# 5. Deep Foundations（深基礎）

Applicability of depth factors for the shallow foundations is limited to a certain depth, because <u>bearing mechanism changes as the embedment depth increases</u>. ***How??***

**Shallow Foundation** → **Deep Foundation**

<u>D/B < 1</u>

$$F_{cd} = 1 + 0.4\frac{D}{B}$$

$$F_{qd} = 1 + 2\tan\phi(1-\sin\phi)^2\frac{D}{B}$$

$$F_{\gamma d} = 1$$

<u>D/B > 1</u>

$$F_{cd} = 1 + 0.4\tan^{-1}\left(\frac{D}{B}\right)$$

$$F_{qd} = 1 + 2\tan\phi(1-\sin\phi)^2\tan^{-1}\left(\frac{D}{B}\right)$$

$$F_{\gamma d} = 1$$

Hansen’s depth factor for shallow foundation

# 5.1 Classification of deep foundation

## 5.1.1 Classification of deep foundation

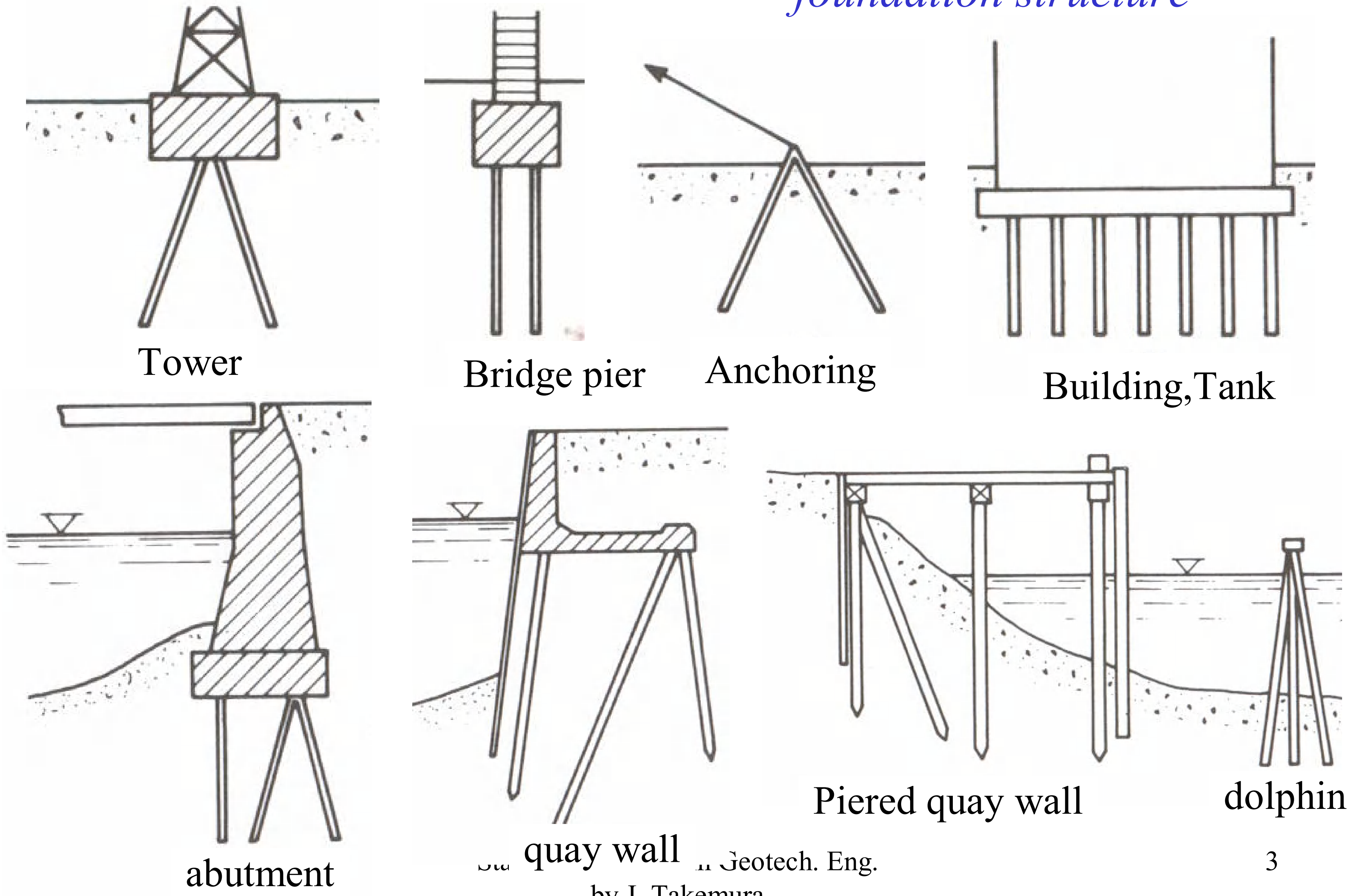
**Pile foundation** -displacement or non-displacement
（杭基礎） -hollow or solid
-material (concrete, steel, timber)
-preformed or cast-in-place (bored pile, drilled pile)
-purposes (**bearing pile**, reinforcement,stabilization)
-conditions of pile (end bearing pile, friction pile,
lateral loaded, uplift, negative skin friction)

Caisson Foundation （ケーソン基礎）

Diaphragm wall foundation （連壁基礎）

# 5.1.2 Examples of use of piles

*one of the most common foundation structure*



## 5.1.3Types of bearing pile

**(Displacement piles：排土杭)**

- driven pile
  - hollow
    - concrete
    - steel
  - solid
    - concrete
    - steel
    - timber

precast reinforced (RC)

precast prestressed (PC)

***economical***

***easy to construct***

***noise***

***vibration***

***limited diameter***

•pile driving method

***-dropping weight***

***-explosion***

***-vibration***

***-jacking against reaction***

- driven cast-in-place

  a tube is driven
  - concrete (closed end tube filled with concrete)
  - steel
    - closed end tube filled with concrete
    - open end (casing method,retrievable tube was removed after filling concrete with reinforcement

Non-displacement

## 5.1.3Types of bearing pile
### (Non-displacement piles：無排土杭)

•cast-in-reinforced concrete pile（場所打ち杭）

| | |
|---|---|
| drilled pile | all casing method |
| bored pile | earth drill method |
| | reverse circulation method |

***low noise***

***low vibration***

***large diameter and flexible cross section (enlarging base)***

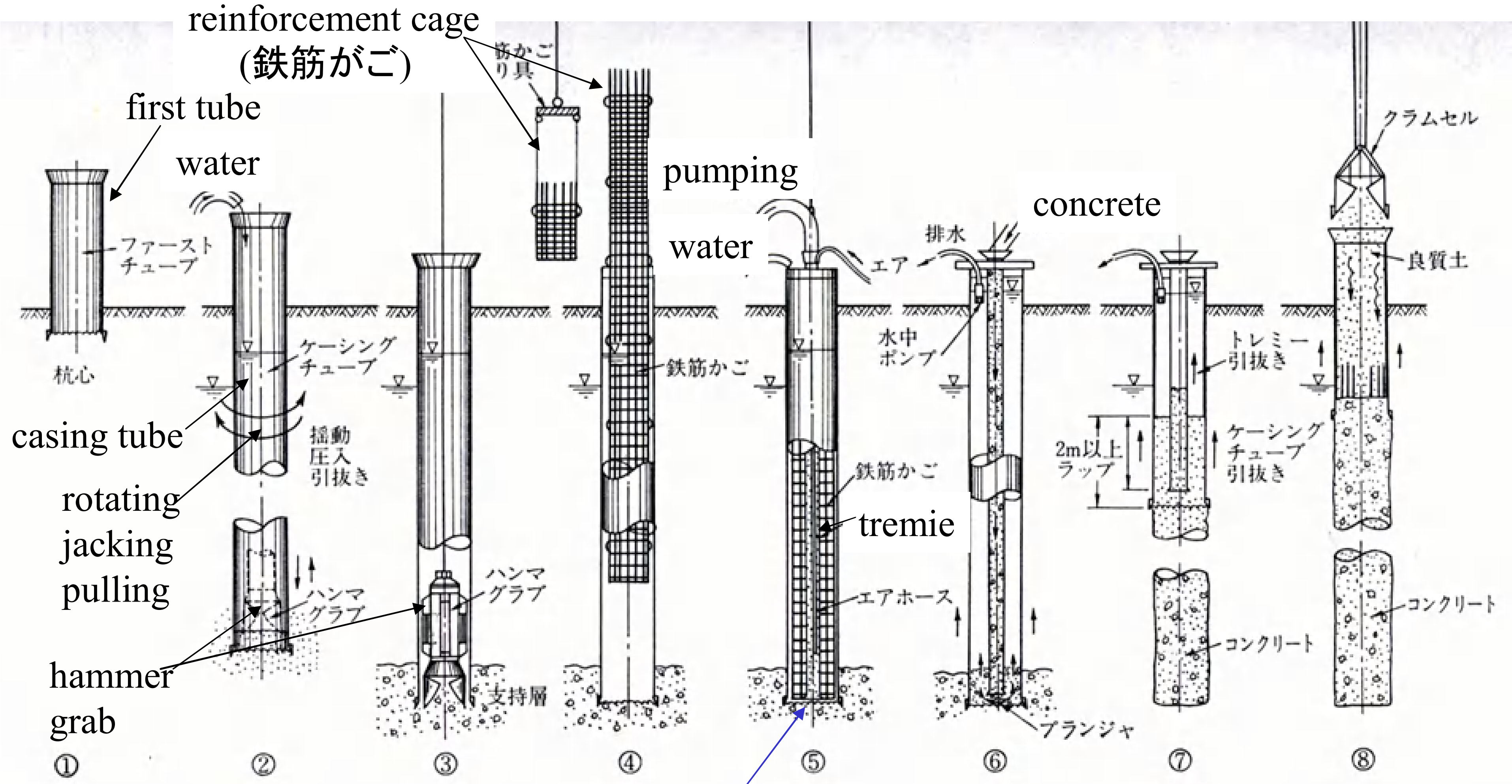
***relatively hard to construct***

•Pre-boring pile installation

•Cement grout mixing with core material (Steel pile)

