Sand Compaction Pile Method

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- Execution, Quality Control and Assurance
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1. Outline of SCP method

Outline of Sand Compaction Pile Method

Definition of soft soil

'Soft ground' can be defined as a ground on which stability of structures subjected to expected external loads can not be assured and/or the magnitude of settlement and deformation during and after construction can not allowed.

	highway			railway		building	fill dam
	water content (%)	*qu* (kN/m^2)	SPT *N* value	SPT *N* value	thickness (m)	bearing capacity (kN/m^2)	SPT *N* value
organic soil	> 100	< 50	< 4	< 0	> 2	< 100	< 20
clayey soil	> 50	< 50	< 4	< 2	> 5	< 100	-
sandy soil	> 30	0	< 10	< 4	> 10	-	-

Principle and classification of Soil Improvement Technique

Principle

1. change type of structure
2. replace soft soil by high quality soil
3. improve properties of soft soil
4. introduce additional material in soil

Classification

1. Light weight method
2. Replacement method
3. Consolidation and drainage method
4. Compaction method
5. Admixture and thermal methods
6. Reinforcement method

Comparison of soil improvement techniques

name	purpose				soil		effect	period	expense
	stren-gth	settle-ment	lique-faction	perme-ability	clay	sand			
Replacement method	good	good	n.g.	n.g.	good	n.g.	Fair	Short	Less
Preloading method	good	good	n.g.	n.g.	good	n.g.	Fair	Long	Less
Vertical drain method	good	good	n.g.	n.g.	good	n.g.	Fair	Mid.	Mid.
Quick lime pile method	good	good	n.g.	n.g.	good	n.g.	Low	Short	Mid.
Vacuum method with vertical drainage	good	good	n.g.	n.g.	good	n.g.	Fair	Mid.	Mid.
Deep mixing method	good	good	fair	fair	good	fair	Well	Short	High
Sand compaction pile method for clay	good	good	n.g.	n.g.	good	n.g.	Well	Short	High
Sand compaction pile method for sand	good	good	good	n.g.	n.g.	good	Well	Short	Mid.
Vibro-flotation method	good	good	good	n.g.	n.g.	good	Fair	Short	Mid.

Comparison of soil improvement techniques

name	purpose				soil		effect	period	expense
	stren-gth	settle-ment	lique-faction	perme-ability	clay	sand			
Vibro-rod method	good	good	good	n.g.	n.g.	good	Fair	Short	Mid.
Gravel drain method	n.g.	n.g.	good	n.g.	n.g.	good	Fair	Short	Mid.
Heavy tamping method	good	good	fair	n.g.	n.g.	good	Fair	Short	Mid.
Blast compaction method	good	good	fair	n.g.	n.g.	good	Fair	Short	Less
Grouting method	fair	n.g.	fair	good	n.g.	good	Well	Short	High
Freezing method	good	n.g.	n.g.	good	good	good	Well	Mid.	Mid.
Temporary method									
Dewatering method	fair	fair	n.g.	n.g.	fair	good	Fair	Mid.	Mid.
Surface treatment Sheet and net method	fair	n.g.	n.g.	n.g.	good	n.g.	Low	Mid.	Mid.
Admixture method	good	n.g.	n.g.	n.g.	good	n.g.	Low	Short	Mid.

Compaction methods

- Sand compaction pile method
- Vibro-floatation method
- Heavy tamping method
- Vibro-tamper method




Sand Compaction Pile Method

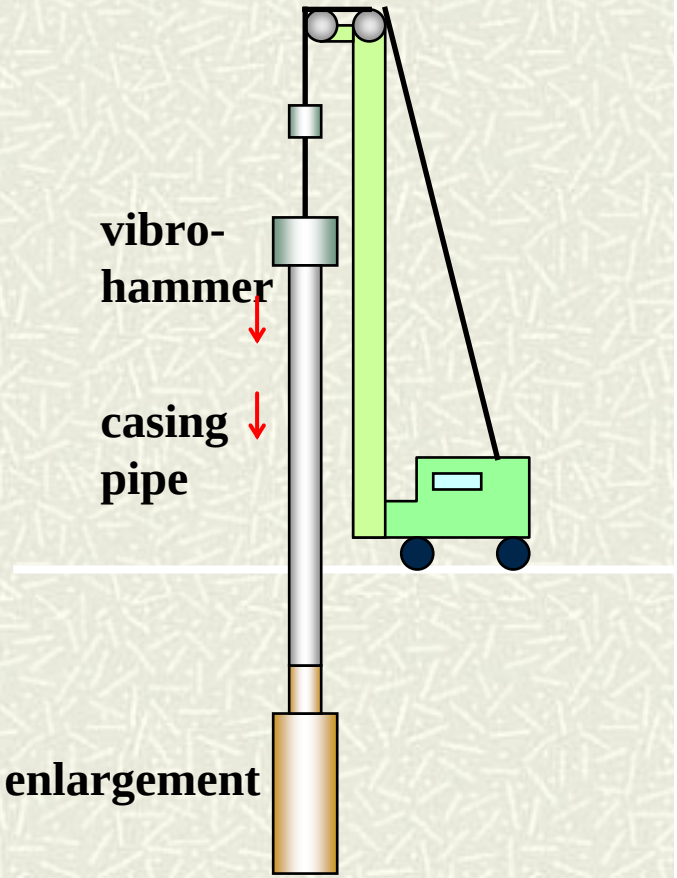
- compacted granular material piles are constructed by help of vibration or static loading
  - for sandy ground

    density increase, liquefaction mitigation
  - for clay ground

    bearing capacity increase

    increase slope stability

    decrease consolidation settlement



Sand Compaction Pile Method

History of SCP Method

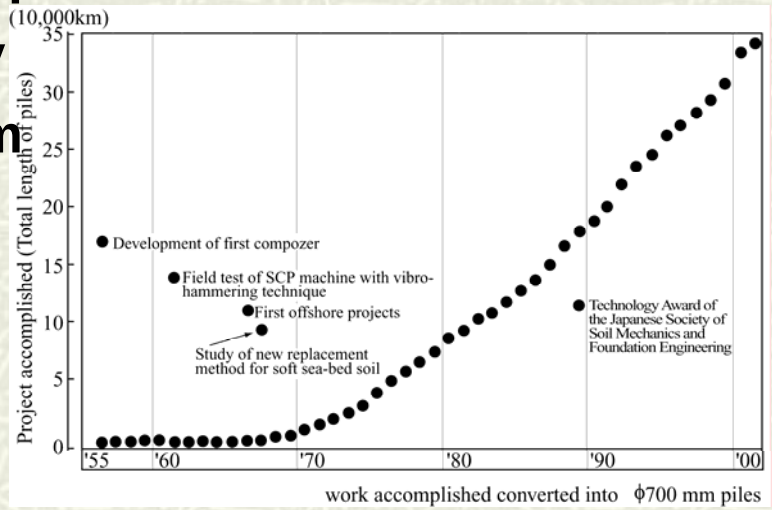
1957 **Proposal of principle of SCP by Murayama et al.**
Development of hammering method

1960 **Application to sand**

1962 **Application to clay (replacement method)**

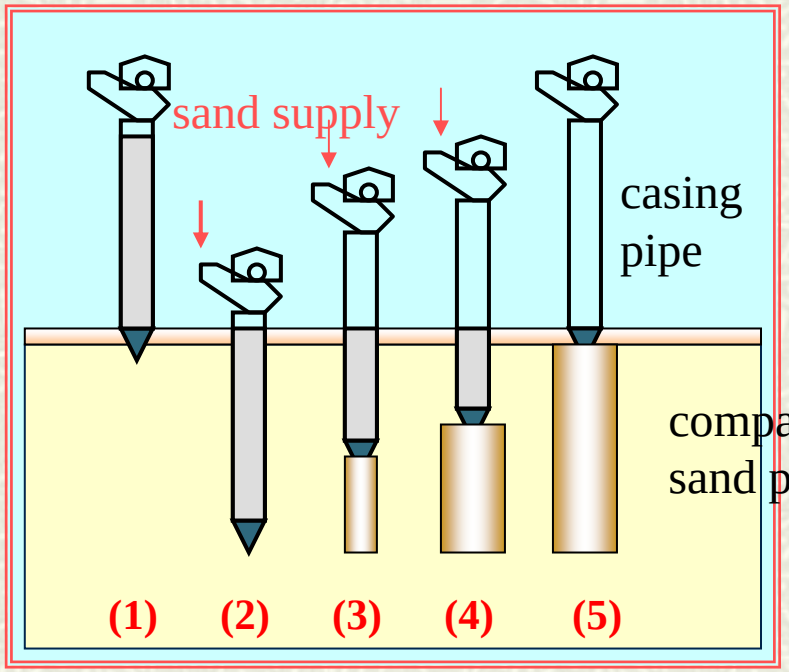
1967 **Development for off-shore application**

1981 **Development of automatically controlled SCP driving system**



Sand Compaction Pile Method

- execution procedure -



(1) The casing pipe is located at the design position.

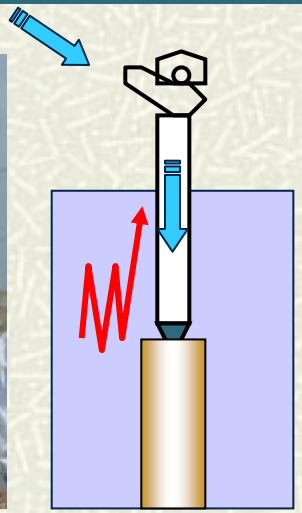
(2) The casing pipe is driven into the ground by the vibratory excitation.

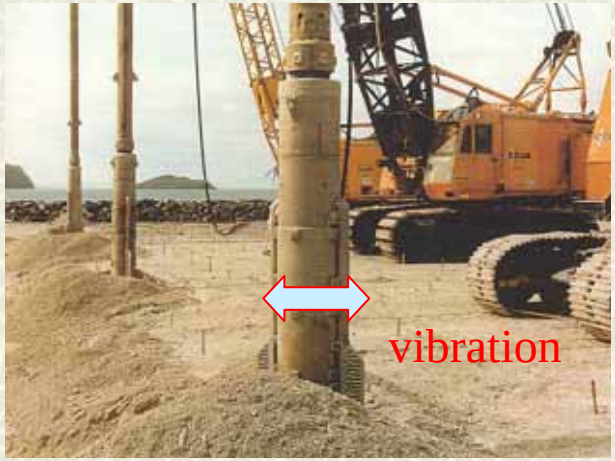
(3) As the casing pipe is retrieved about few meters, the sand is fed into the ground.

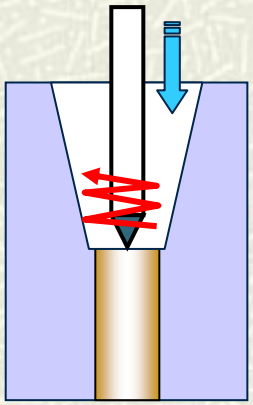
(4) The sand is compacted by the vibratory excitation of the casing pipe in the vertical vibration.

(5) The casing pipe is retrieved few meters again and the procedure is repeated up to the ground level.

difference from vibro-flotation





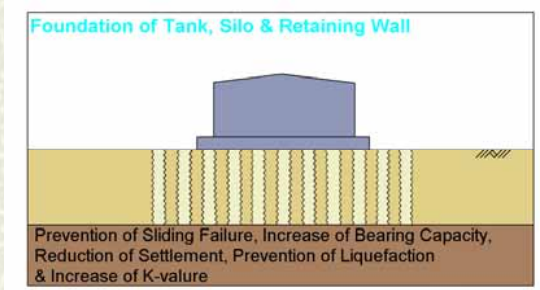


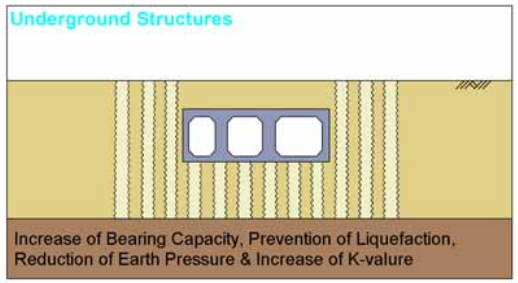
Sand Compaction Pile Method

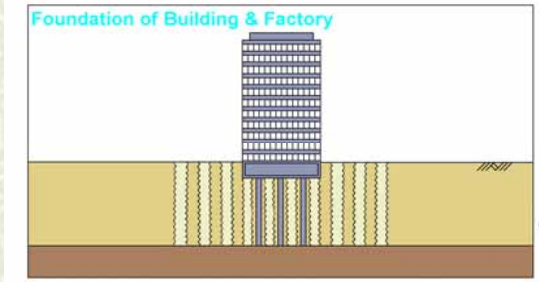
- difference from SD method -

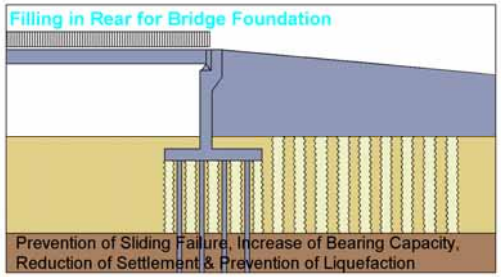
	Sand Drain Method	Sand Compaction Pile Method
Purpose of method	accelerate consolidation	reinforcement (accelerate consolidation)
Diameter of sand pile	12cm - 50cm	50cm - 100cm
Interval of sand piles (replacement ratio)	1m - 3m (few %)	1m - 3m (30% - 78%)
Quality control	Continuity & permeability	Strength (permeability)

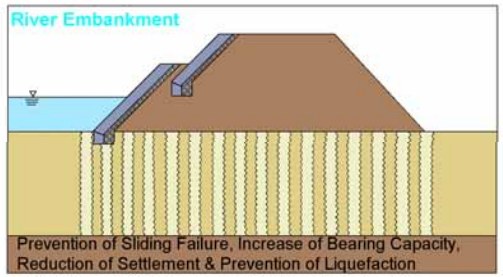
Applications to on-land works



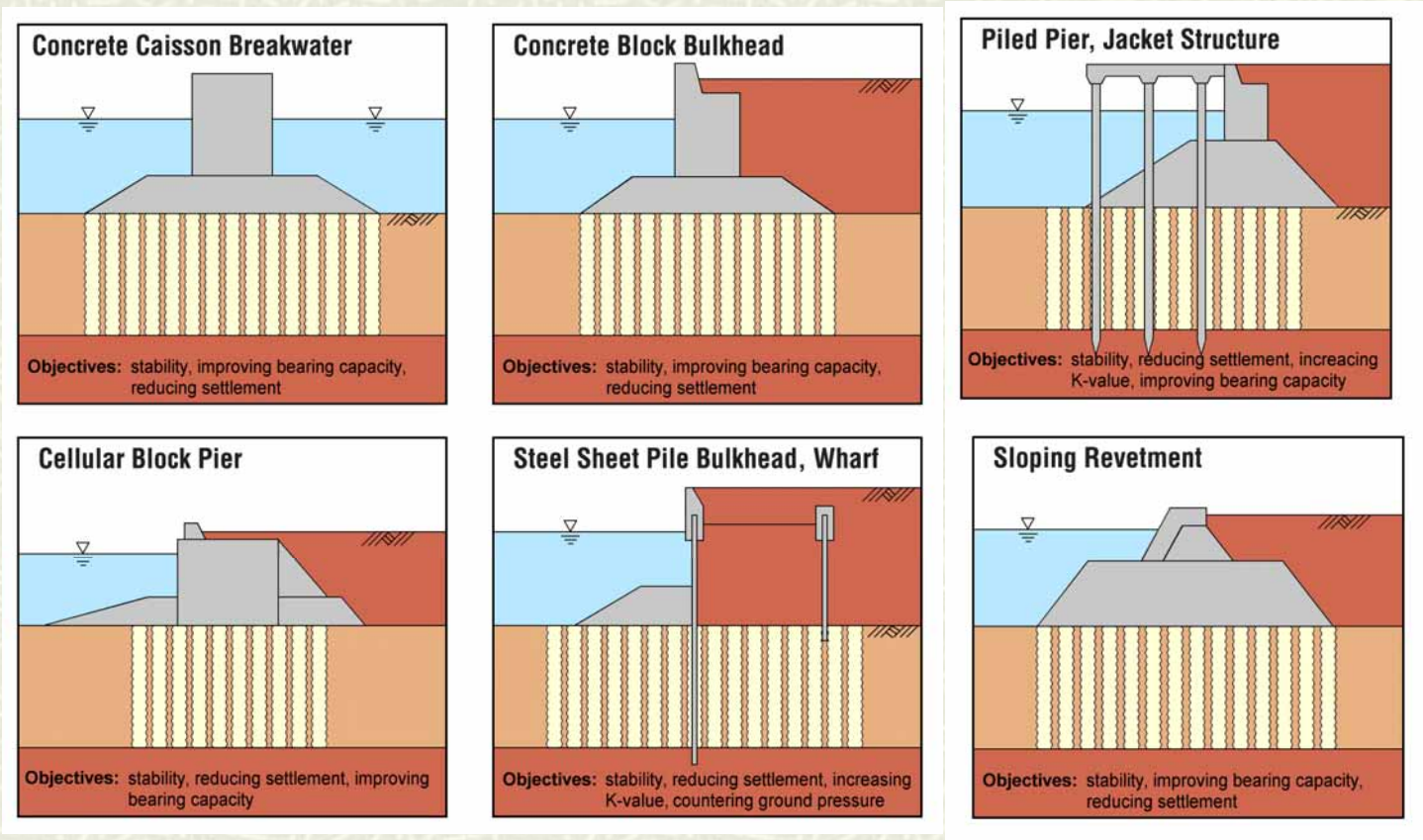




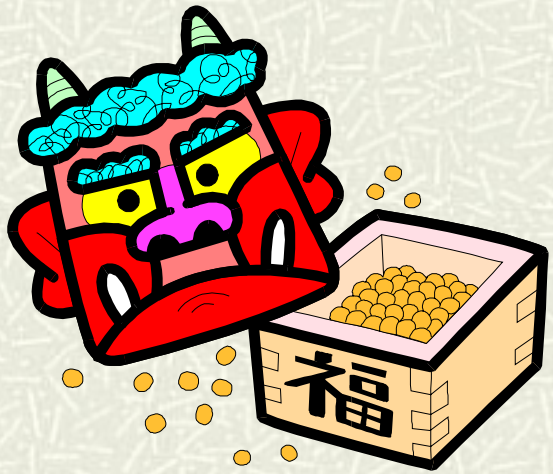




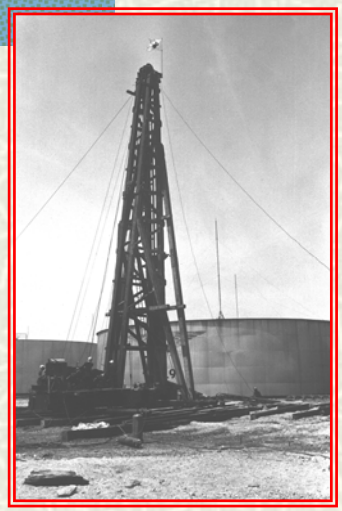
Applications to marine works



2. Development of SCP machine

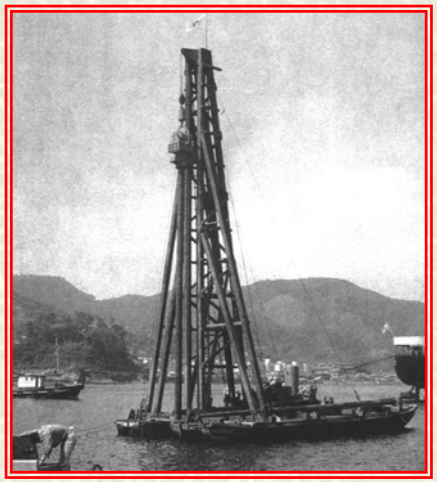


Development of SCP machines



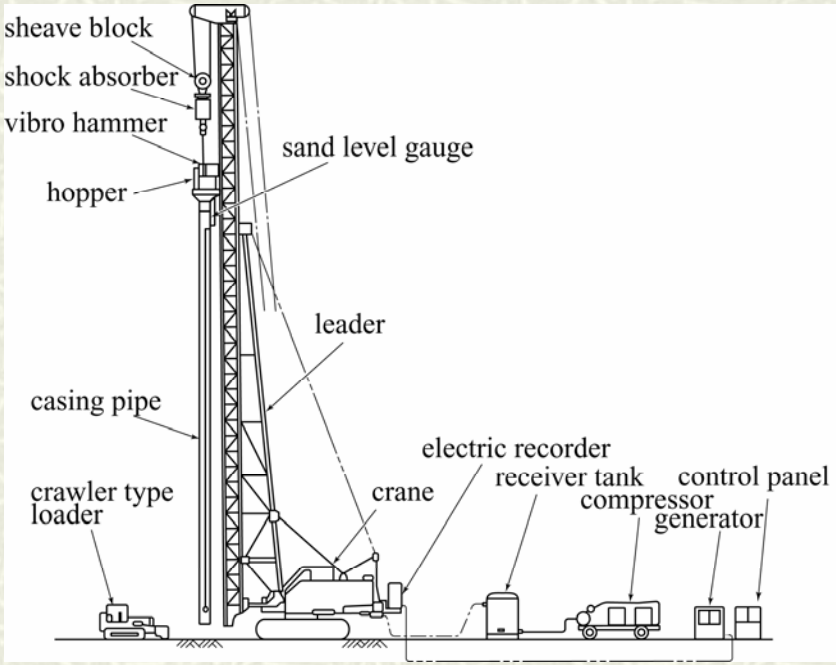
SCP machine with hammering compaction technique in 1952.

SCP machine with vibrating compaction technique in 1959.



SCP barge at Saganoseki Port in 1961.

SCP Machine for On-land Work



Vessels for marine works

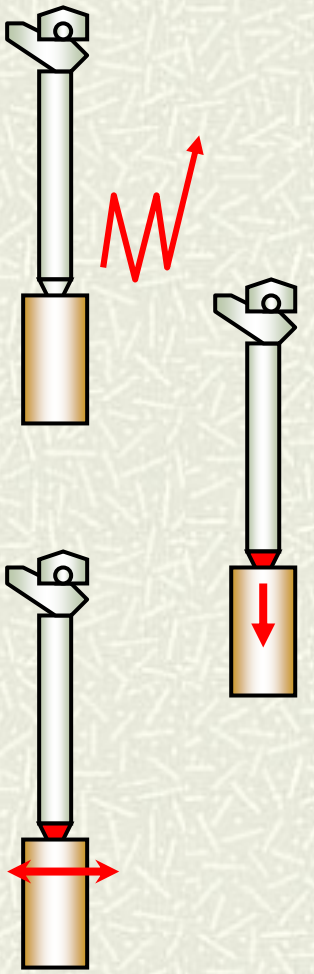
length	70m
width	31m
depth	4.6m
draft	2.3m
Max. depth	70m
Max. dim.	2m

Execution procedures
- with vibration -

- **Vertical vibration technique**
  compact by vertical vibrate excitation during retrieve and penetration movements.

- **Piston vibration technique**
  compact by vertical vibration of piston prove installed at bottom of casing pipe.

- **Horizontal vibration technique**
  compact by horizontal excitation of vibro-float at bottom of casing pipe.

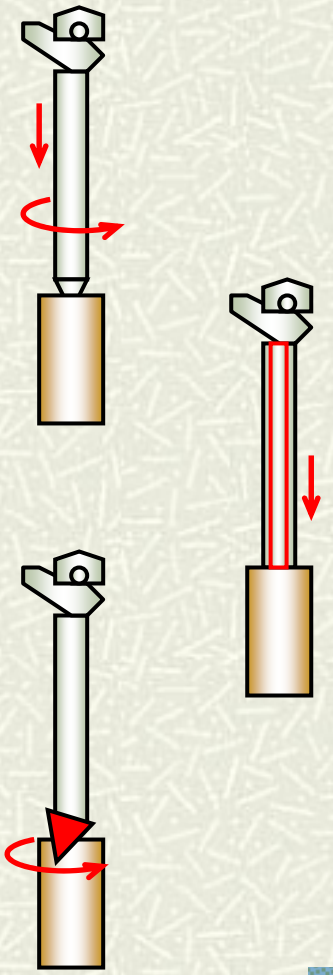


Execution procedures
- without vibration -

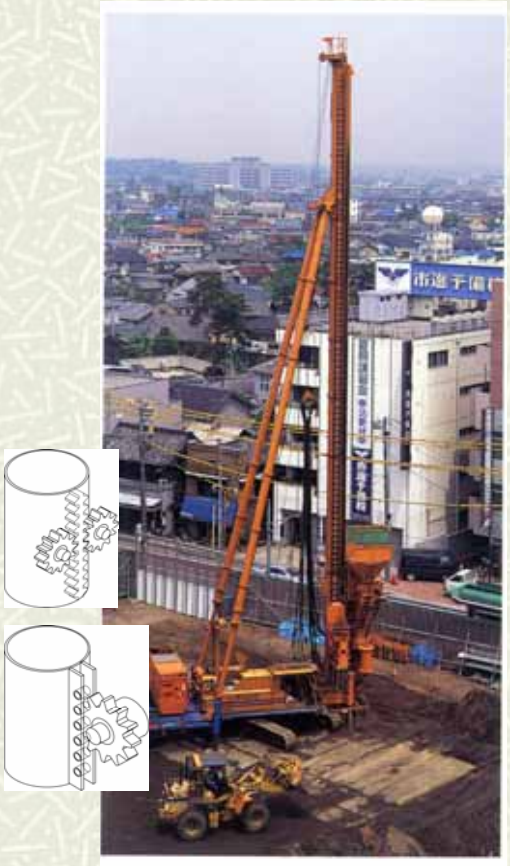
- **Rotation and wave compaction technique**
  compact by rotating the casing pipe, and a driving and lifting movement.

