



# Soil – Pipeline Interaction

## development of p-y analysis: some challenges

Prof. George Mylonakis  
Head of Earthquake & Geotechnics Research Group  
University of Bristol, UK



# Outline

- Introduction
- Load types
- p-y curves (review of theory for piles)
- Summary of main research challenges

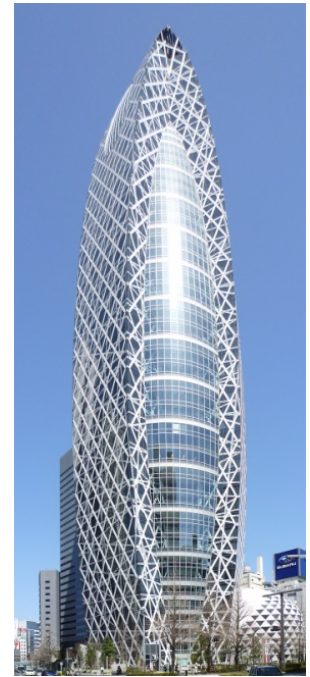


# Structural Engineering





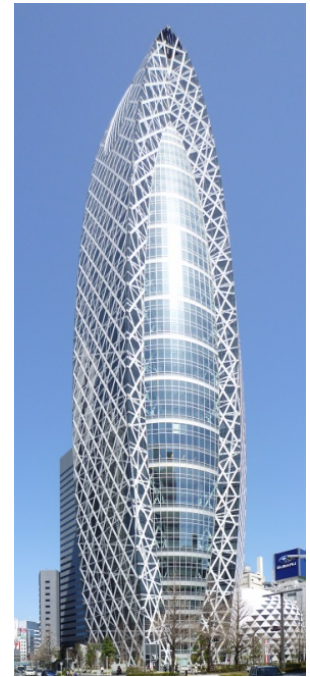
# Structural Engineering





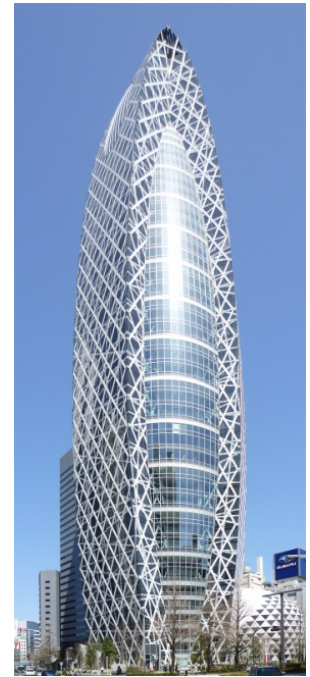
Structural  
Engineering