Soil cement –hybrid steel pile

# Bored pile (all casing method)

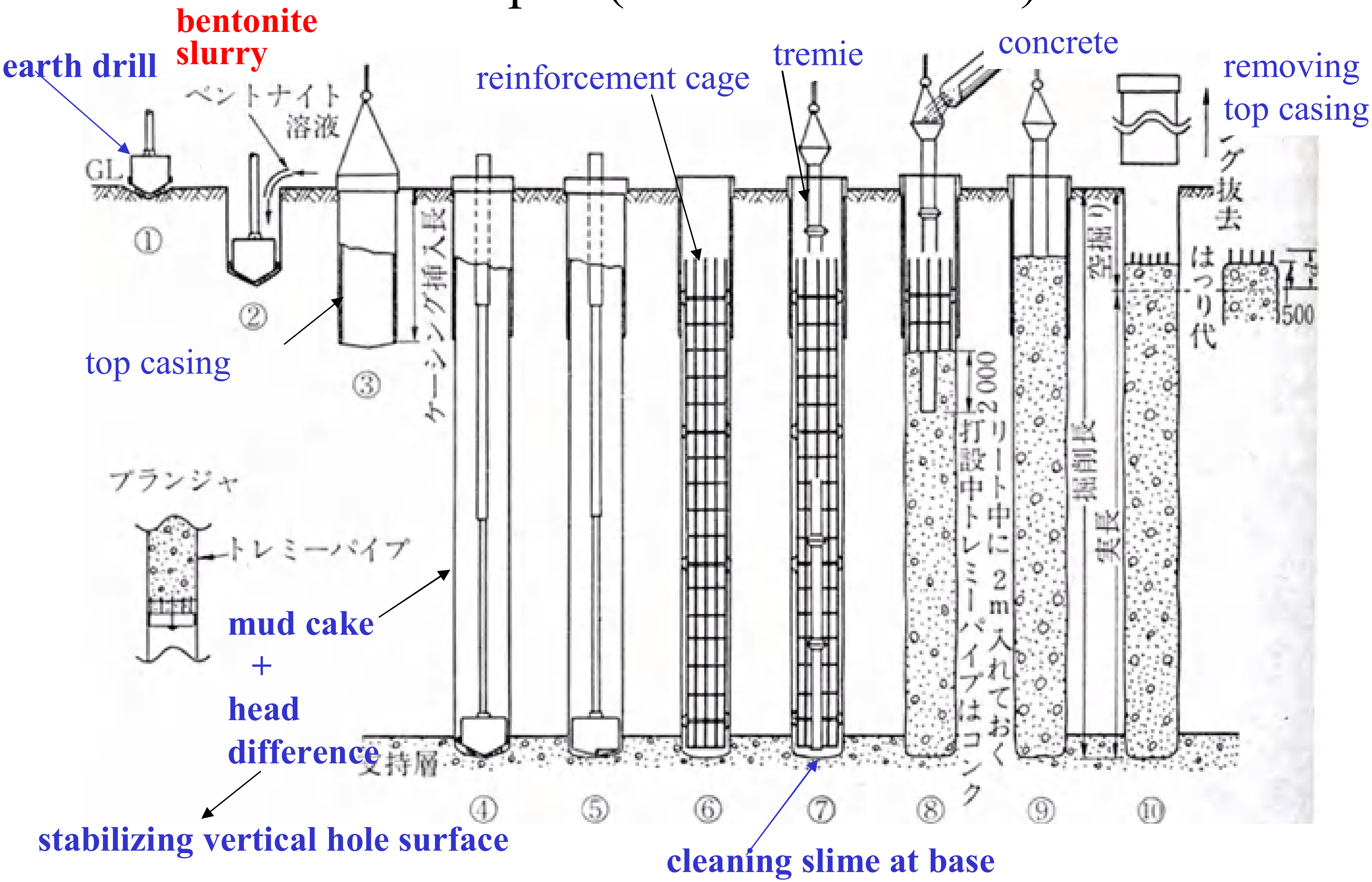



cleaning slime at base
(スライム処理)