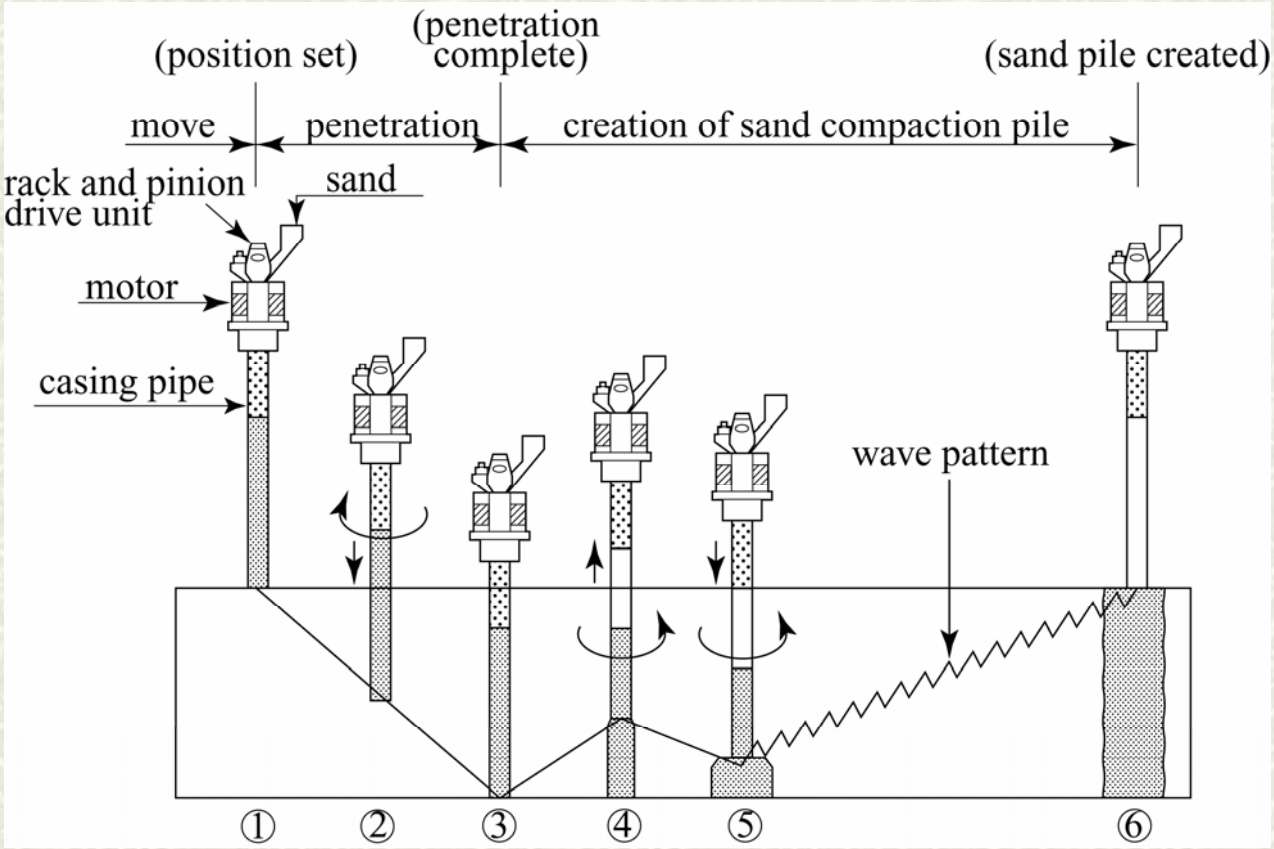
- **Double casing pipes compaction technique**
  compact by driving and lifting the inner casing pipe.

- **Rotary compaction-device technique**
  compact by rotating a excavation and expanding head.

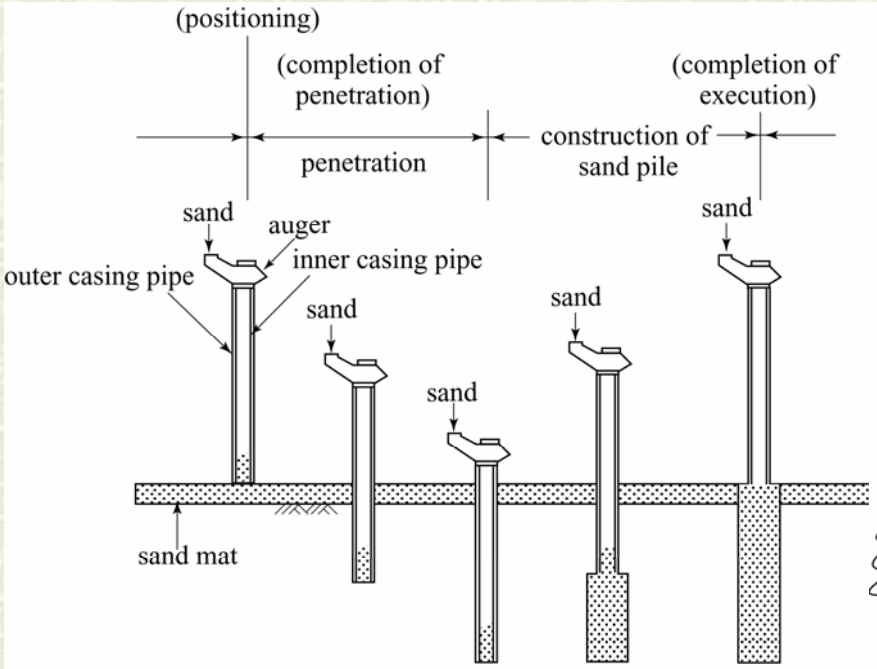


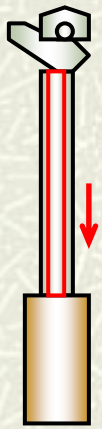
Rotation and wave compaction technique

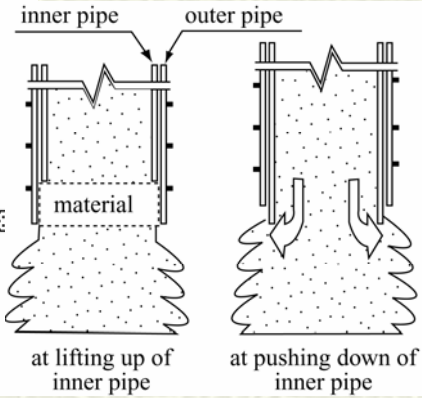




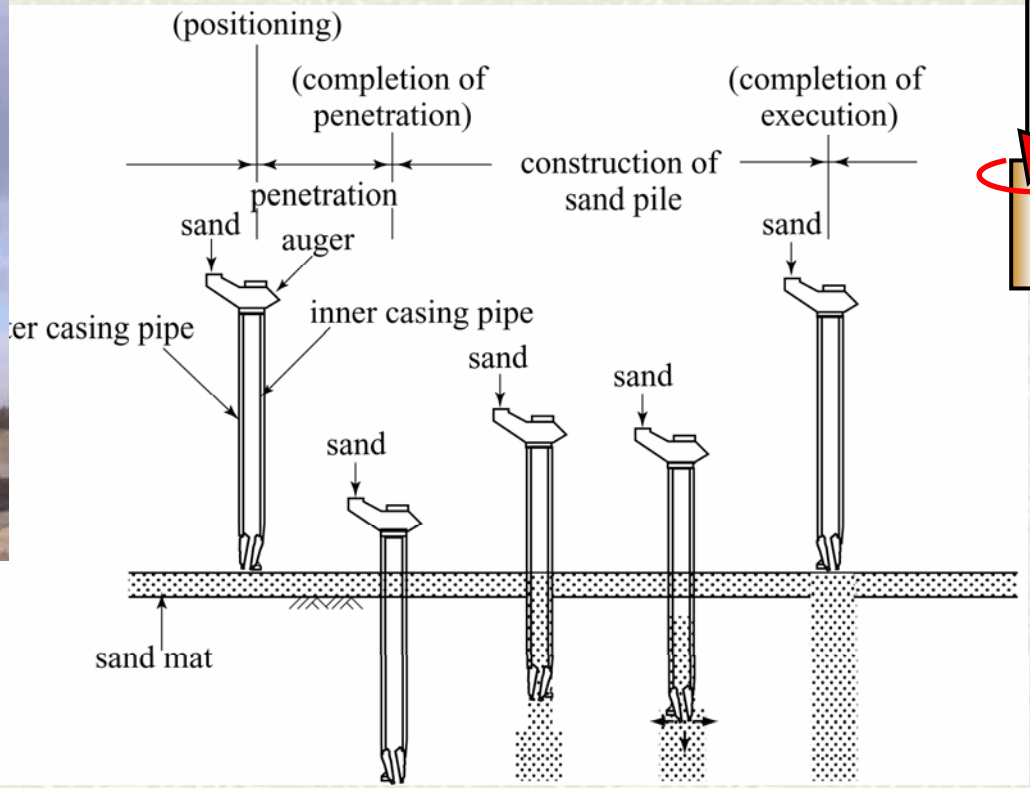
Double casing pipes compaction technique

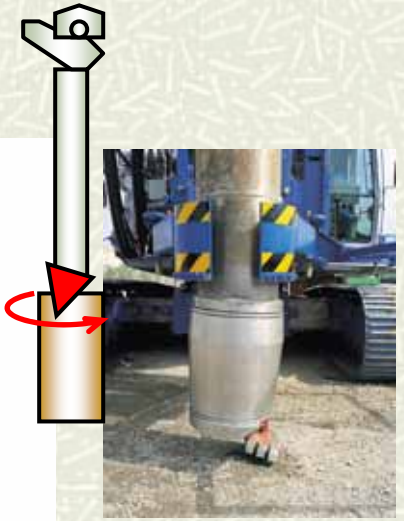


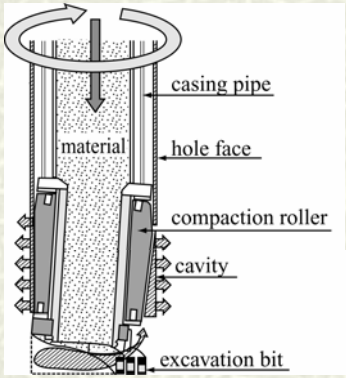




Rotary compaction-device technique

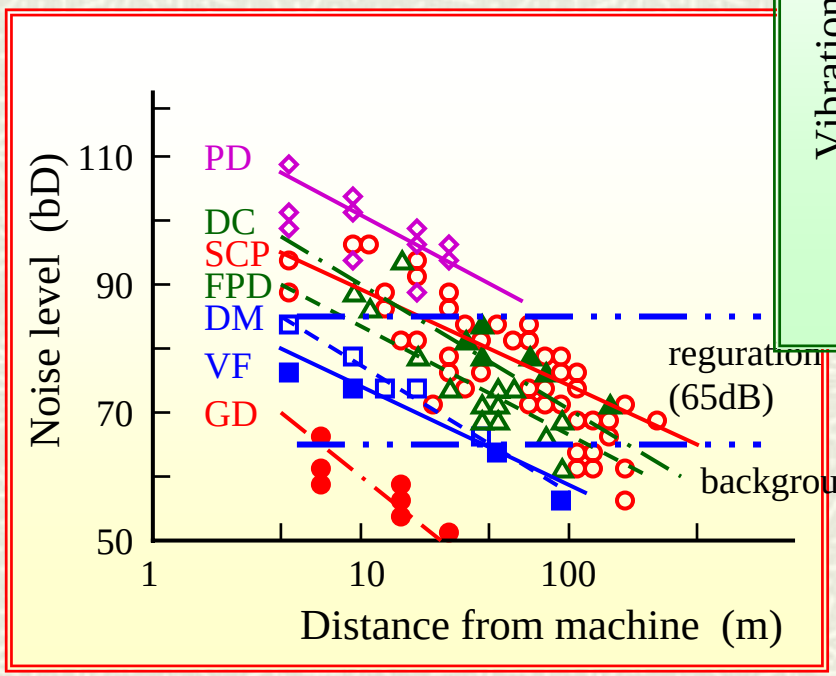


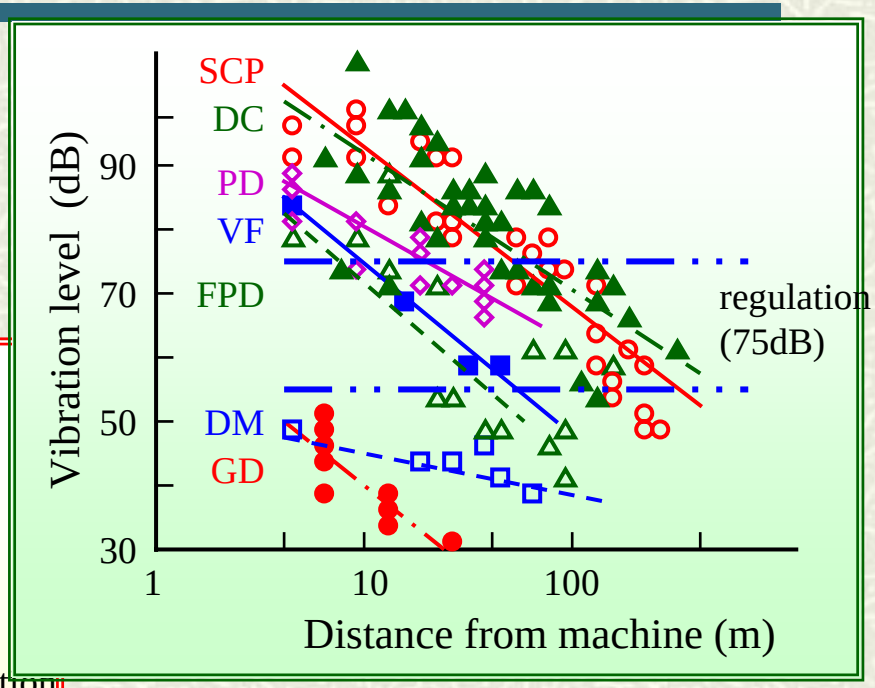




Adverse influence to surrounding

- noise and vibration during execution -

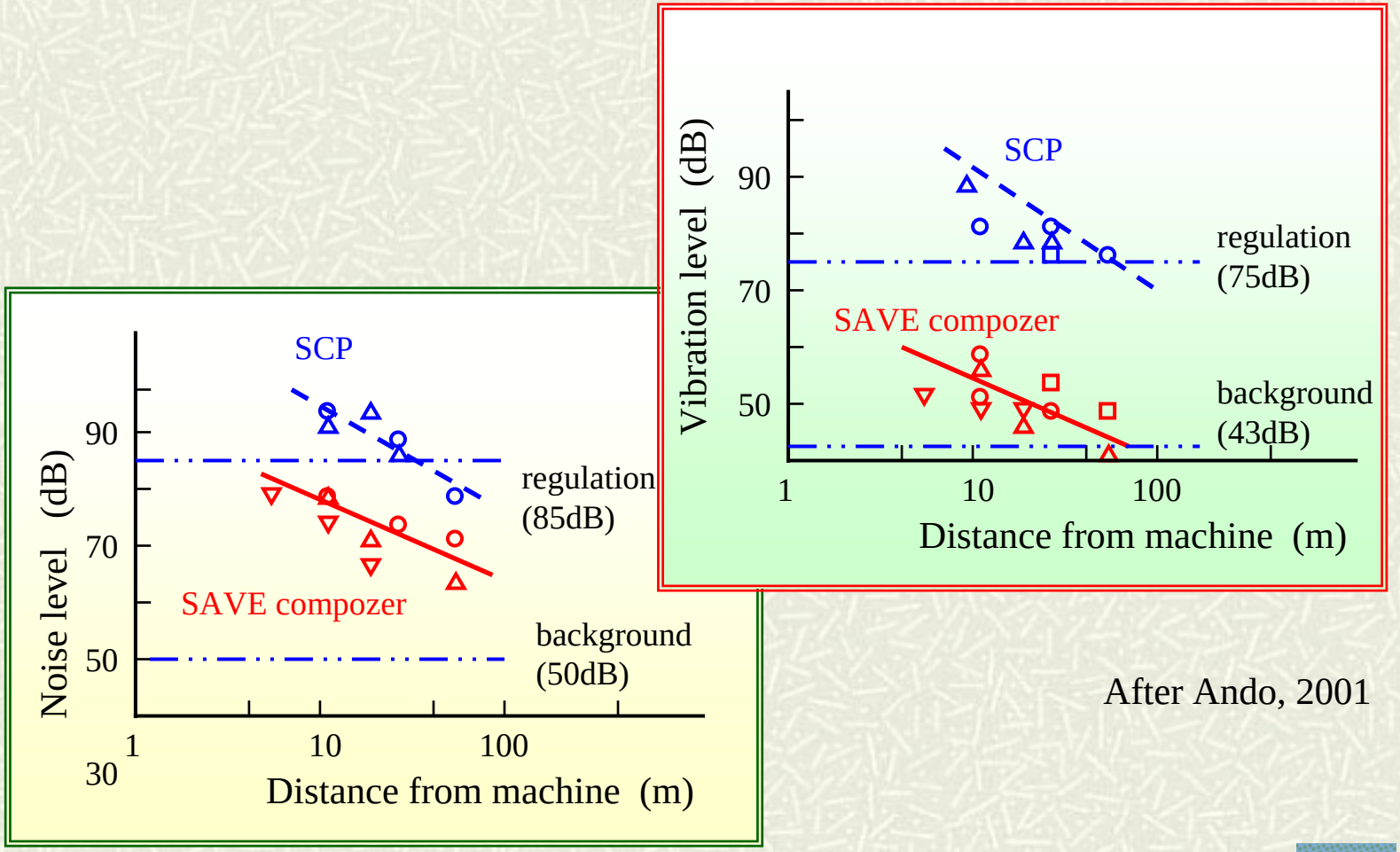




- diesel hammer pile (PD)
- SCP, SD (SCP)
- fabri-pack drain (FPD)
- deep mixing method (DM)
- gravel drain method (GD)
- dynamic consolidation method (DC)
- vibro-floatation method (VF)

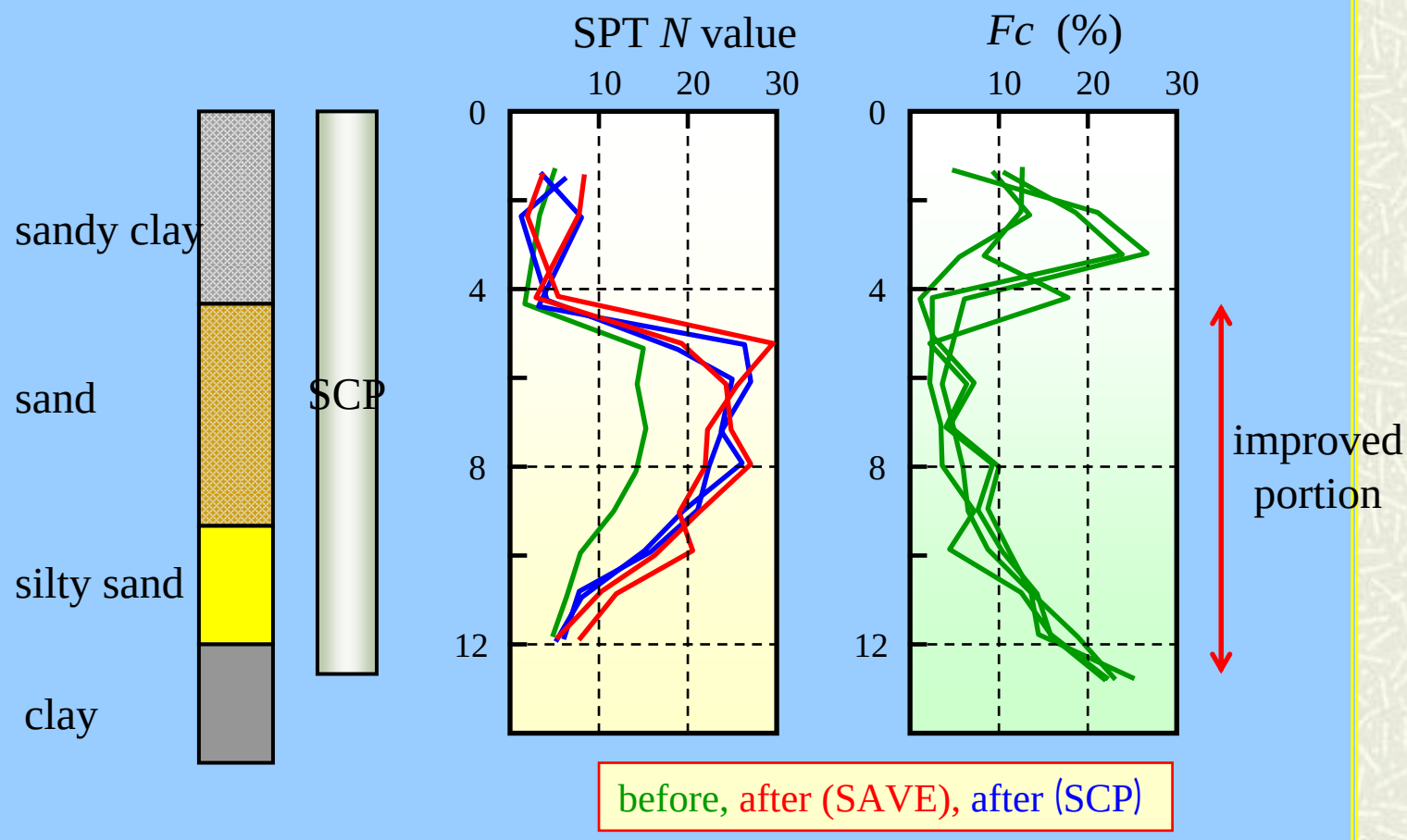
Adverse influence to surrounding

- noise and vibration during execution -



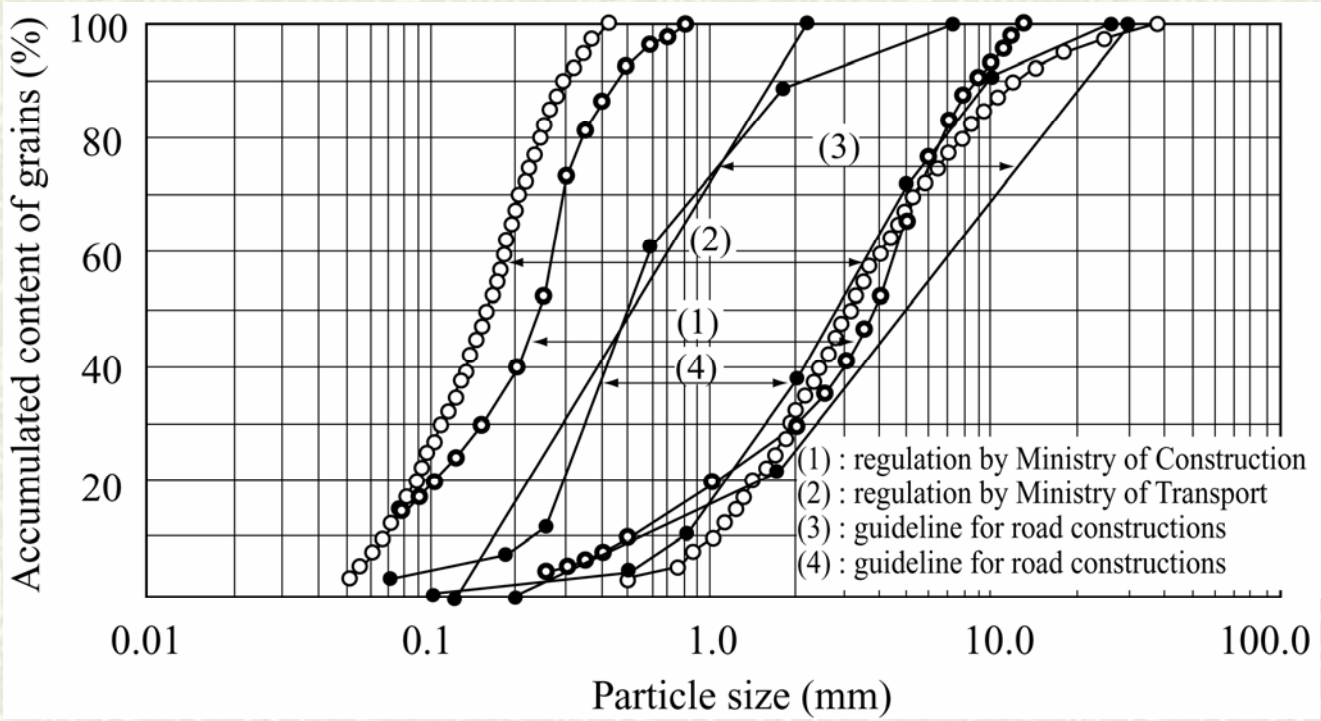
After Ando, 2001

Improvement effect by static compaction technique



after Ando, 2001

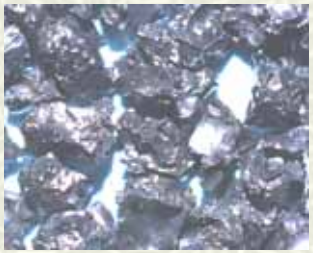
Material development



Soil particle distribution suitable for SCP method

Material development

Material	Applied for
Gravel, crushed sand	Vibrating compaction technique
Crushed concrete	Vibrating compaction technique
Steel slag	Vibrating compaction technique
Copper slag	Vibrating compaction technique
Ferro-nickel slag	Vibrating compaction technique
Oyster shell	Vibrating compaction technique
Blast furnace slag	Static compaction technique
Subsoil material	Static compaction technique
Mixture of slag, lime and aluminum	Static compaction technique
Granular material	Static compaction technique
Asphalt and concrete	Static compaction technique