Geotechnical  
Engineering





Structural  
Engineering



Geotechnical  
Engineering

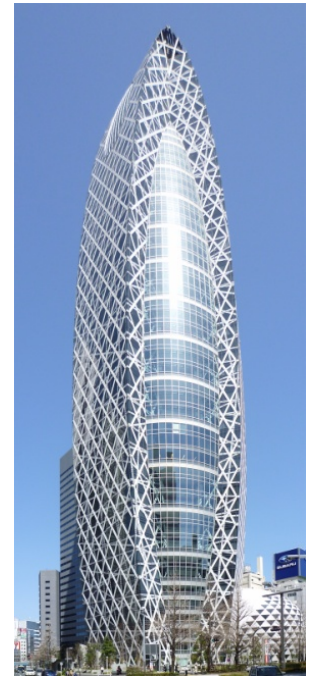




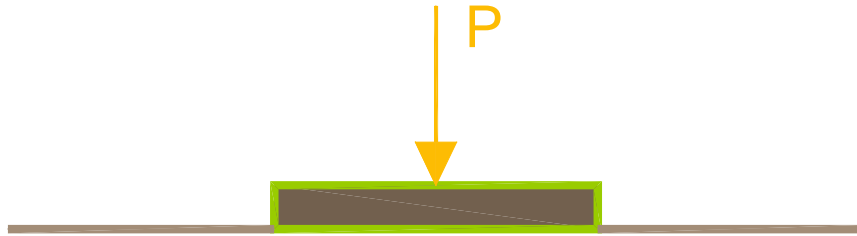
Structural  
Engineering

**SSI**

Geotechnical  
Engineering



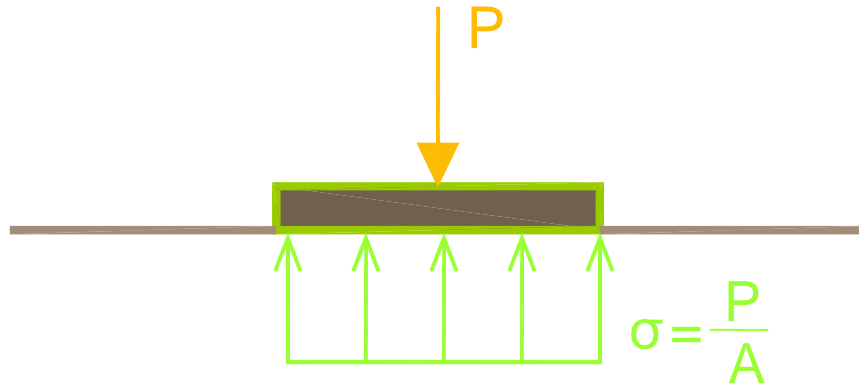
# SSI in Classical & Earthquake Geotechnics



Footing



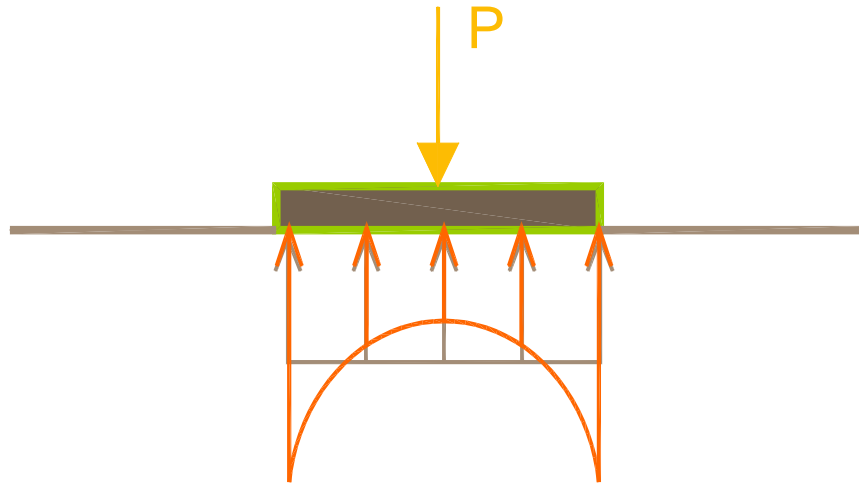
# SSI in Classical & Earthquake Geotechnics



Footing



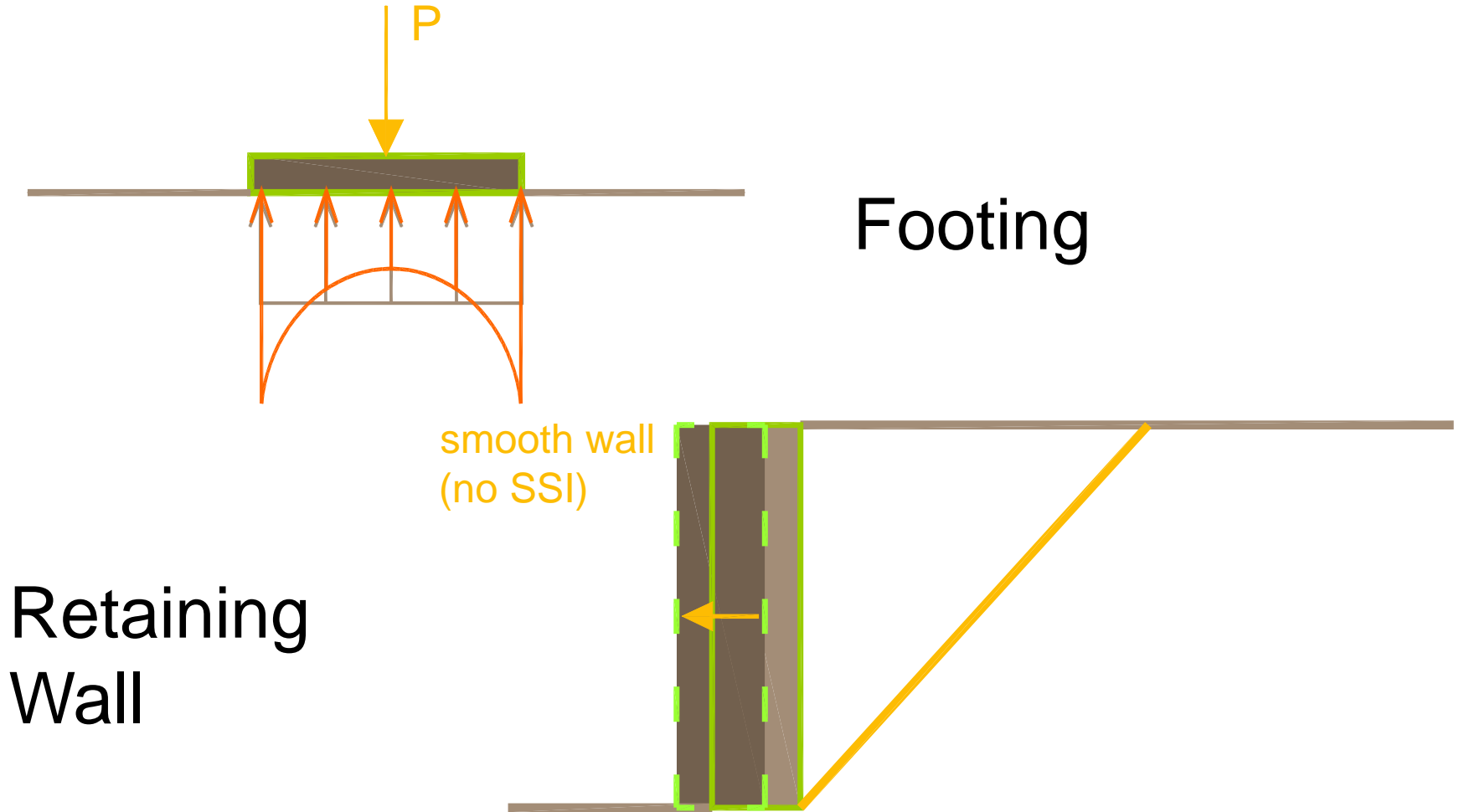
# SSI in Classical & Earthquake Geotechnics