withdrawal of casing and tremie

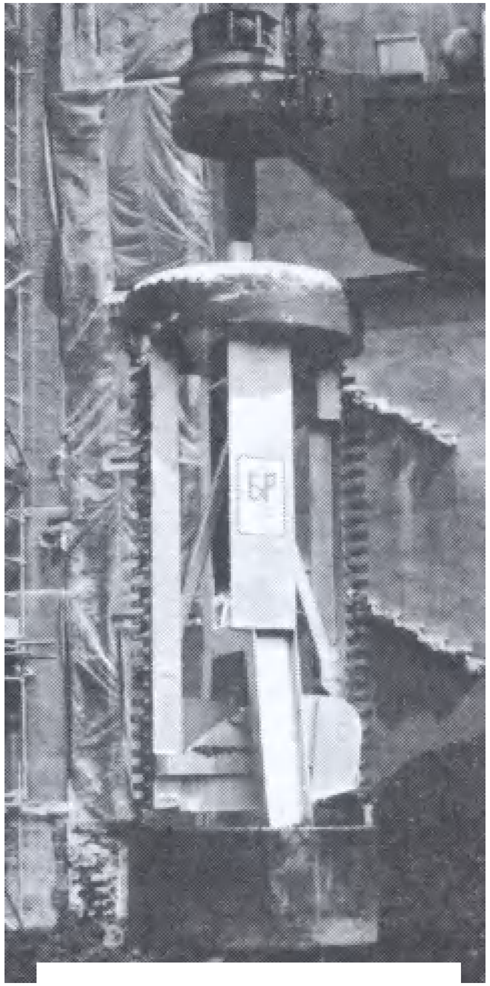
refilling top portion

# Bored pile (earth drill method)

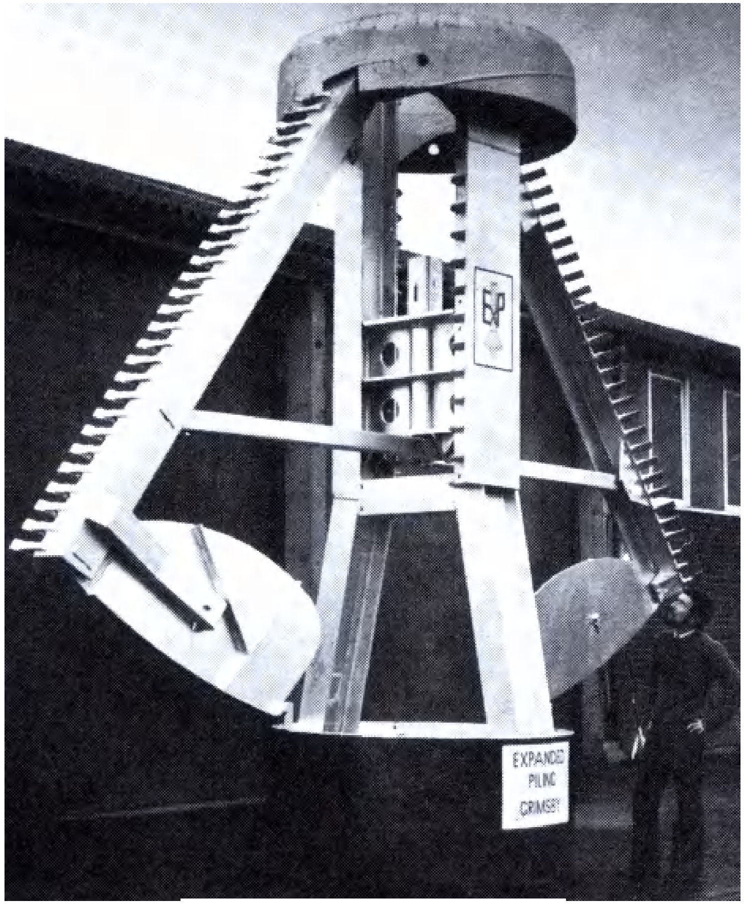


# enlargement of base diameter

## Under-reaming tool

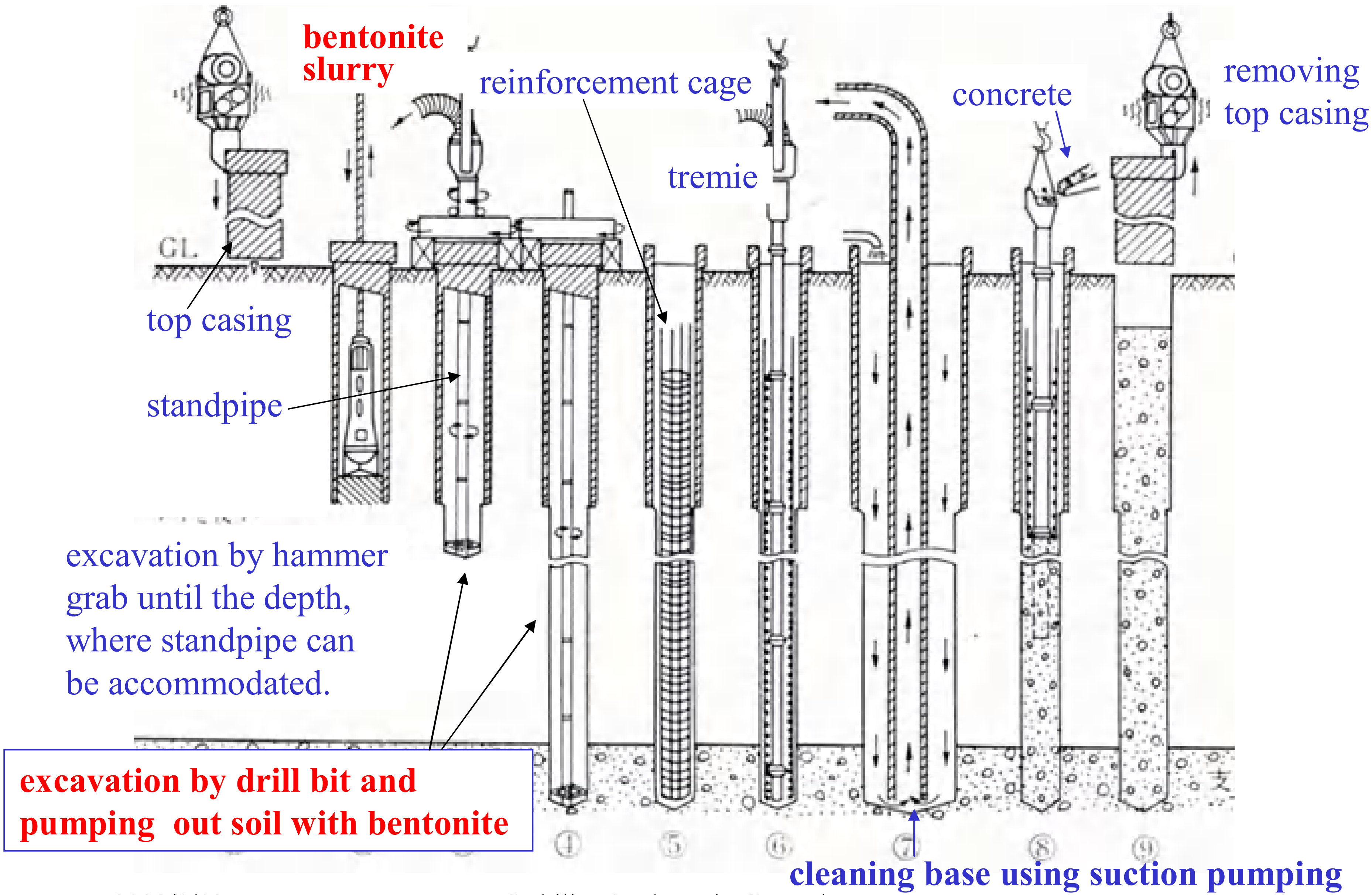



closed position



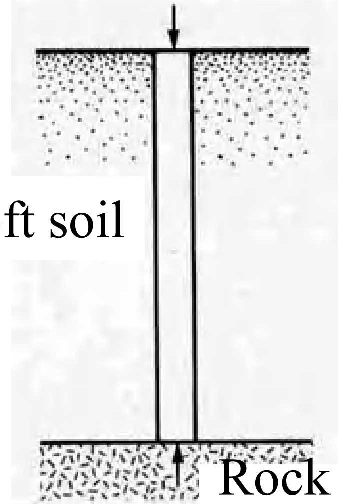

open position

# Bored pile (reverse circulation method)

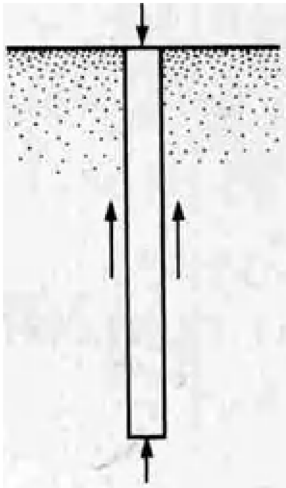


# 5.1.4 Types and loading conditions of pile foundations

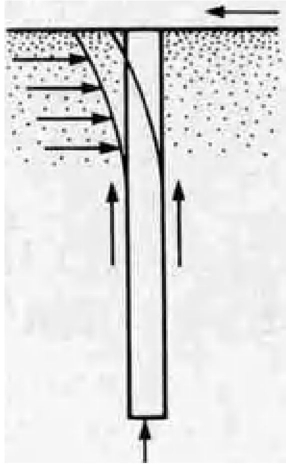
Das:



