Deep Cement Mixing Method,
- mixing and geotechnical designs, construction, and quality control and assurance -

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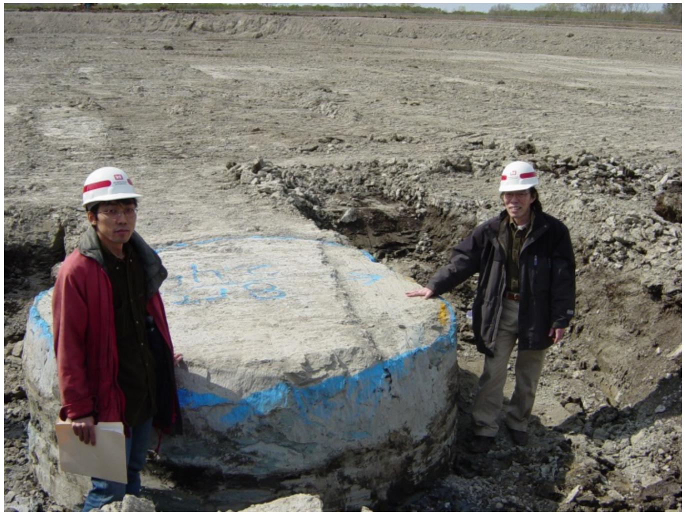
Contents of lecture

- Outline of deep mixing method
- Design
- DM machine and construction
- Quality control and assurance
- Concluding remarks

Deep Mixing Method

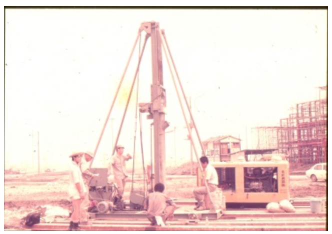
A deep in-situ soil admixture stabilization technique using cement or lime
column diameter : 1 to 1.5 m
column strength : 200 to 2,000 kPa