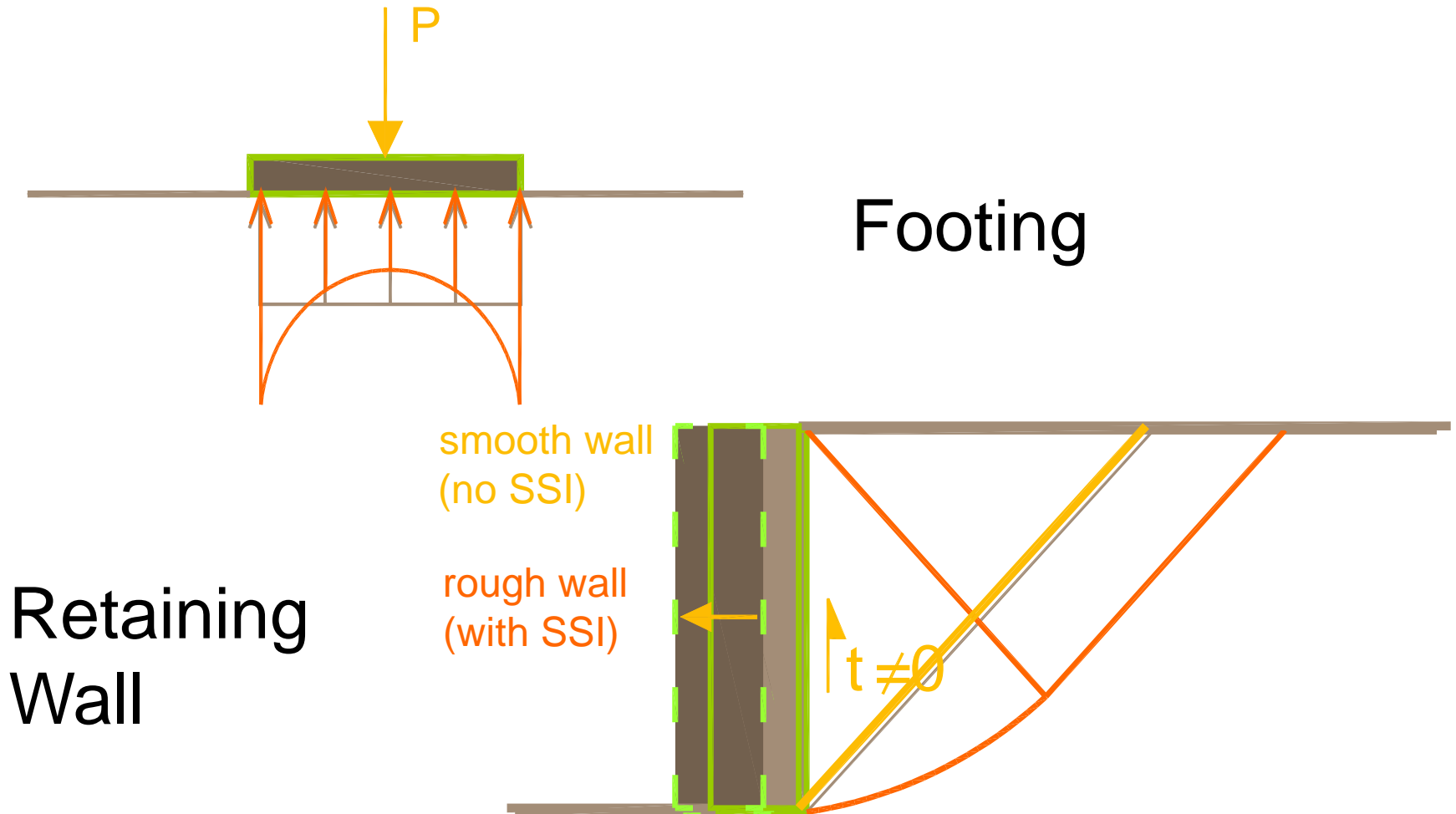
Footing



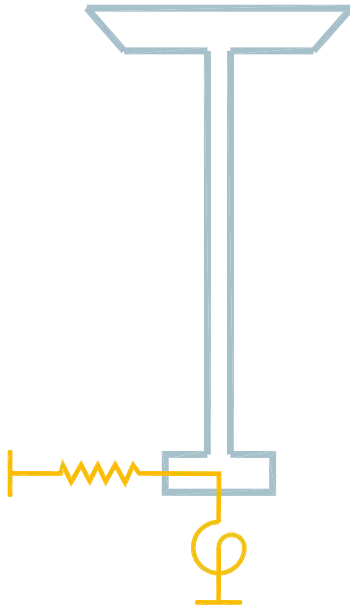
# SSSI in Classical & Earthquake Geotechnics



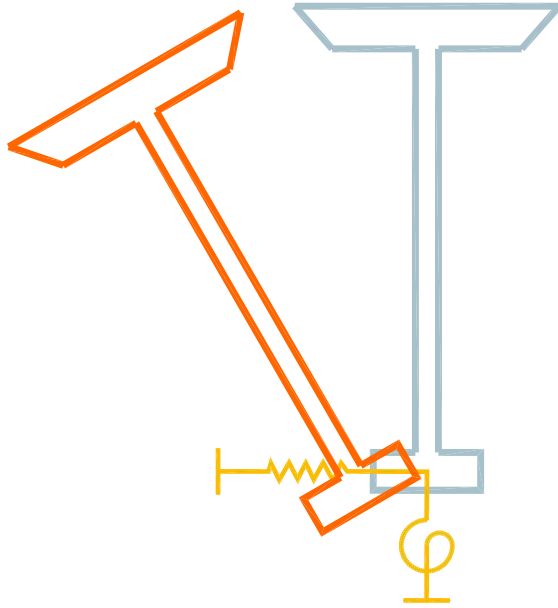
# SSI in Classical & Earthquake Geotechnics