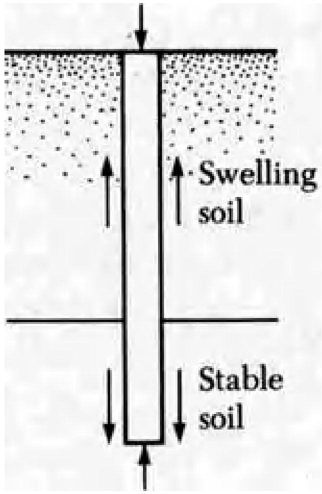

(a) End bearing pile（先端支持）



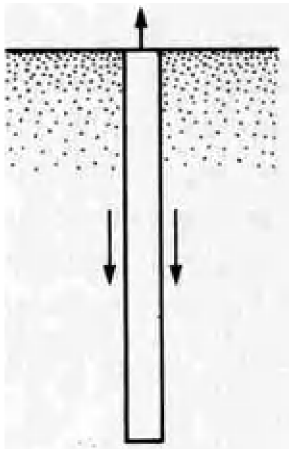
(b) Friction pile(摩擦）



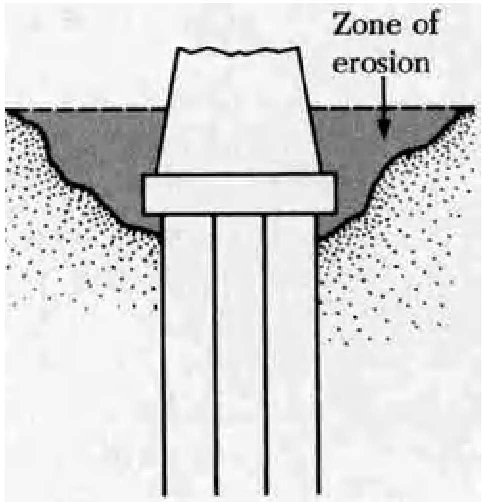
(c) Laterally loaded pile




(d) Pile in expansive or collapsible soil



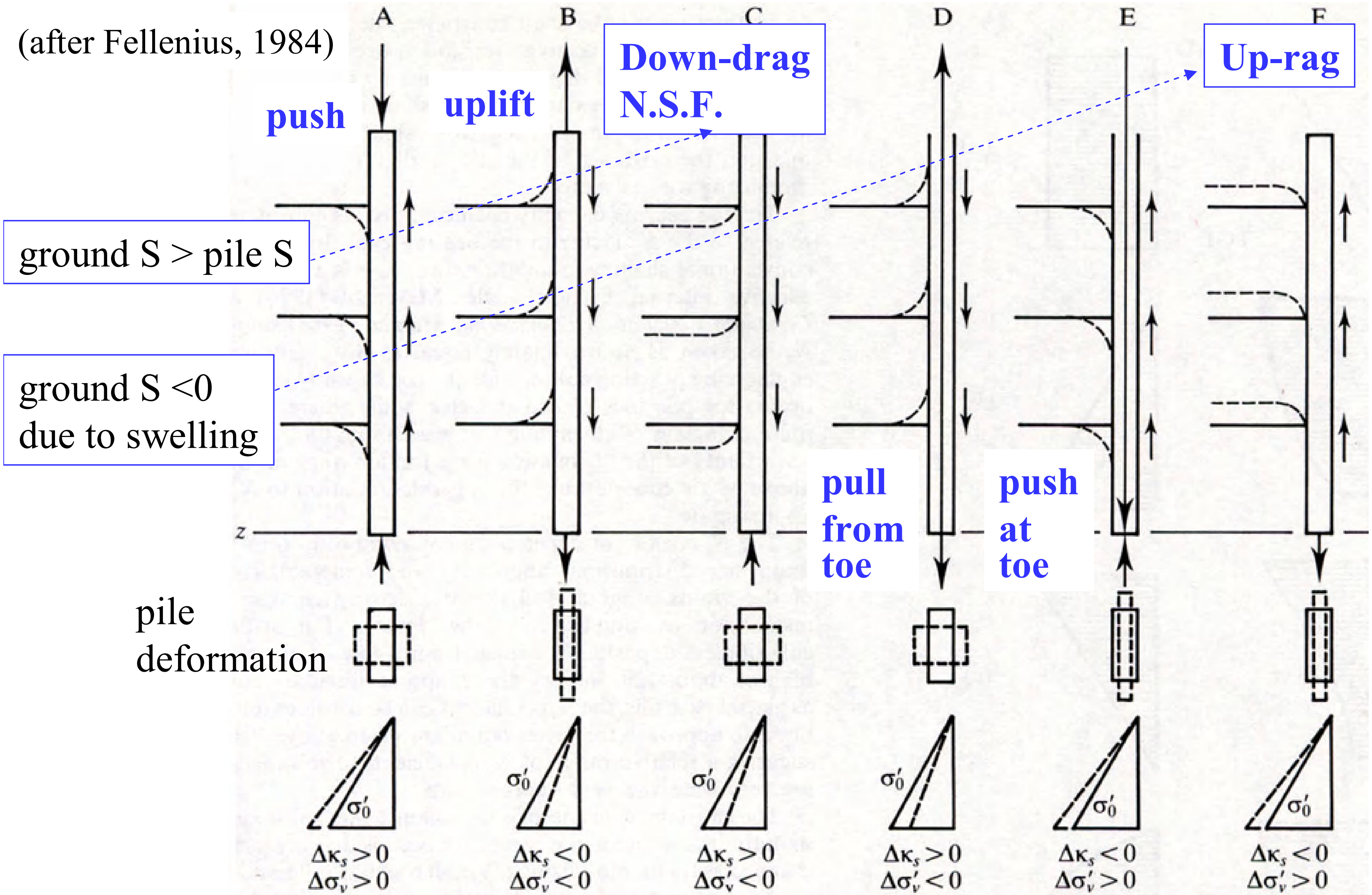
(e) Pullout pile（引抜）




(f) Pile against possible loss of bearing capacity

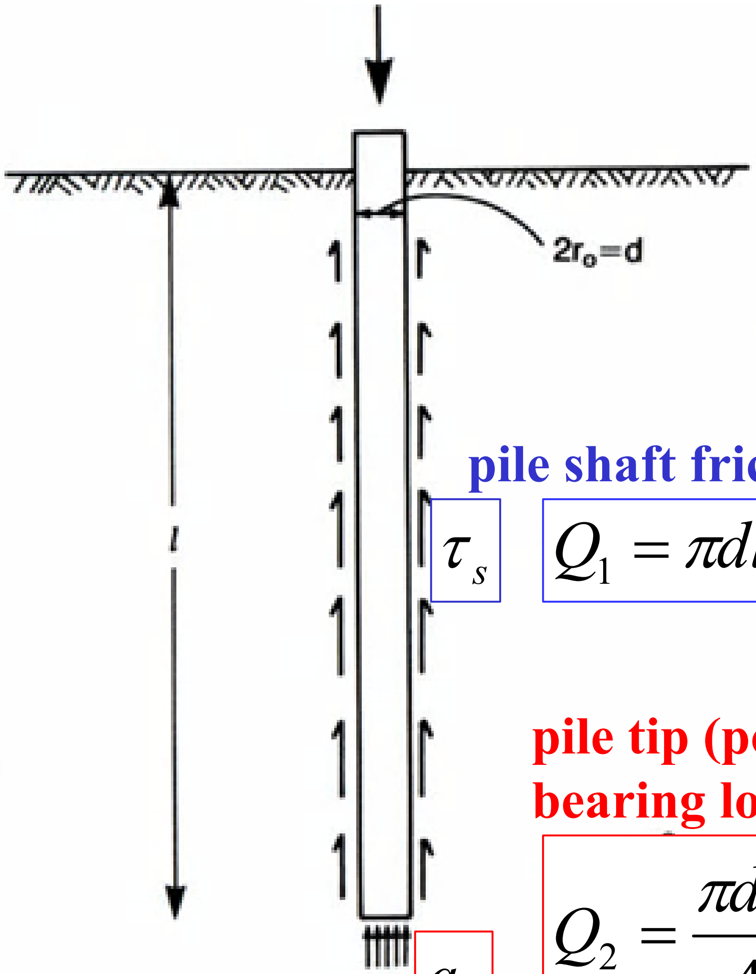
# Behavior mode of a pile subjected to six different axial conditions

(after Fellenius, 1984)