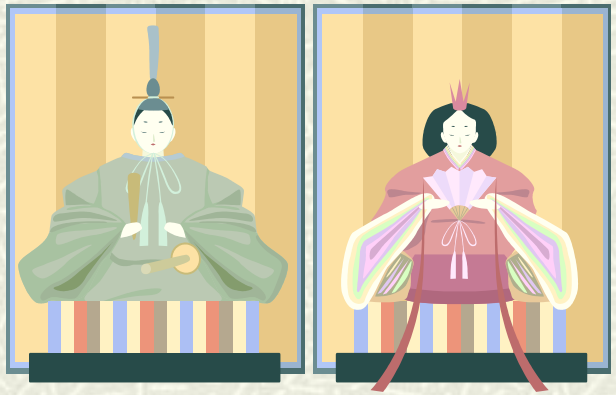


copper slug

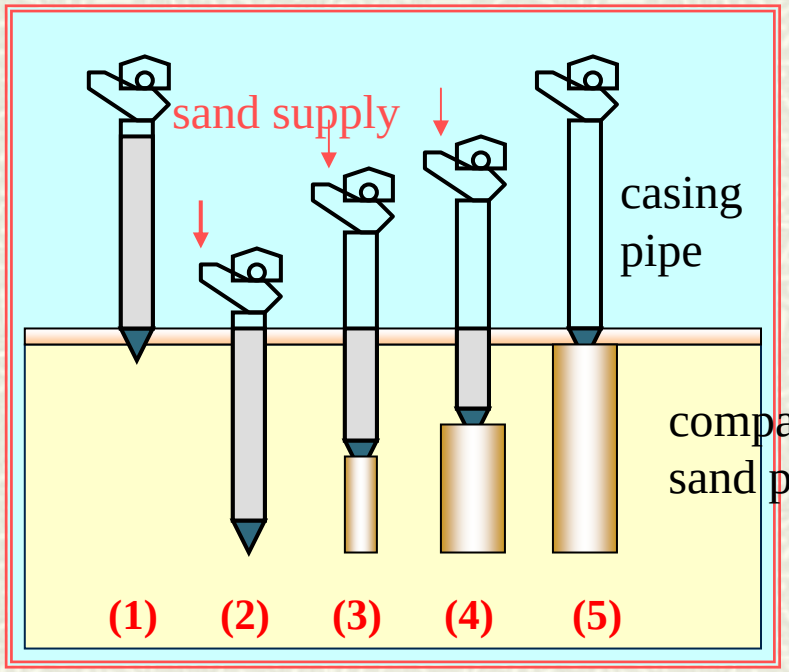
cement treated fly ash

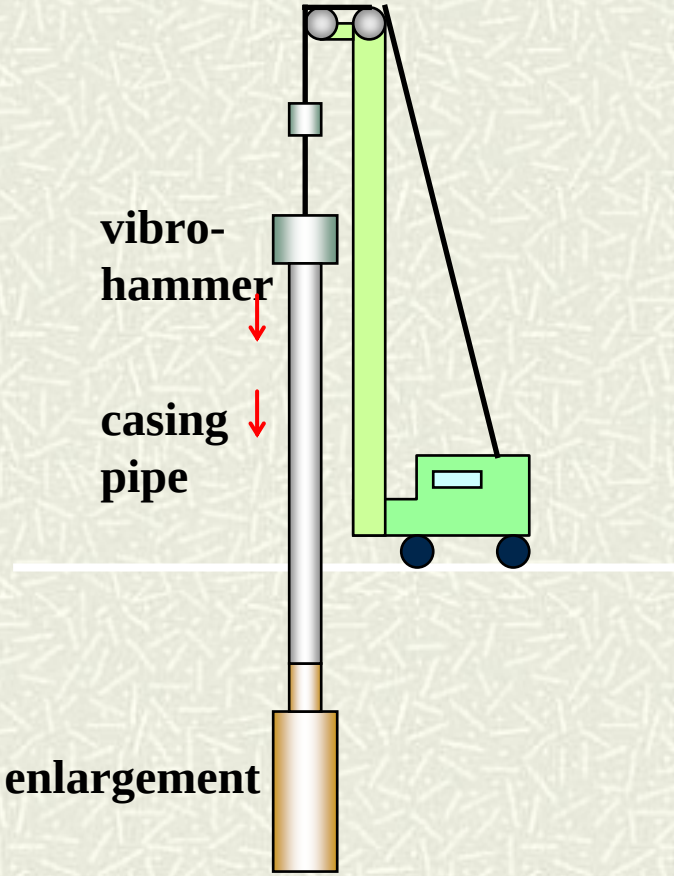
crushed oyster shell

3. Execution, quality control and assurance

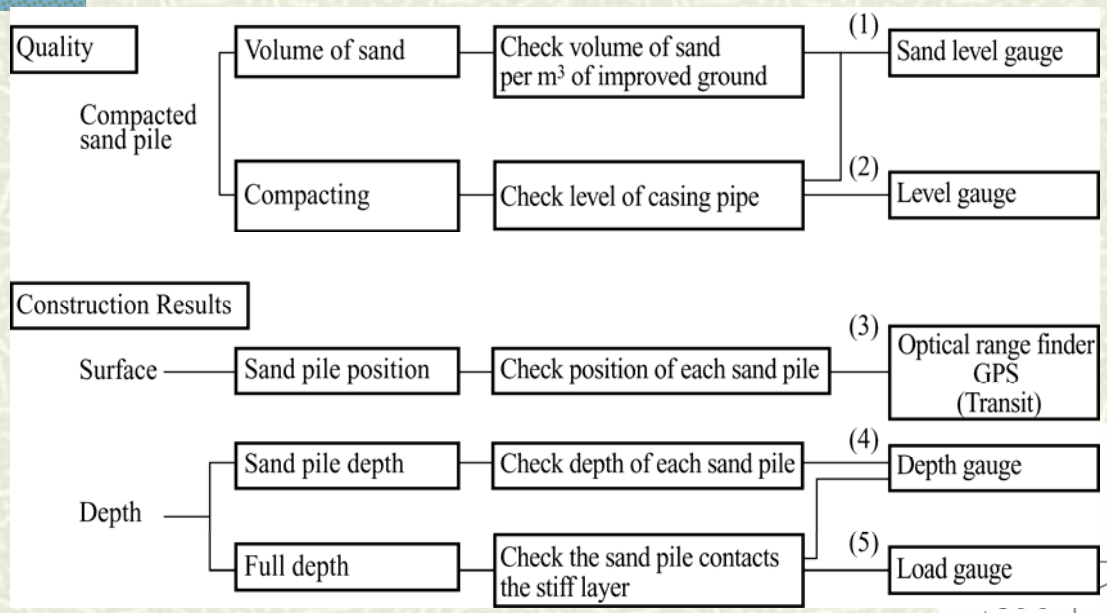


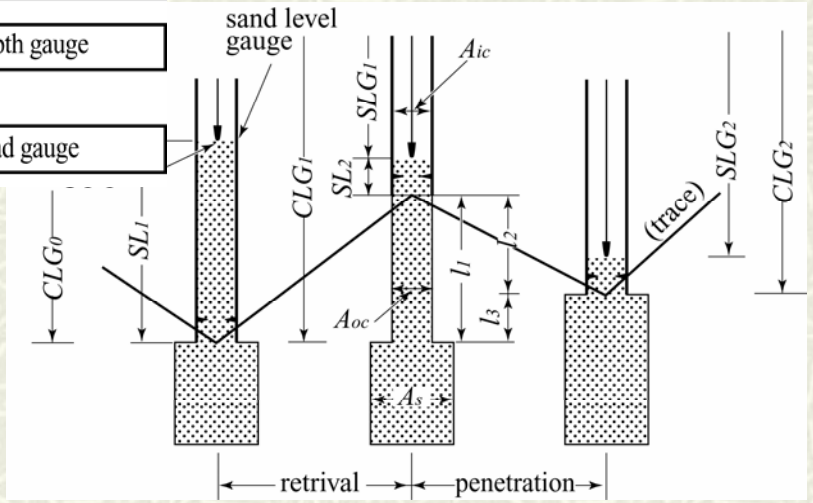
Execution, Quality control and assurance





Quality control during execution



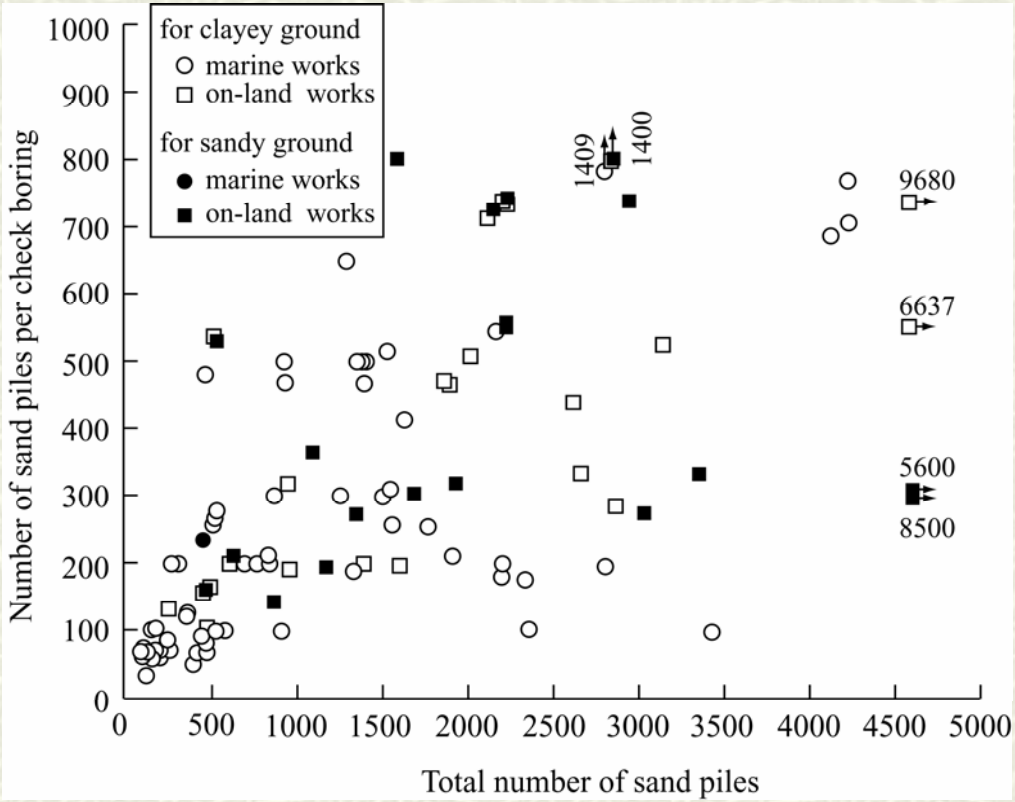


Quality assurance
- Standard Penetration Test -

Internal friction angle of sand piles

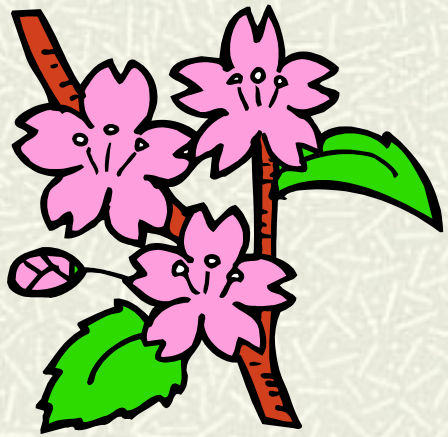
$$\phi = \sqrt{12 \cdot N} + 15$$

SPT *N* value	friction angle
10	25
15	28
20	30

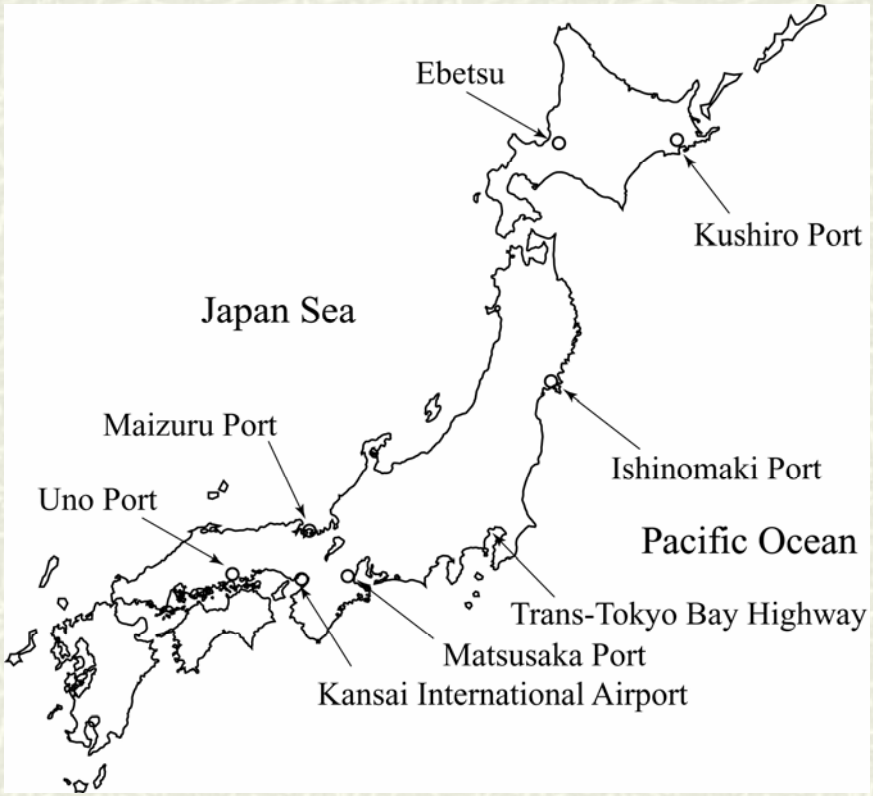


frequency of SP Test

4. Case histories



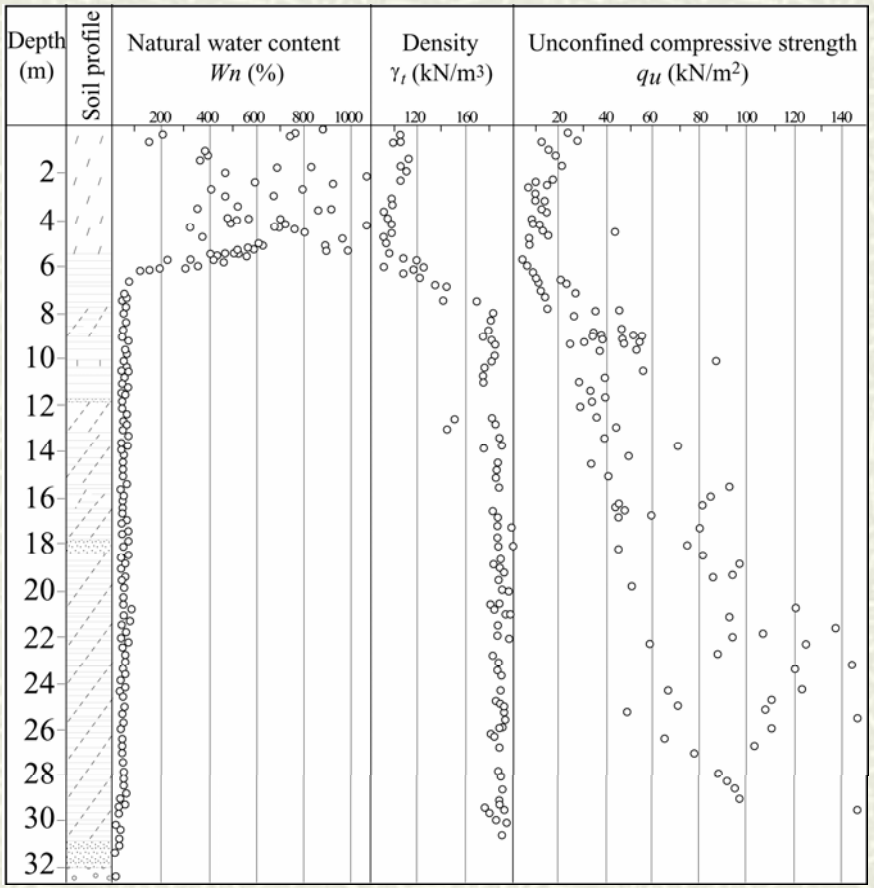
Case histories

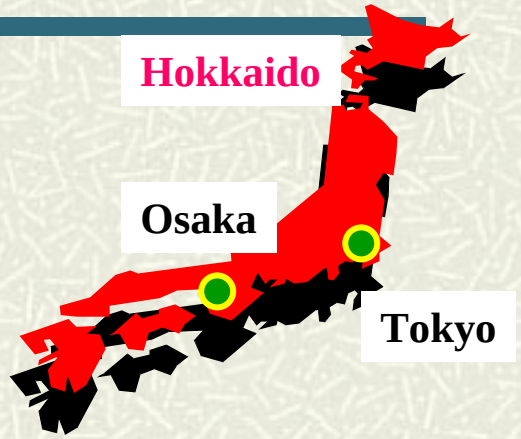


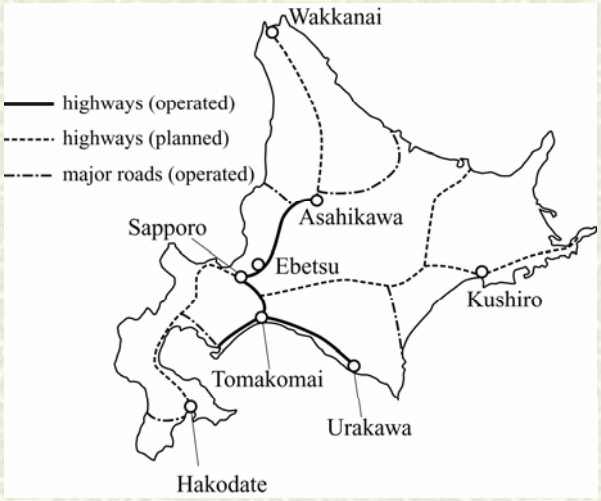
to clay ground
- Hokkaido highway, Ebetsu
- Maizuru Port
- Trans-Tokyo Bay Highway
- Kaisai International Airport
- Uno Port

