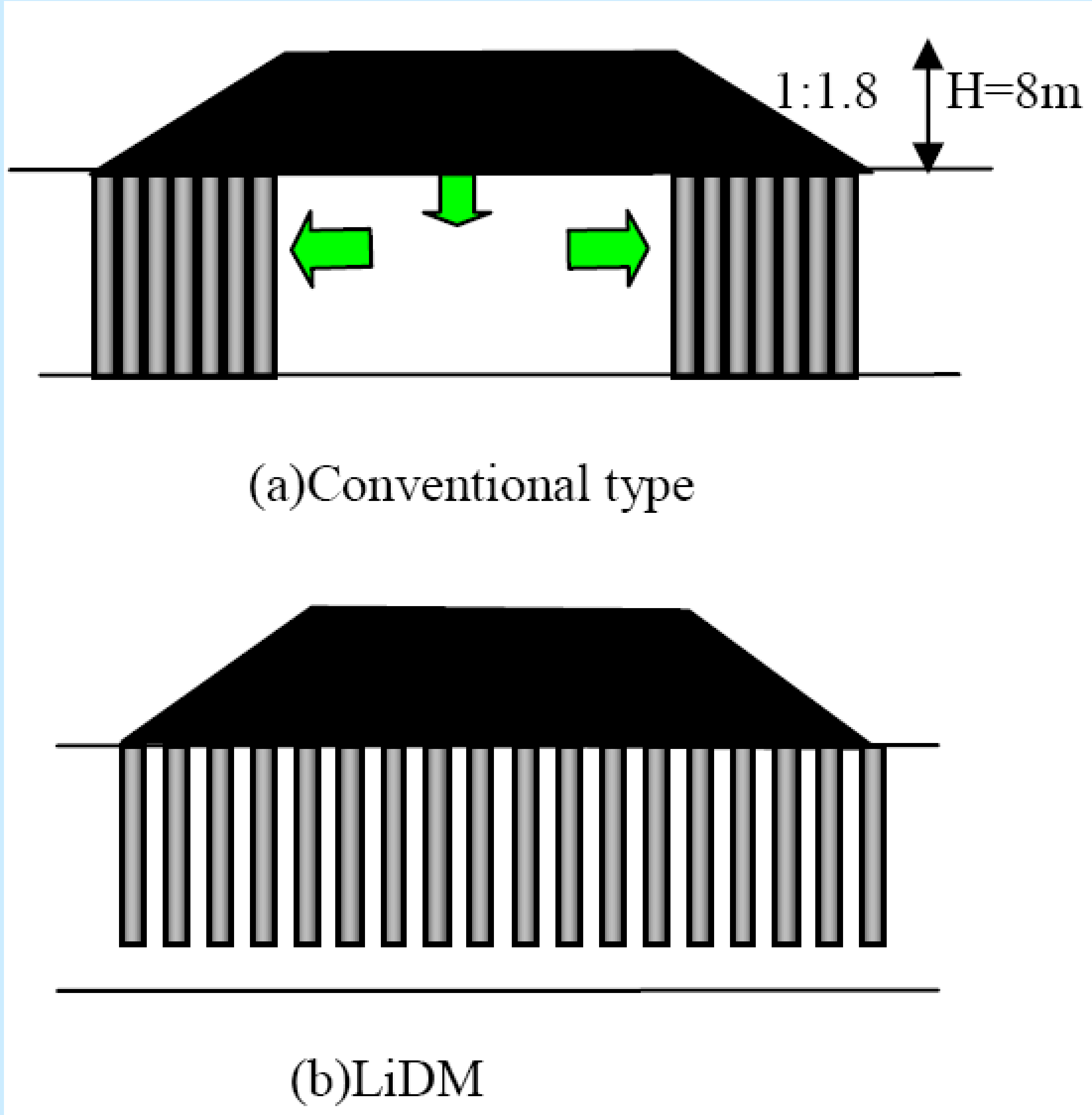


Figure 7.1 Comparison of improvement pattern

	Total settlement	Differential settlement	
		Surface Improvement*1)	No surface Improvement
Floating type	(a) Estimate Young modulus of composite ground and stress distribution in the unimproved area	(b) FEM*2) (d) New Modeling of loading (Miki 2004 b)	(b)FEM*2) (d) New Modeling of loading (Miki 2004 b)
End bearing type (improved up to the bottom of layer)	(c) Modeling of loading between each columns (Miki. 1997)	(b) FEM*2) (d) New Modeling of loading (Miki 2004 b)	(c)Modeling of loading (Miki. 1997)

*1) The case that the ground surface is improved by such as shallow stabilization.

*2) Soil-water coupled two-dimensional FEM analysis using such as Cam-Clay model is considered to be available for these cases.