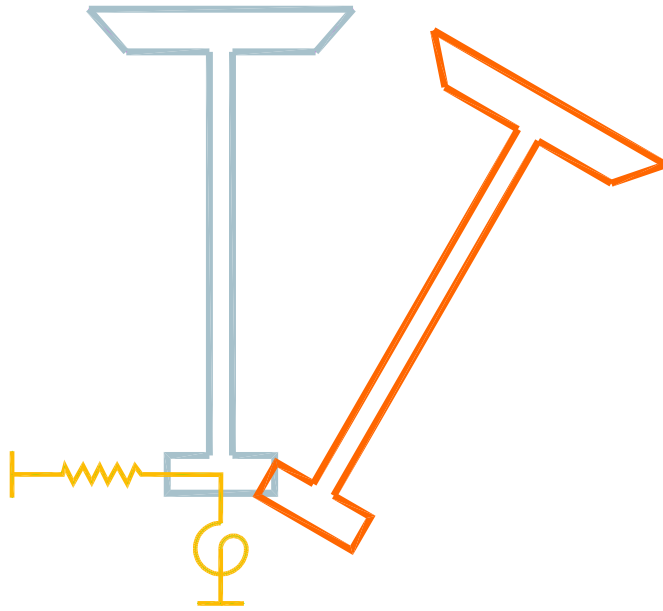
# Bridge



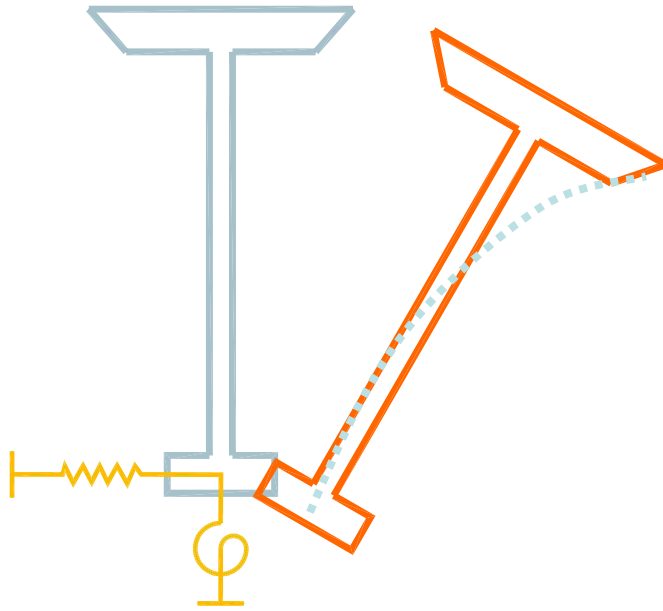
# Bridge



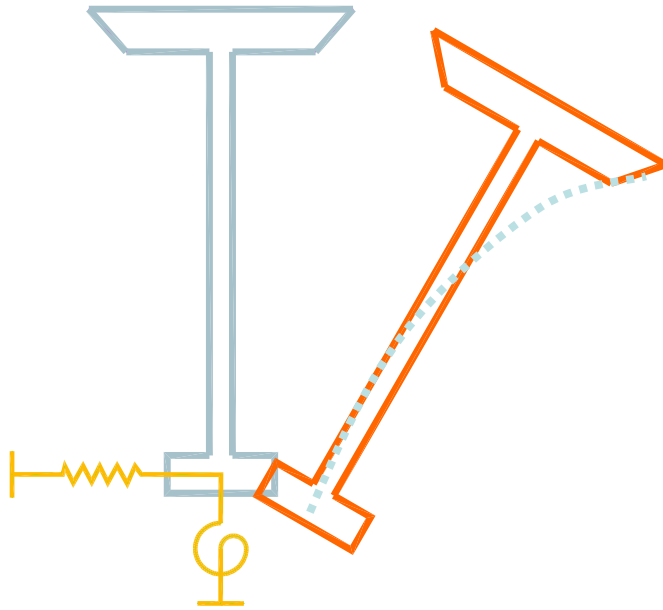
# Bridge



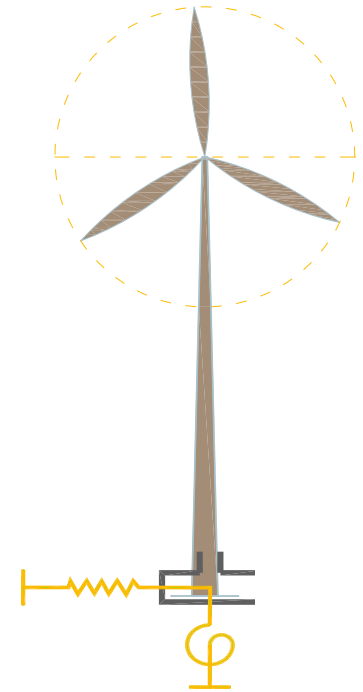