to sand ground
- Kushiro Port
- Miyagi, Hokkaido
- Matsusaka Port

Hokkaido Highway project at Ebetsu

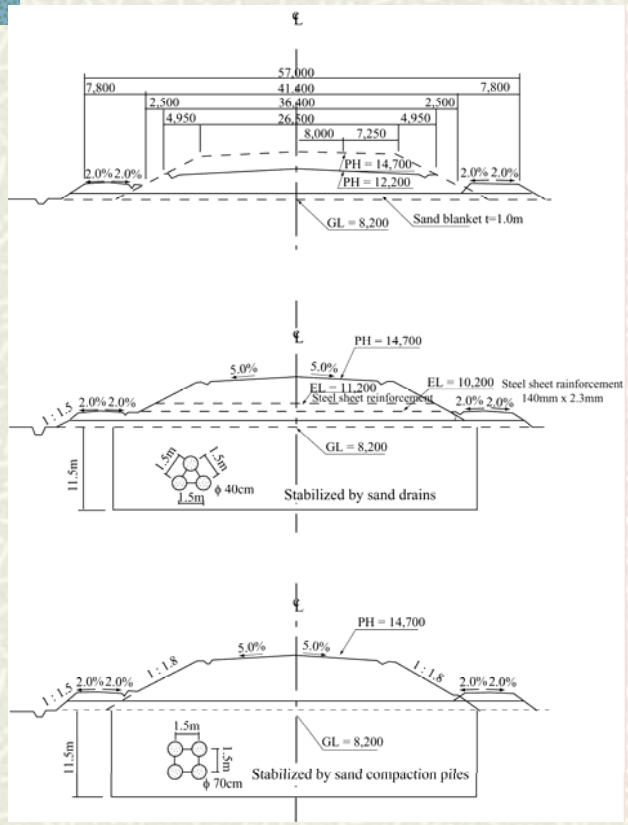


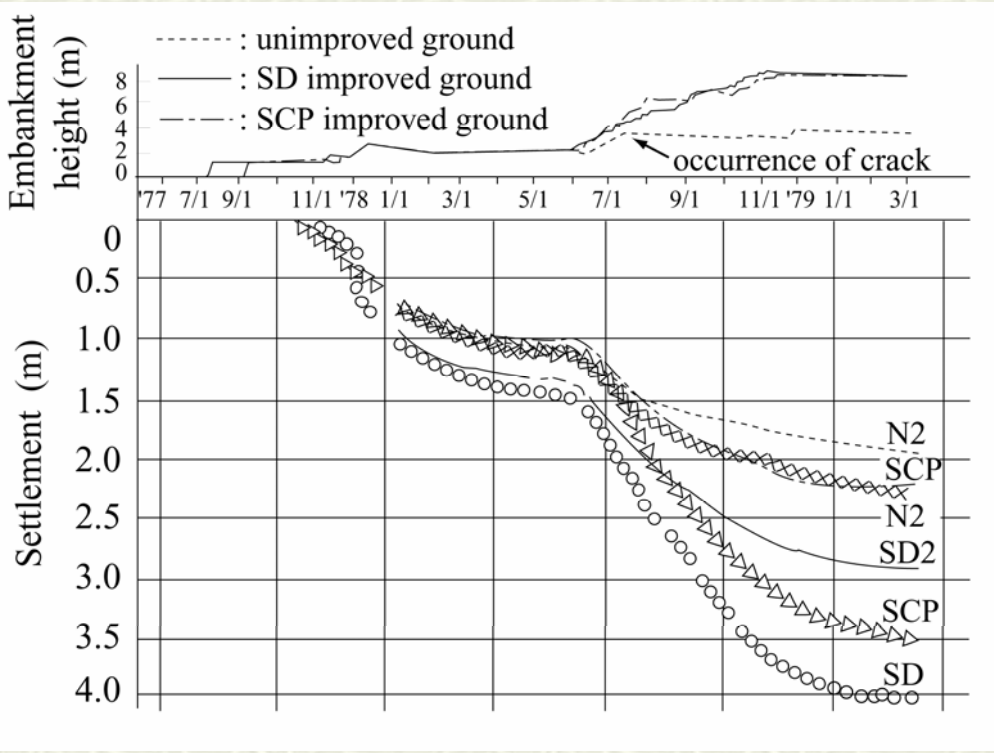




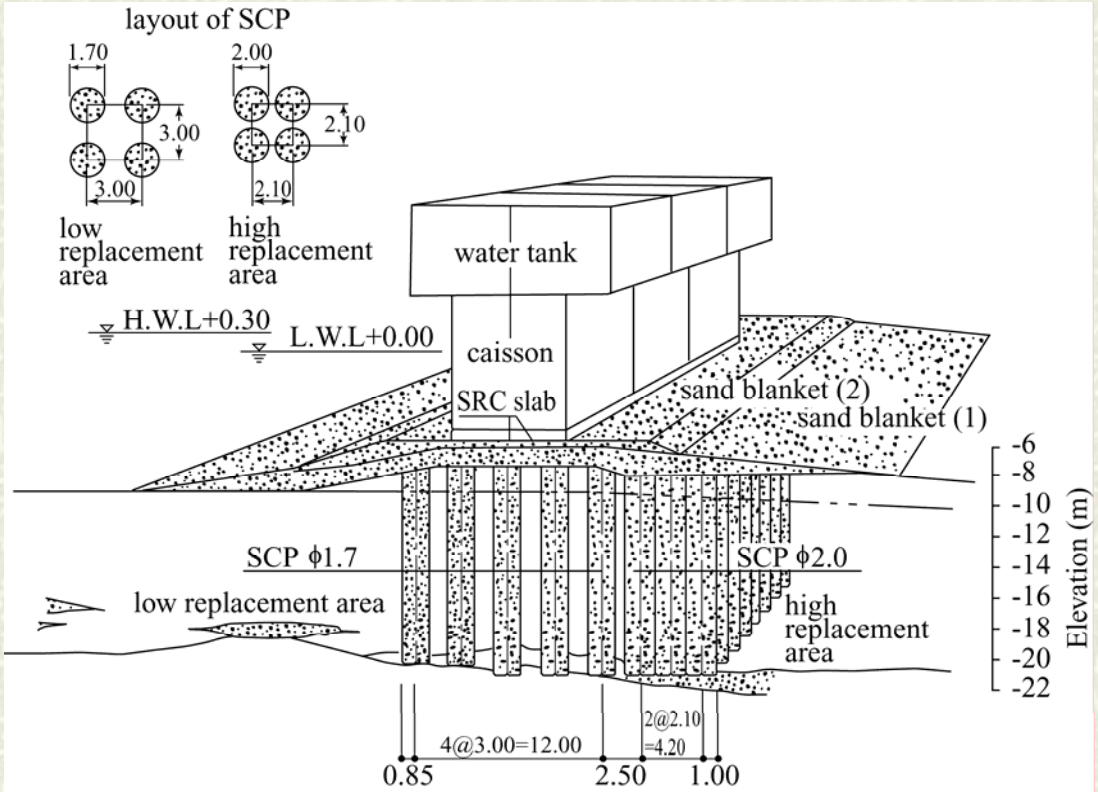
The Hokkaido Highway project

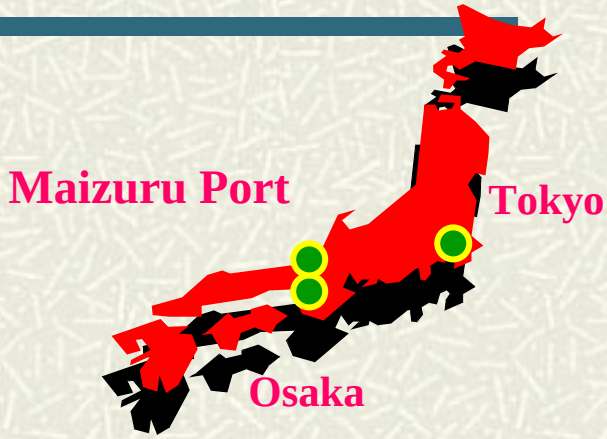
- comparison of improvement -



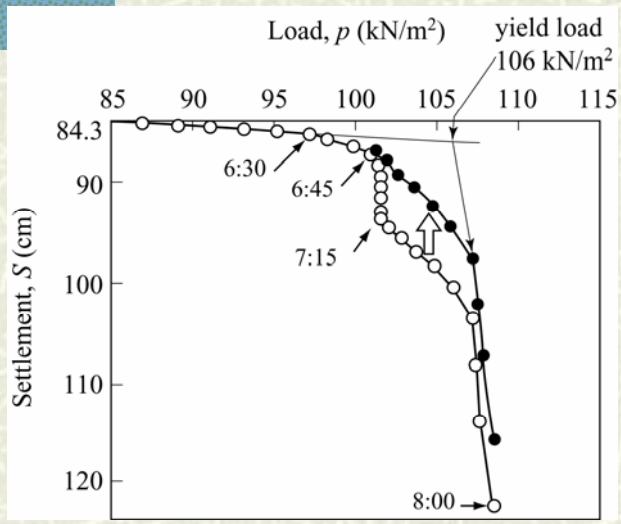


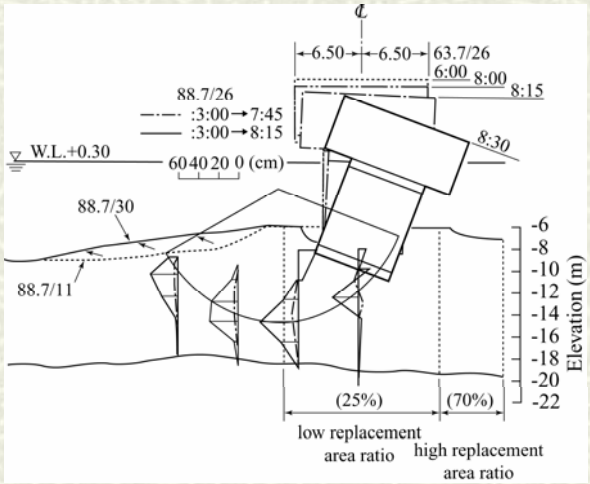
Maizuru port
- field loading tests -





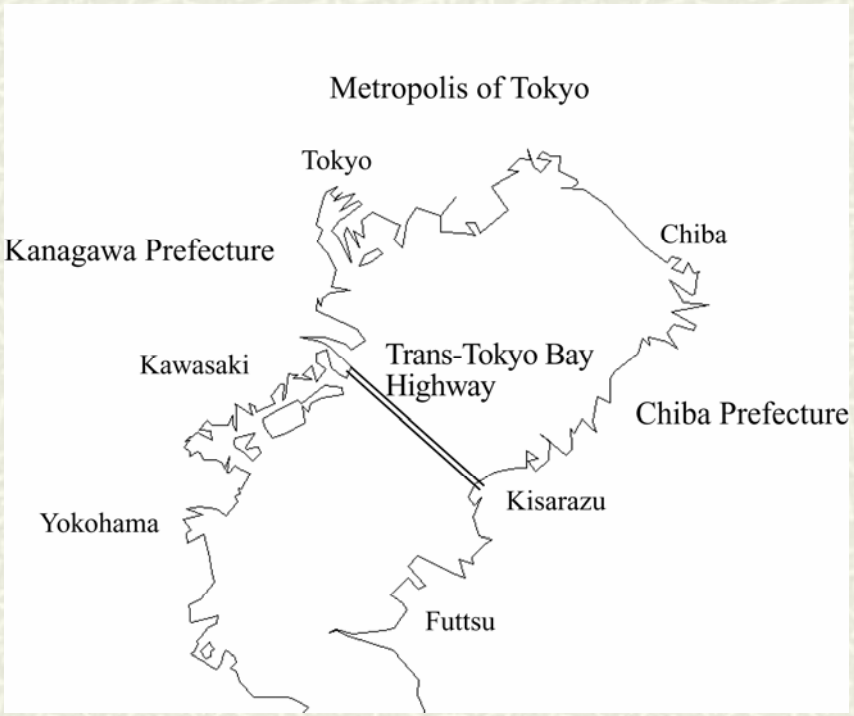
test results

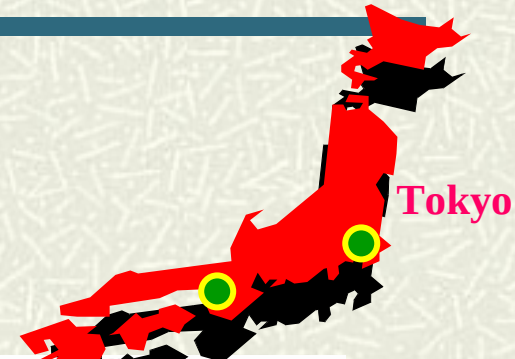


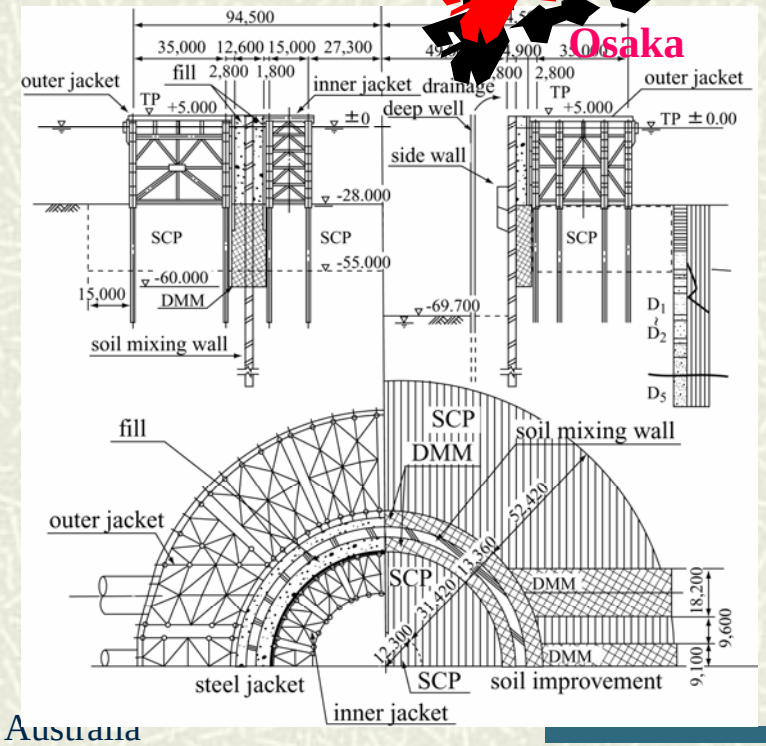


Trans-Tokyo Bay Highway

- horizontal resistance -





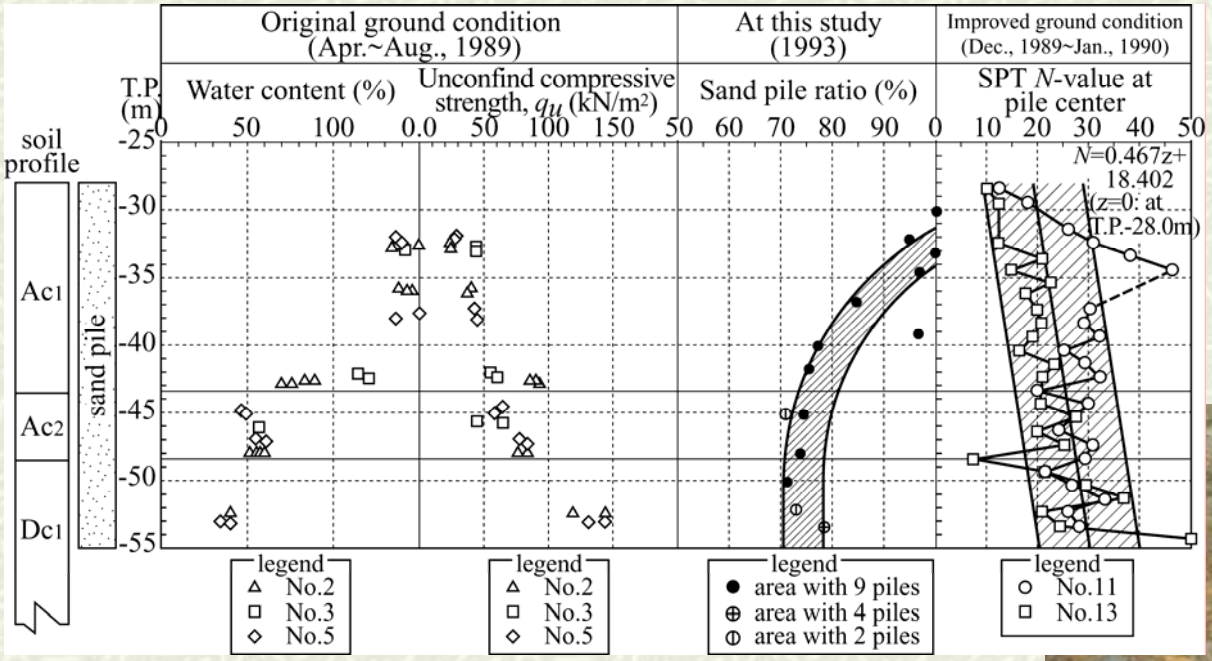


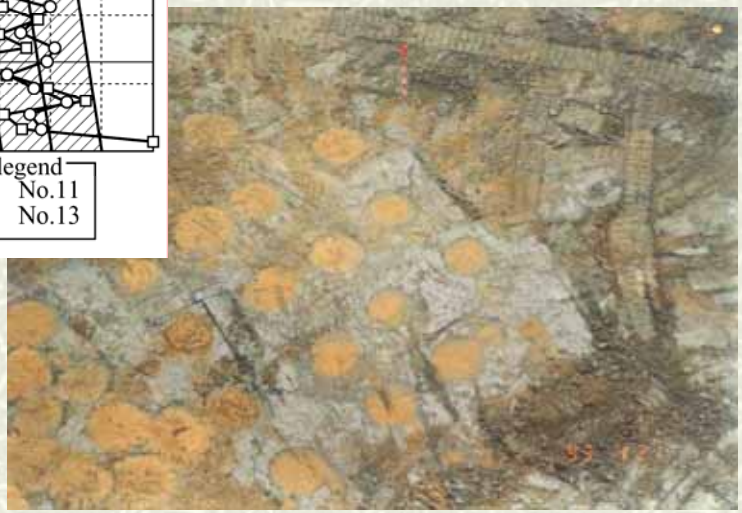
Trans-Tokyo Bay Highway

- execution -

Trans-Tokyo Bay Highway

- sand piles after 4 years -

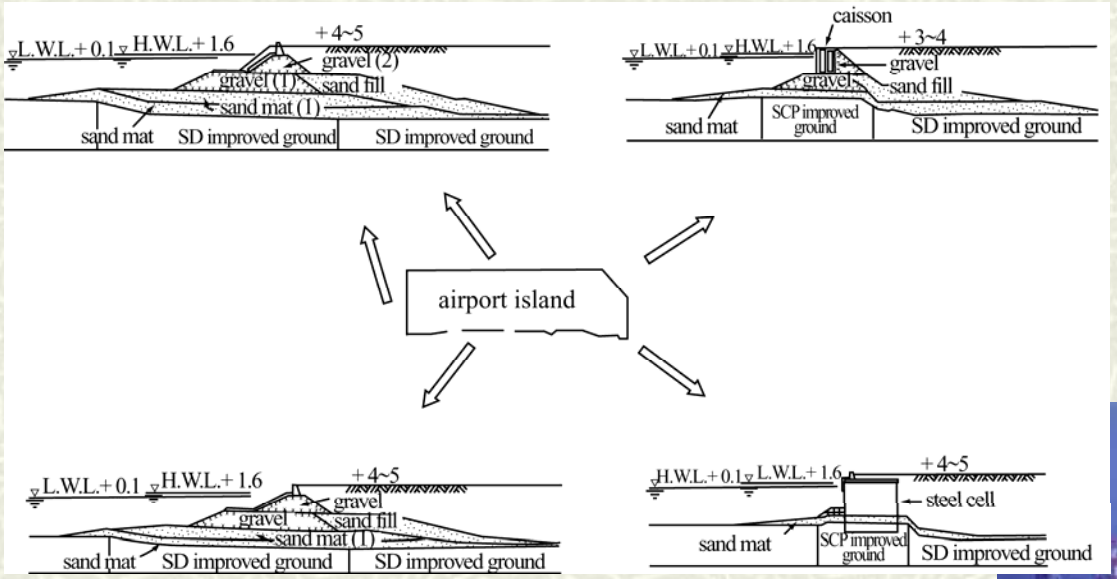


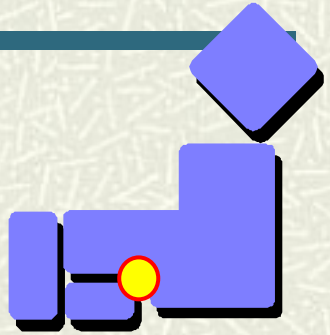


no clay particle squeezed
into the sand piles

a_s=30.1%

Kansai International Airport

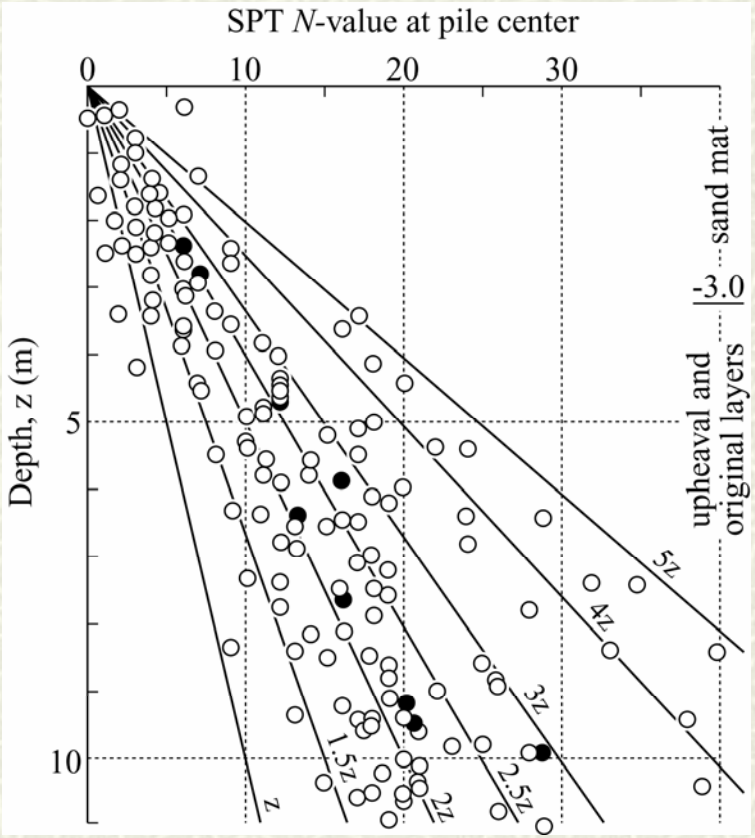




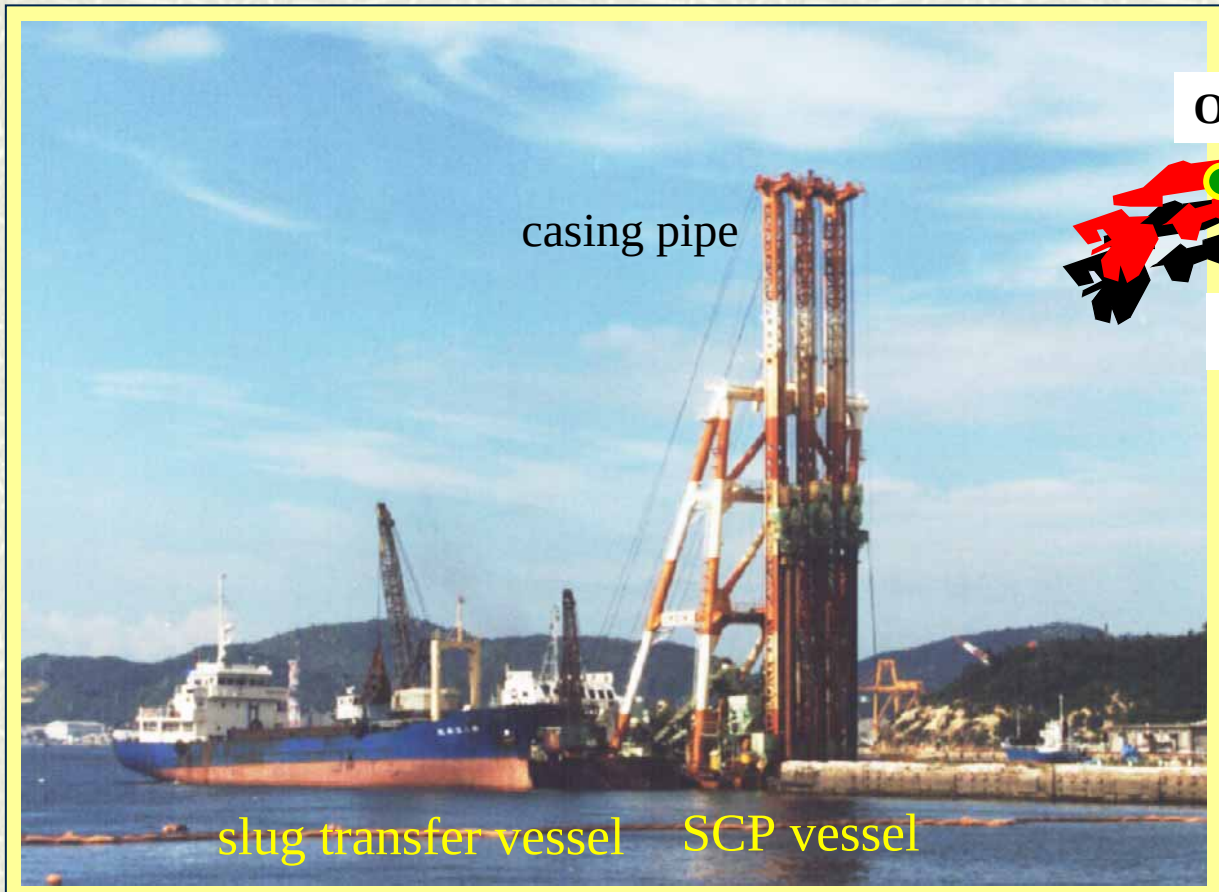
Osaka

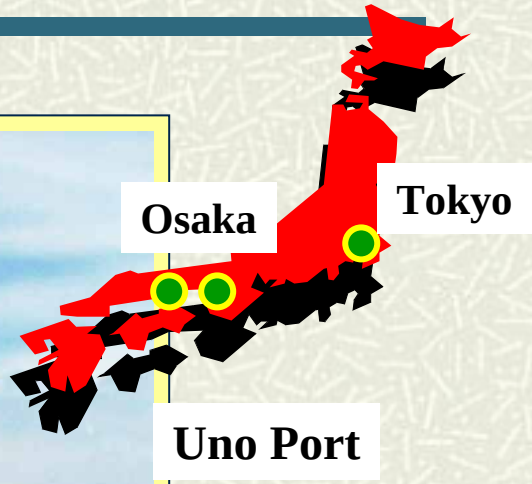
Kansai International Airport

- SPT *N* value -



Copper slug as SCP material
- Uno Port -

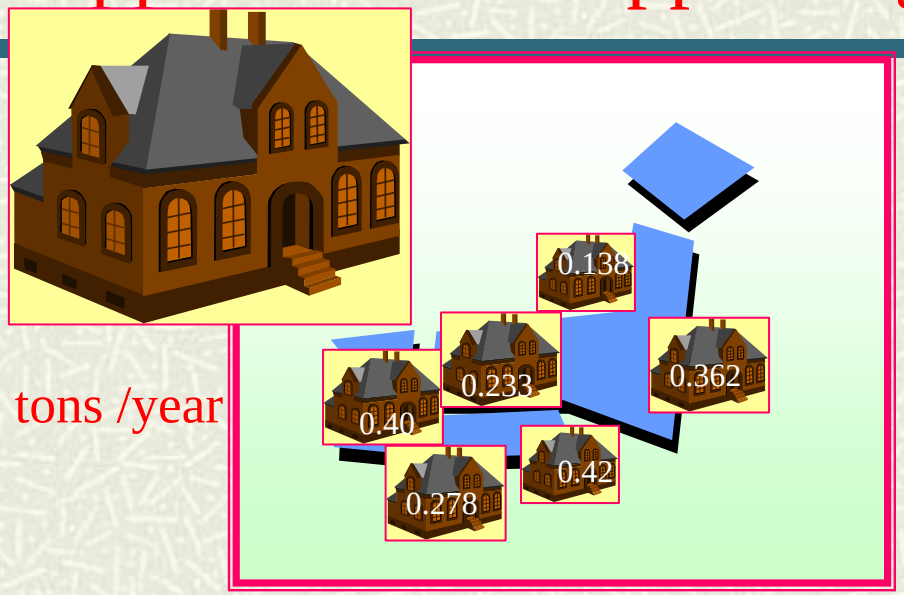




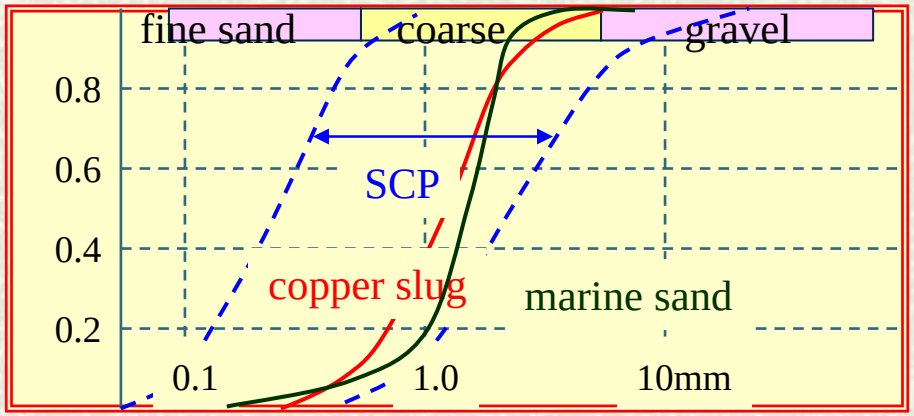
Kitazume, et al., 1998

Uno Port

- application of copper slag -

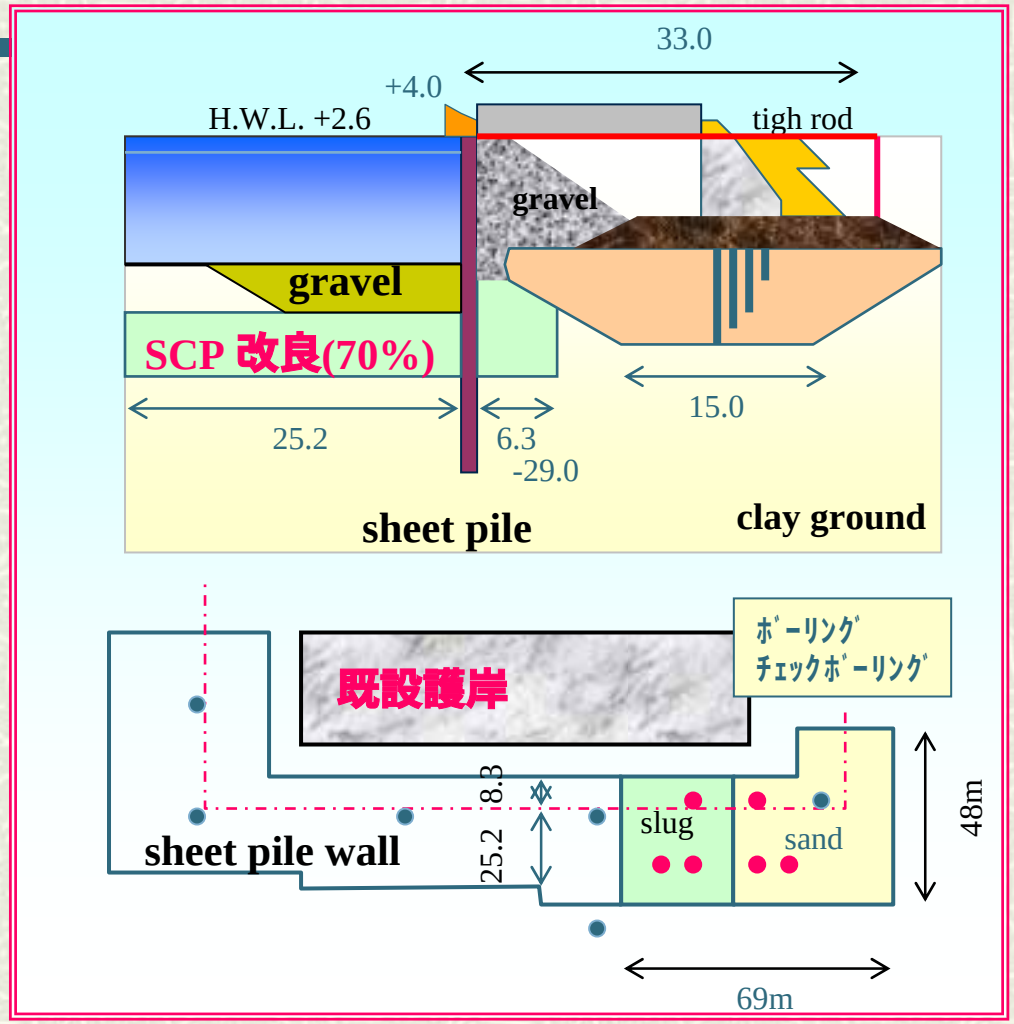


1.8 mil. tons /year



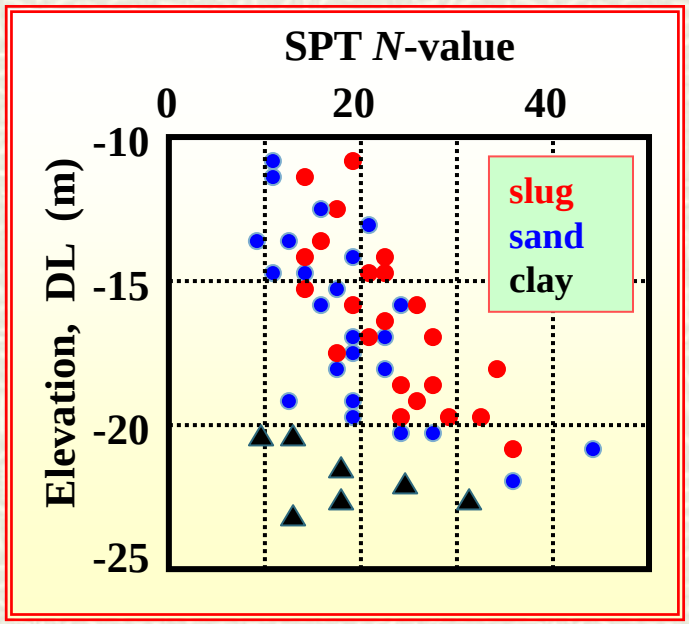
Kitazume, et al., 1998

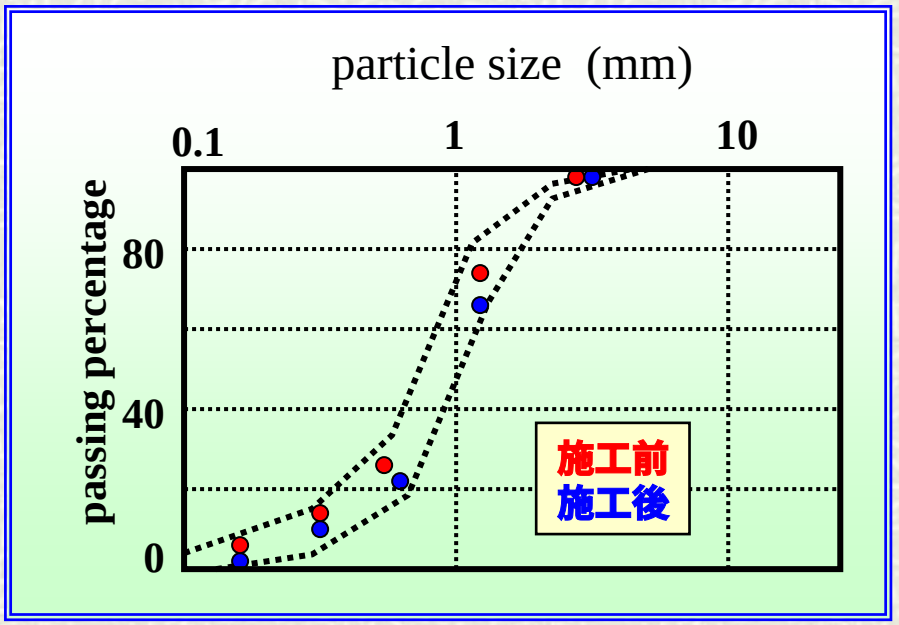
field condition



Copper slug as SCP material

- test data -





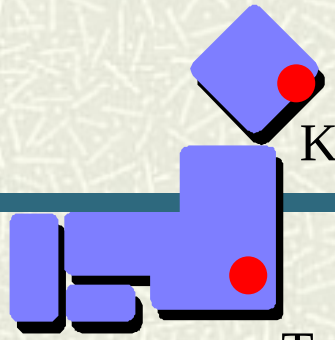
SPT *N* value of slug increases with depth, similar to marine sand