Table 7.1 Settlement estimation for LiDM

Table 8.1 Check-boring in Asian region

Country	Procedure	Merits	Note
Japan	Core Boring with core-pack sampler (see Figure 8.1) and Unconfined Compression Test	The actual samples could be seen and confirmed directly.	It is easy to have a crack in the specimen at the moment of core sampling. So, skilled person and special core sampler with vinyl pack are required.
Thailand	Pull out the column and Unconfined Compression Test (see Figure 8.3)	The actual columns could be seen and confirmed directly.	The case of diameter 600mm is only possible.
Thailand, Vietnam	Loading Test (see Figure 8.4)	Special core sampler is not necessary.	The quality through all depth could not be confirmed. Large facility is required if the diameter is large.

Figure 8.3 Pulling out the column in Thailand

Figure 8.4 Machine in Vietnam and Column Loading test using Concrete block as counter weight

Deep Mixing Methods

Bergado et al

Deep Mixing Methods

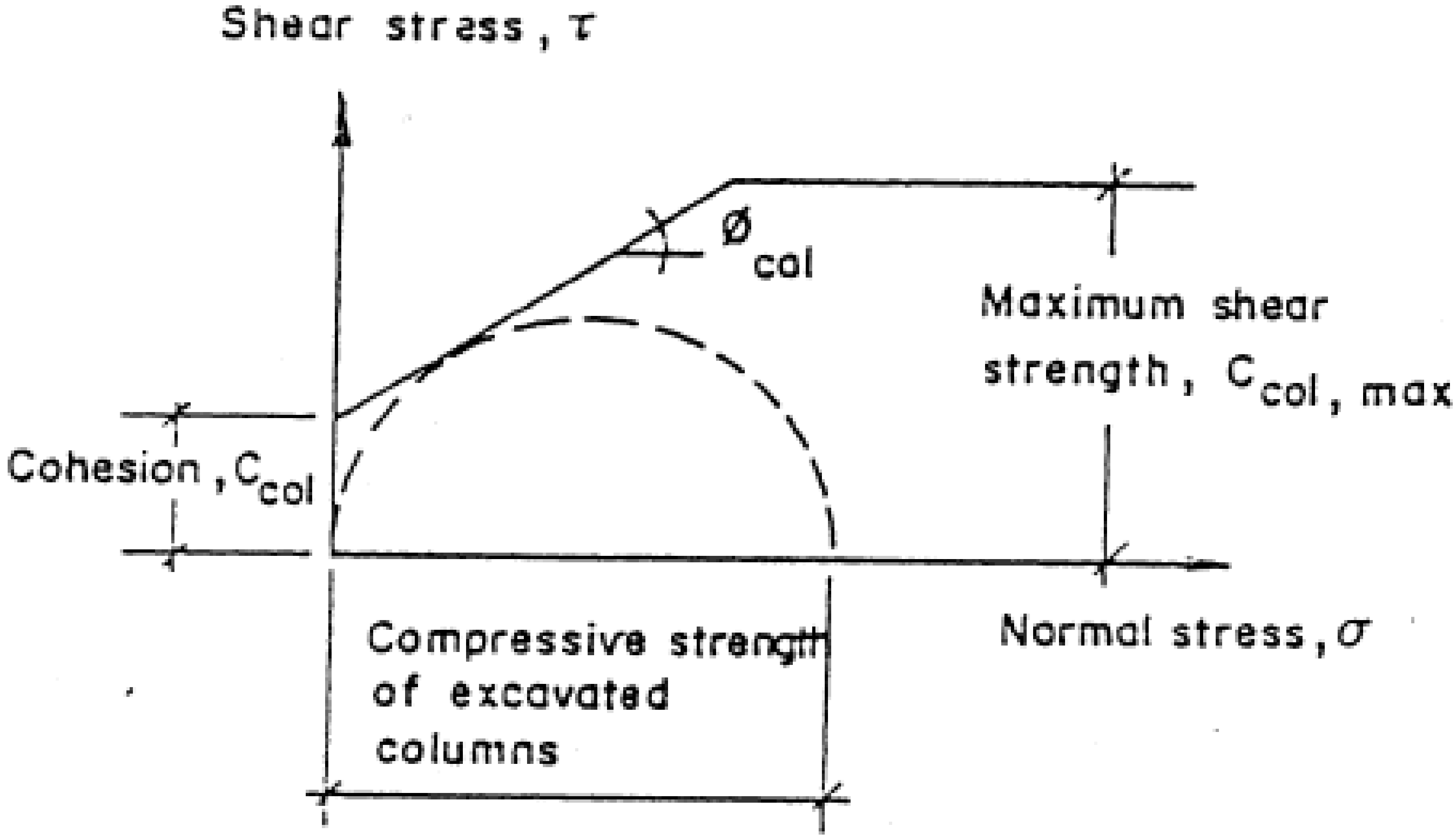


Fig. 7.2 Assumed Failure Diagram of Lime Stabilized Soil

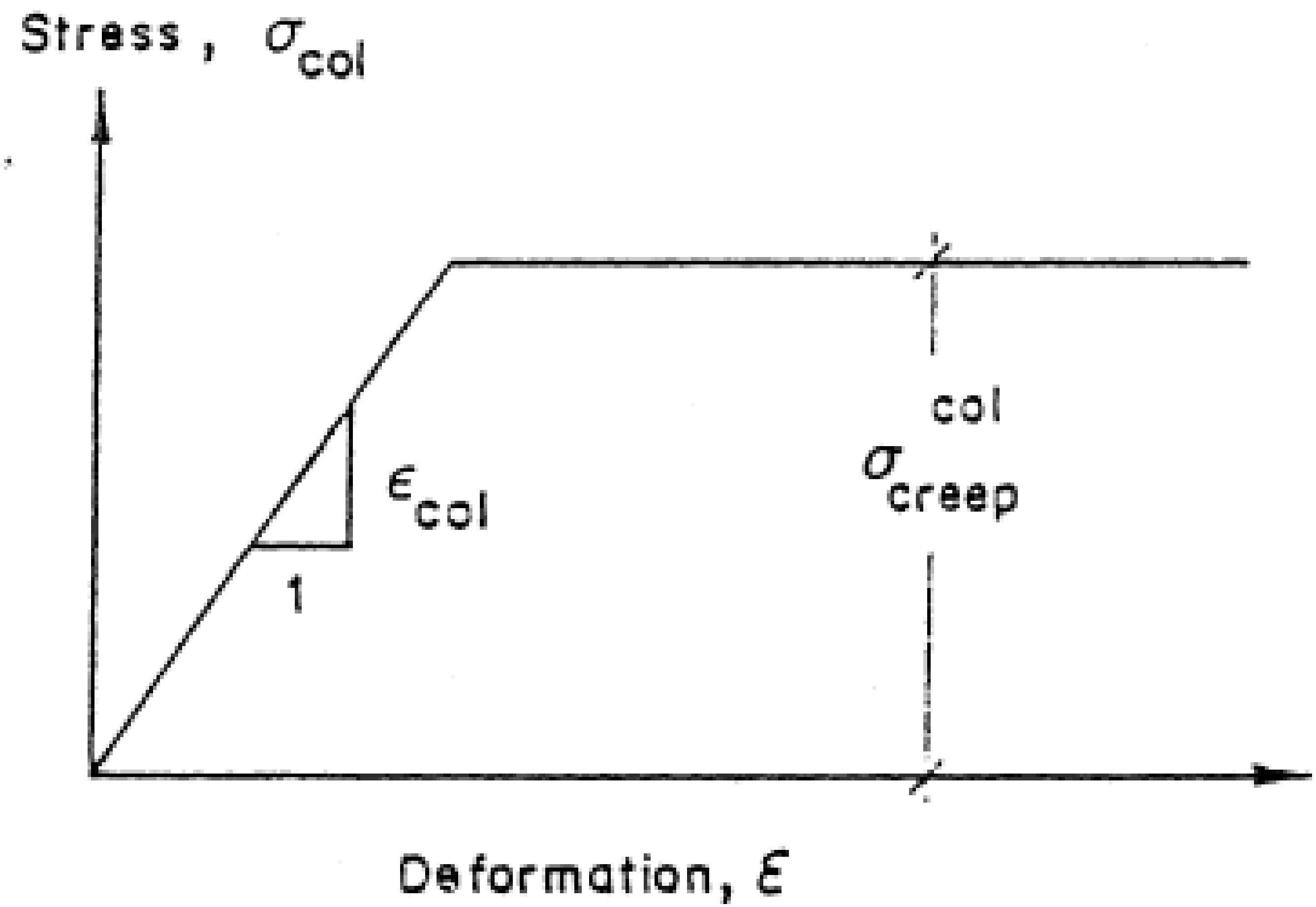


Fig. 7.3 Assumed Stress-Strain Relationship of Lime Stabilized Soil

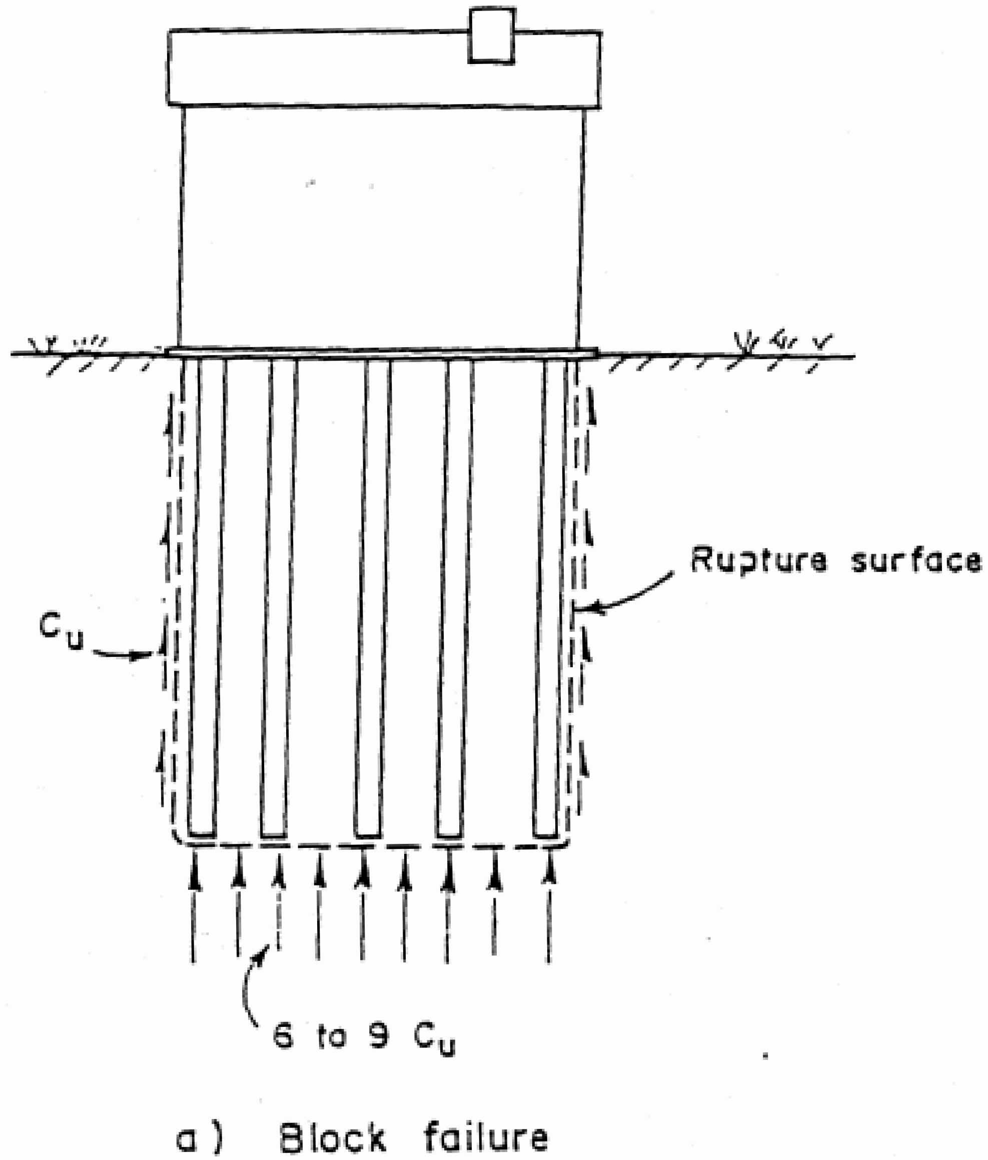
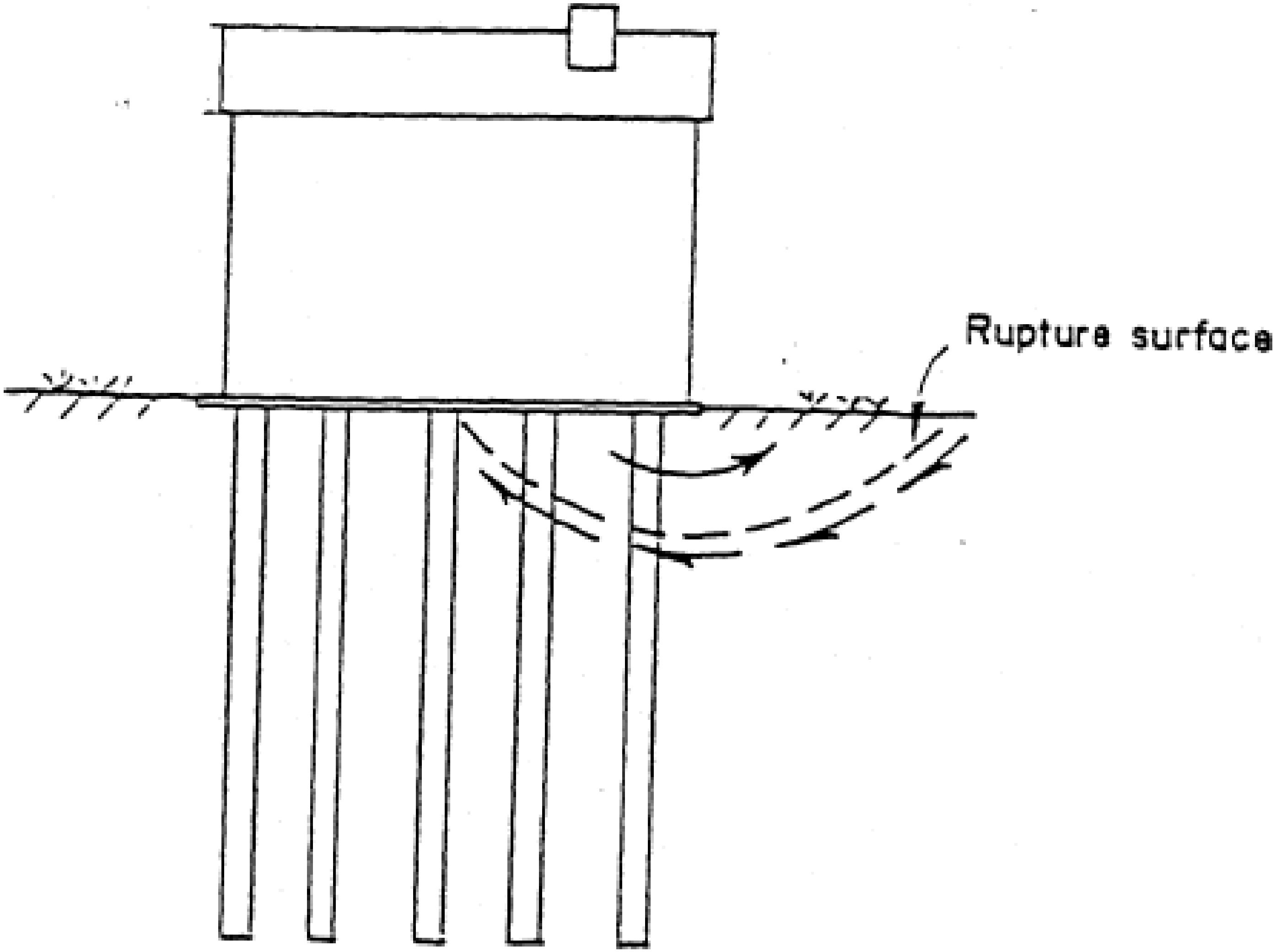