# Bridge



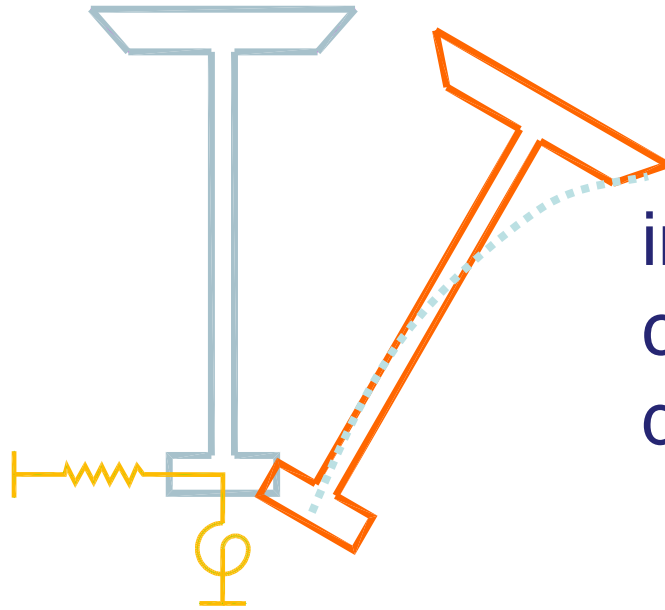
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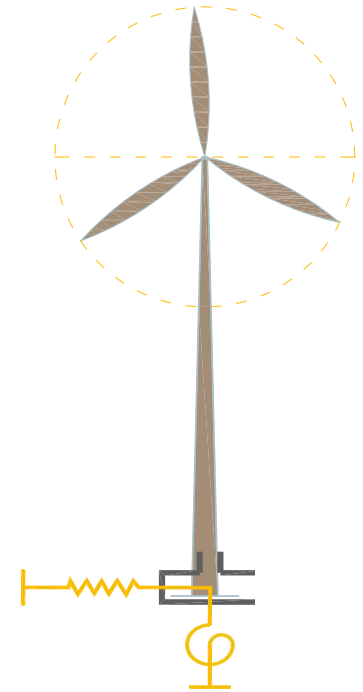
# Wind Turbine