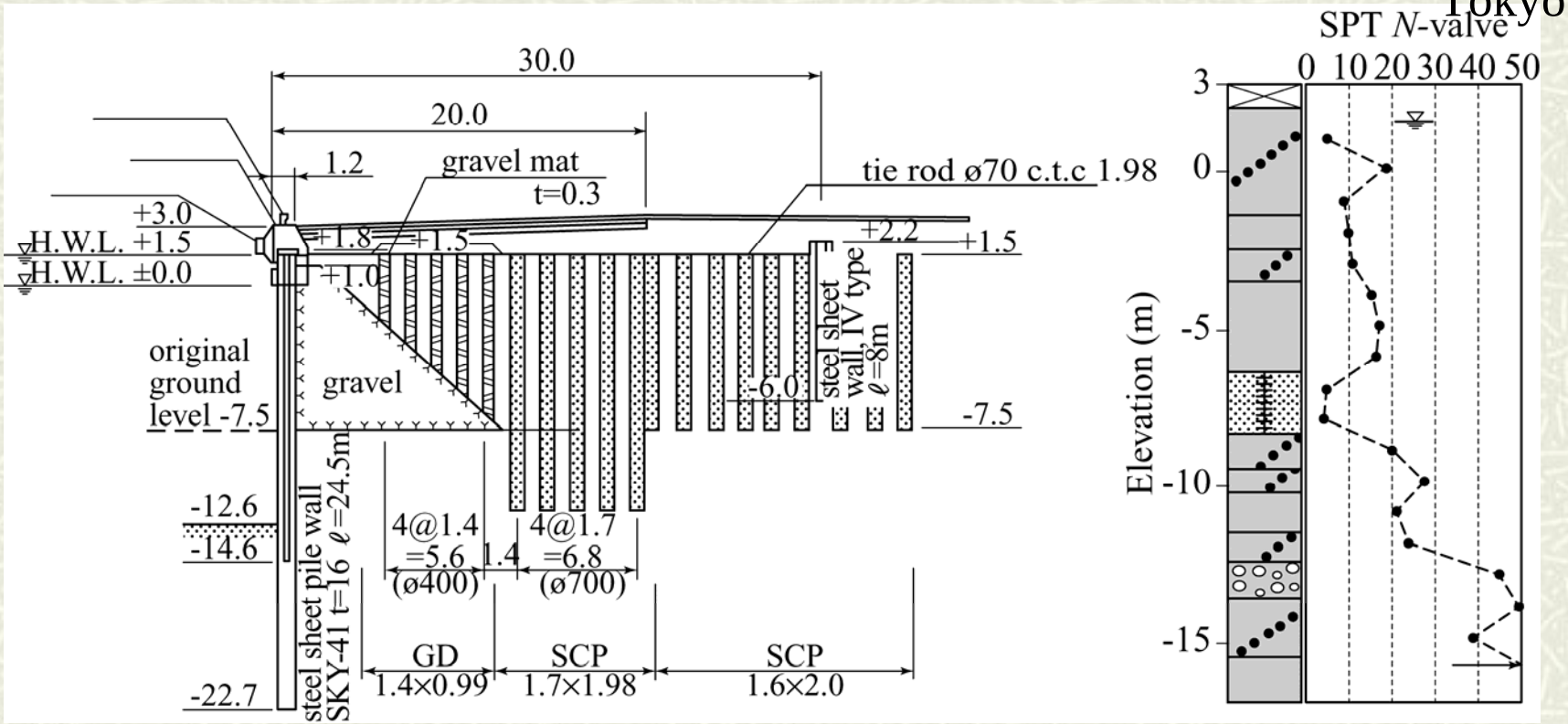
Some of slug particles are crushed due to installation, no influence to strength and permeability.

Kitazume, et al., 1998

liquefaction prevention

- Kushiro Port -

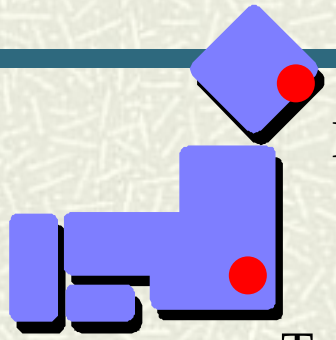




liquefaction prevention

- Kushi oki earthquake in 1993 -

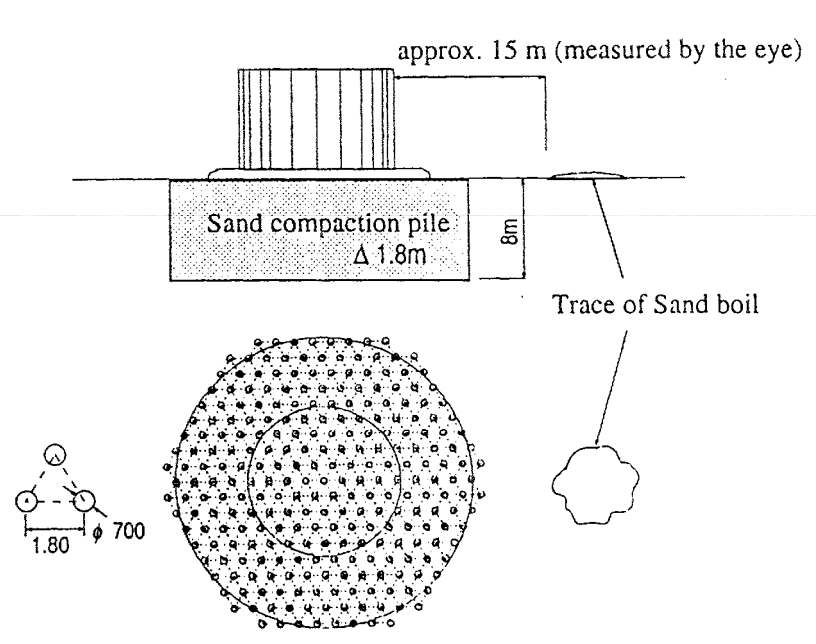
unimproved area

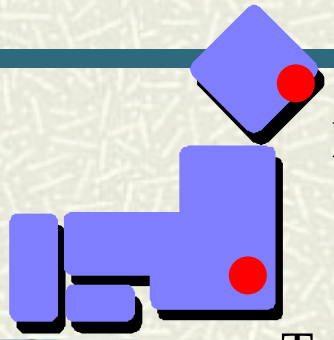


improved area

liquefaction prevention

- Kushi oki earthquake in 1993 -

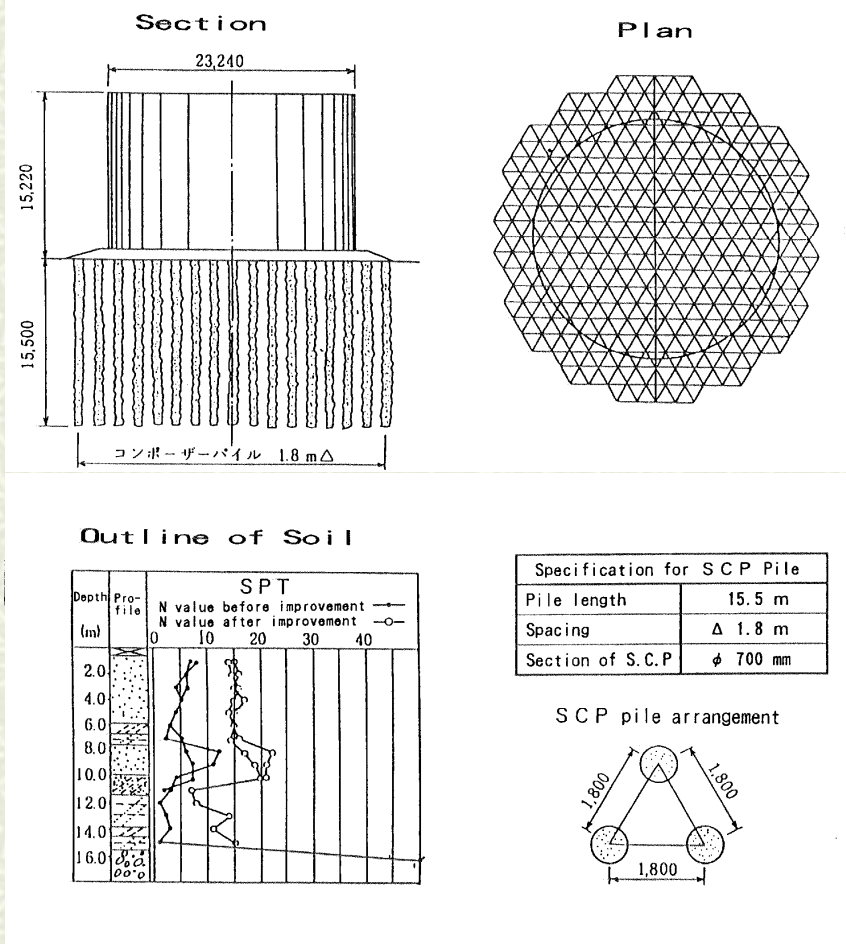


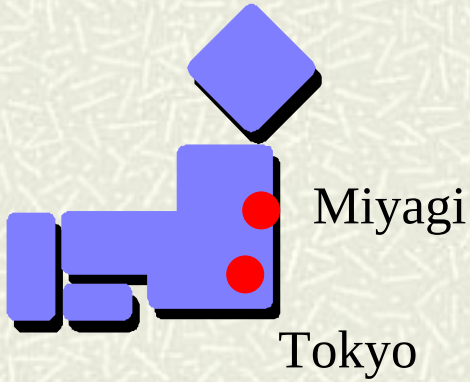


Kushiro

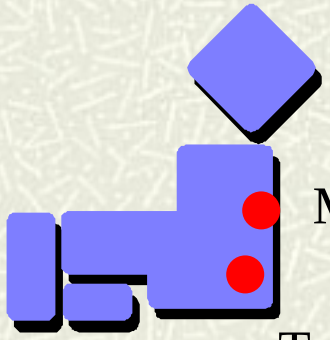
Tokyo

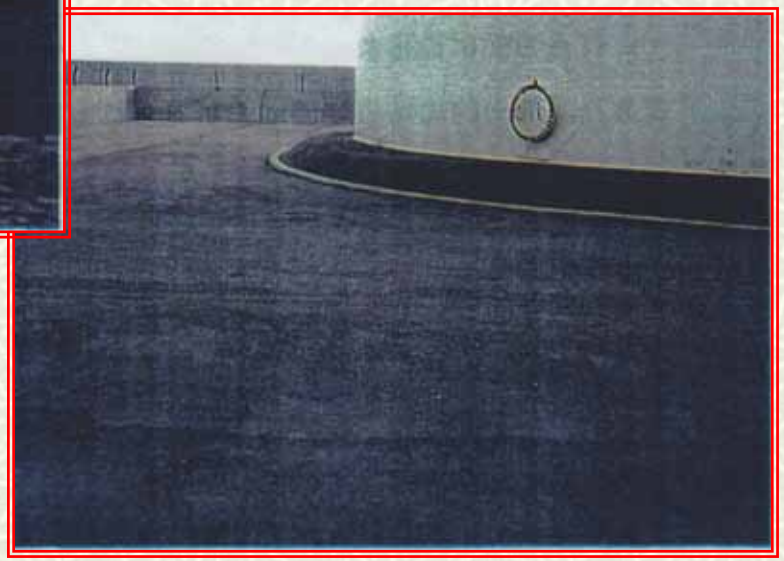
Miyagi-ken-Oki Earthquake
- January 1978, M=7.4 -





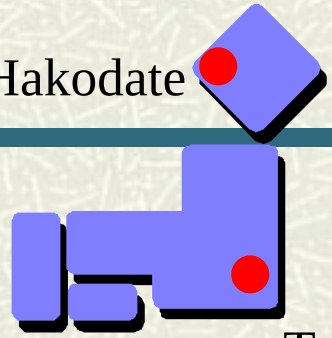
Miyagi-ken-Oki Earthquake
- January 1978, M=7.4 -