Fig. 7.4 Failure Modes of Lime Column Foundations



b) Local shear failure

Fig. 7.4 Failure Modes of Lime Column Foundations

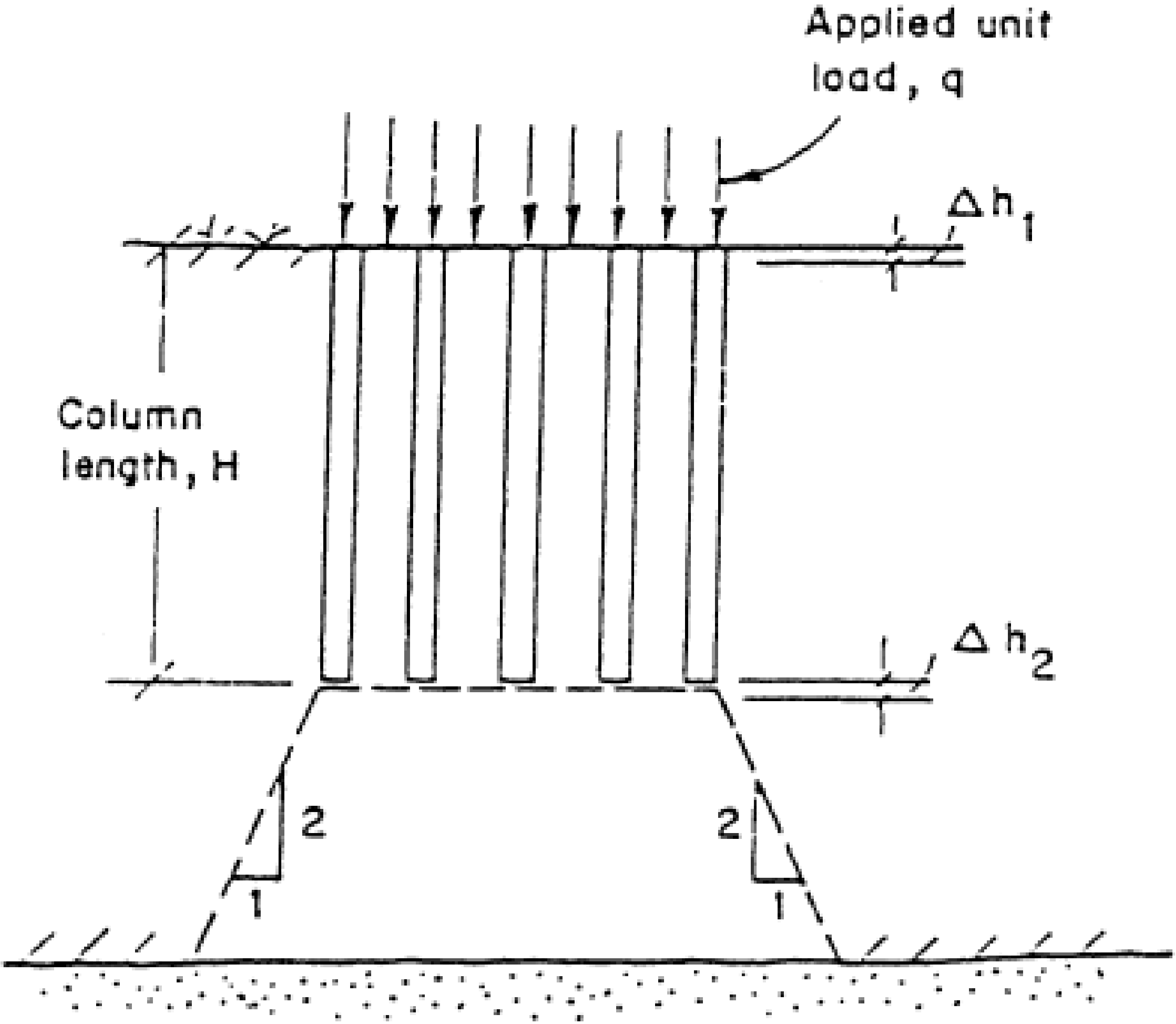


Fig. 7.5 Calculation of Settlement When the Creep Strength of Lime Columns is Not Exceeded