# Bridge

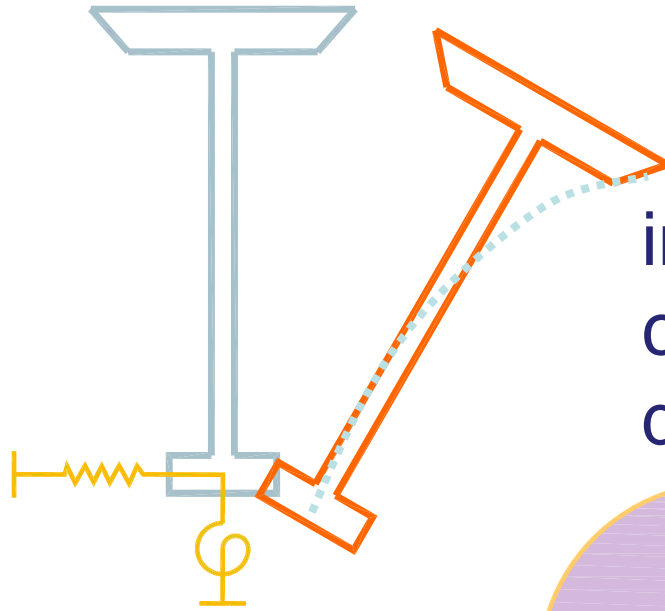


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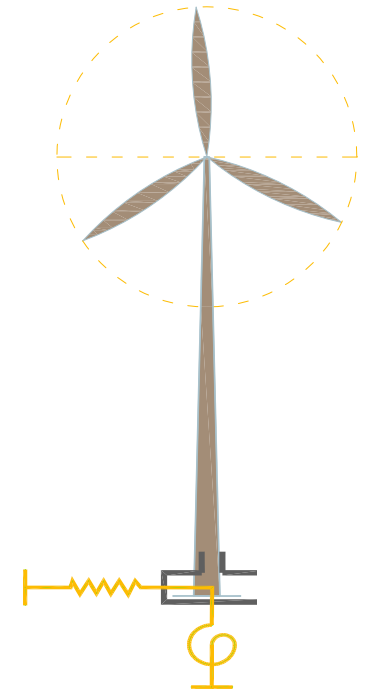