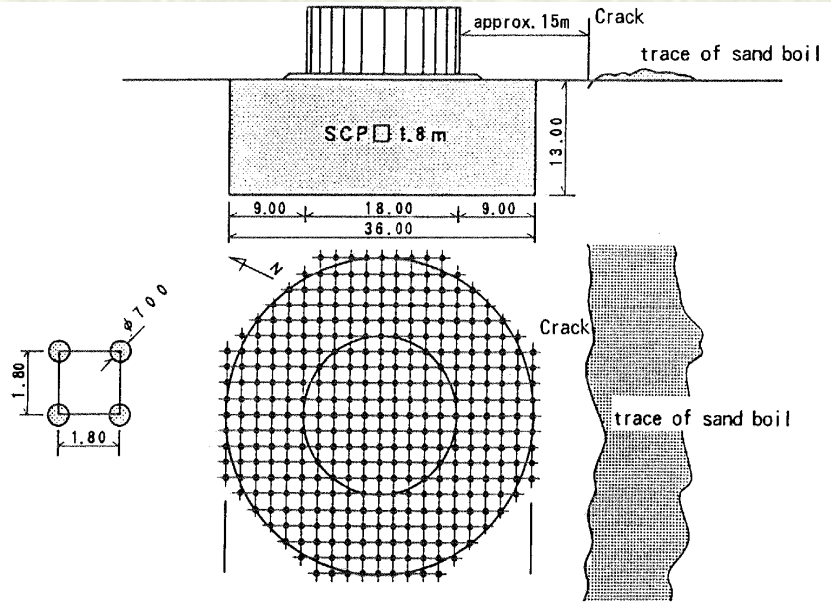




Hokkaido Nansei Oki Earthquake

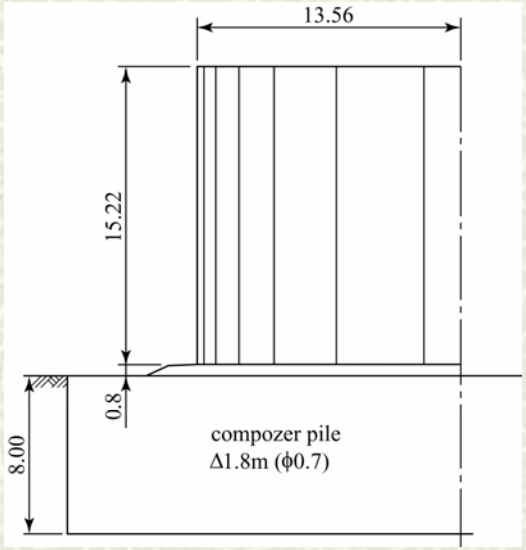
- January 1993, M=7.8 -

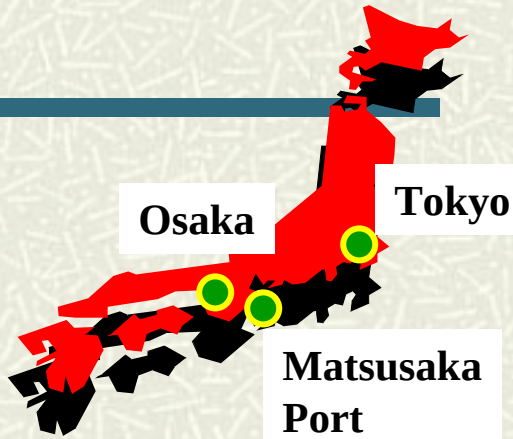


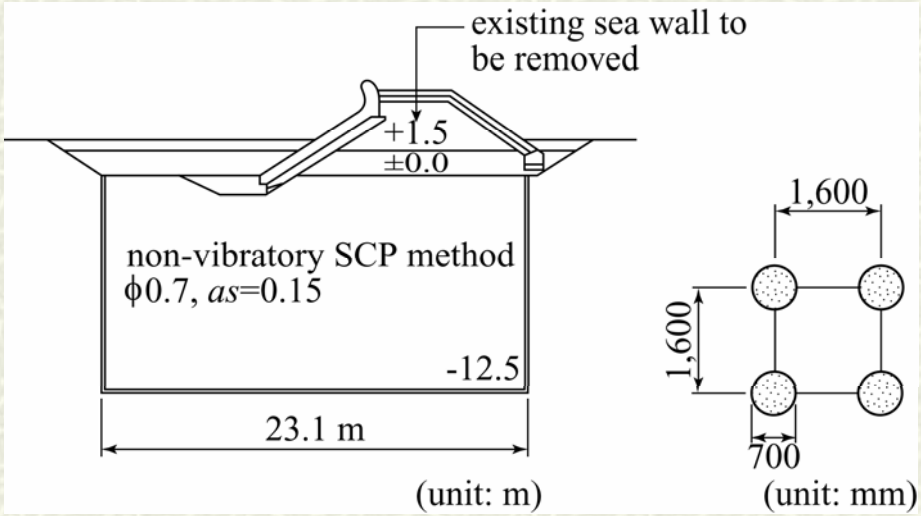


static compaction technique

- Matsusaka Port -

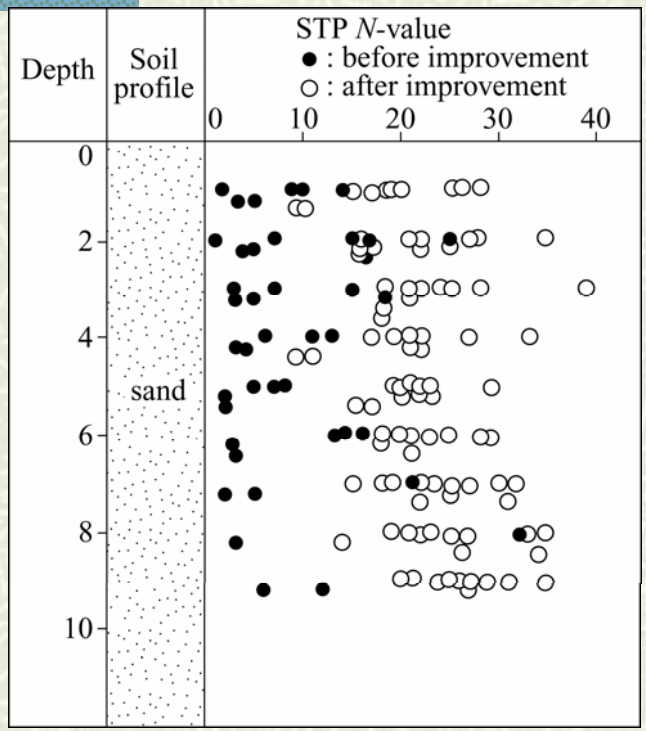


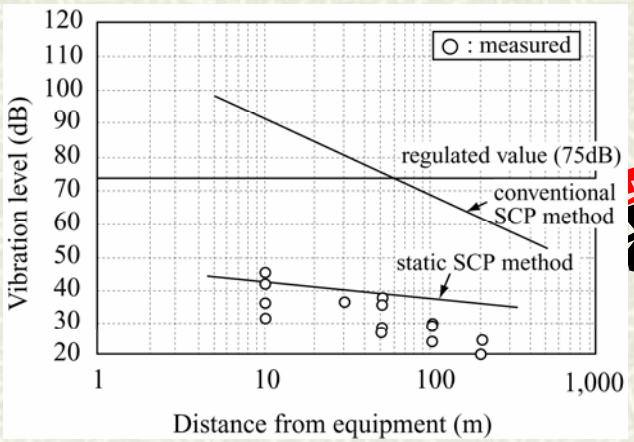


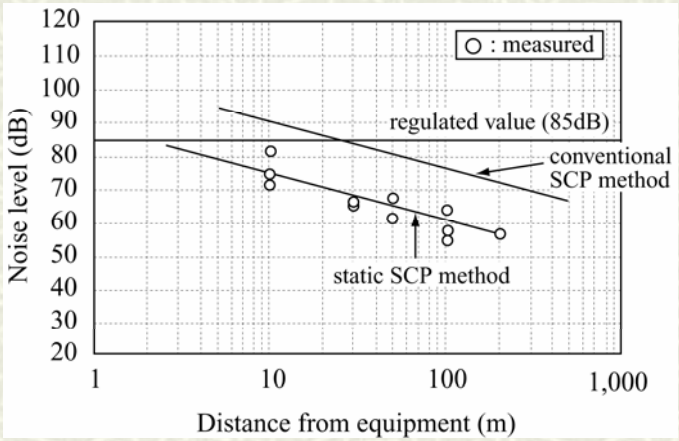


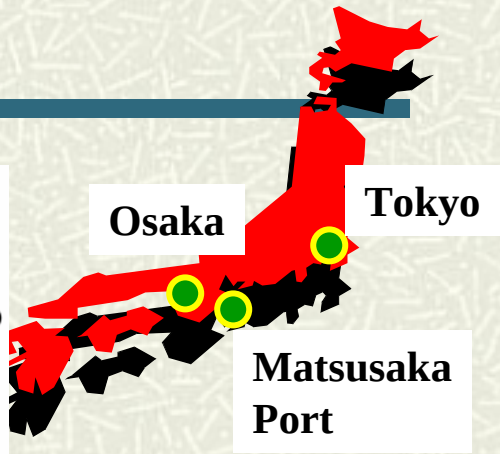
static compaction technique

- Matsusaka Port -



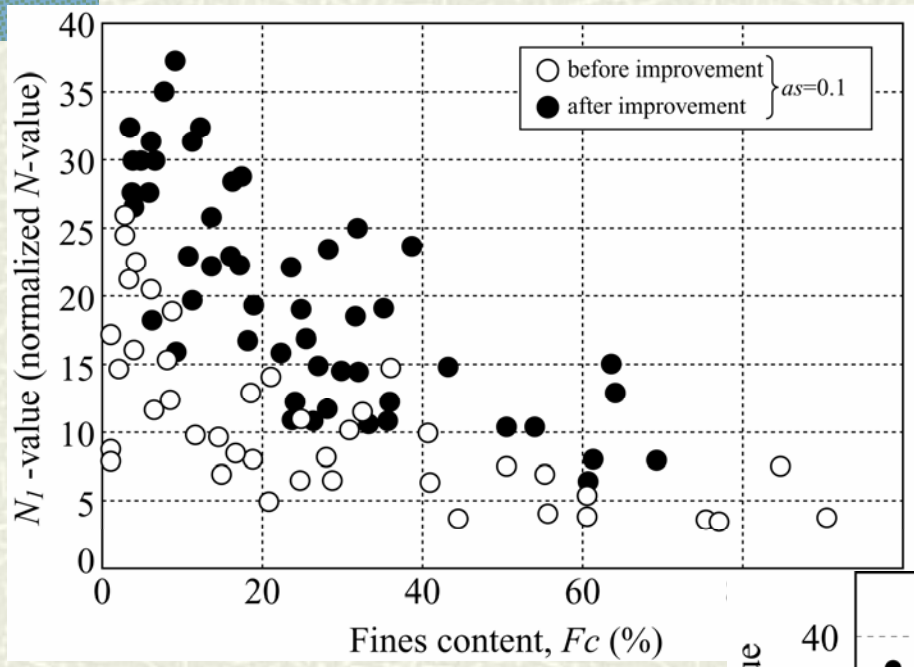


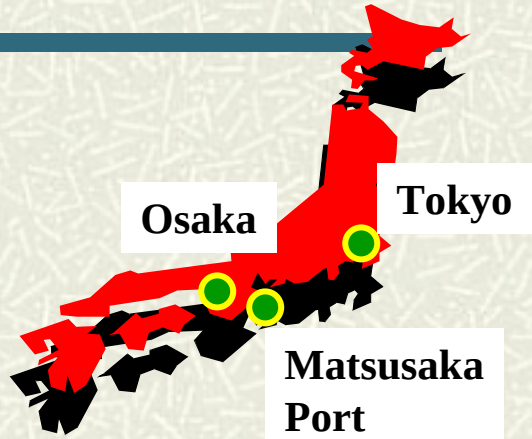


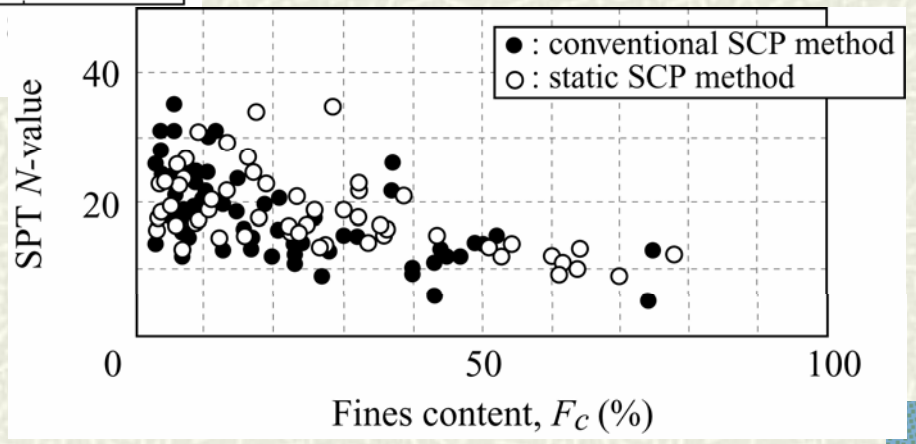


static compaction technique

- Matsusaka Port -

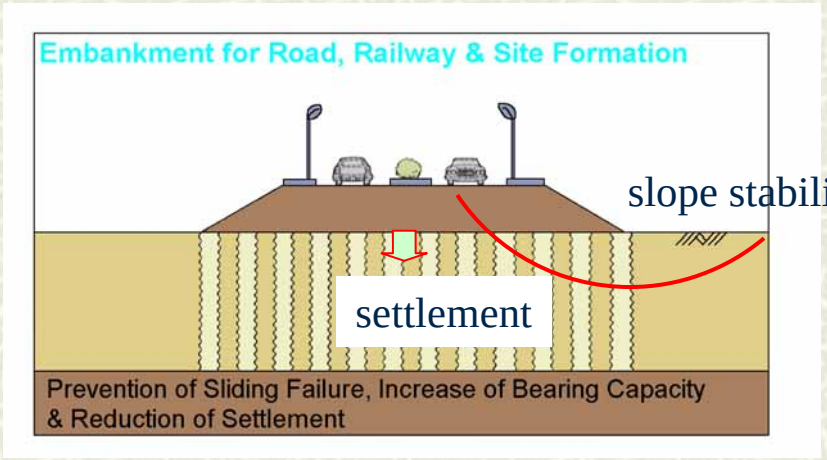






5. Design procedure for clay ground

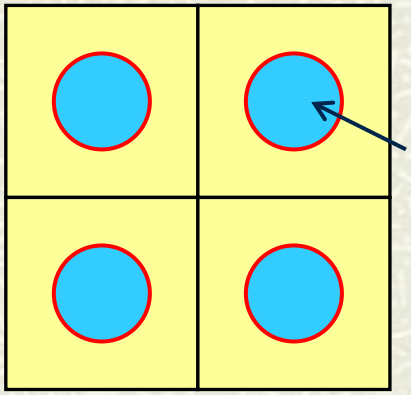
Design procedure for clay ground



basic concepts

improvement area ratio

a_s = sand pile / covered area



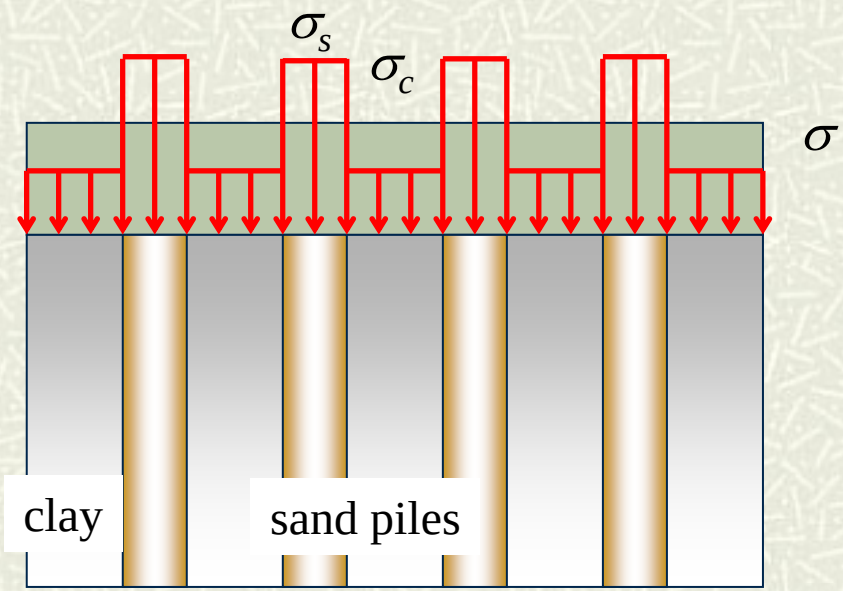
stress concentration ratio

$n = \sigma_s/\sigma_c$

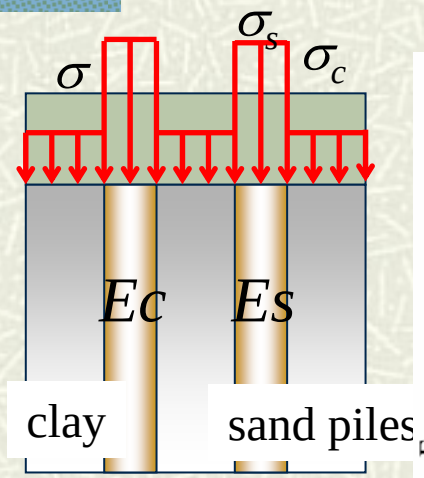
stress concentration coefficient

$\mu_c = \sigma_c/\sigma = 1/(1+(n-1)a_s)$

$\mu_s = \sigma_s/\sigma = n/(1+(n-1)a_s)$



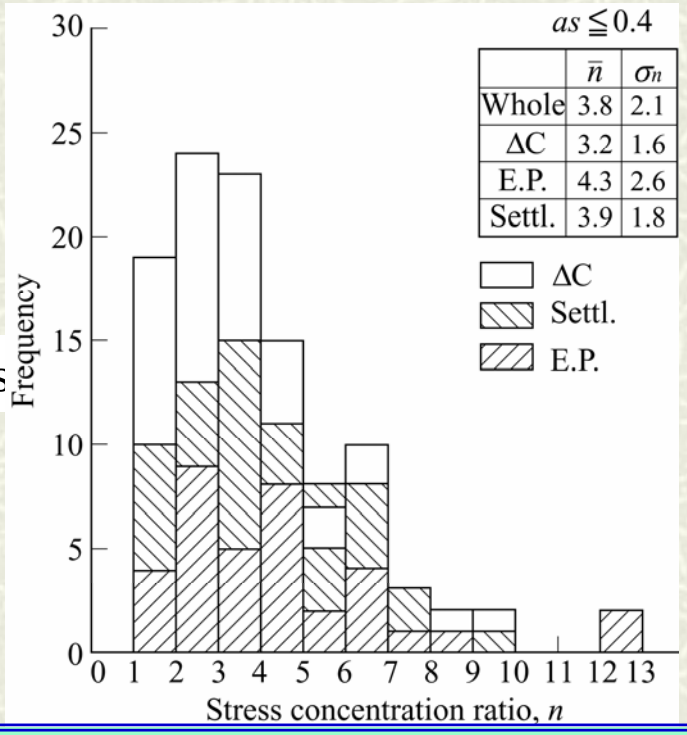
Stress concentration ratio

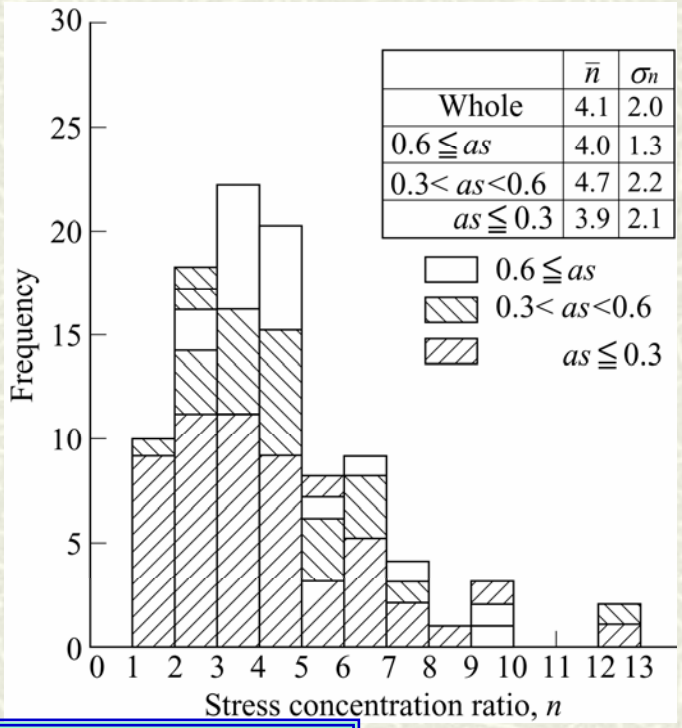


definition

$n = \sigma_s/\sigma_c$

$= Es/Ec$





The *n* value measured or estimated in the field is dependent upon type, and improved area ratio.

Bearing capacity of isolated sand pile

vertical stress

$$P = \sigma \cdot A$$
$$= \sigma_s \cdot A_s + \sigma_c \cdot A_c$$
$$= \sigma_c (A_s \cdot n + A_c)$$

horizontal stress equiblium

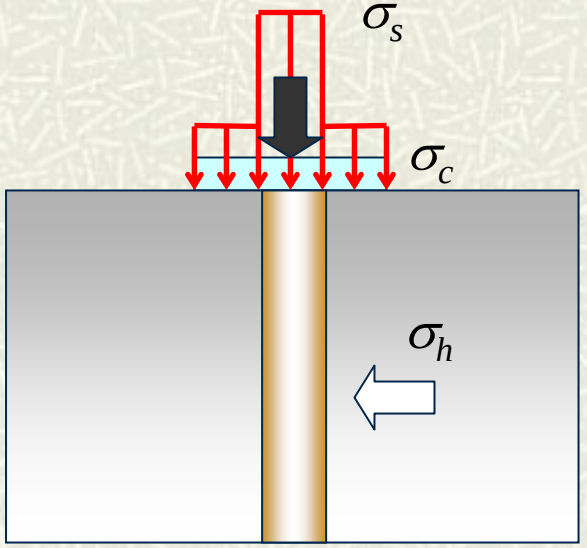
$$\sigma_h \geq \frac{1-\sin\phi_s}{1+\sin\phi_s} \cdot \sigma_s$$

$$\sigma_h \leq \sigma_c + \sigma_u$$

bearing capacity

$$P = \sigma_u \cdot \frac{1+\sin\phi_s}{(n-1)+(n+1)\cdot\sin\phi_s} \cdot (A_s \cdot n + A_c)$$

$$P = 0.7 \cdot q_u \cdot \frac{1+\sin\phi_s}{(n-1)+(n+1)\cdot\sin\phi_s} \cdot (A_s \cdot n + A_c)$$

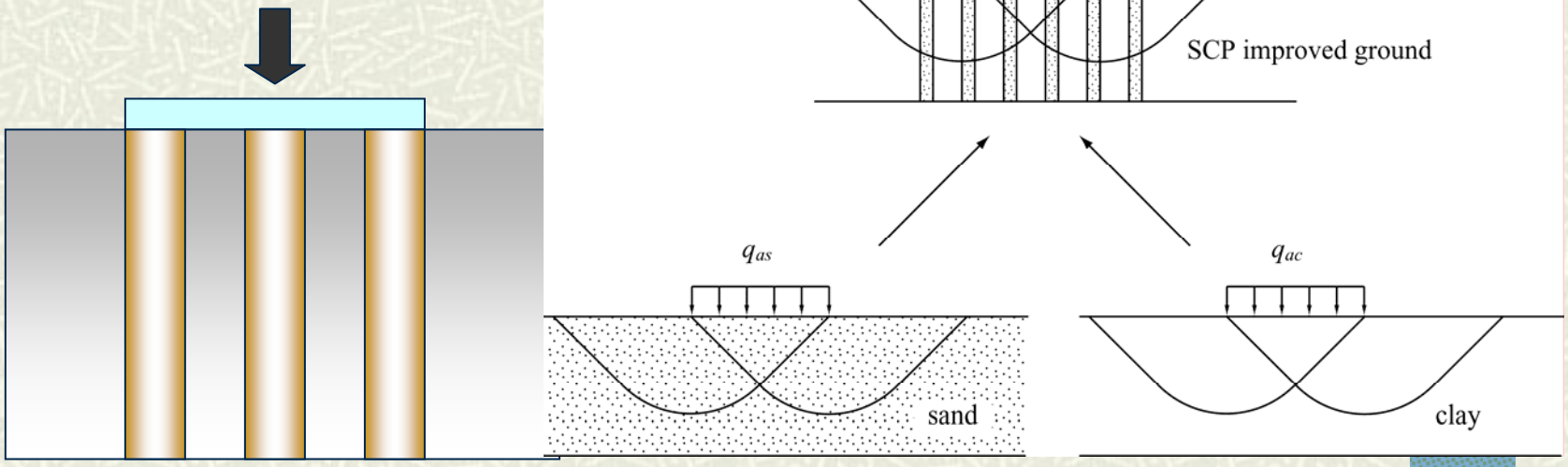


Bearing capacity of sand piles

$$P = q_a \cdot A$$

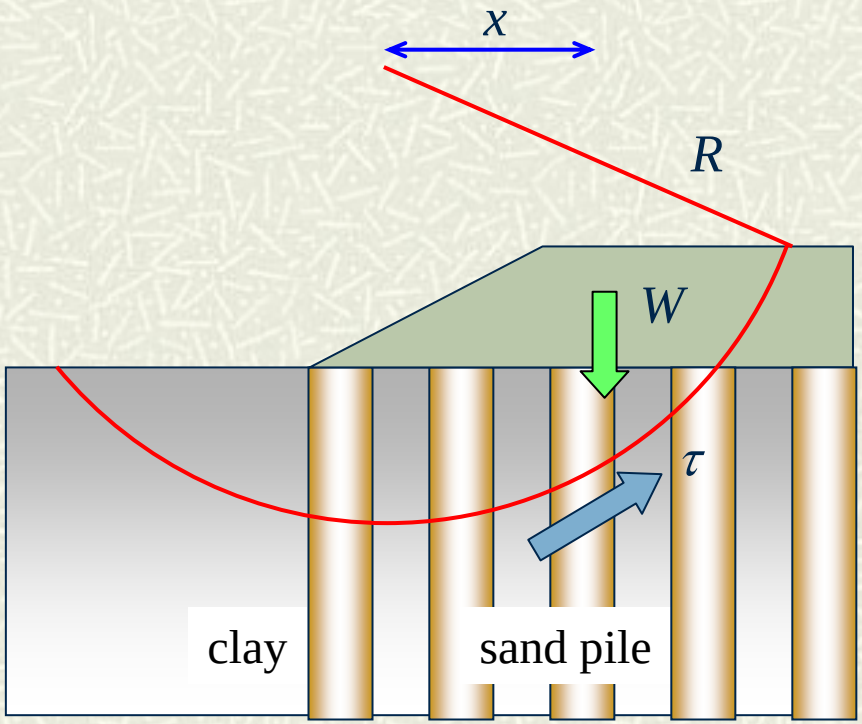
$$= \{a_s \cdot q_{as} + (1 - a_s) \cdot q_{ac}\} \cdot A$$

$$= \frac{1}{Fs} c \cdot N_c + \frac{1}{Fs} \cdot \frac{1}{2} \cdot B \cdot \gamma_s \cdot N_\gamma$$



Stability calculation

Slip circle analysis (Fellenius method)

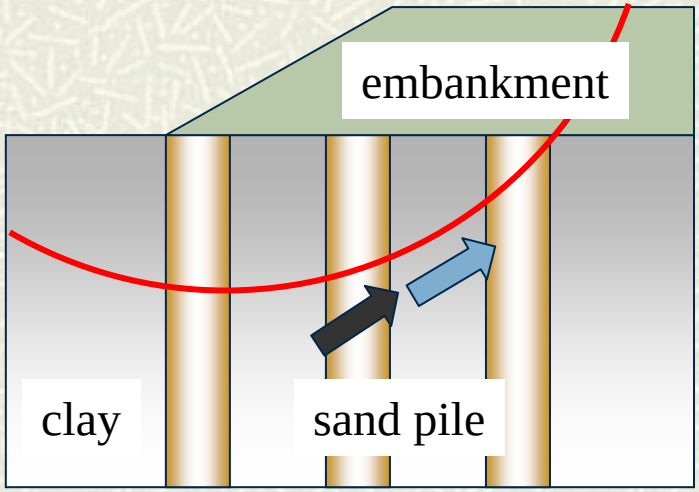


$$Fs = \frac{M_R}{M_D} = \frac{\tau \cdot R}{W \cdot x}$$

Stability calculation

Average shear strength of improved ground

$$\tau = (1 - a_s)(c_0 + k \cdot z + \mu_c \cdot \Delta\sigma_z \cdot c_u / p \cdot U) +$$
$$(\gamma_s \cdot z + \mu_s \cdot \Delta\sigma_z) \cdot a_s \cdot \tan\phi_s \cdot \cos 2\theta$$



where

τ : average shear strength

a_s : improvement area ratio

$c_0 + kz$: undrained shear strength of clay

μ_c : stress concentration factor of clay

μ_s : stress concentration factor of sand pile

n : stress concentration ratio

U : consolidation degree of clay

ϕ_s : friction angle of sand pile

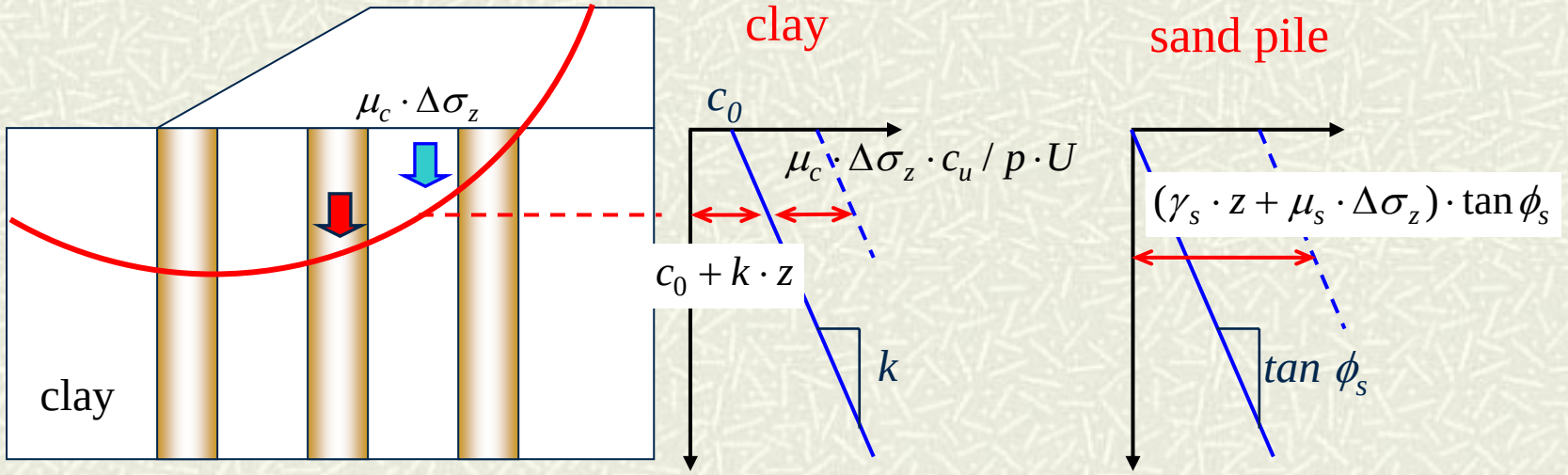
γ_s : desnity of sand pile

Stability calculation

Average shear strength of improved ground

$$\tau = (1 - a_s)(c_0 + k \cdot z + \mu_c \cdot \Delta\sigma_z \cdot c_u / p \cdot U) +$$

$$(\gamma_s \cdot z + \mu_s \cdot \Delta\sigma_z) \cdot a_s \cdot \tan\phi_s \cdot \cos^2\theta$$



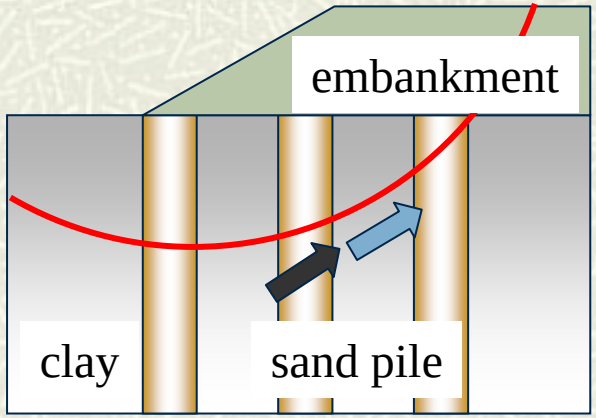
Average shear strength

$$\tau = (1 - a_s)(c_0 + k \cdot z + \mu_c \cdot \Delta\sigma_z \cdot c_u / p \cdot U) +$$
$$(\gamma_s \cdot z + \mu_s \cdot \Delta\sigma_z) \cdot a_s \cdot \tan\phi_s \cdot \cos^2\theta$$

$$\tau = (1 - a_s)(c_0 + k \cdot z) +$$
$$(\gamma_m \cdot z + \Delta\sigma_z) \cdot \mu_s \cdot a_s \cdot \tan\phi_s \cdot \cos^2\theta$$

$$\tau = (\gamma_m \cdot z + \Delta\sigma_z) \cdot \tan\phi \cdot \cos^2\theta$$

$$\tau = (\gamma_m \cdot z + \Delta\sigma_z) \cdot \tan\phi_m \cdot \cos^2\theta$$



Consolidation settlement
- amount of settlement -

settlement of unimproved ground, S_0

$$S_0 = \frac{\Delta e}{1+e_0} H$$

$$S_0 = m_v \cdot \sigma \cdot H$$

$$S_0 = H \cdot Cc \cdot \log \sigma / \sigma_0$$

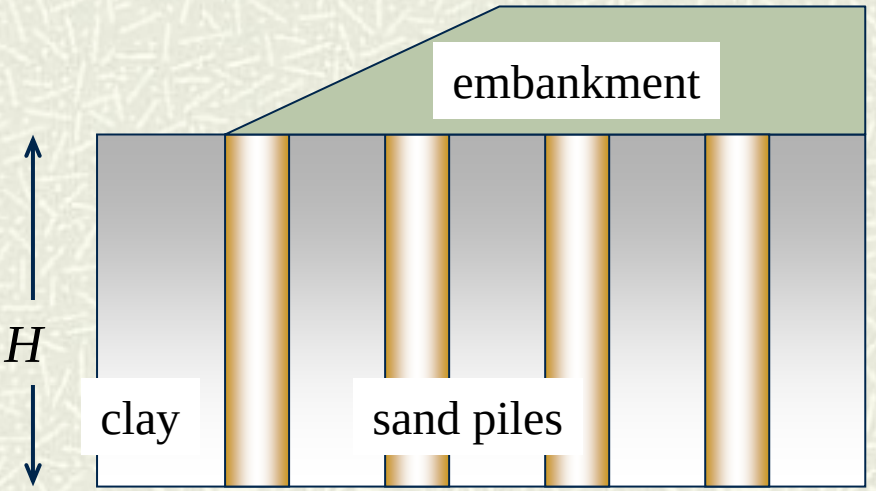
settlement of improved ground, S

$$S_0 = \frac{\Delta e}{1+e_0} H$$

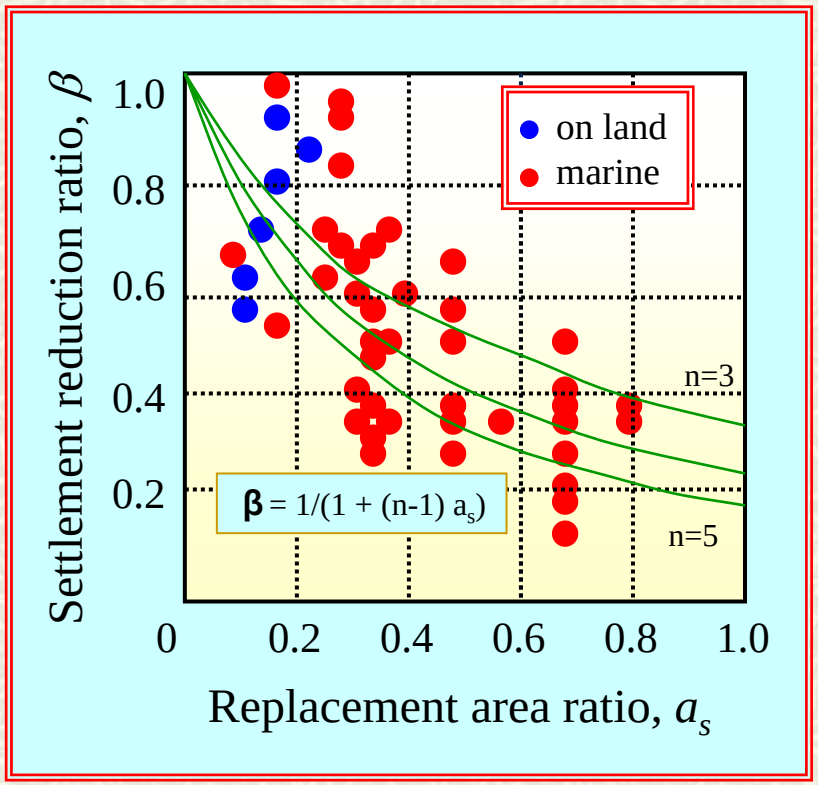
$$S = \beta \cdot S_0$$

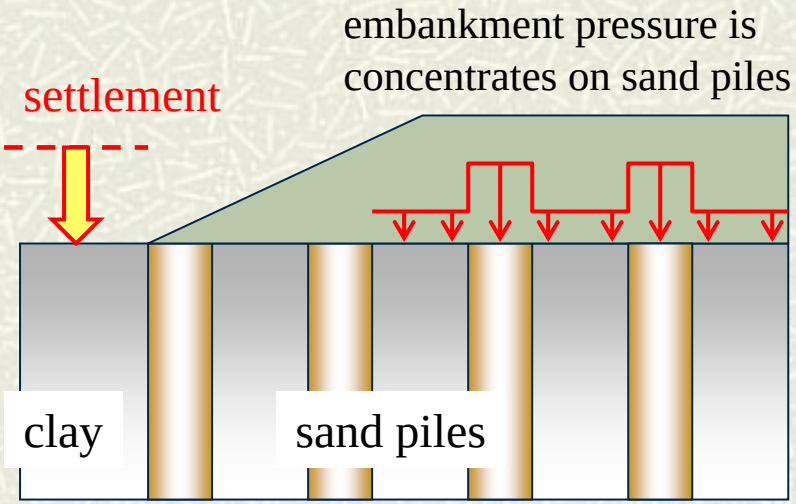
$$= \mu_c \cdot S_0$$

$$= \frac{1}{1+(n-1)\cdot a_s} \cdot S_0$$



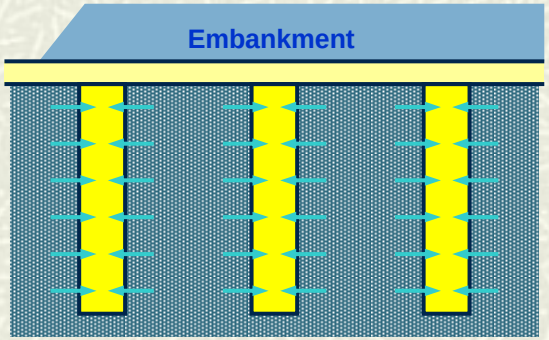
Consolidation settlement
- amount of settlement -