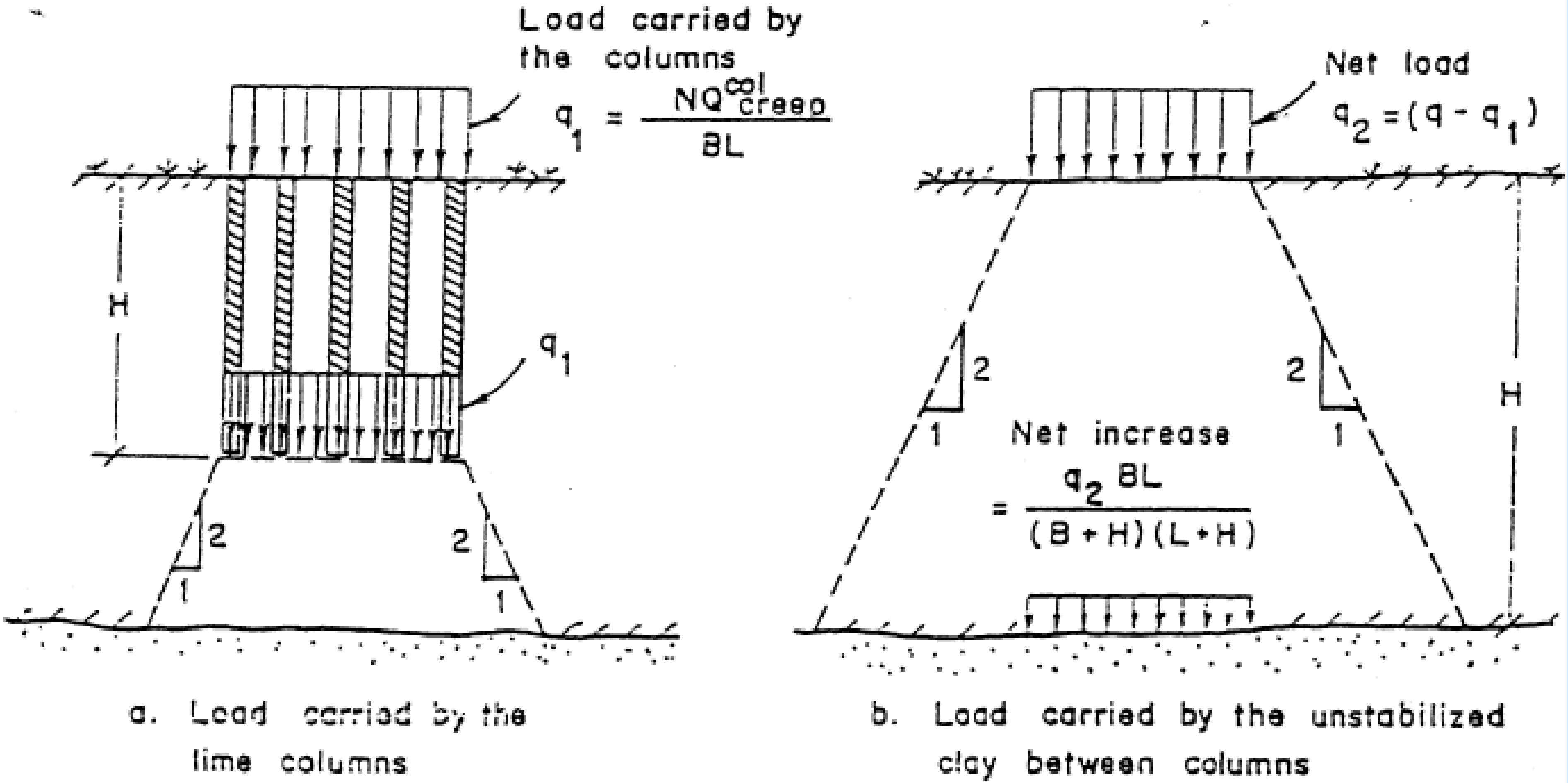


Fig.7.6 Calculation of Settlement When the Creep Strength of Lime Columns is Exceeded