increased  
compliance &  
damping

Bridge

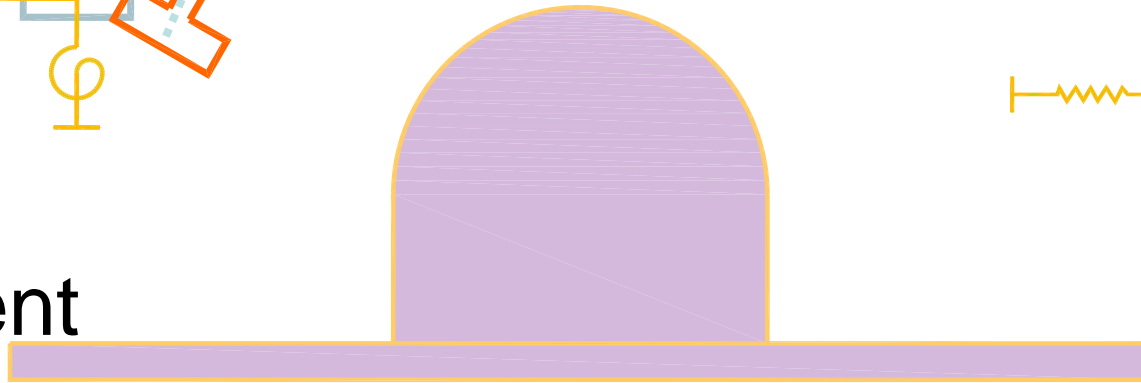


Wind Turbine

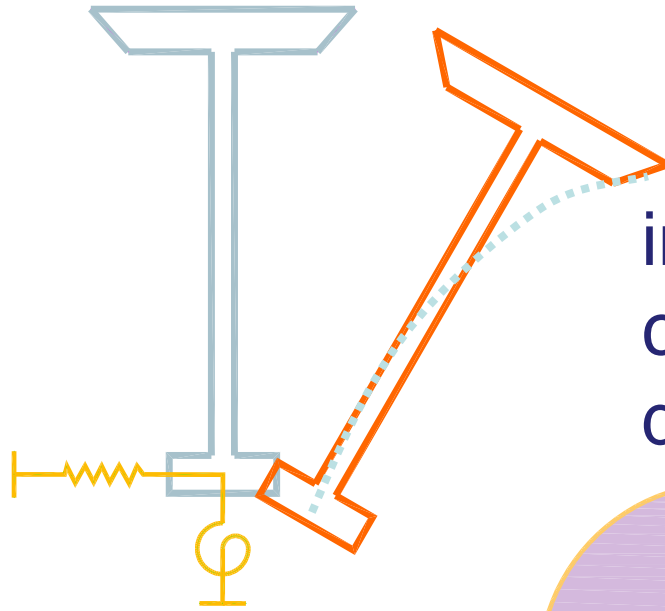


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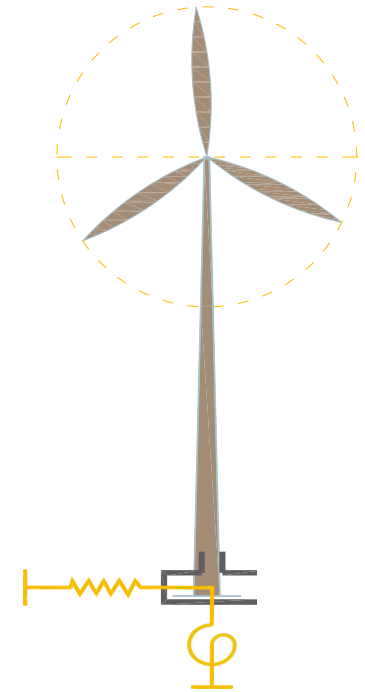
Nuclear  
Containment  
Structure