Deep Mixing Method
-historical review of R&D in Japan-

1970 1980 1990 2000 2010

machine development





projects

1968, field trial

1971, first work

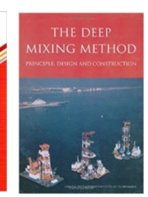
1994, Kansai Airport

2010, Haneda Airport

Design standard & manual

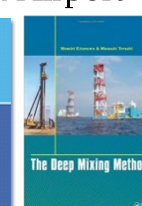
1979, lab. test


1990, design, lab. test



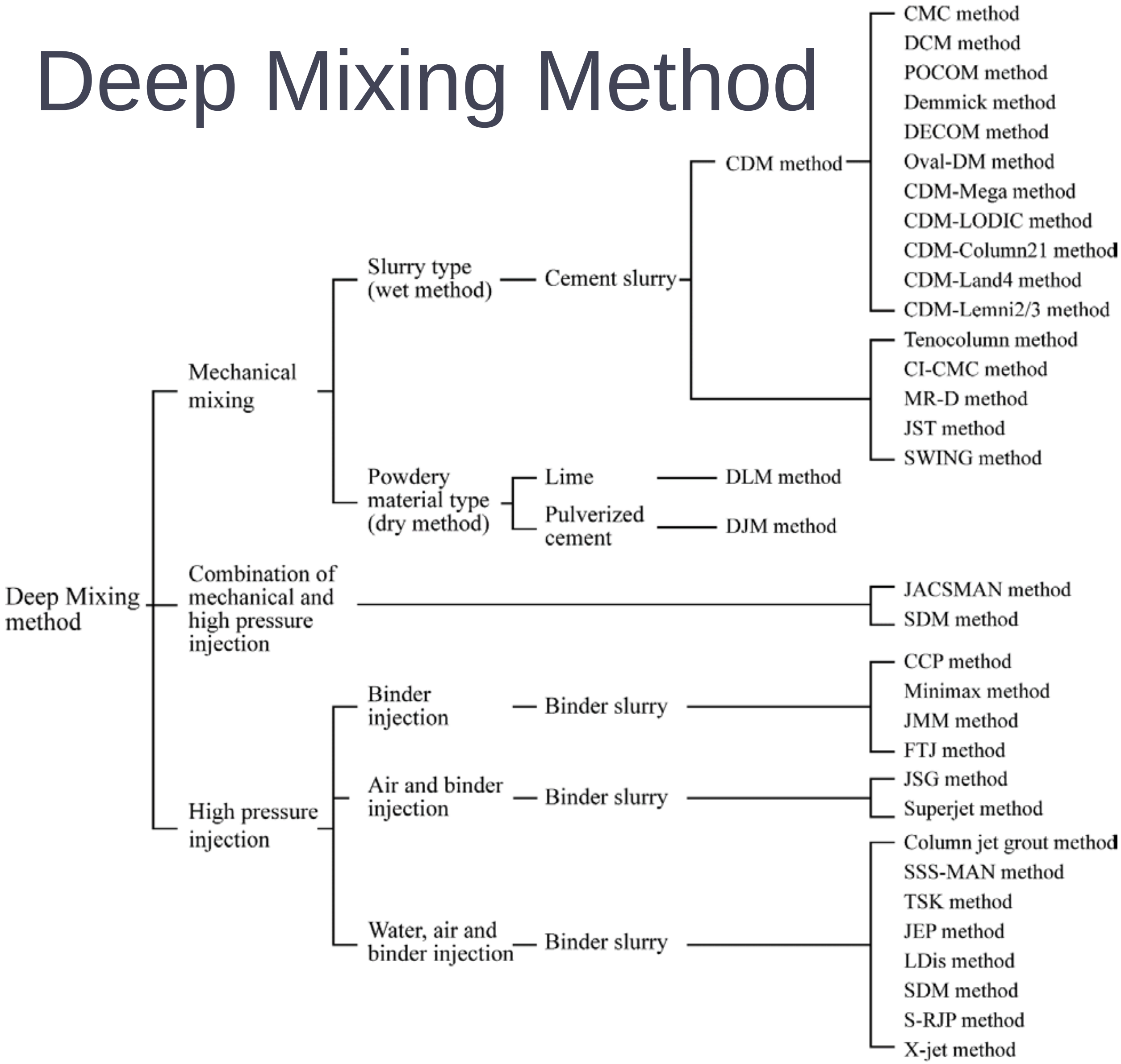
2002

2007, design



2013

Deep Mixing Method



DM design

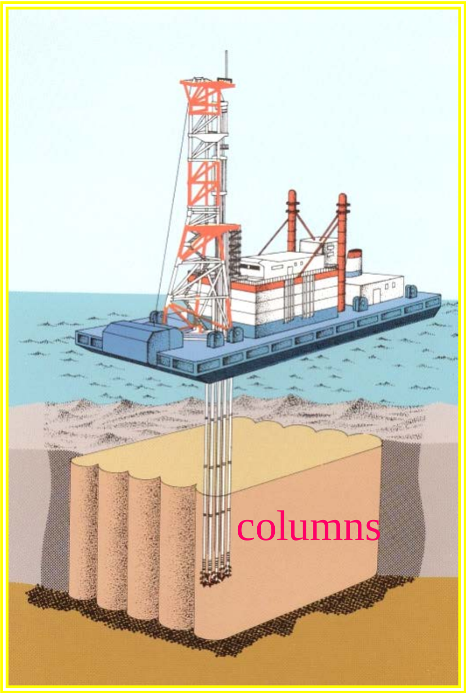
Factors Affecting Strength Increase

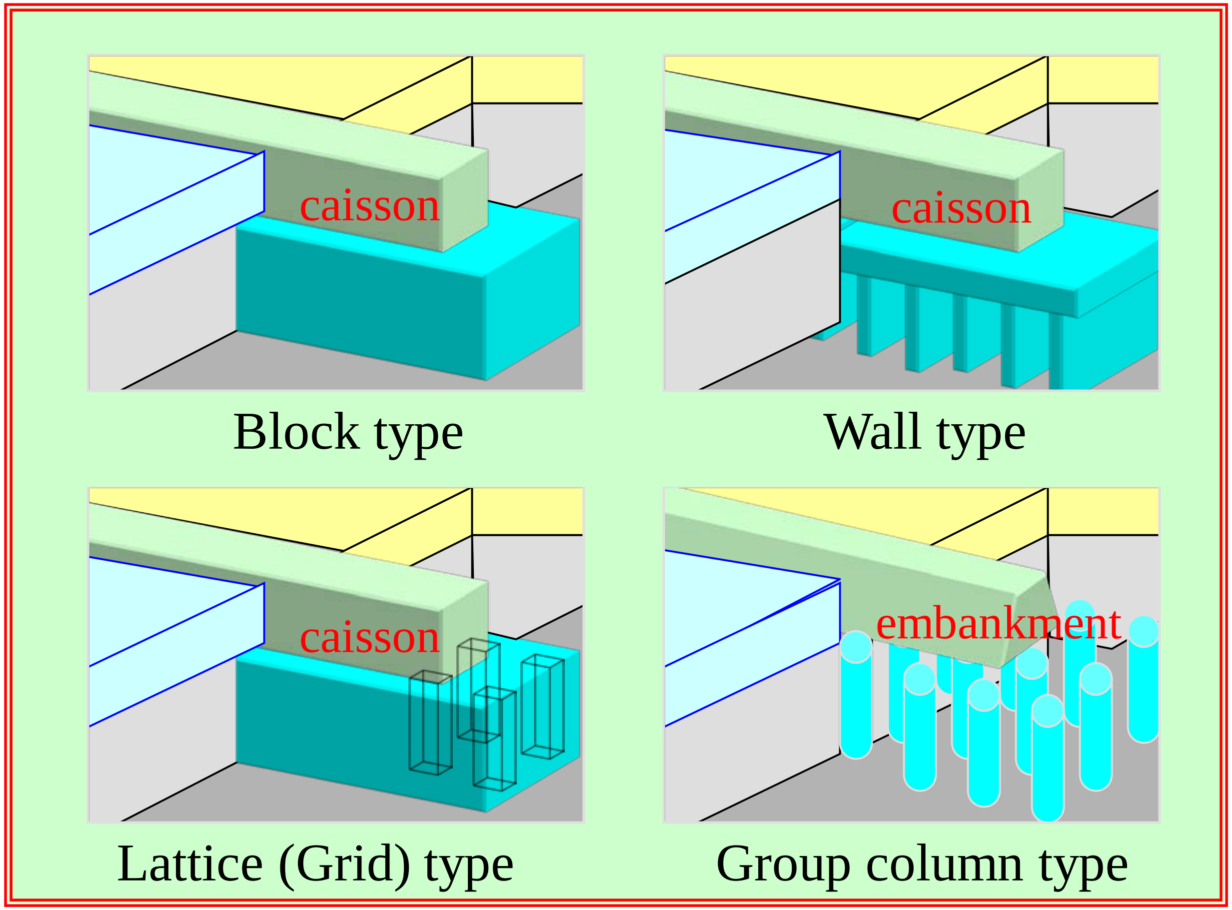
1.	Characteristics of binder	Type of binder Quantity Mixing water and additives
2.	Characteristics and conditions of soil	Physical, chemical and mineralogical properties of soil Organic content pH of pore water Water content
3.	Mixing conditions	Degree of mixing Timing of mixing/re-mixing Quantity of binder
4.	Curing conditions	Temperature Curing time Humidity Confining pressure Wetting and drying/freezing and thawing, etc.

Effect of binder
- Japanese experiences -

binder		O.P. cement	B. F. cement	cement type binder	lime type binder	quick lime
soil type, property	sand	○	○	○	△	△
	clay	○	○	◎	◎	◎
	volcanic soil	○	△	◎	◎	◎
	organic soil	△	○	◎	○	○
	highly organic soil	×	△	◎	△	△
	low water content soil	○	○	○	○	○
	high water content soil	△	△	○	△	△
binder form	slurry	○	○	○	×	×
	dry	△	△	△	○	○
purpose	temporary treatment	△	△	△	○	◎
	quick strength	△	△	○	○	△
	long term strength	○	○	○	○	○

typical improvement patterns



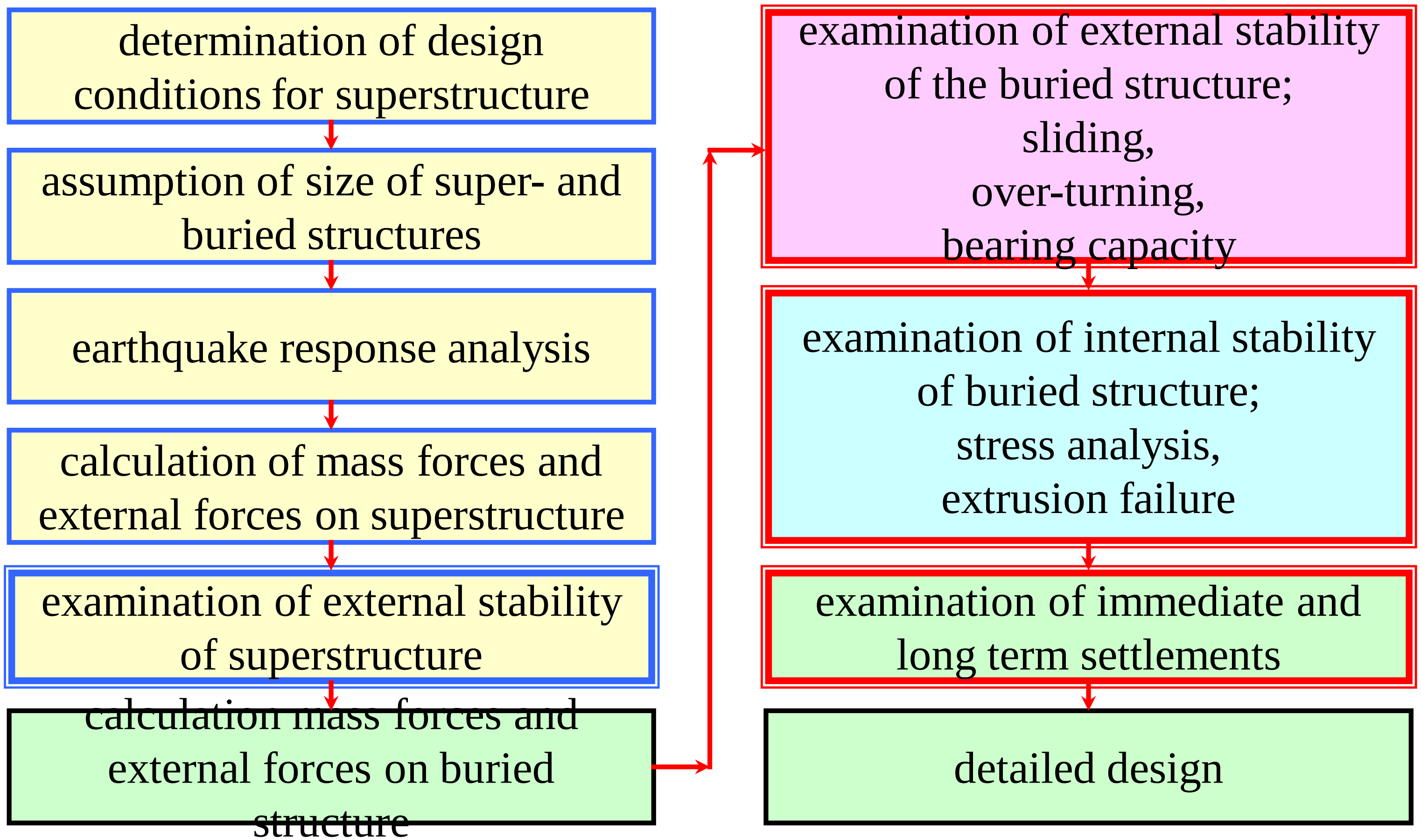


Back ground of the current design procedure

- Large difference of engineering characteristics between treated & untreated soils
  - high unconfined compressive strength
  - small strain at failure
  - low tensile and bending strength
  - low permeability