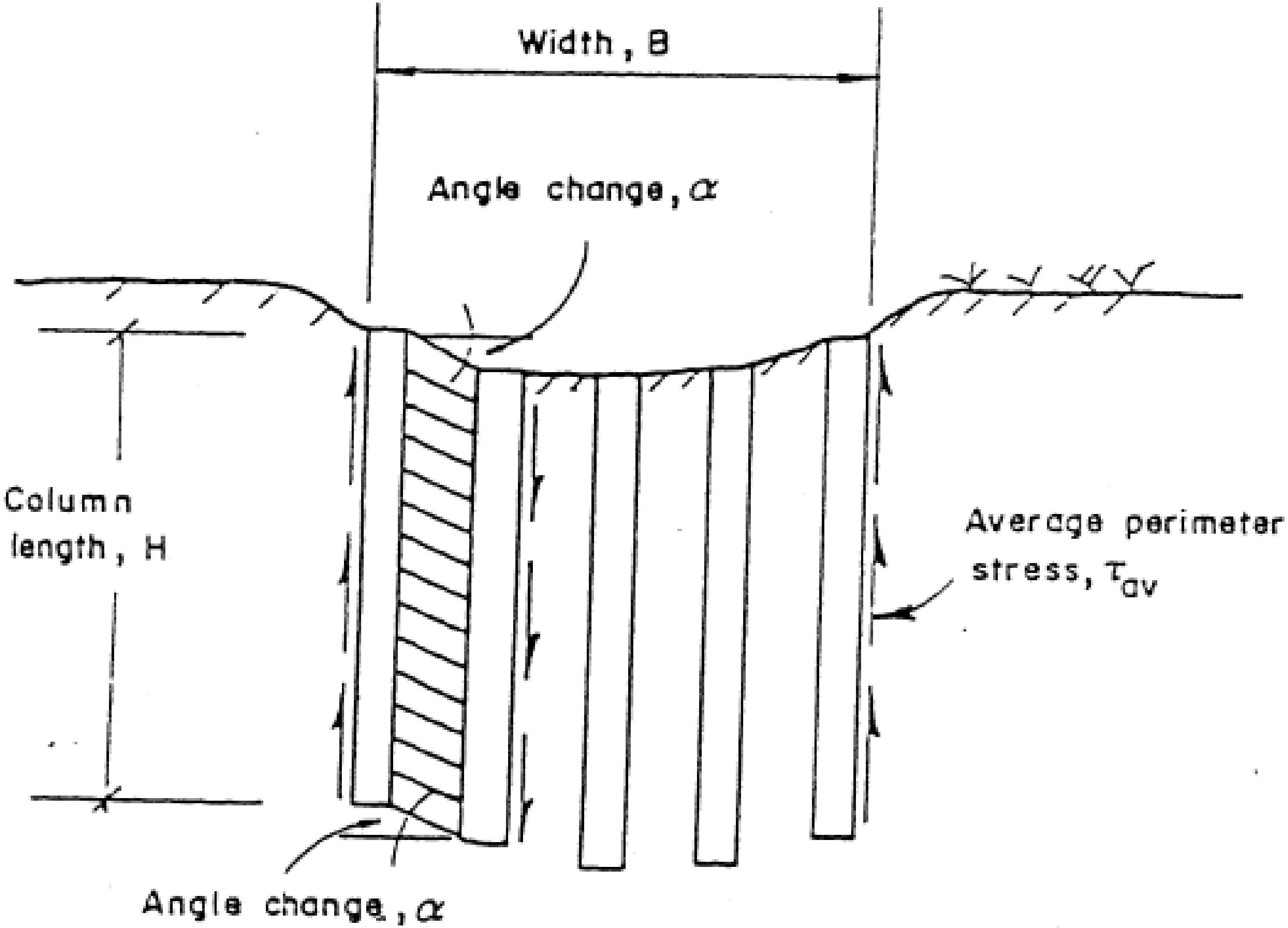


Fig. 7.7 Calculation of Differential Settlement