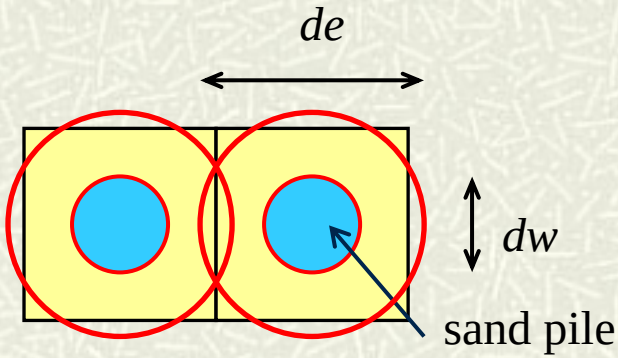




Consolidation settlement

- settlement speed -





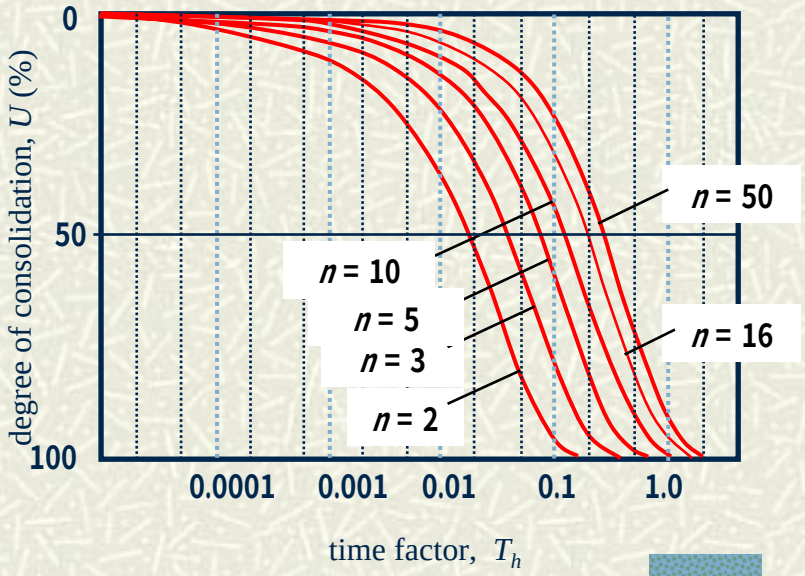
Barron's theory

$$U = 1 - \exp\left(-\frac{8\,Th}{F(n)}\right)$$

$$F(n) = \frac{n^2}{n^2 - 1}\log_e n - \frac{3n^2 - 1}{4n^2}$$

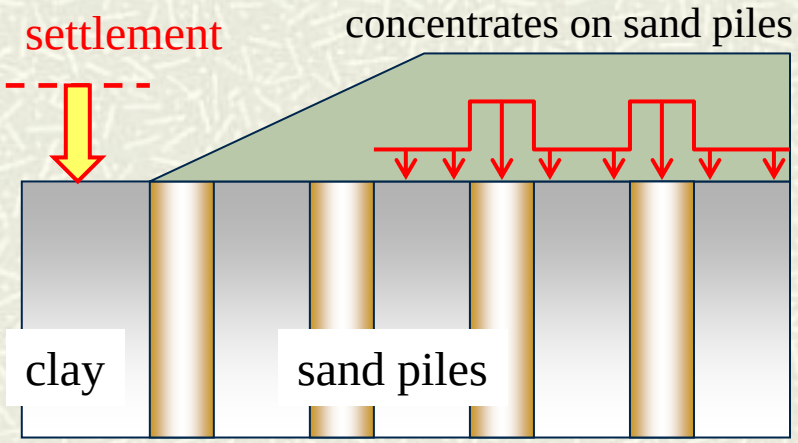
$$n = \frac{de}{dw}$$

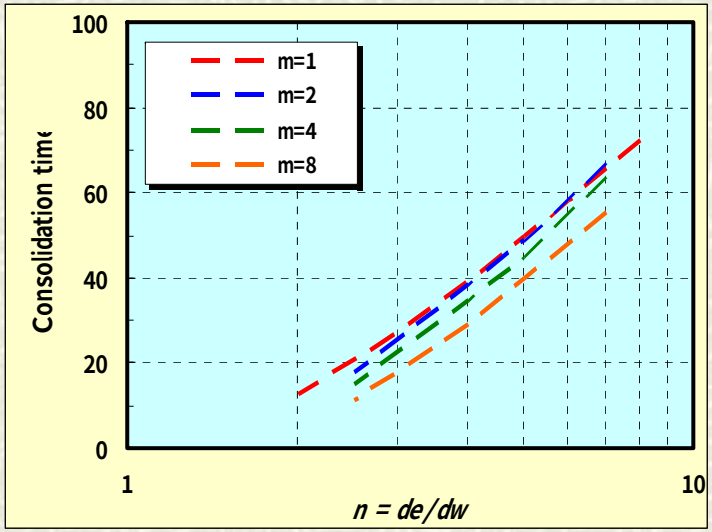
$$Th = \frac{Ch \cdot t}{de^2}$$



Consolidation with stress concentration

by Yoshikuni & Nakanodo

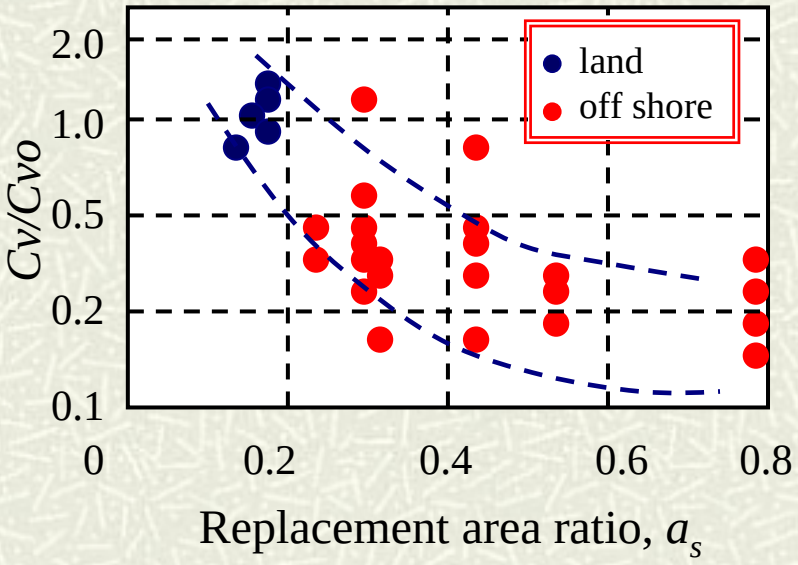




according to the theory, consolidation proceeds fast with increasing the stress concentration.

However, the consolidation of SCP ground proceeds slower than the theory

Field measurements in SCP ground



However, the consolidation of SCP ground proceeds slower than the theory

Soil disturbance effect

Consolidation settlement
- settlement speed -

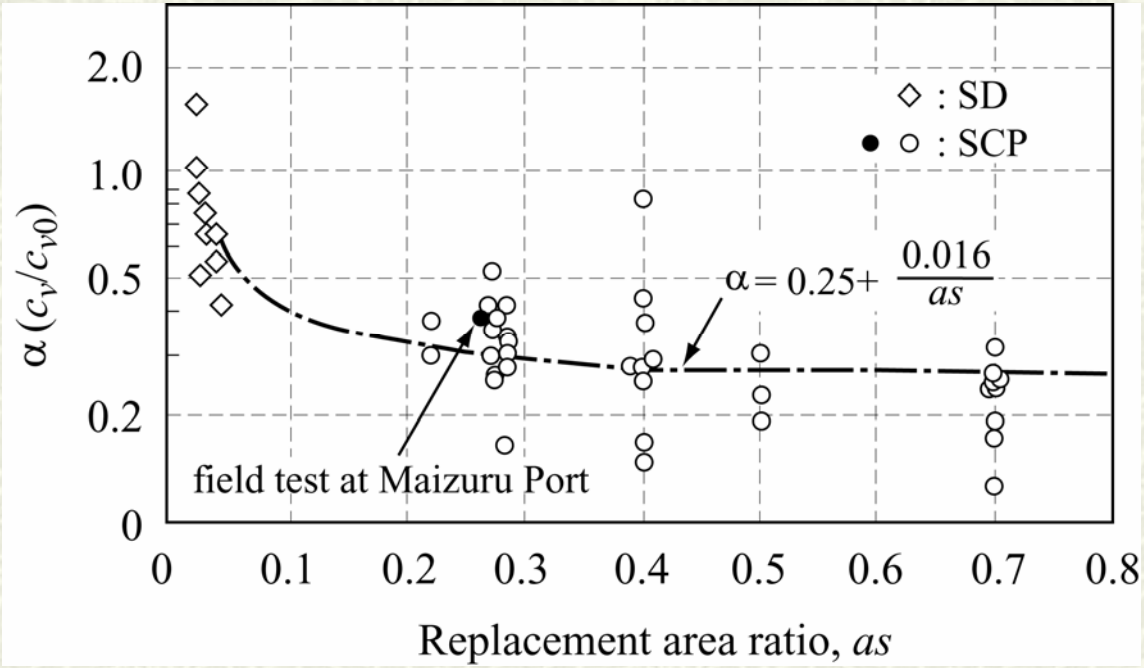
Vertical drain Theory with c_h empirical adjustment

$$U = 1 - \exp\left(-\frac{8Th}{F(n)}\right)$$

$$F(n) = \frac{n^2}{n^2 - 1}\log_e n - \frac{3n^2 - 1}{4n^2}$$

$$n = \frac{de}{dw}$$

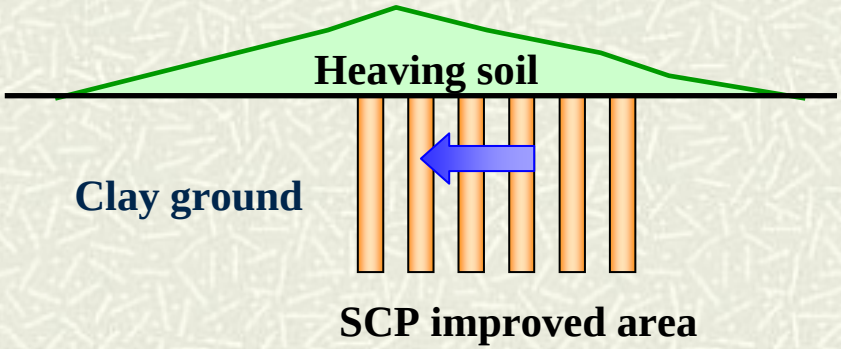
$$Th = \frac{Ch \cdot t}{de^2}$$



Important issues on design procedure for clay ground

- ground heaving due to piles installation
- strength decrease and recover
- soil disturbance effect on consolidation

Ground heaving due to SCP installation

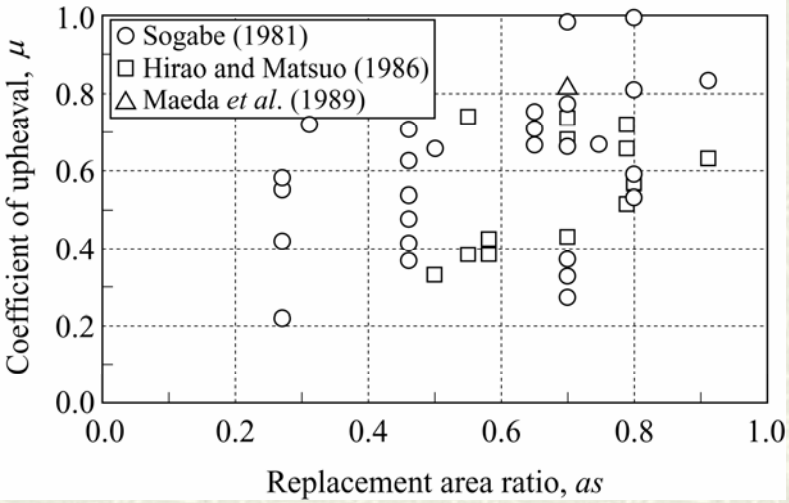


Heaving ratio

$$\mu = 0.316 \cdot a_s - 0.028 \cdot L + 0.0037 \cdot q_u - 0.7$$

$$\mu = 2.803 \cdot L^{-1} + 0.356 \cdot a_s + 0.112$$

$$\mu = 2.477 \cdot L^{-1} + 0.400 \cdot a_s + 0.101 \cdot D + 0.011$$



where

a_s: replacement area ratio

D: diameter of sand pile (m)

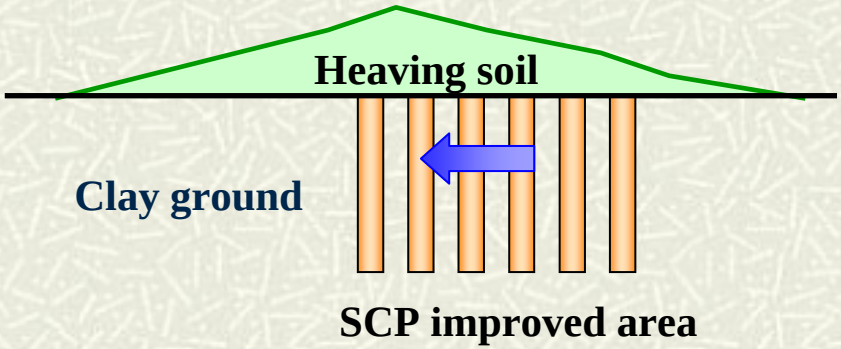
L : sand pile length (m)

V : heaving volume

q_u: strength of original ground at the depth of L/3

μ: coefficient of upheaval

Flow of predicting shape of upheaval portion



Improvement conditions

a_s, B, L, Vs

↓

Calculation of coefficient of upheaval

$\mu = 2.803(1/L) + 0.356\, as + 0.112$

↓

Calculation of volume of upheaval portion, V

$V = \mu Vs$

↓

Set of shape factors

α_1, α_2, β, θ_1, θ_2

↓

Calculation of maximum height of upheaval portion, H_{max}

$$H_{max} = \frac{\mu Vs}{C_1 B + C_2 L}$$

↓

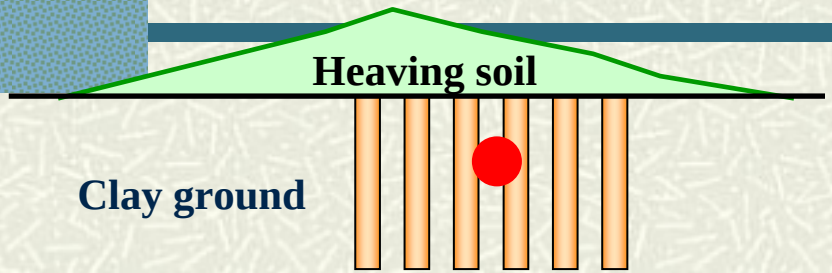
Estimation of shape of upheaval portion

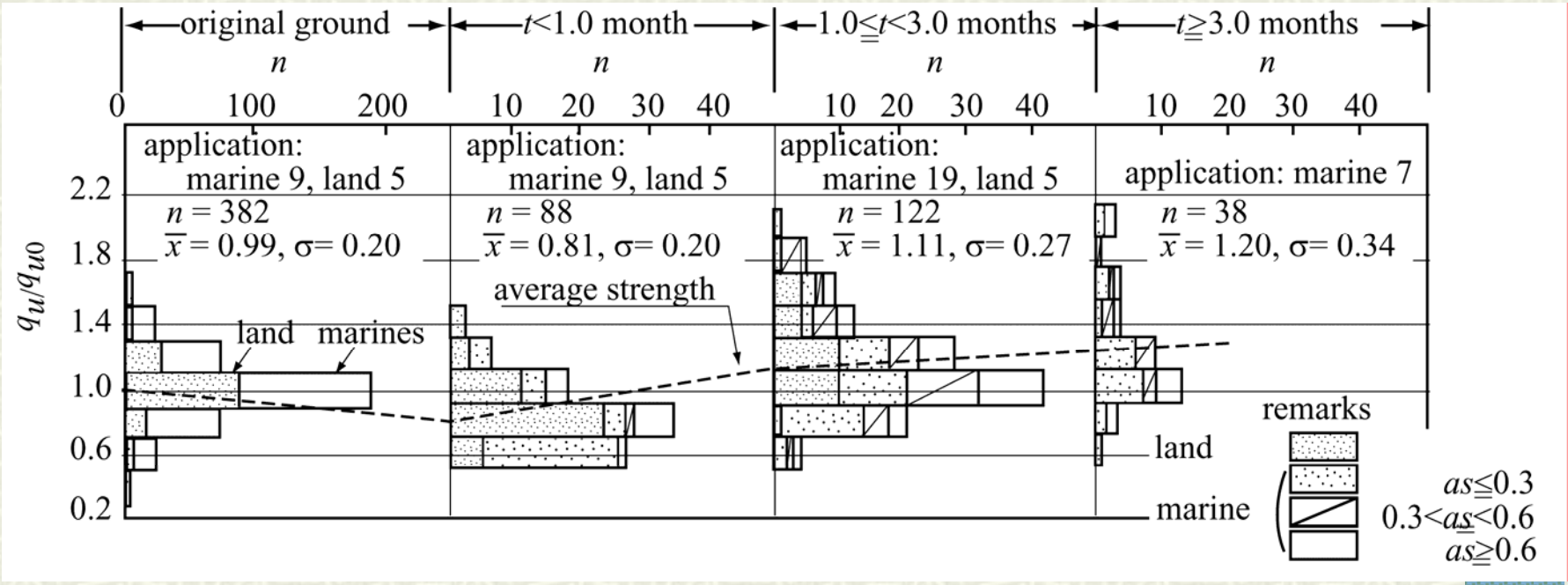
$H_1 = \alpha_1 H_{max}$, $H_2 = \alpha_2 H_{max}$, $x = \beta(B/2)$

$l_1 = L \tan \theta_1$, $l_2 = L \tan \theta_2$

Strength decrease and recover

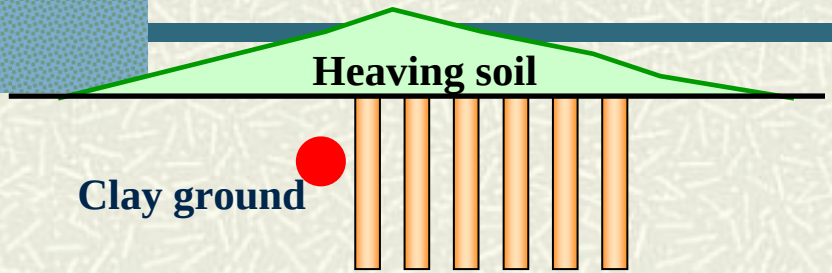
clay in improved area

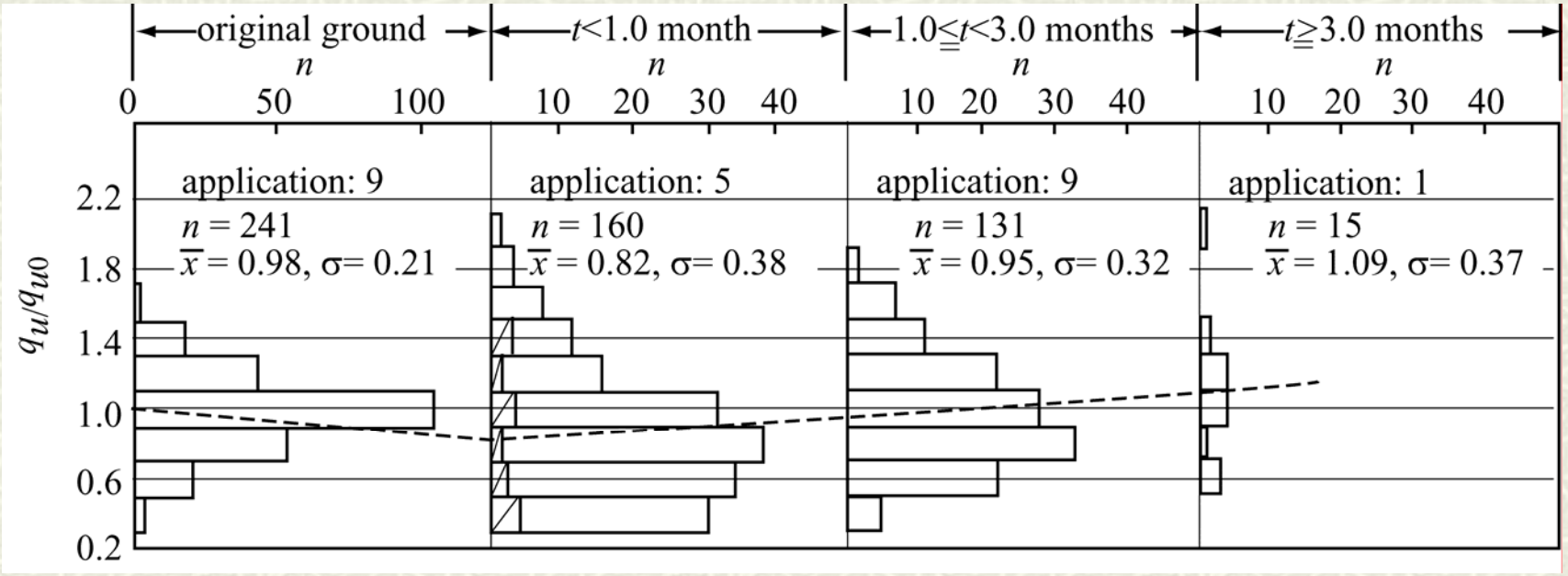




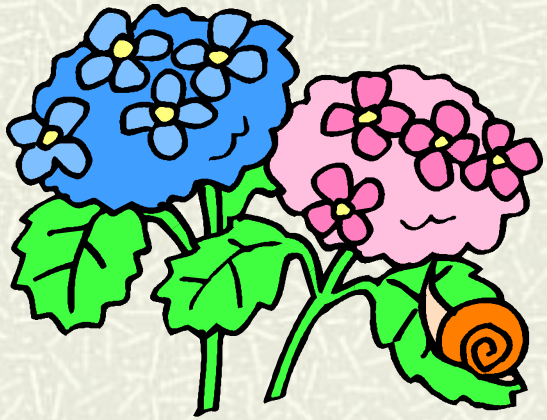
Strength decrease and recover

clay periphery of improved area





6. Design procedure for sand ground



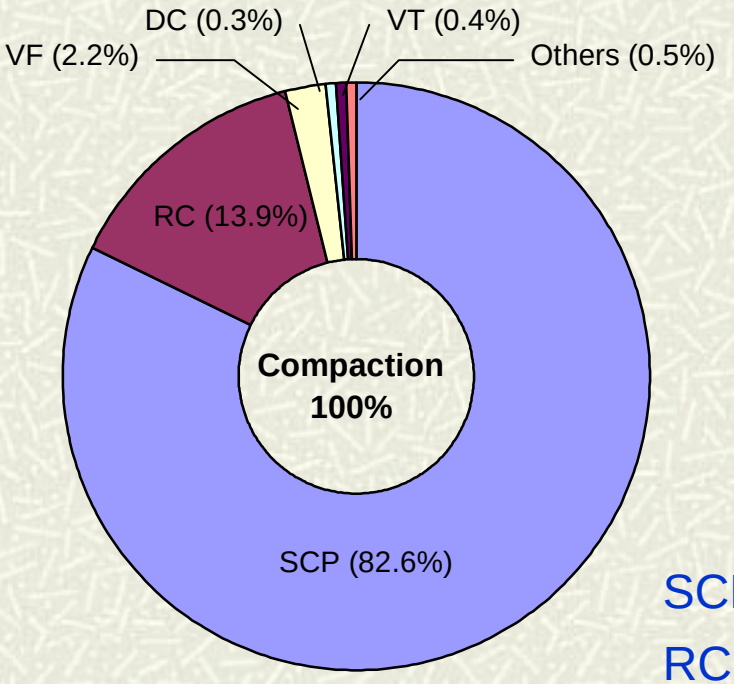
Design procedure for sandy ground

Niigata earthquake in 1964

Purpose of improvement

- bearing capacity increase
- settlement decrease
- liquefaction prevention

liquefaction prevention techniques in Japan

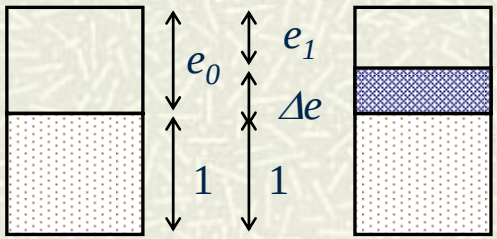


SCP : Sand Compaction Pile

RC : Rod Compaction
VF : Vibro-Floatation
DC : Dynamic Consolidation
VT : Vibro-Tamper