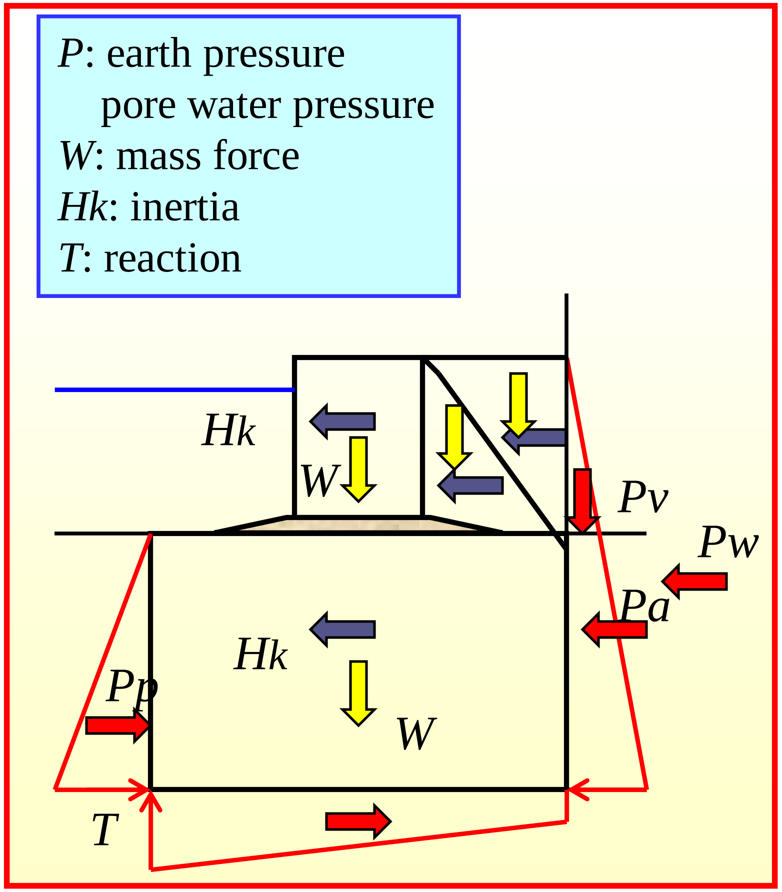
  ---- <u>difficult to assume the improved ground to be an uniform ground, but considered a rigid structural member</u>

Design flow for block and wall type improvements



(Ministry of Transport, 1999)

Schematic diagram of design loads



Design loads

- mass force
- active earth pressure
- passive earth pressure
- cohesion
- pore water pressure
- inertia force
- reaction at bottom

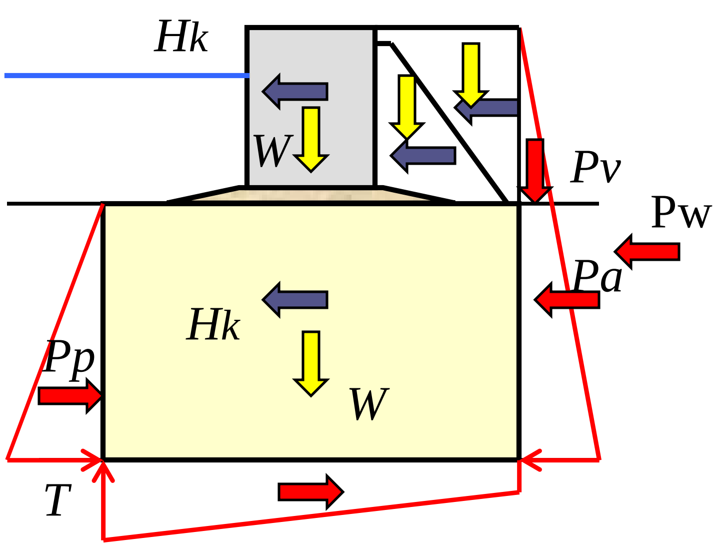
External stability

sliding failure

$$Fss = \frac{P_P + F_R}{P_A + P_W + \sum HKi}$$

overturning failure

$$Fso = \frac{\sum M_R}{\sum M_A}$$



F_R : shear strength (kN/m^2)

Fss : safety factor against sliding failure

Fso : safety factor against overturning failure

P_A : active earth pressure (kN/m^2)

P_P : passive earth pressure (kN/m^2)

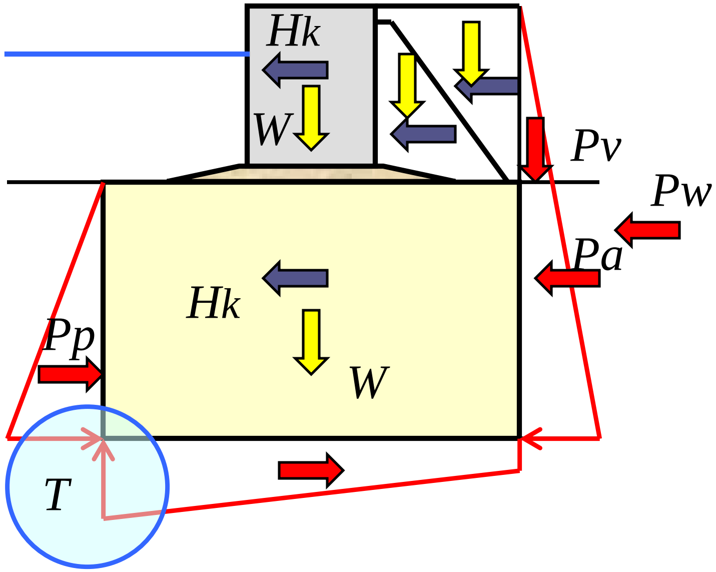
P_W : residual water pressure (kN/m^2)

ΣHKi : sum of seismic inertia forces (kN/m^2)

ΣM_A : sum of overturning moment forces (kN/m)

ΣM_R : sum of resistant moment forces (kN/m)

Bearing capacity



pressure at bottom of improved ground, *T* should be lower than the allowable value.

For sandy ground

- *T* < 500 kN/m^2
  for static condition
- *T* < 750 kN/m^2
  for dynamic condition

Internal stability

Induced stresses of the improved ground calculated by the elastic theory should be lower than the allowable strength of treated soil.

compressive

$$\sigma_{ca} = \alpha\,\beta\,\gamma\, qu_f / Fs$$

$$\sigma_{ca} = \alpha\,\beta\,\gamma\ \lambda qu_l / Fs$$

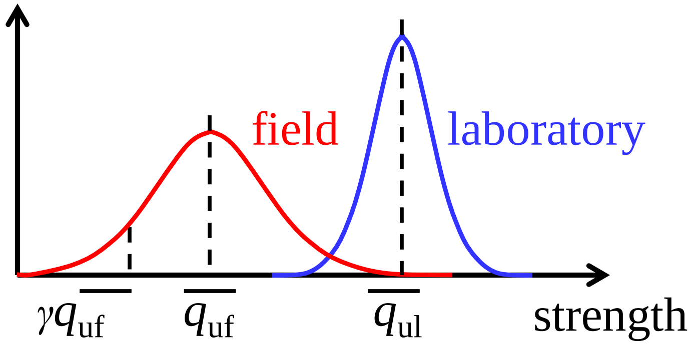
shear strength

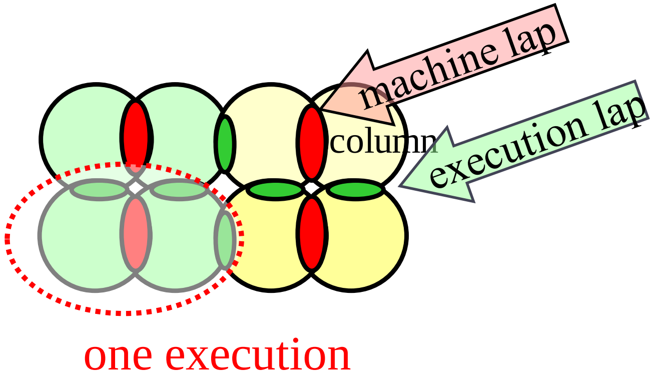
$$\tau_a = \sigma_{ca} / 2$$

tensile strength

$$\sigma_{ta} = 0.15 \cdot \sigma_{ca} \leq 200\, kN / m^2$$

where
α: coefficient of effective width of treated soil column (0.7-0.9)
β: reliability coefficient of over-lapping (smaller than unity)
γ: correction factor for scattered strength (0.5-0.6)
λ: ratio of q_{uf} / q_{ul}