# 5.2 Vertical load - settlement relation

Q:load acting on pile top




**pile shaft friction**

$\tau_s$

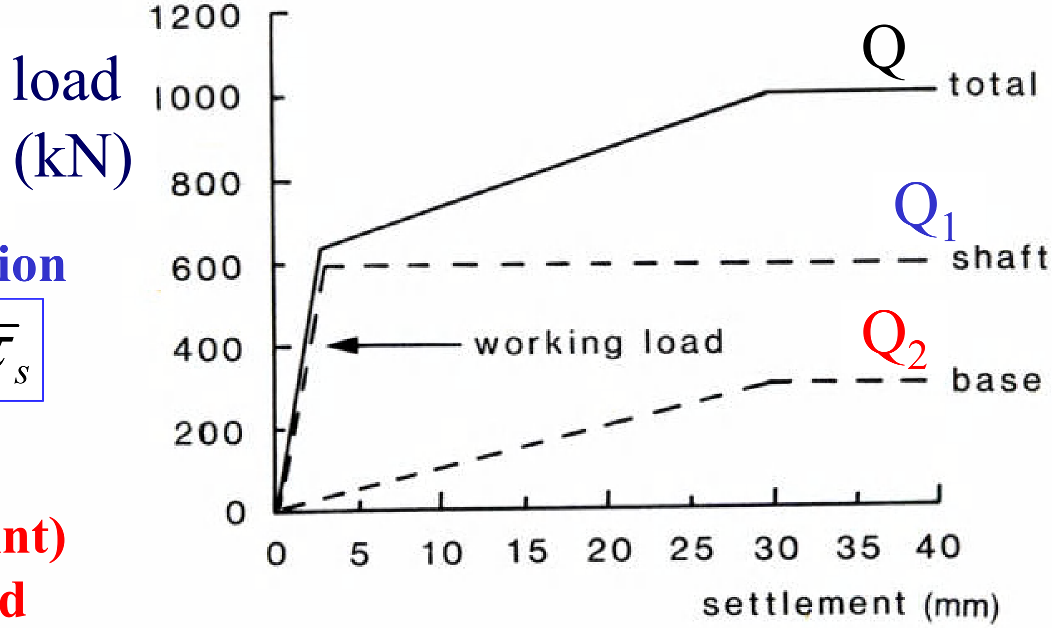
$$Q_1 = \pi d l \bar{\tau}_s$$

**pile tip (point) bearing load**

$$Q_2 = \frac{\pi d^2}{4} q_b$$

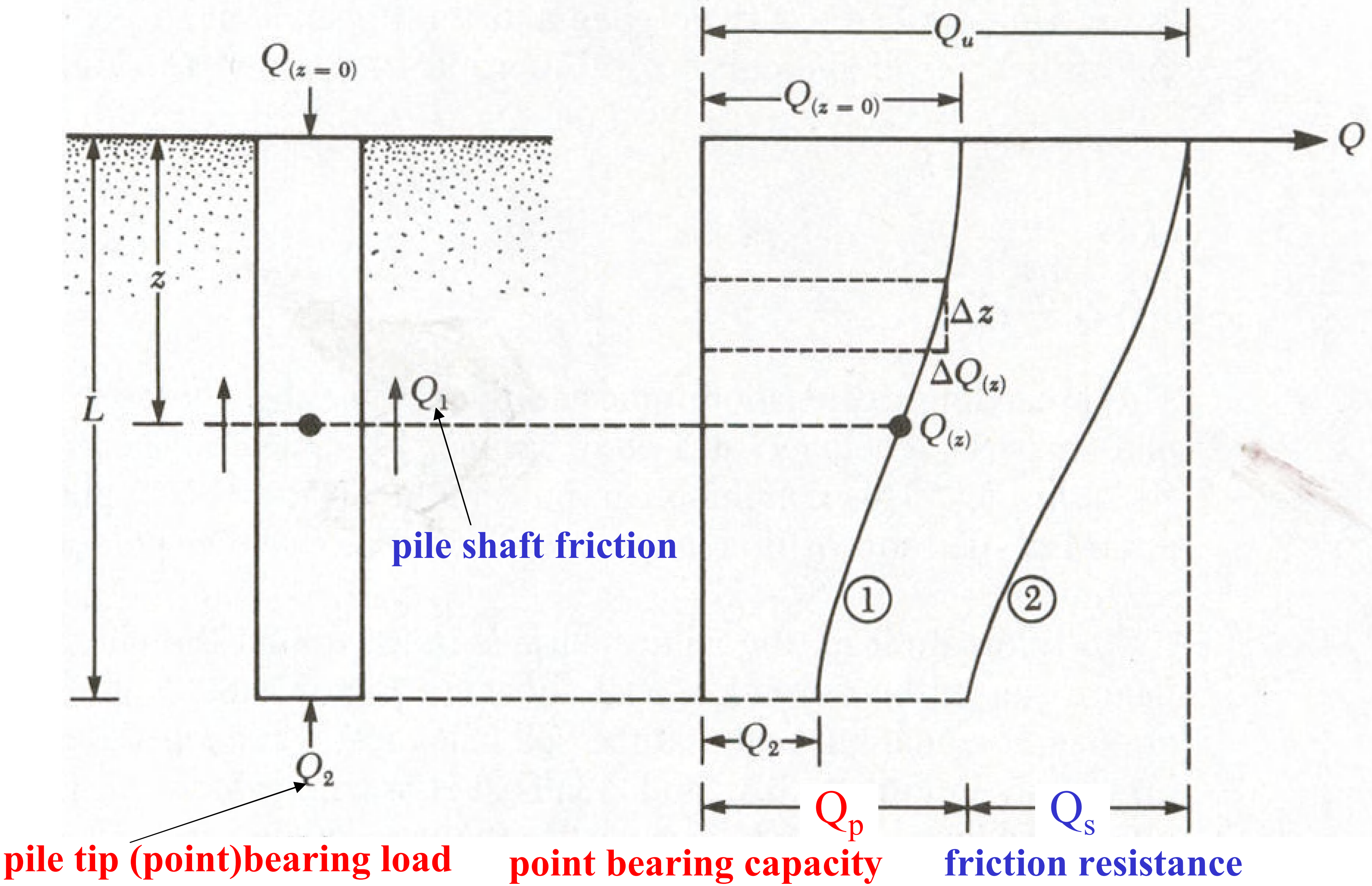
$q_b$

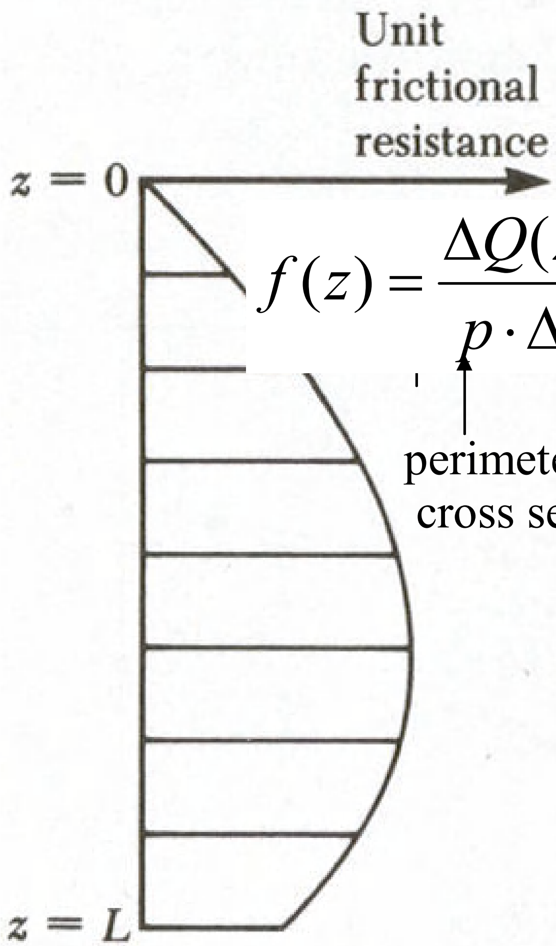
forces acting on axially loaded pile




Idealized load settlement response

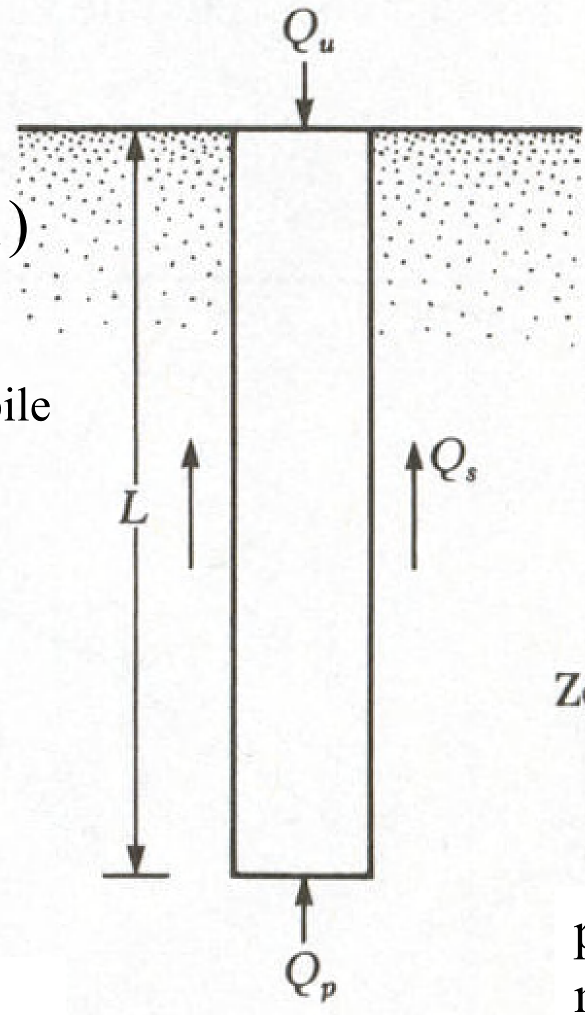
# 5.2 Vertical load transfer mechanism

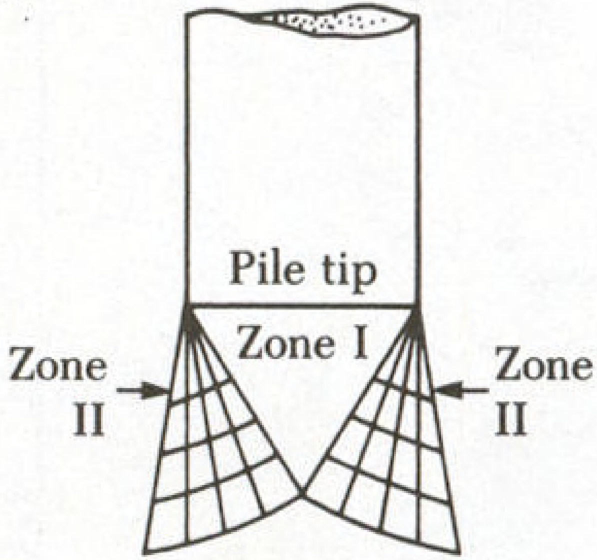





$$f(z) = \frac{\Delta Q(z)}{p \cdot \Delta z} \quad (1)$$

perimeter of pile cross section



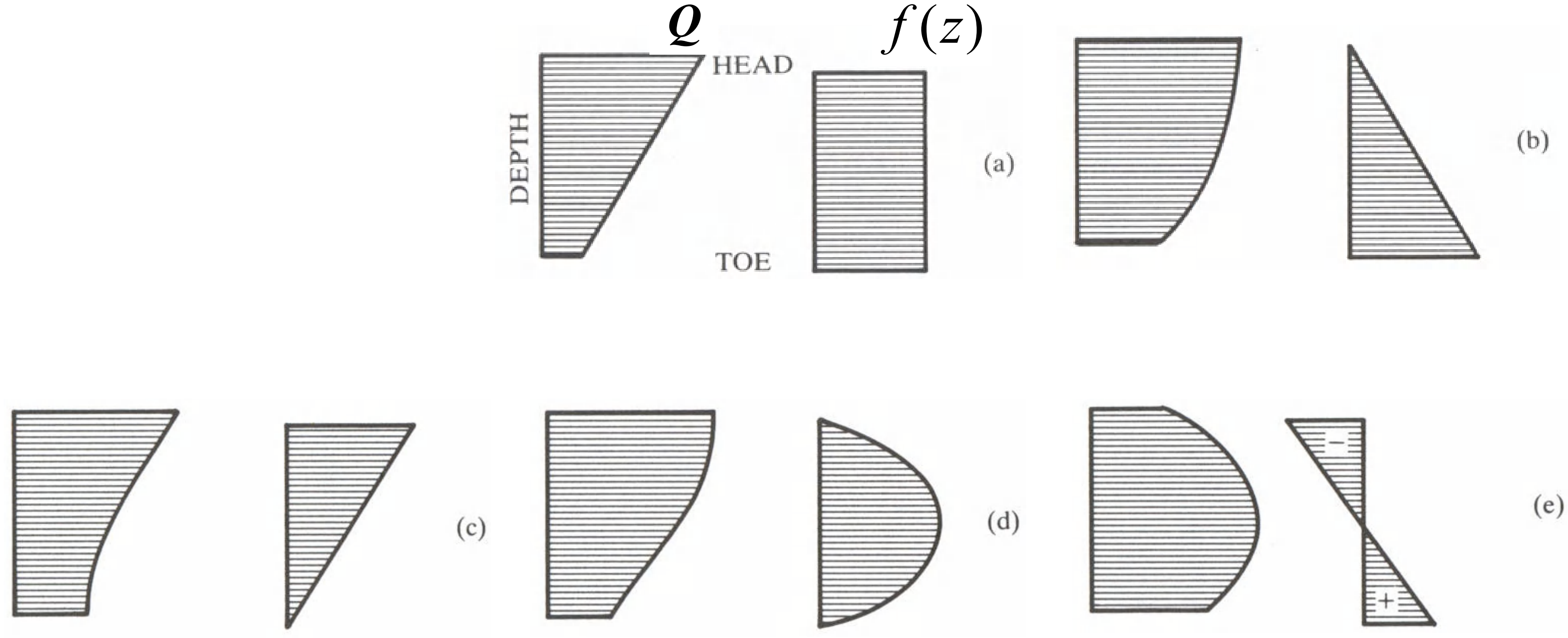

point bearing capacity mechanism: ***local shear***

**Unit frictional resistance**

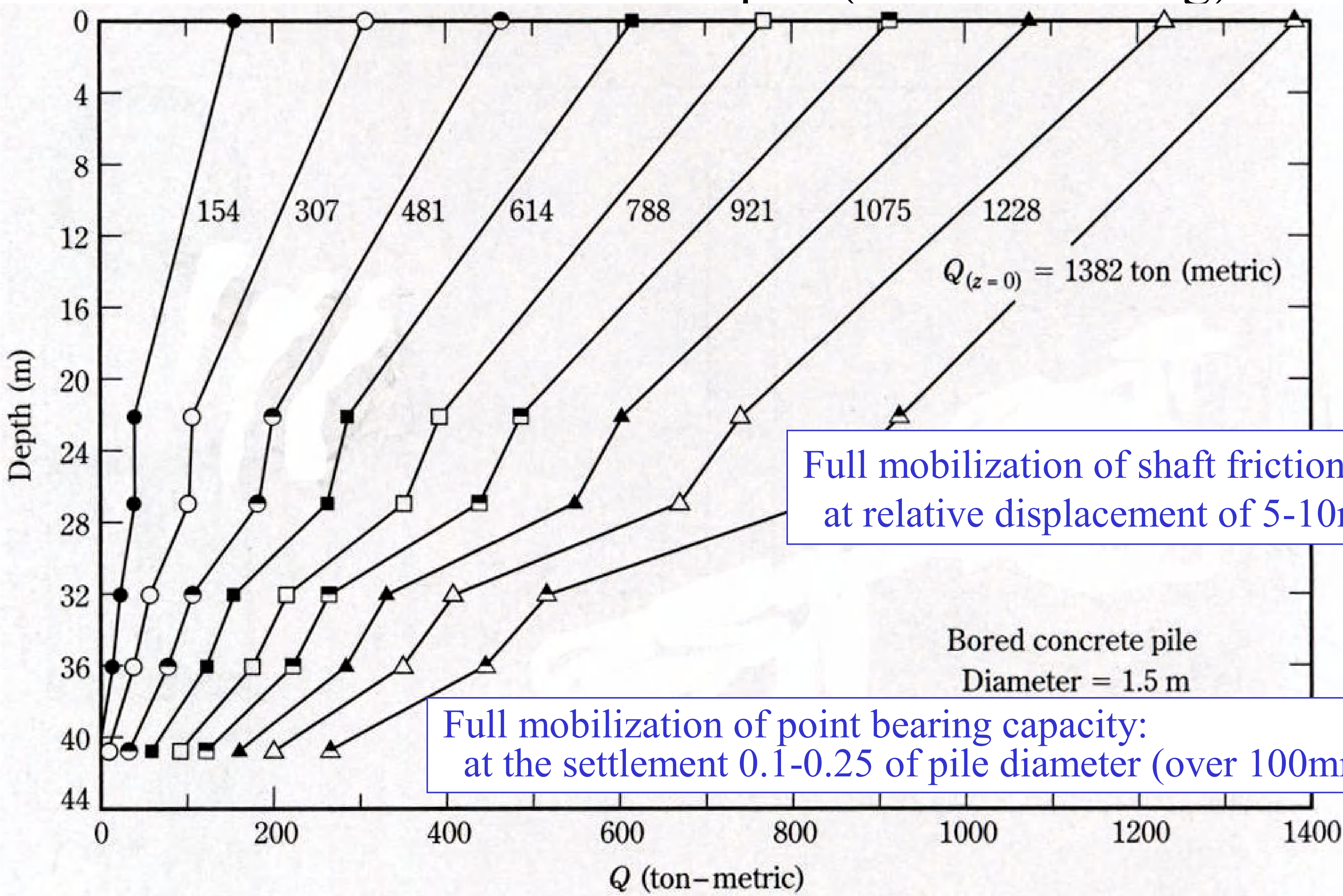
**=f(δ, $\sigma'_h$, relative displacement)**