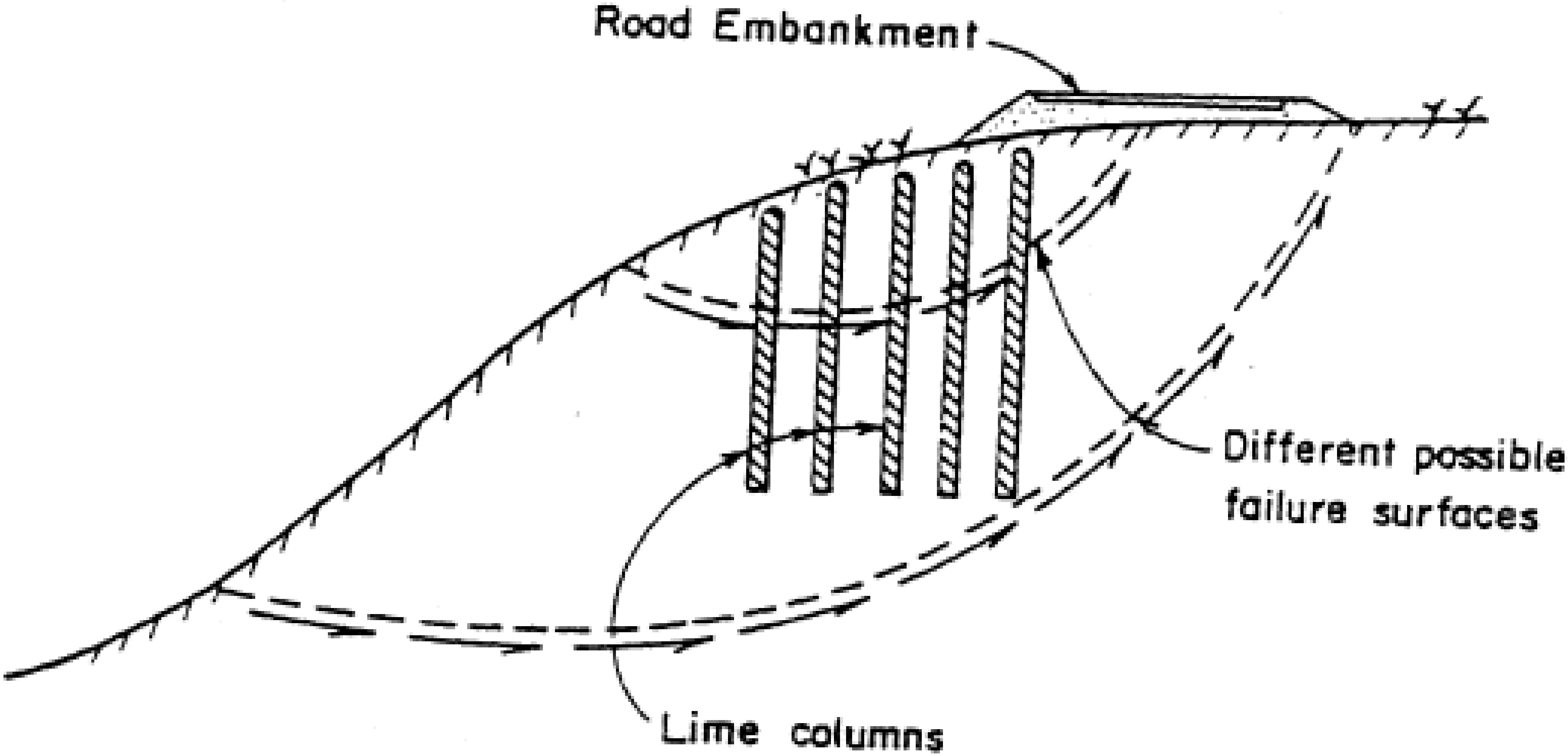


Fig.7.8 Stabilization of a Slope with Lime Columns