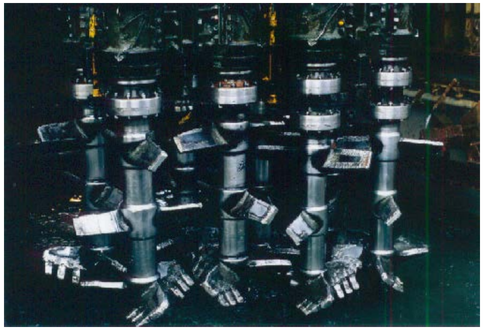




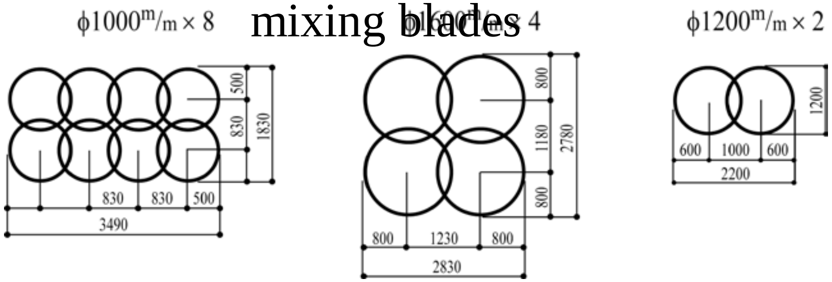
DM machine and Construction

CDM machine for marine construction

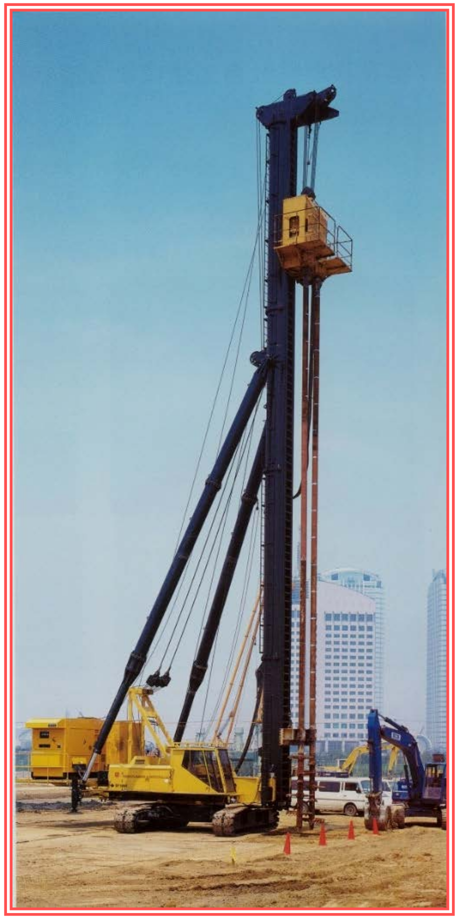
number of mixing shaft: 2 - 8
diameter of mixing blade: 1 - 1.6 m
maximum depth : W.L. -70 m
improvement capacity: 160 m^3/hr
rotating speed of blade: 20 - 60 rpm
penetration speed of shaft:1.0 m/min
withdrawal speed of shaft:1.0 m/min



mixing blades



CDM machine for on land work



diameter of mixing blade:	1.0 to 1.3 m
number of mixing shaft:	1 to 4
maximum depth:	48 m
rotating speed of blade:	20 to 40 rpm
penetration speed of shaft:	1.0 m/min
withdrawal speed of shaft:	0.7 to 1.0 m/min

Line up of Cement Deep Mixing Method machines







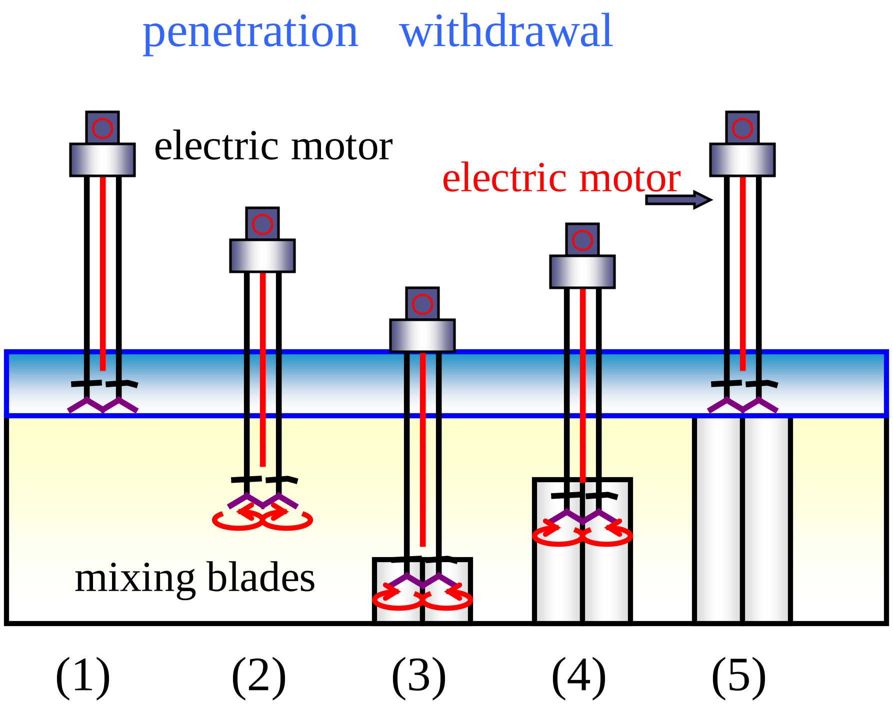

construction

construction for wet method

slurry plant, 1 m^3
agitator, 2 m^3

slurry pump
300-500 kPa

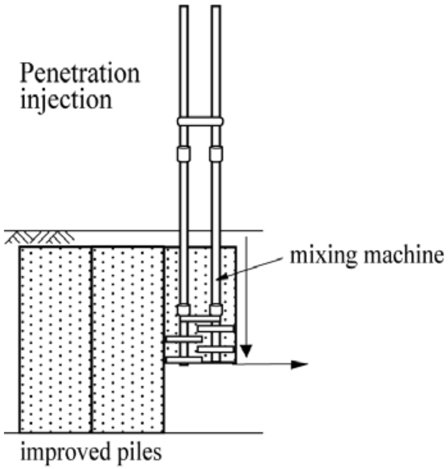
construction of DM



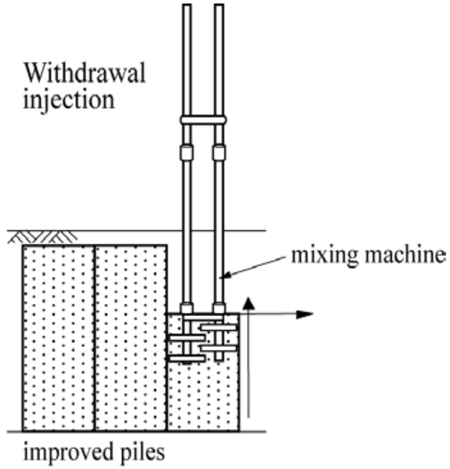
1. mixer blades are correctly positioned
2. mixer blades rotate and penetrate
3. bottom-end of column is mixed with care, when the blades reach the required depth
4. cement slurry is discharged as the mixer blades rotate and raise
5. treated soil columns are formed by hydration and lime-pozzolanic reaction.

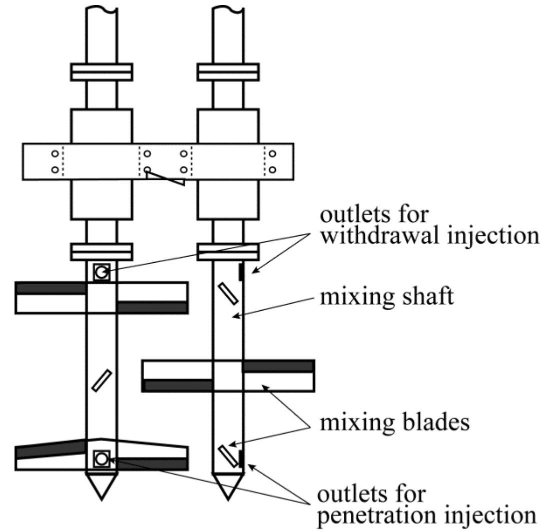
construction procedure

penetration injection



withdrawal injection





The penetration injection method:
beneficial for the homogeneity of column strength by mixing original soil twice.
risk to deadlock or cause serious damage to the machine during penetration.

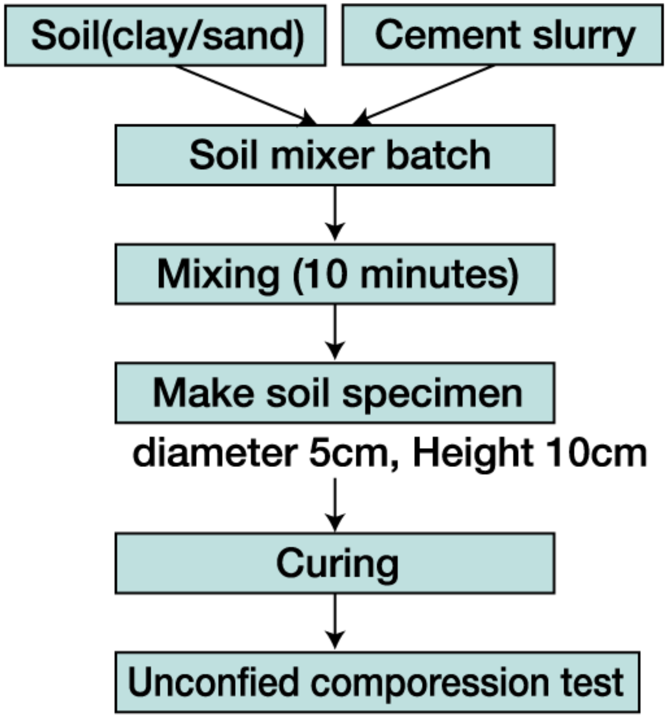
Injection outlet should be installed according to the injection method.