# Load transfer functions for distributions of shaft resistance

**(Vesic,1970)**



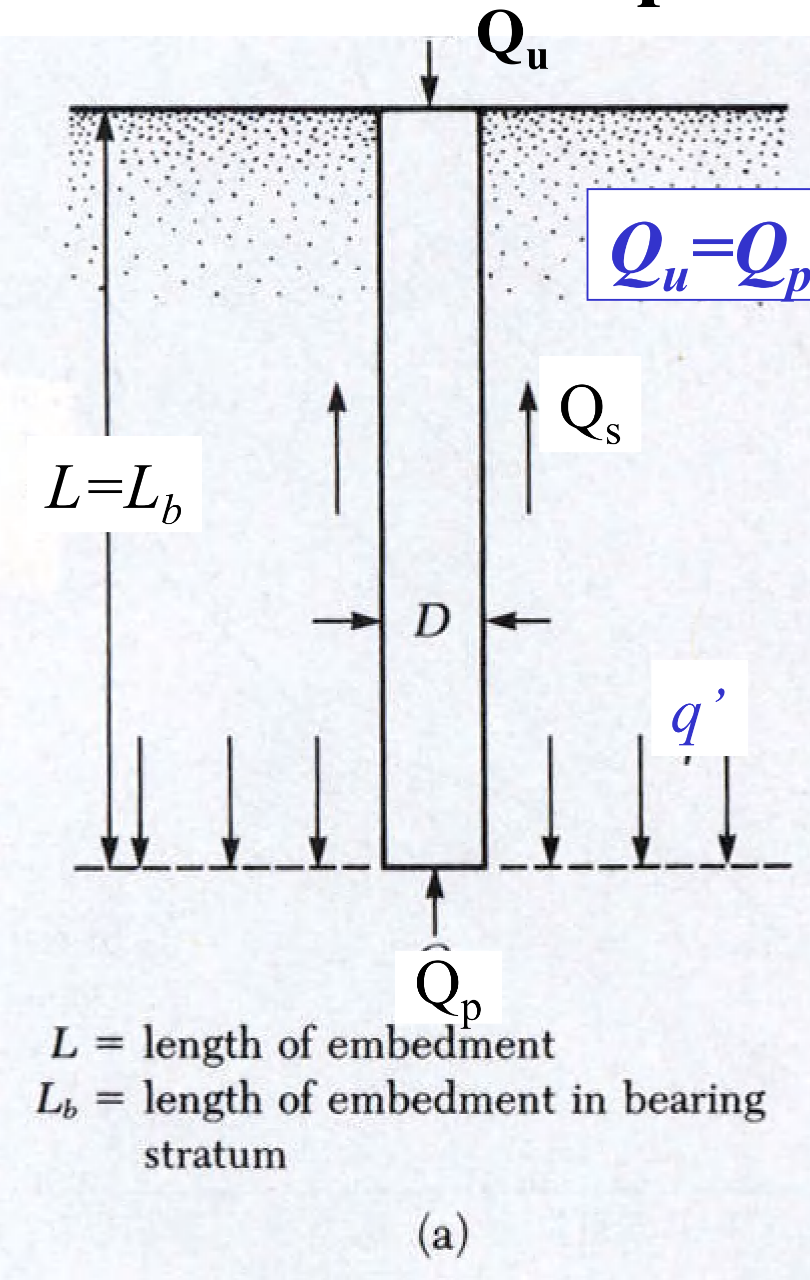
# Load transfer curves for a pile (Woo and Juang)



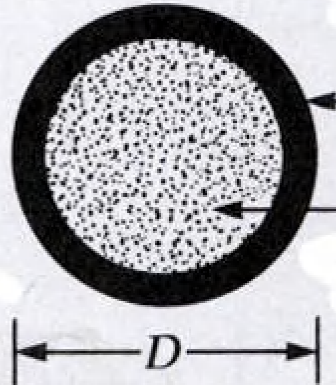

Full mobilization of shaft friction:
at relative displacement of 5-10mm

Full mobilization of point bearing capacity:
at the settlement 0.1-0.25 of pile diameter (over 100mm)

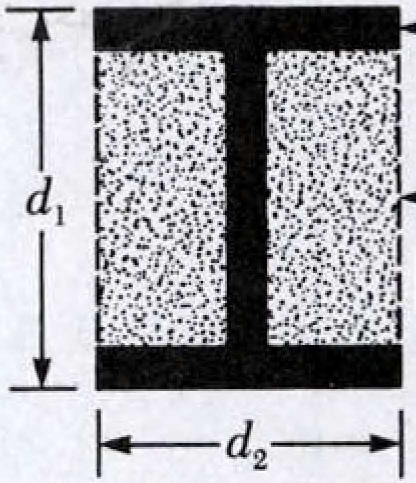
# 5.3 Estimation of pile capacity against vertical load




$$Q_u = Q_p + Q_s \quad (2)$$




(b) Open-end pipe pile section




(c) H-shape pile section

(*Note*: $A_p$=area of steel+soil plug)

# 5.3.1 Point bearing capacity, $Q_p$

Bearing capacity equation similar to that of shallow foundation:

$$Q_p / A_p = q_p = cN_c^* + q' N_q^* + \gamma D N_\gamma^* \quad (3)$$

$N^*_c$, $N^*_q$, $N^*_\gamma$: bearing capacity factors which include the shape and depth factors

***Pile:circular or square shape***

D << L => γD << γL=*q*'

$$(3) \Rightarrow \quad Q_p = A_p(cN_c^* + q' N_q^*) \quad (4)$$

Many method to evaluate the point bearing capacity,

Meyerhof (LEM, N-value:Das text book p 585,586)

Vesic (cavity expansion theory considering compressibility of soil

:Das text book p 587,589)

Janbu (LEM:Das text book p 589,590)

# 5.3.2 Friction resistance, $Q_s$

From the equation of unit friction resistance (eq.(1)),

$$Q_s = \sum p \Delta L f_{(z)} \qquad (5)$$

$$f_{(z)} = \sigma'_h \tan \delta \qquad (6)$$

$\delta$: surface roughness, $\sigma'_h$: lateral stress

$$\sigma'_h = K \sigma'_v$$

$\delta$ and $\sigma'_h$ may be affected by several factors,

***what is proper K?***

*pile type*:

*pile installation method*: the higher displacement, the higher $\sigma'_h$

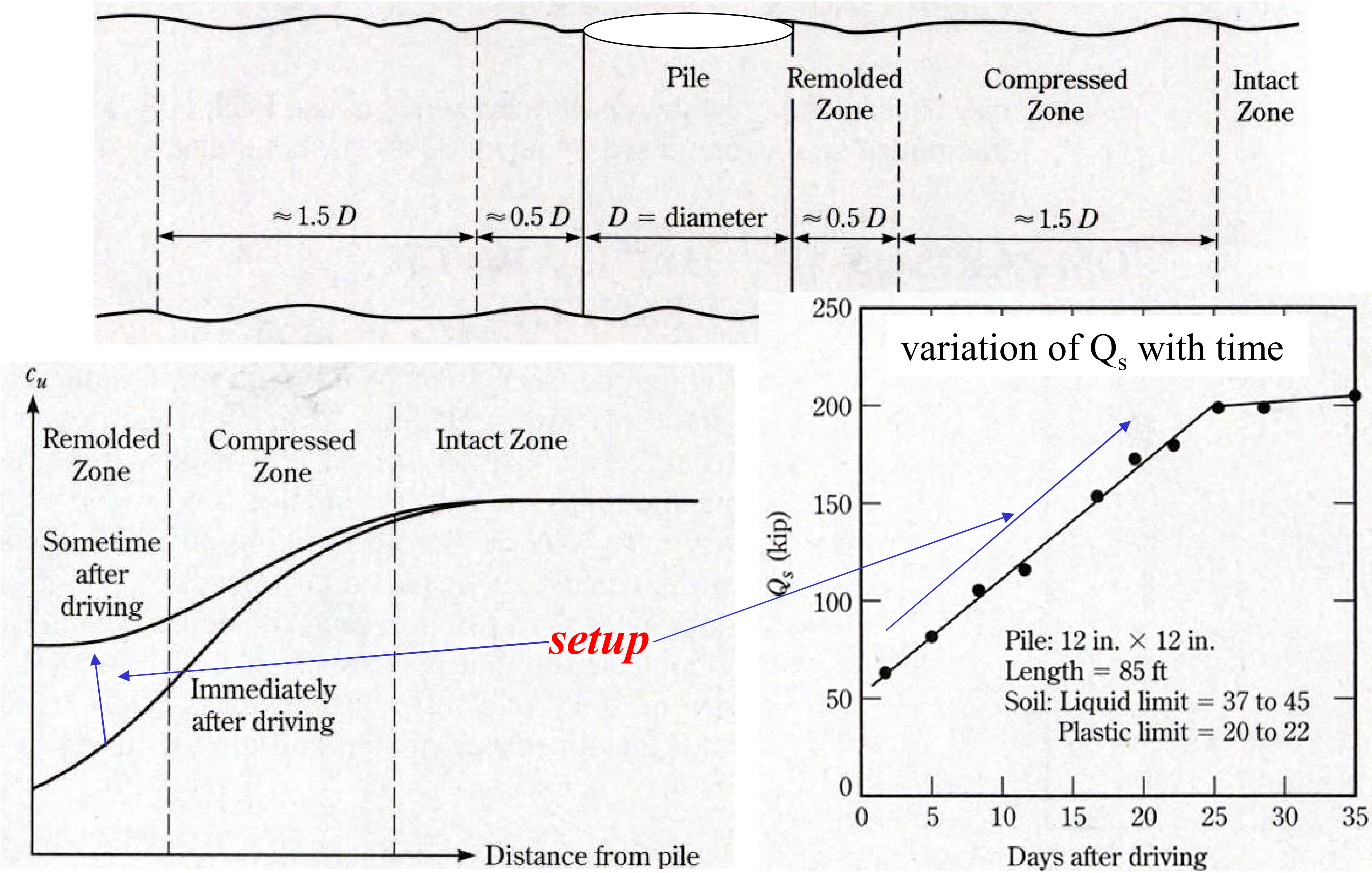
*soil conditions*:the higher density, the higher $\delta$ and $\sigma'_h$