Design of SCP Method for Sandy Soil

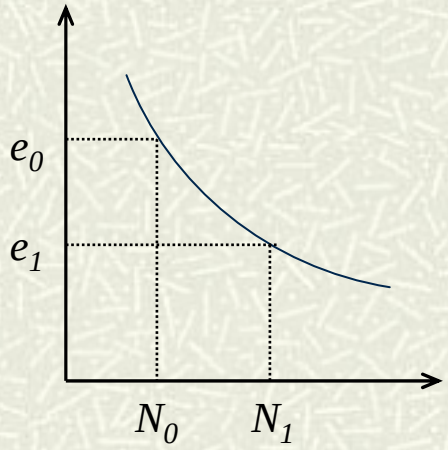
increase density



void

sand pile

soil particle



improvement area ratio

$$a_s = \frac{e_0 - e_1}{1 + e_0}$$

sand volume to be driven

for square pattern

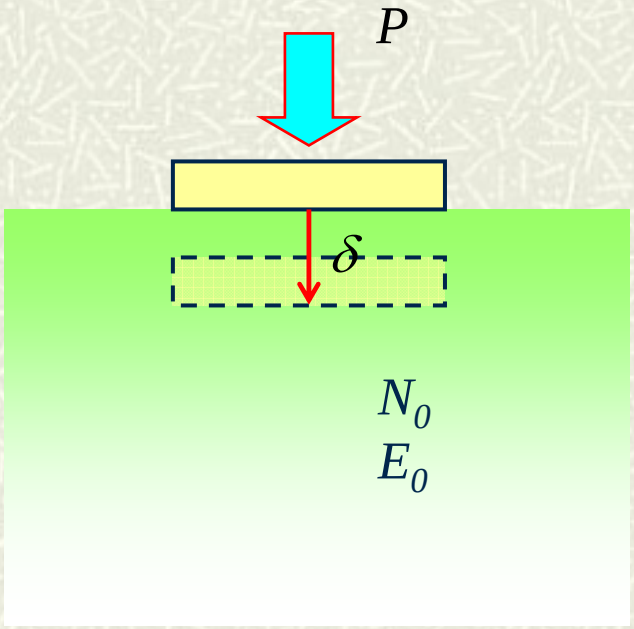
$$V = a_s \cdot D^2, \quad d = 2D\sqrt{\frac{a_s}{\pi}}$$

for equilateral triangular pattern

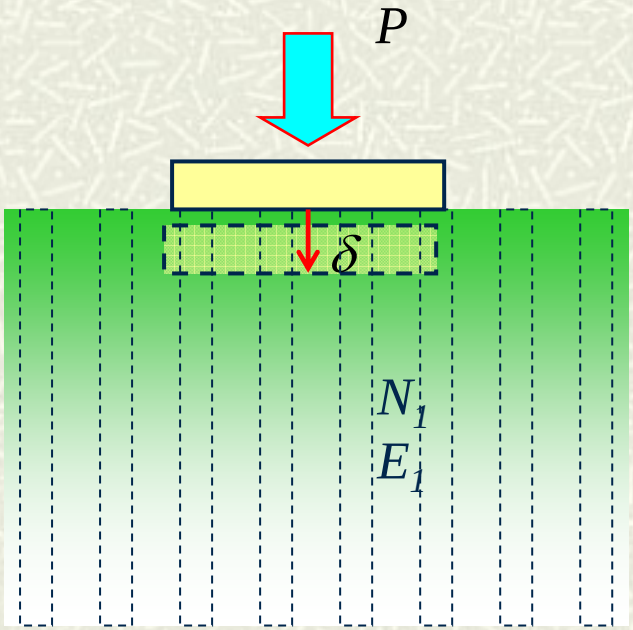
$$V = a_s \cdot \frac{\sqrt{3}}{2} \cdot D^2, \quad d = 2D\sqrt{\frac{a_s \cdot \sqrt{3}}{2\pi}}$$

improvement effect

Before



After



design procedures for sandy soil

- procedure A
- procedure B
  - effect of uniformity coefficient and overburden pressure are taken into account
- procedure C
  - effect of fines content is taken into account
- procedure D
  - effect of fines content is taken into account
  - ground upheaving effect is taken into account

Procedure A

average SPT N value after improvement

$$N = (1 - a_s) \cdot N_{ti} + a_s \cdot N_{ts}$$

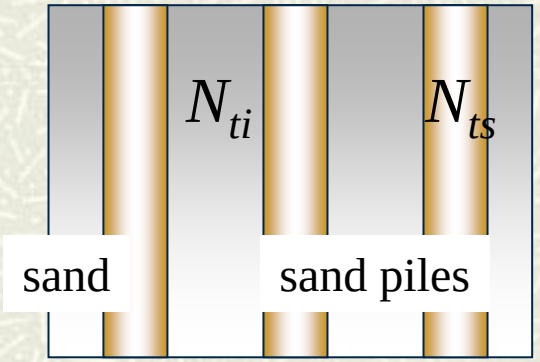
where

a_s : improvement area ratio

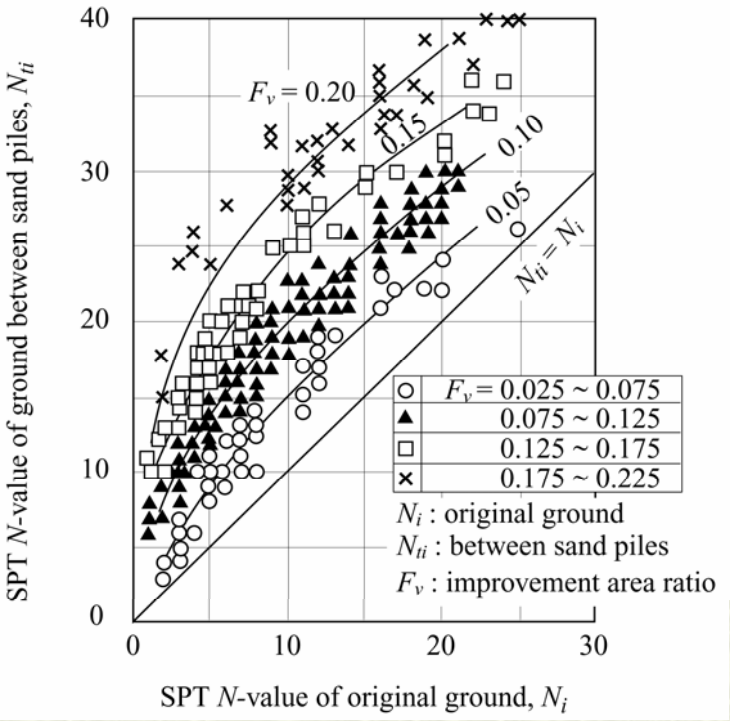
N : average SPT N value

N_{ti} : SPT N value between sand piles

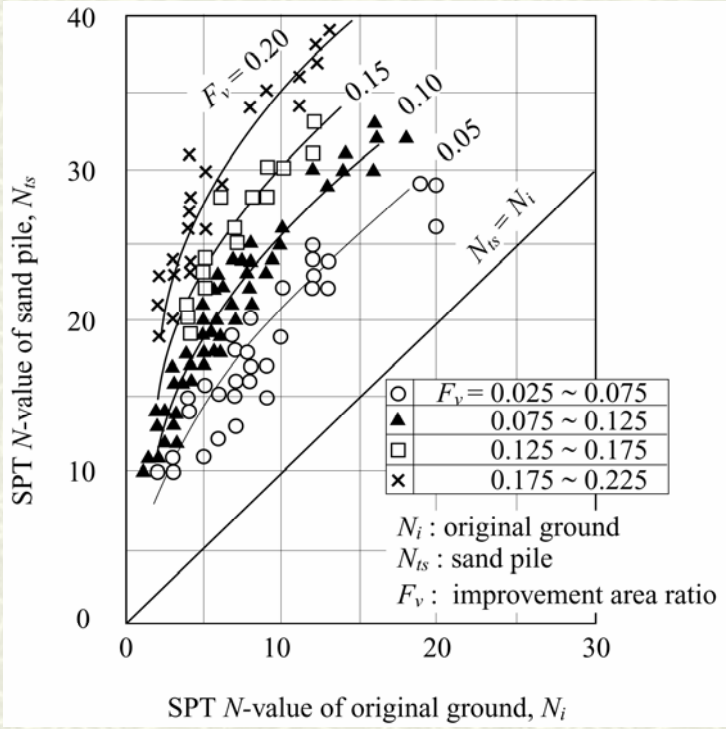
N_{ts} : SPT N value of sand pile



SPT *N* value



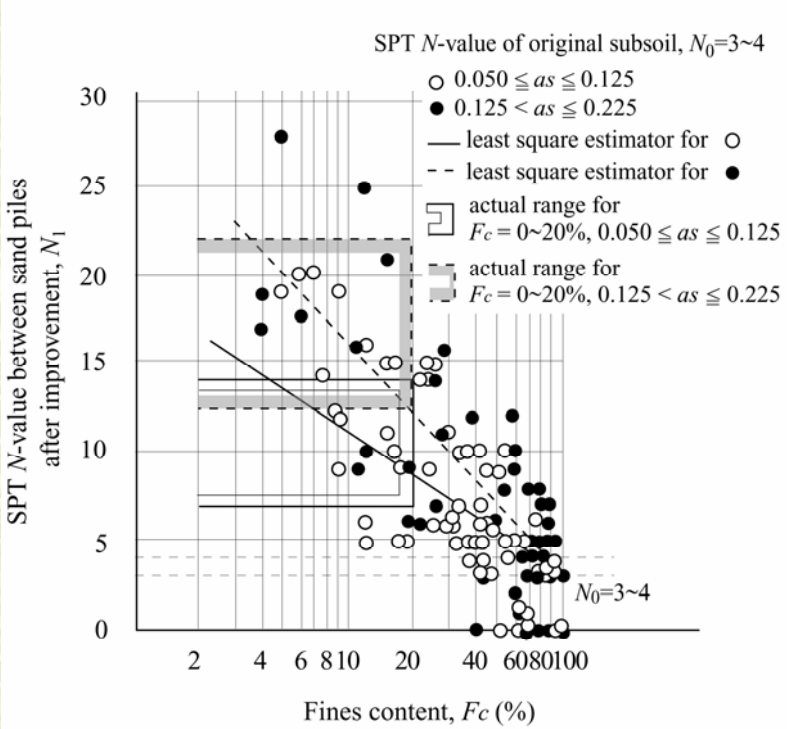
between sand piles



center of sand piles

limitation of Procedure A

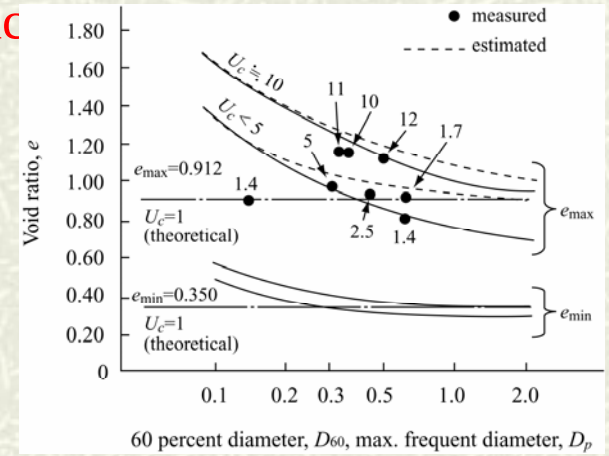
improvement effect is decreased wit for fine soil

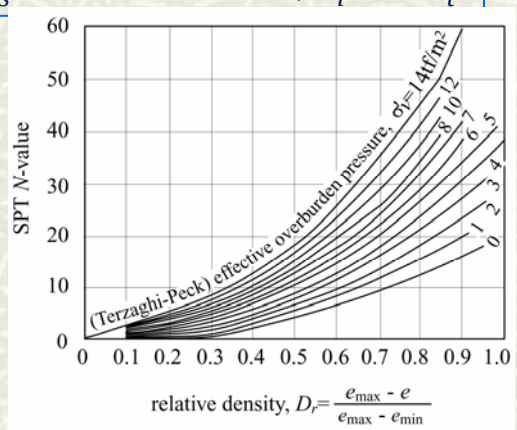


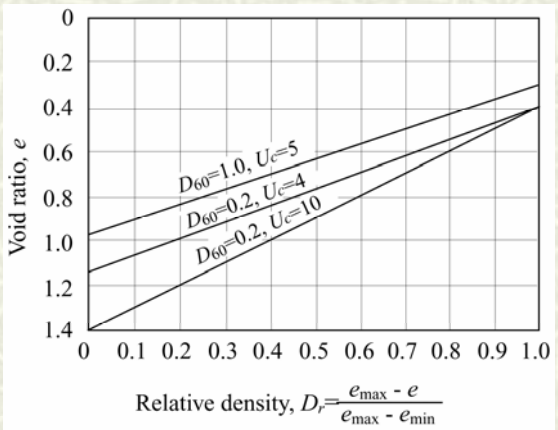
Procedure B

effect of uniformity coefficient and overburden pressure is taken into ac

1. The e_{max} and e_{min} of ground are estimated.
2. relative density is estimated from SPT N value.
3. obtain the void ratio of ground, e_i.
4. obtain the void ratio for target N value, e_t by taking account of σ'_v.
5. calculate a_s from void ratios, e_i and e_t.







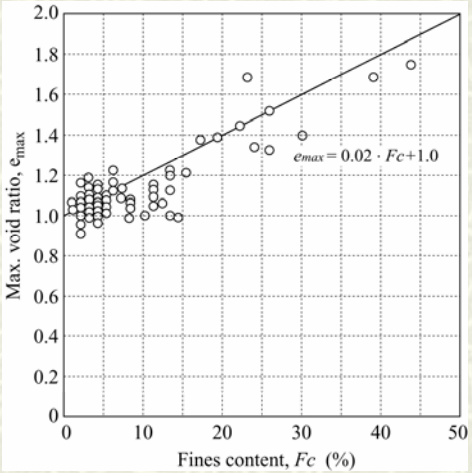
Procedure C

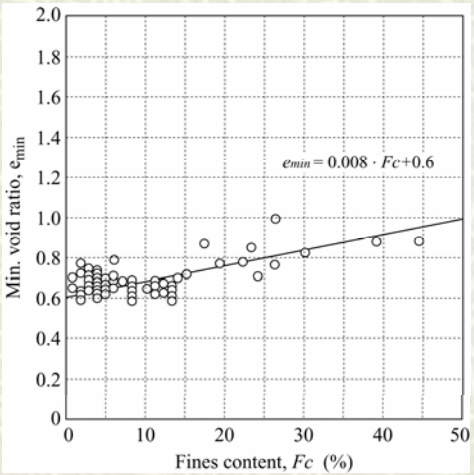
effect of uniformity coefficient and overburden pressure is taken into account

1. The e_{max} and e_{min} of ground are estimated by fines content, *Fc*.
2. relative density is estimated from SPT *N* value by Meyerhof's proposal.

$$D_r = 21\sqrt{\frac{100 \cdot N}{70 + \sigma'_v}}$$

3. obtain the void ratio of ground, e_i.
4. obtain the void ratio for target *N* value, e_t by taking account of σ'_v and *Fc*.
5. calculate a_s from void ratios, e_i and e_t.





Procedure C

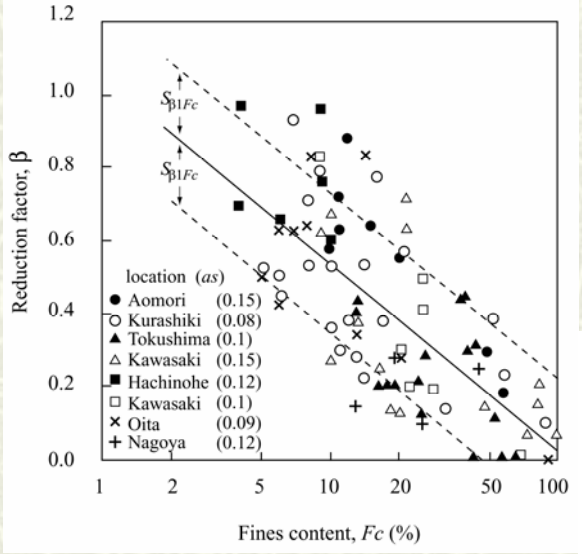
- reduction factor for *Fc* effect -

A reduction factor, β, is introduced to incorporate the effect of fines content on the SPT *N* value.

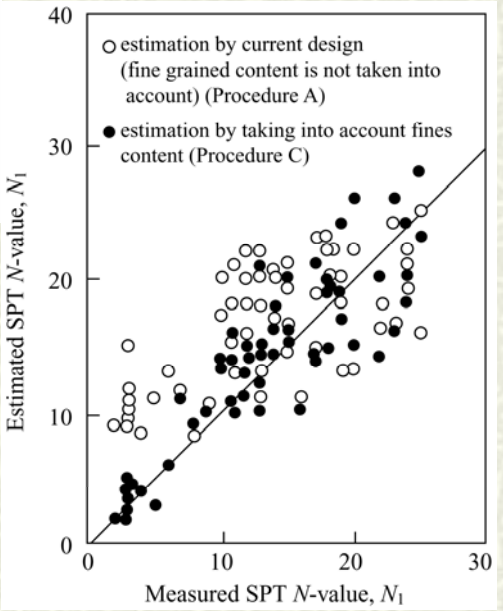
$$\beta = \frac{\Delta N}{\Delta N'} = \frac{N_t - N_i}{N'_t - N_i}$$

Target SPT *N* value is obtained

$$N_t = N_i + \frac{N'_t - N_i}{\beta}$$



$$\beta = 1.05 - 0.51 \cdot \log_{10} Fc$$



Procedure D

effect of ground upheaving is incorporated.

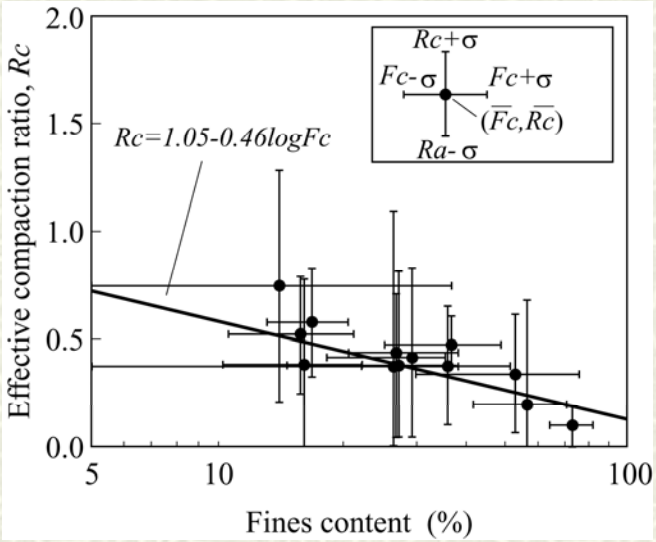
1. The e_{max} and e_{min} of ground are estimated by fines content, Fc.
2. relative density is estimated from SPT N value by Meyerhof's proposal.

$$D_r = 21\sqrt{\frac{100 \cdot N}{70 + \sigma'_v} + \frac{\Delta N_f}{1.7}}$$

3. obtain the void ratio of ground, e_i.
4. obtain the void ratio for target N value, e_t by taking account of σ'_v and Fc.
5. calculate a_s from void ratios, e_i and e_t.

$$a_s = \frac{e_i - e_t}{Rc \cdot (1 + e_i)}$$

fines content	ΔN_f
0 to 5	0
5 to 10	interpolate
higher than 10	$0.1Fc+4$

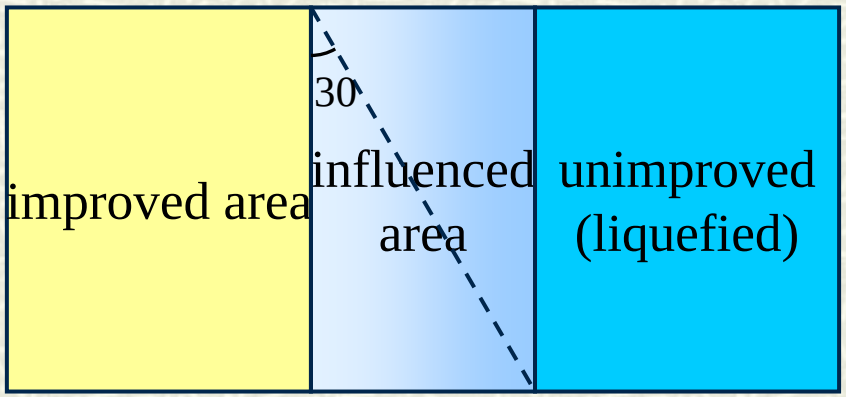


Extent of improved ground

- propagation of excess PPW
- water pressure by liquefied area
- shear strength decrease of liquefied area

Extent of improved ground

propagation of excess PPW



Extent of improved ground

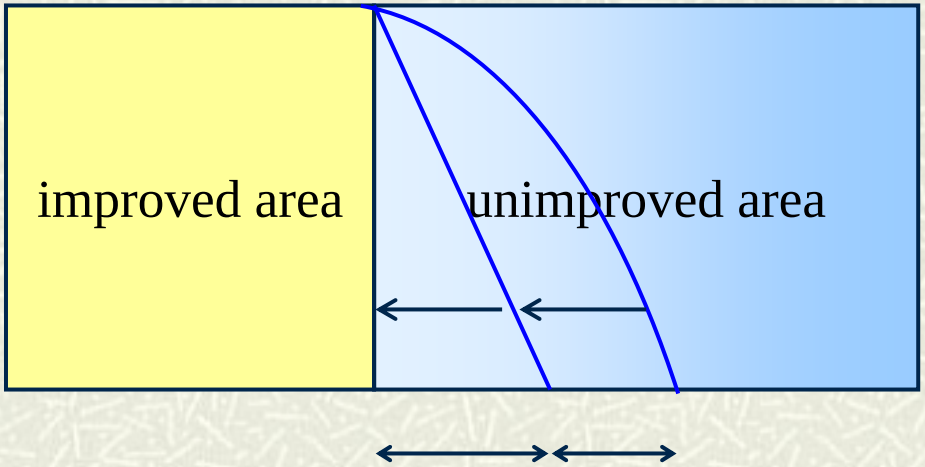
- water pressure from liquefied area -

static water pressure

$$p_{ws} = \gamma' \cdot z$$

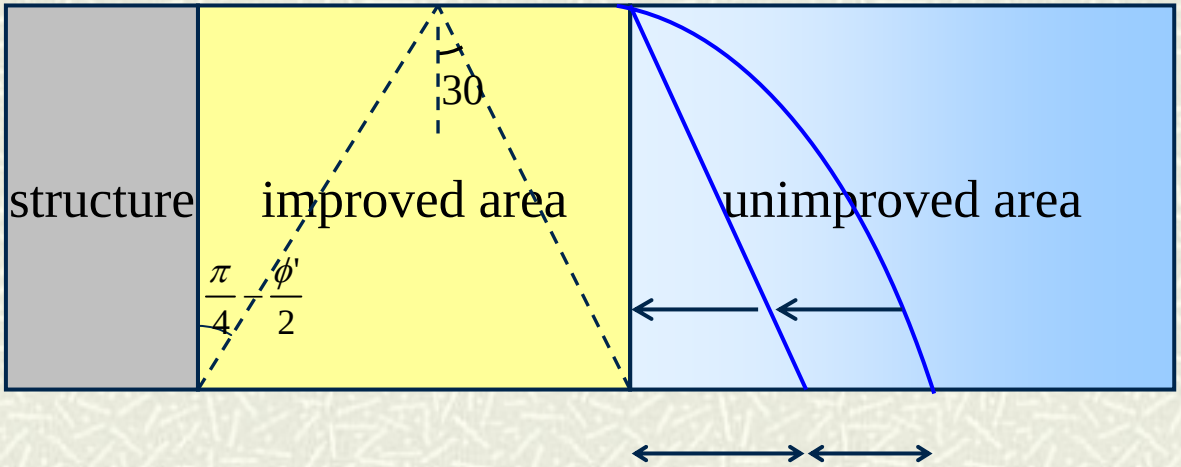
dynamic water pressure

$$p_{wd} = \frac{7}{8} \cdot \frac{a}{g} \cdot \gamma_{sat} \cdot \sqrt{z \cdot H}$$



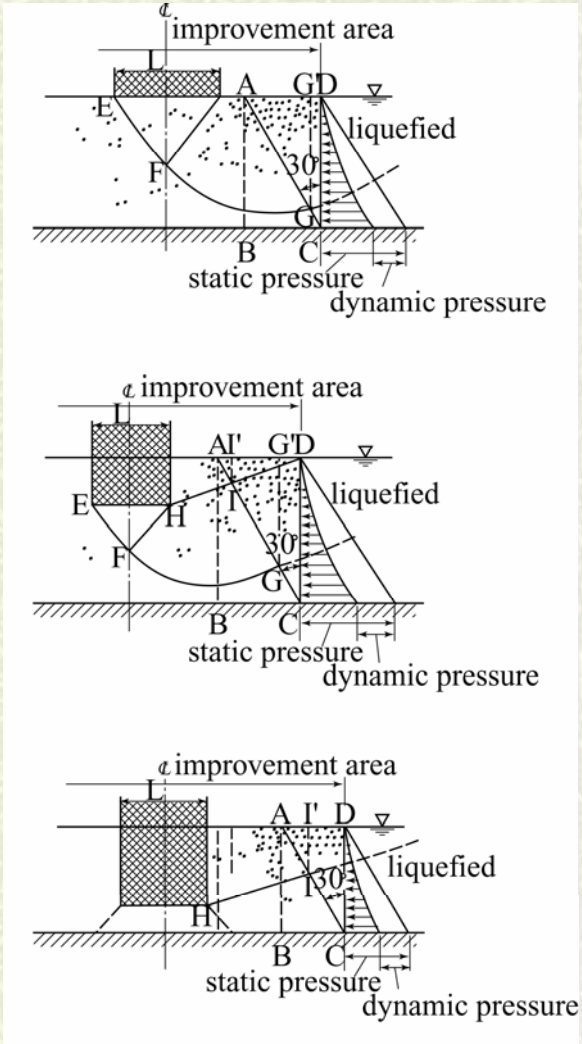
Extent of improved ground

- water pressure from liquefied area -



Extent of improved ground

- shear strength decrease of liquefied area -



Thank you for your attention