Quality control and assurance




Laboratory mix test

OBJECTIVES:
To obtain the mixing condition to achieve the design strength at field.

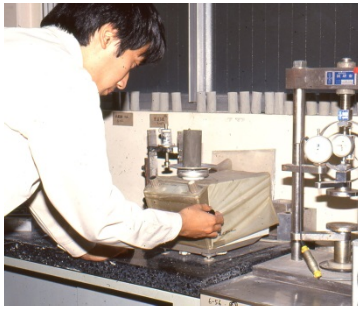


mixing

trimming

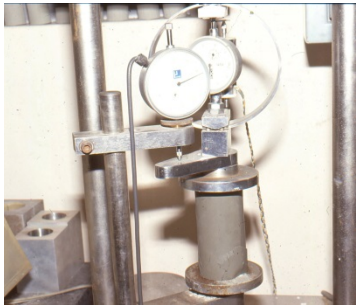
molding

measuring

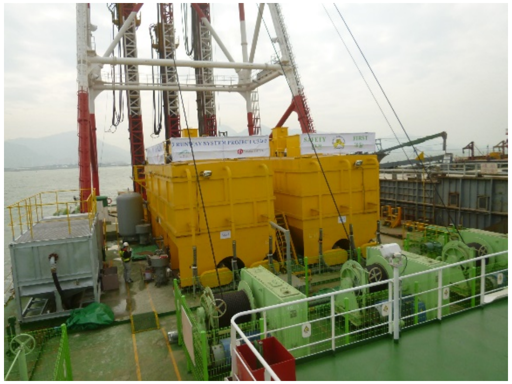


capping

testing



Construction



cement silo

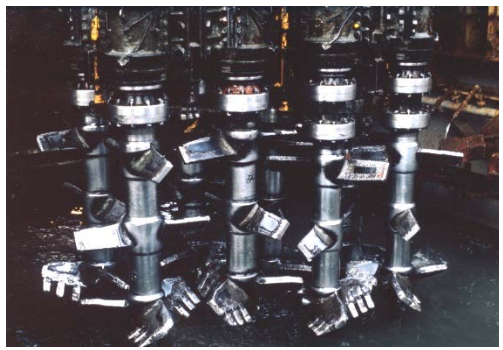
slurry plant & agitator

slurry pumps

Key factors for quality

Mixing blades

Japan



Nordic countries

USA

Key factors for quality

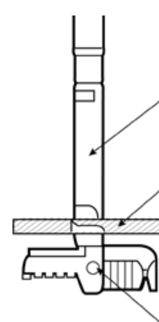
- Effect of blade shape -

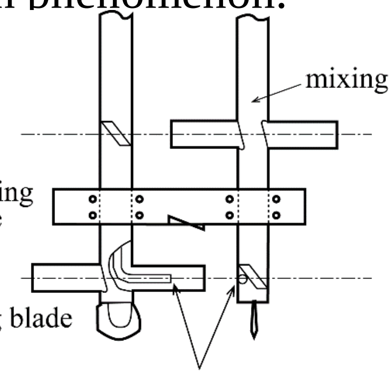
Rake angle

large rake angle enhances the up-down movement of soil together with the horizontal movement, that is effective for uniform mixing

Free blade and bracing plate

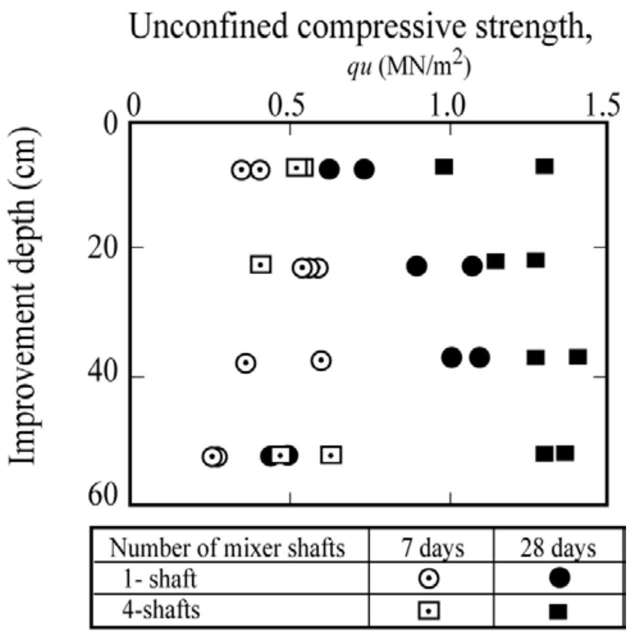
to prevent the "entrained rotation phenomenon."





Key factors for quality

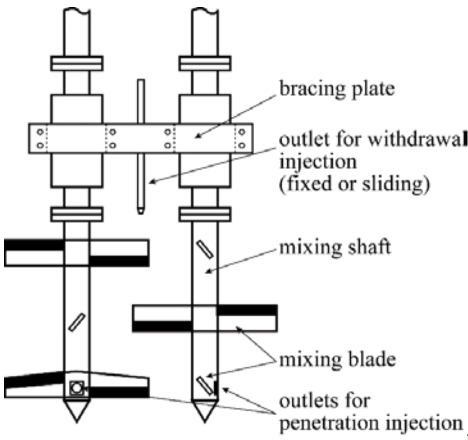
- Effect of number of blades -

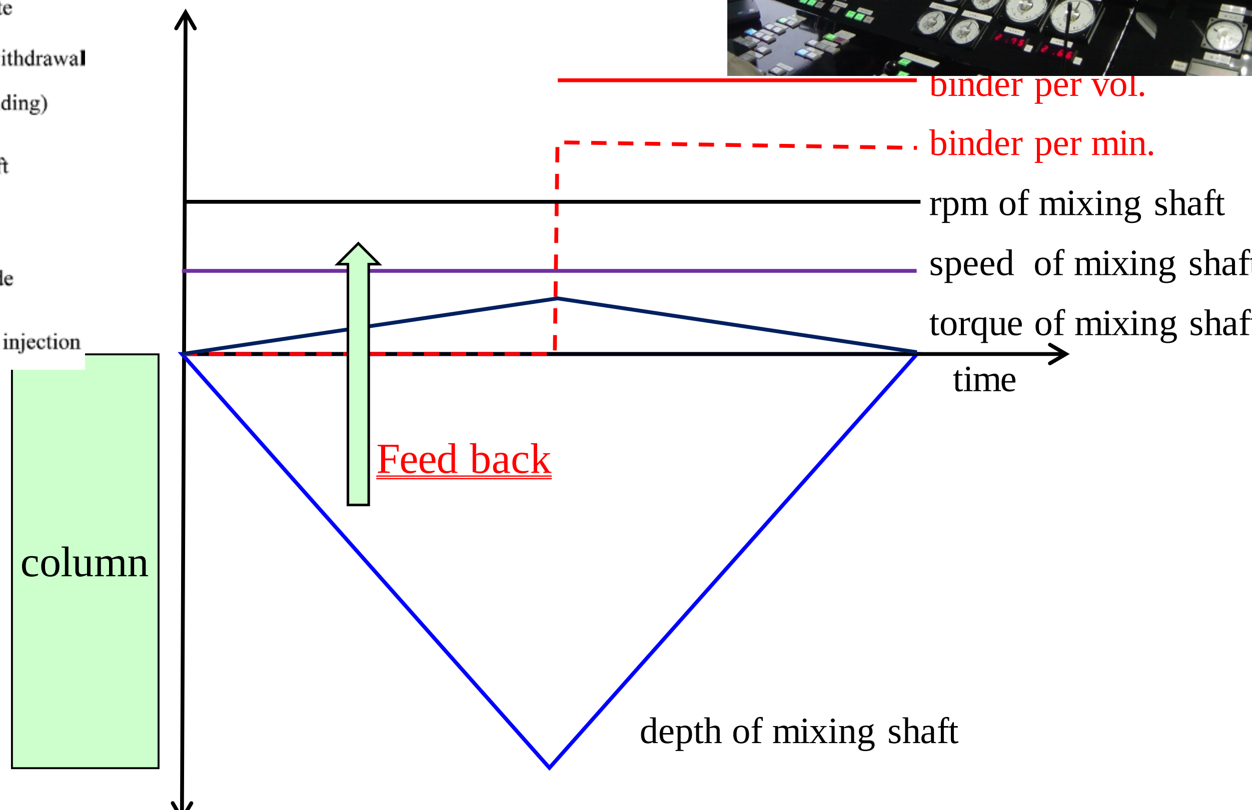


After Nishibayashi et al., 1985

Entrained rotation phenomenon, disturbed soft soil adheres to and rotates with the mixing blade without efficient mixing, may take place in one shaft blade, which decrease degree of mixing.