the larger OCR, the larger $K_0$

*time*:consolidation

many proposals both for sand and clay :see Das text book

# time effects




Variation of $c_u$ with time

# 5.4 Other important evaluations for pile foundation

1. **Settlement** = settlement of pile tip + compression of pile
2. **Negative skin friction**: large settlement of surrounding ground due to consolidation => direction of relative displacement becomes negative and $\Delta Q_s < 0$
3. **Pullout resistance:** $T_{ug} = \underline{T_{un}} + W$

   net resistance: ***adhesion or friction***
4. **Lateral resistance**: load

   -active pile

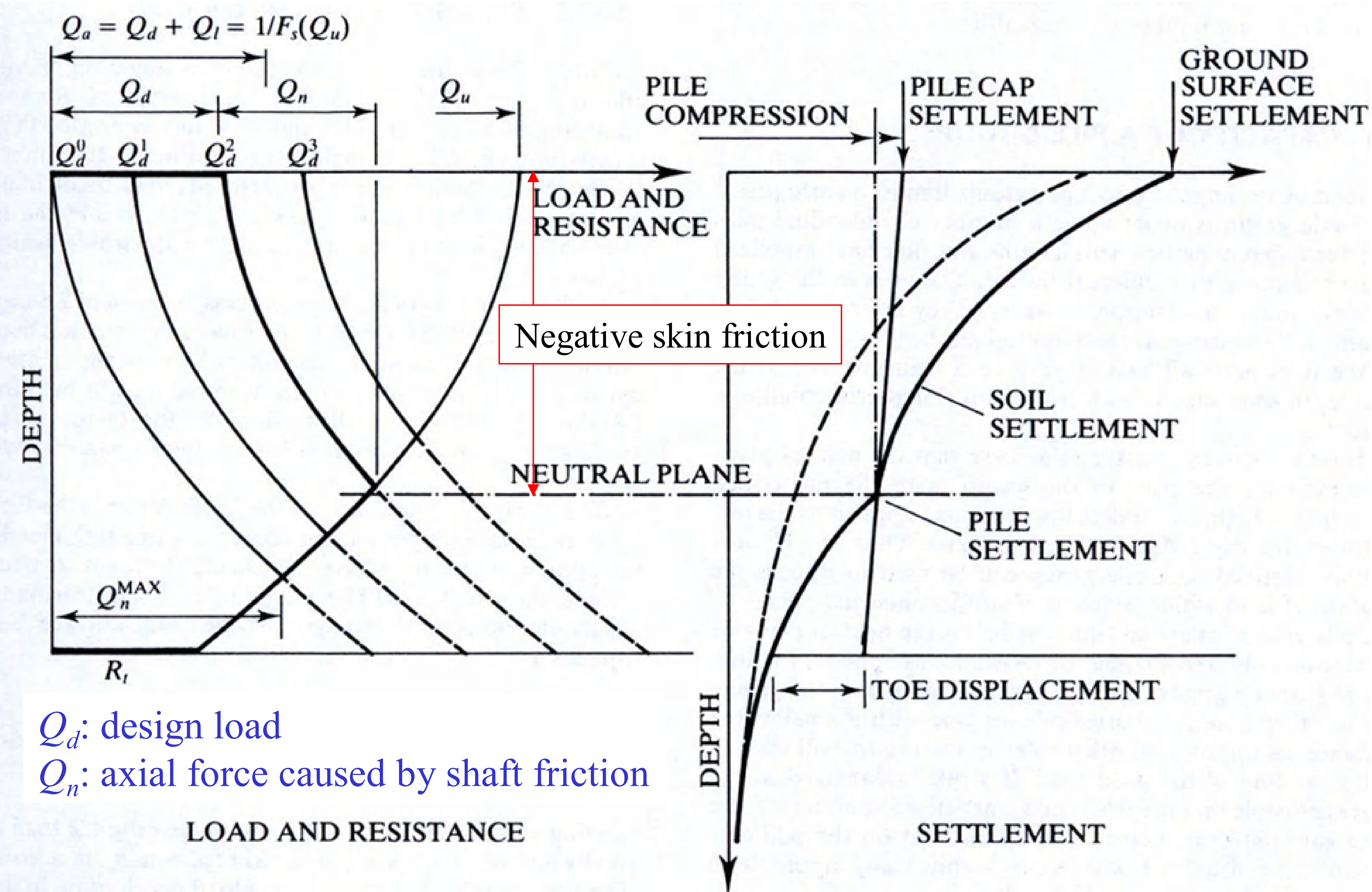
   (external load from superstructure by wind and earthquake)

   -passive pile (large lateral movement of the surrounding ground)

   elastic solution for deflection
   plastic theory for ultimateload
5. **Pile group effect**: interaction between piles => group efficiency

   η = (contribution of one pile in group pile) / (single pile)

Diagram of load and resistance and of settlement showing dependence of settlement on the location of neutral plane. (After Fellenius)