Construction procedure





QC/QA

blade rotation number

$$T = \Sigma M \cdot \left(\frac{N_d}{V_d} + \frac{N_u}{V_u} \right)$$

where

T : blade rotation number (n/m)

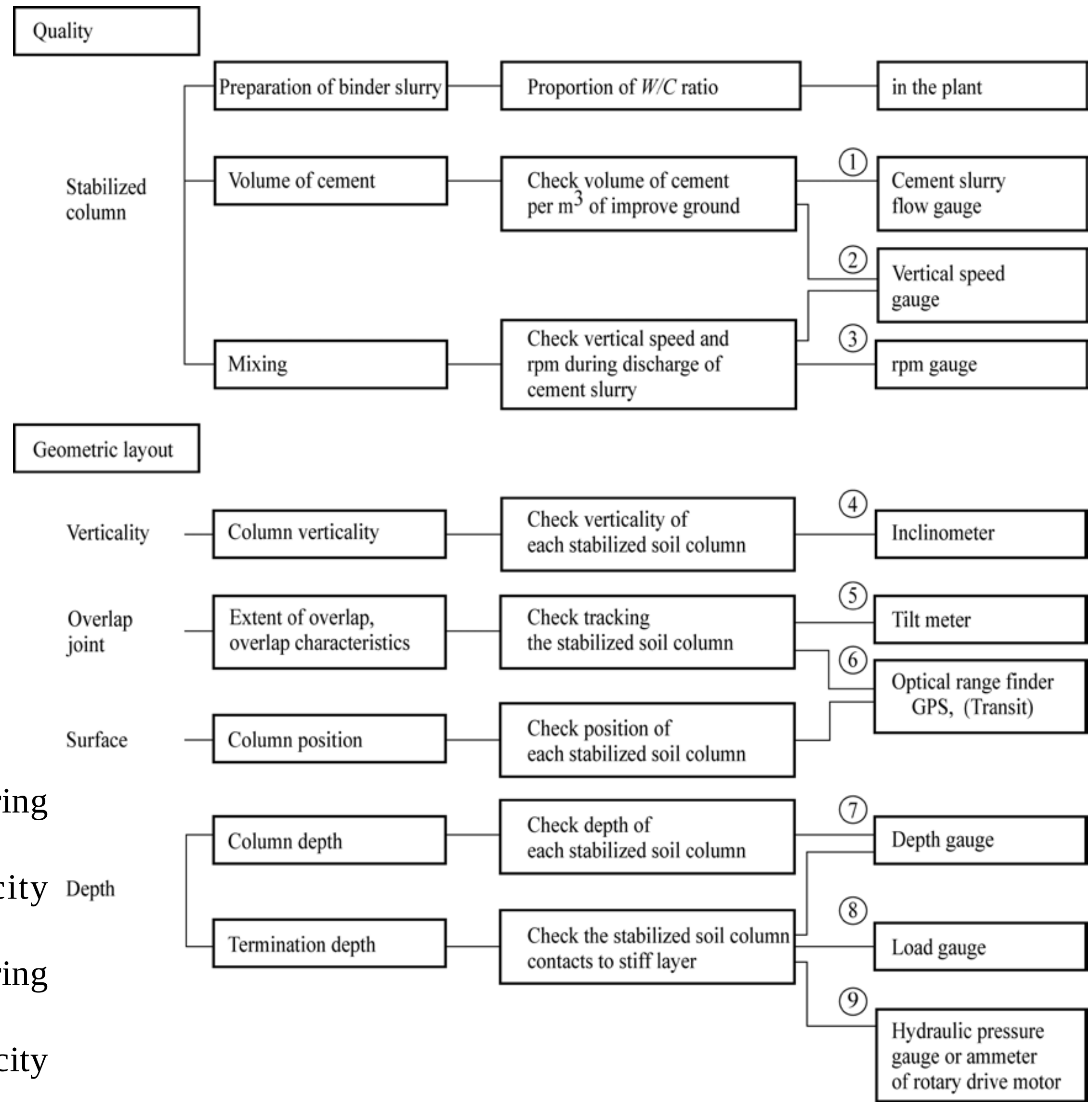
ΣM : total number of mixing blades

N_d : rotation speed of the blades during penetration (rpm)

V_d : mixing blade penetration velocity (m/min)

N_u : rotational speed of the blades during withdrawal (rpm)

V_u : mixing blade withdrawal velocity (m/min)



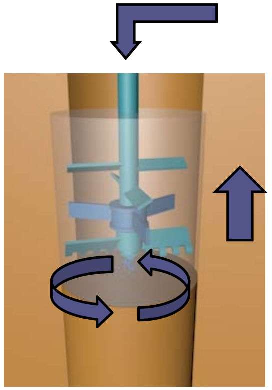
Principle of quality control

cement factor, *F*

$$F = \frac{4 \cdot f \cdot \gamma_{slurry}}{v \cdot \left(1 + \dfrac{1}{w/c}\right)}$$

where

F	:	cement factor (kg/m^3)
f	:	flow rate of cement slurry (m^3/min)
v	:	speed of mixing blade (m/min)
w/c	:	water cement ratio of cement slurry
γ_{slurry}	:	unit weight of cement slurry (kg/m^3)



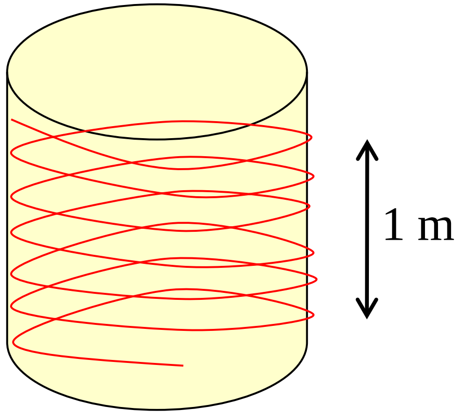
blade rotation number, *T*

$$T = \Sigma M \cdot \left(\frac{N_d}{V_d} + \frac{N_u}{V_u}\right)$$

where

T	:	blade rotation number (n/m)
$\sum M$	:	total number of mixing blades
N_d	:	blade rotation speed during penetration (rpm)
V_d	:	blade penetration speed (m/min)
N_u	:	blade rotational speed during withdrawal (rpm)
V_u	:	blade withdrawal speed (m/min)

Blade rotation number



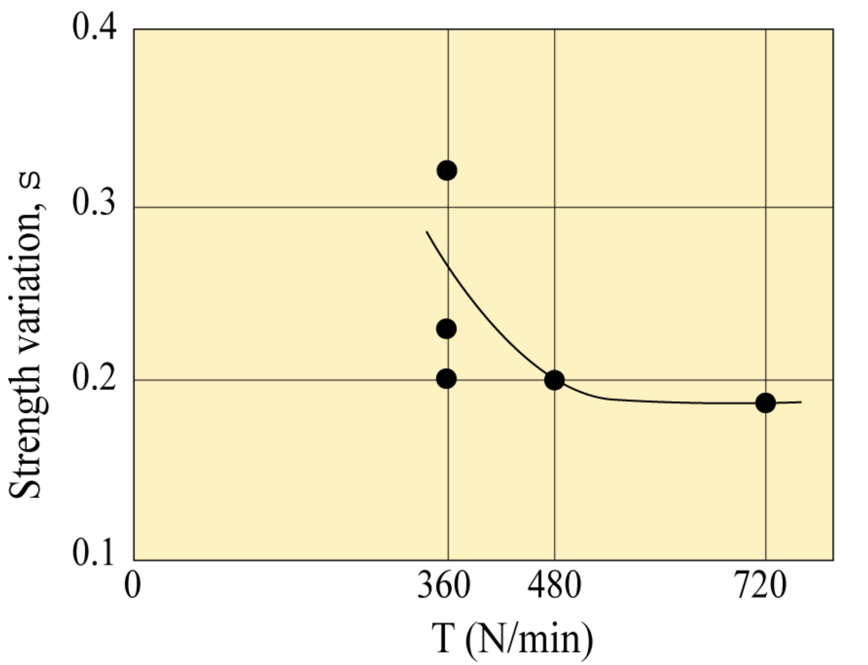
$$T = \Sigma M \cdot \left(\frac{N_d}{V_d} + \frac{N_u}{V_u} \right)$$

where

T : blade rotation number (n/m)
ΣM : total number of mixing blades
N_d : rotation speed of the blades during penetration (rpm)
V_d : mixing blade penetration velocity (m/min)
N_u : rotational speed of the blades during withdrawal (rpm)
V_u : mixing blade withdrawal velocity (m/min)