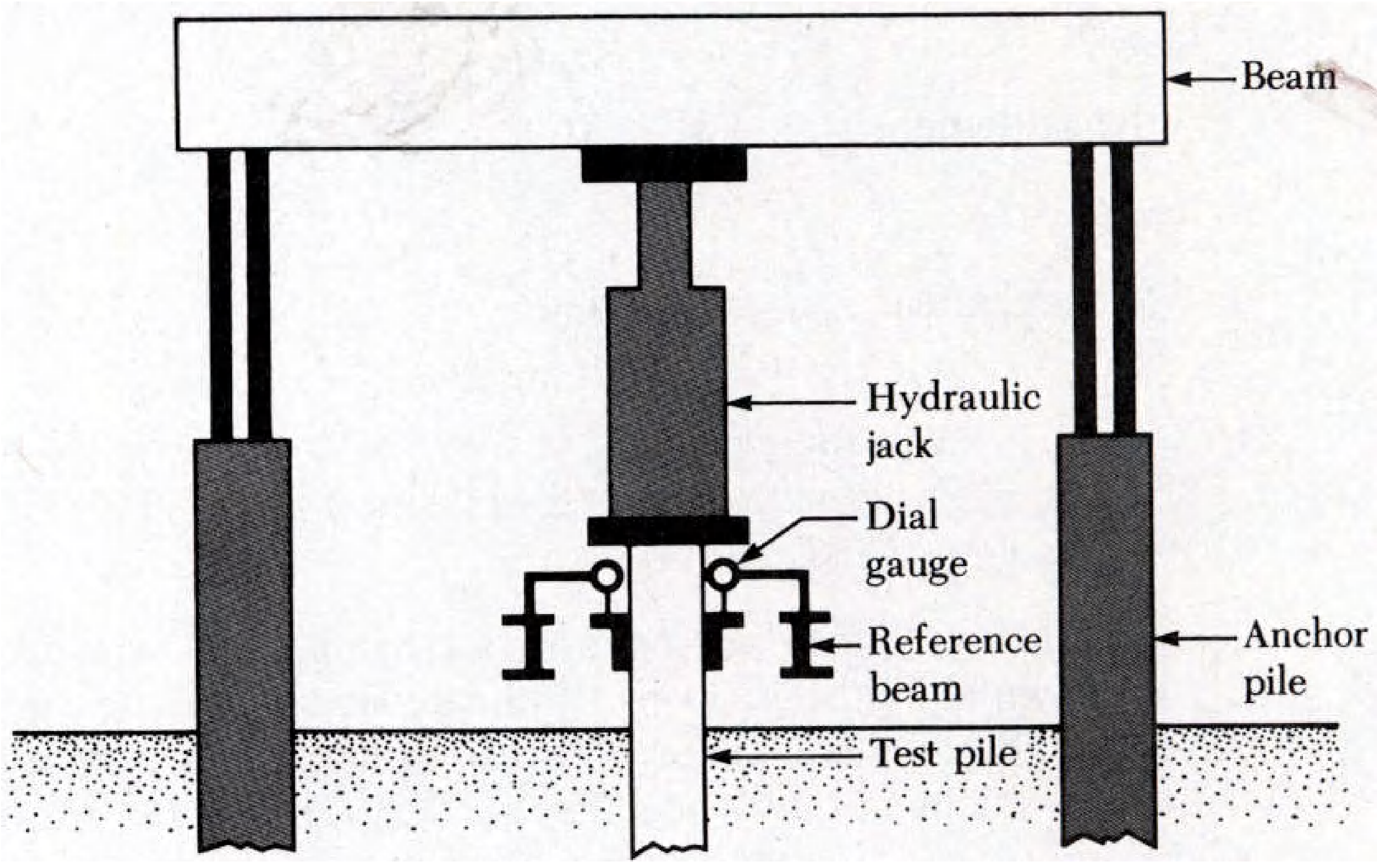



$Q_d$: design load

$Q_n$: axial force caused by shaft friction

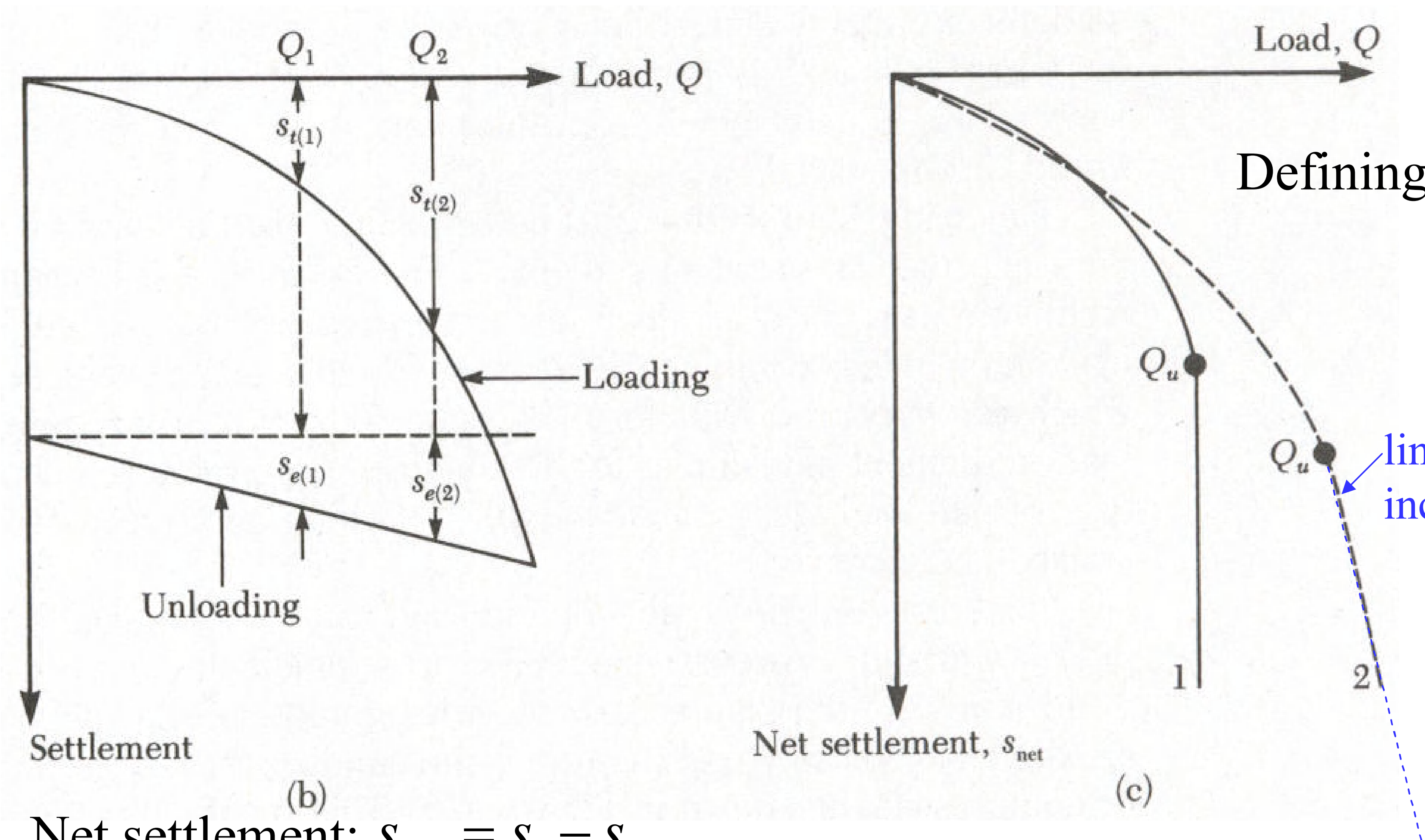
# 5.5 Confirmation of bearing capacity of pile:

Pile load tests: Das text



# Typical load settlement relation in pile loading test

Das text



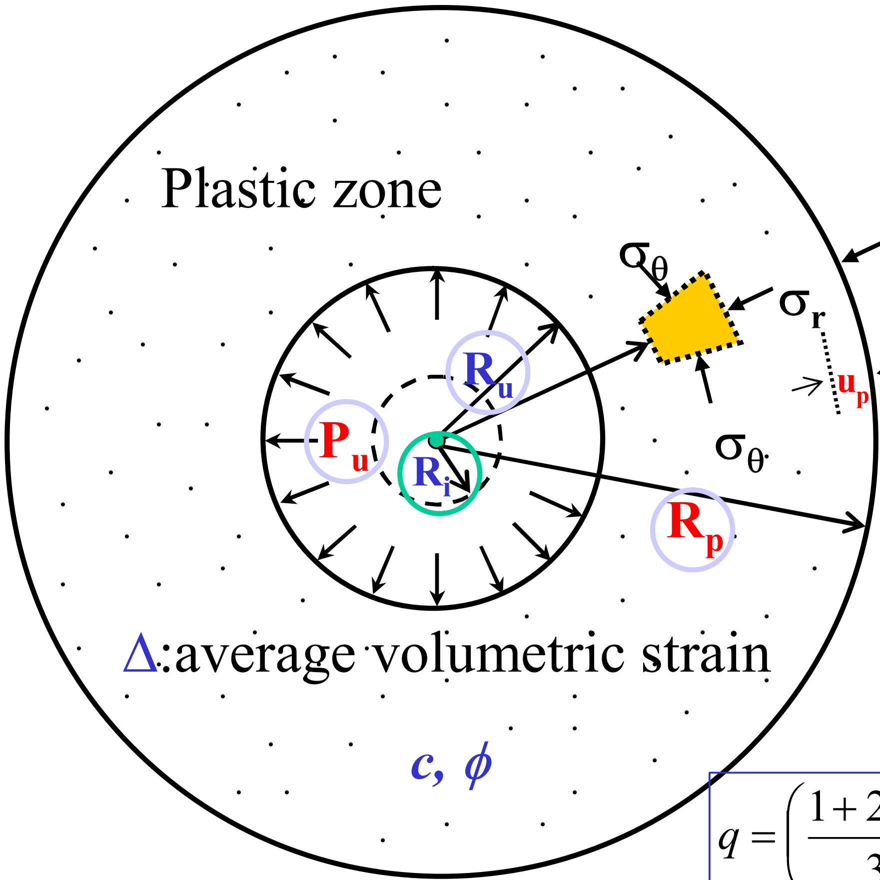

Net settlement: $s_{net} = s_t - s_e$

# Other pile loading tests

- Static test (conventional, Osterburg sampler)
- Stanamic test (using explosion)
- Dynamic test (impact force)

# Expansion of Cavity in infinite soil by Vesic (1972)

Elastic zone: *E, ν*




$$q = \left( \frac{1 + 2K_0}{3} \right) \sigma_v$$

**Problem of spherical cavity**

***-Equilibrium(1)***

$$\frac{\partial \sigma_r}{\partial r} + 2\frac{\sigma_r - \sigma_\theta}{r} = 0$$

***-Failure criterion (2)***

$$(\sigma_r - \sigma_\theta) = (\sigma_r + \sigma_\theta)\sin\phi + 2c\cos\phi$$

***-Stress Boundary Condition+(1)(2)***

$$\sigma_r = P_u \text{ for } r = R_u$$

$$\sigma_r = (p_u + c\cot\phi)\left(\frac{R_u}{r}\right)^{\frac{4\sin\phi}{(1+\sin\phi)}} - c\cot\phi$$

$$\phi = 0 \Rightarrow \quad \sigma_r = p_u - 4c\ln\frac{r}{R_u}$$

***-change of cavity volume=>***

$$R_u^3 - R_i^3 = R_p^3 - (R_p - u_p)^3 + (R_p^3 - R_u^3)\Delta$$

***-radial displacement at P-E B. $u_p$ =>***

**Lame's solution** $$u_p = \frac{1+\nu}{2E} R_p (\sigma_p - q)$$

Stress increment

$$P_u = \left(\frac{R_p}{R_u}\right)^{\frac{4\sin\phi'}{(1+\sin\phi')}} \frac{3(q + c\cot\phi)(1+\sin\phi')}{3-\sin\phi'} - c\cot\phi$$

$$\Downarrow \leftarrow \sqrt[3]{1+\Delta} \approx 1, \quad (3-\sin\phi)/3\cos\phi \approx 1$$

⇦ insignificant error

($\Delta$<0.15 and 0<$\phi$<$45^0$)

$$P_u = cF_c + qF_q$$

$$F_q = \frac{3(1+\sin\phi')}{3-\sin\phi'}(I_{rr})^{\frac{4\sin\phi'}{3(1+\sin\phi')}}$$

$$F_c = (F_q - 1)\cot\phi$$

$$I_r = \frac{E}{2(1+\nu)(c+q\tan\phi)} = \frac{G}{s}: \text{ Rigidity index}$$

$$I_{rr} = \frac{I_r}{1+I_r\Delta}: \quad \text{Reduced rigidity index}$$

$\phi$=0, ($\Delta$=0)

$$P_u = cF_c + qF_q$$

$$F_q = 1$$

$$F_c = \frac{4}{3}(\ln I_r + 1)$$

$$P_u \equiv f(\phi, \Delta, I_r)$$

***$\phi$,$\Delta$, G are all stress dependent***