Key factors for quality

- Effect of mixing efficiency -



Penetration velocity □	1.0□	0.5 □	0.5 (m/min)
Withdrawal velocity□	1.0□	1.0□	0.5 (m/min)

Blade rotation number, *T* (times/m)

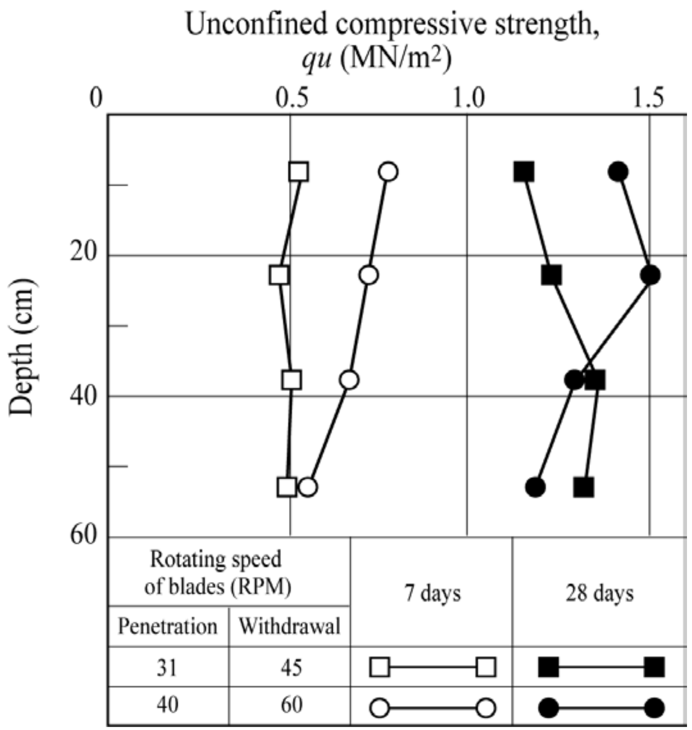
$$T = \Sigma M \cdot \left(\frac{N_d}{V_d} + \frac{N_u}{V_u} \right)$$

where

- T : blade rotation number (n/m)
- ΣM : total number of mixing blades
- N_d : blade rotation speed during penetration (rpm)
- V_d : blade penetration speed (m/min)
- N_u : blade rotational speed during withdrawal (rpm)
- V_u : blade withdrawal speed (m/min)

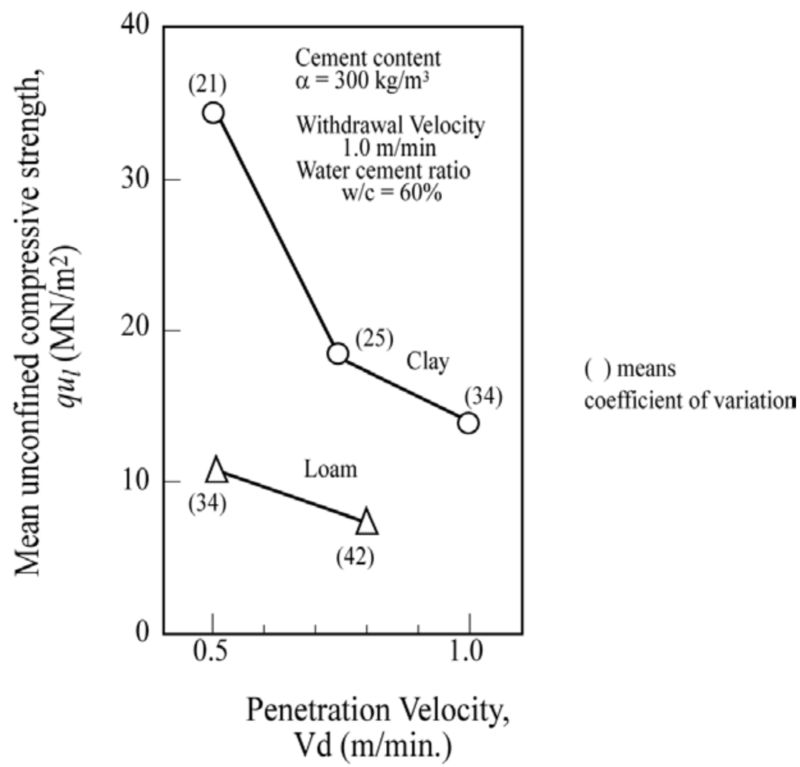
Key factors for quality
- Effect of speed -

effect of rotation speed



After Nishibayashi et al., 1985

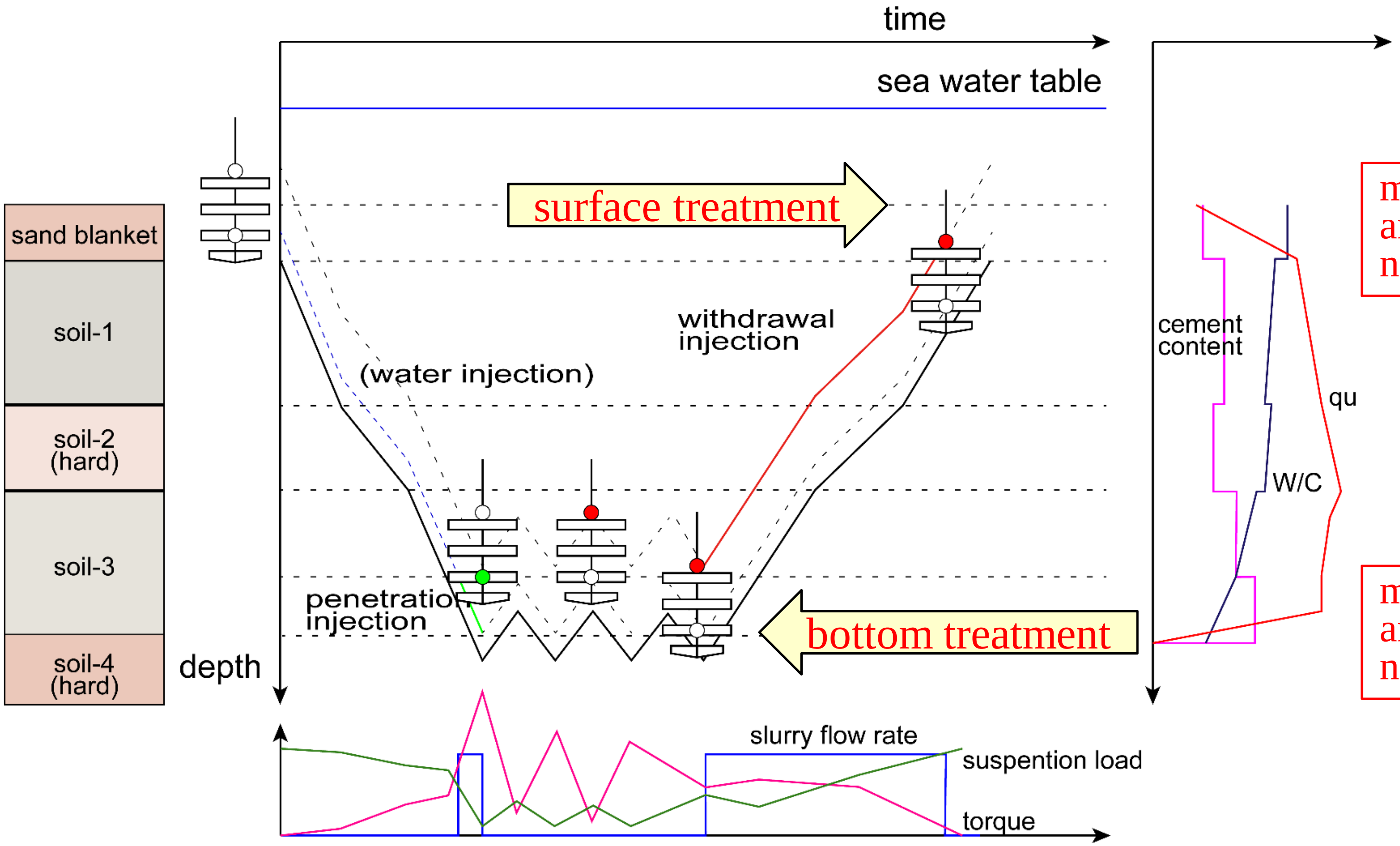
effect of penetration speed



After Enami et al., 1986

Construction procedure

- switching penetration injection to withdrawal injection, bottom and surface treatment -



more cement and mixing are necessary

more cement and mixing are necessary

Strategy for quality control

large rake angle of mixing blade

up-down movement of soil enhances uniform and large strength
large resistance requires large capacity mixing motor, low rpm is required
chemical additive or air mist for reducing mixing energy

small rake angle of mixing blade

no up-down movement of soil makes uniform and large strength
small resistance requires small capacity mixing motor, high rpm can be achieved
no facility for chemical additive or air mist for reducing mixing energy

Strategy for quality control

inject small amount of slurry with low *w/c* ratio

economic, low ground heaving
small size slurry pipe, easy to control flow rate of slurry
low *w/c* ratio (large viscosity) of slurry requires large pump capacity
chemical additives for reducing viscosity, install facility

inject large amount of slurry with high *w/c* ratio

less economic, large ground heaving
large size slurry pipe, difficult to control flow rate of slurry in the case of low flow rate
large *w/c* ratio (low viscosity) of slurry does not require large pump capacity
no facility for chemical additives

Quality of overlapping

soil resistance force
during withdrawal

soil resistance force
during penetration

buoyancy force

rolling and pitching of barge

tidal wave,

buoyancy force and soil resistance

force of mixing shafts and blades

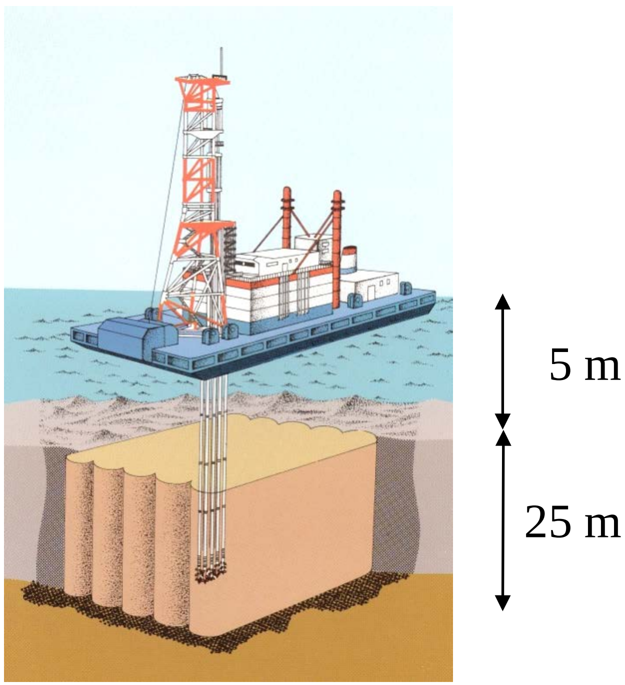
weight loss of cement injected

multiple mixing units enhance barge movements

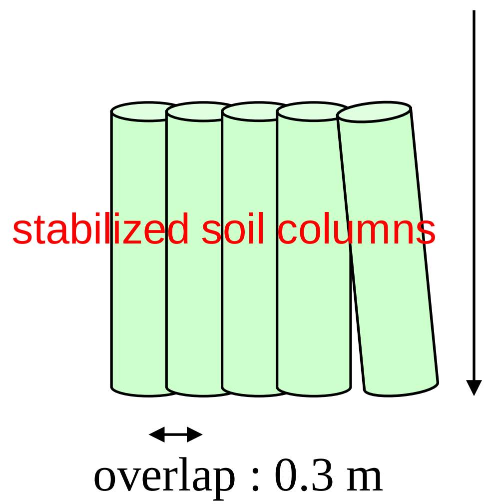
sufficient anchoring & ballast tanks are required to minimize the barge movements.

Quality of overlapping

- tolerance of verticality -



verticality



$$verticality < \frac{0.3\,m}{30\,m} = \frac{1}{100}$$

Quality assurance
- Core sampling -

A Denison type sampler, double tube core sampler, or triple tube core sampler are recommended.
A large diameter such as 86 mm or 116 mm is recommended.

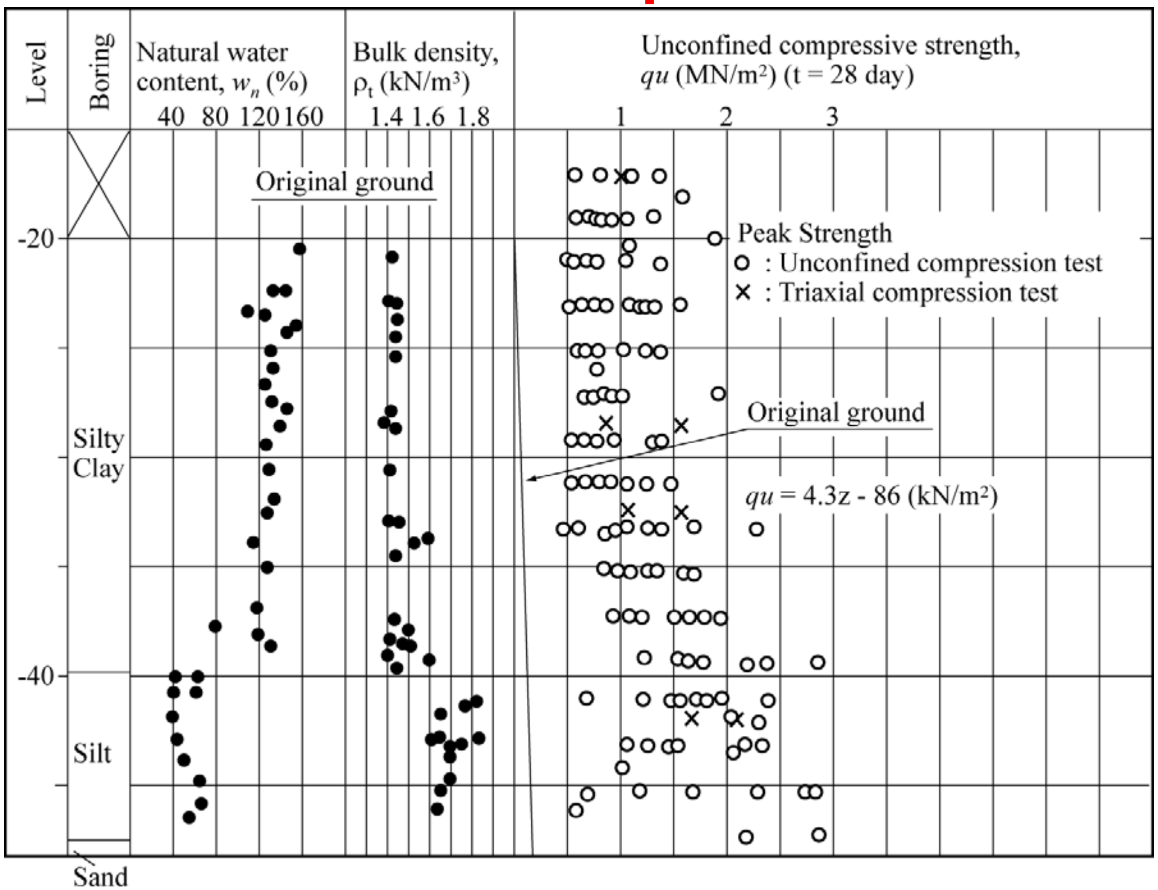
The acceptance criteria

The *RQD* (*Rock Quality Designation*) index

$$RQD = \frac{\sum \text{length of core pieces} > 10\text{cm}}{\text{Total core run length}}$$

RQD	description of rock quality
0 - 25%	very poor
25 - 50%	poor
50 - 75%	fair
75 - 90%	good
90 - 100%	excellent

Strength of stabilized soil
- distribution with depth -



Concluding remarks

DM method

wide varieties of machine and applications

Design

many factors influence stabilized soil strength

external and internal stabilities

DM machine

wide varieties of machine and mixing blades

Quality control and assurance

quality control is essential for assuring the uniformity and strength and the verticality of stabilized soil column

core sampling and unconfined compression test are necessary

Thank you for your kind attention