Bridge

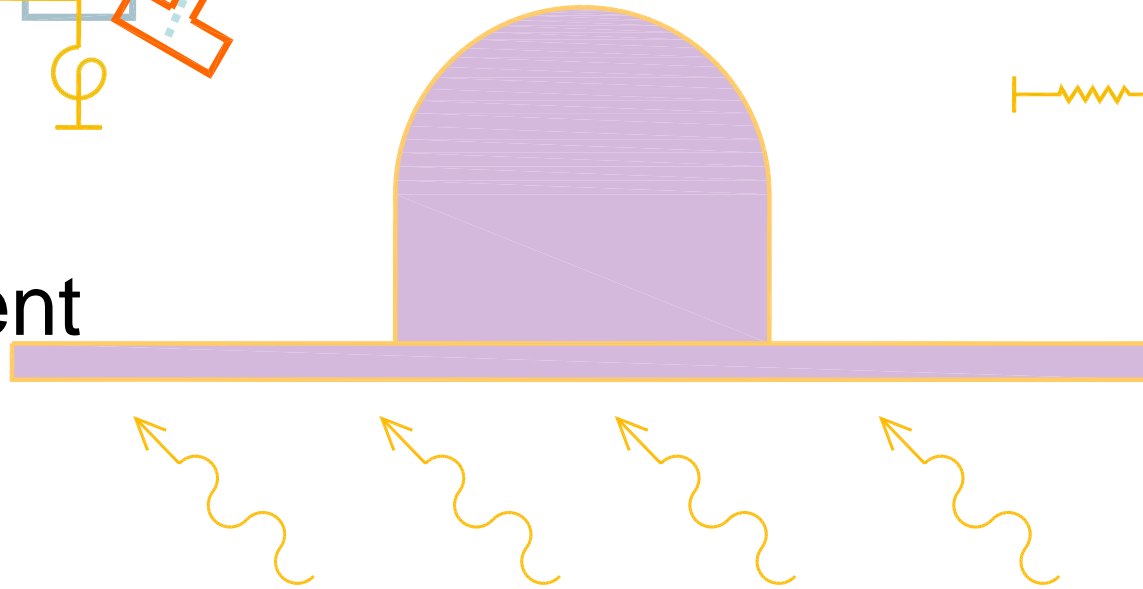


Wind Turbine

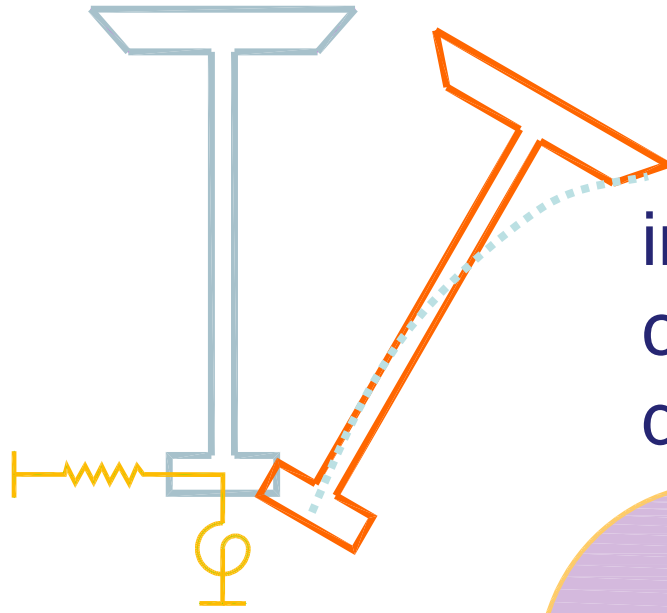


increased compliance & damping

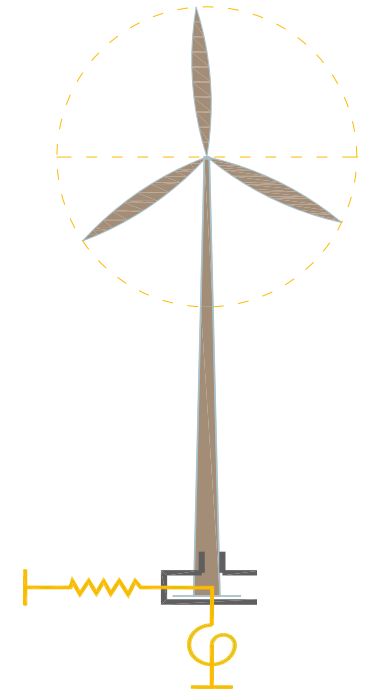
Nuclear Containment Structure



Bridge

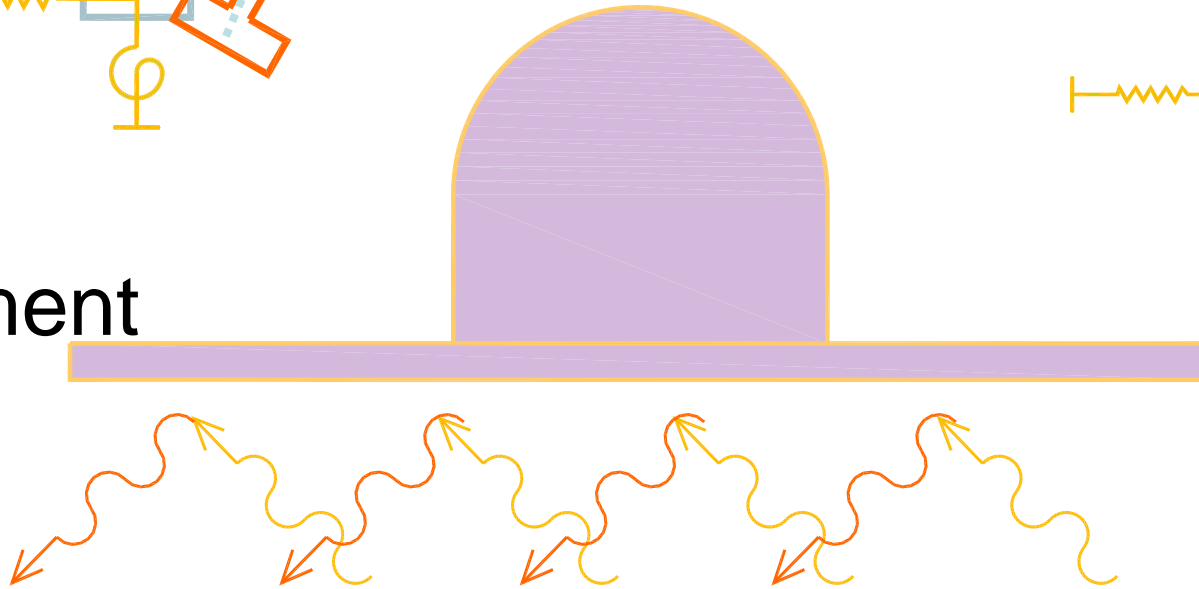


Wind Turbine

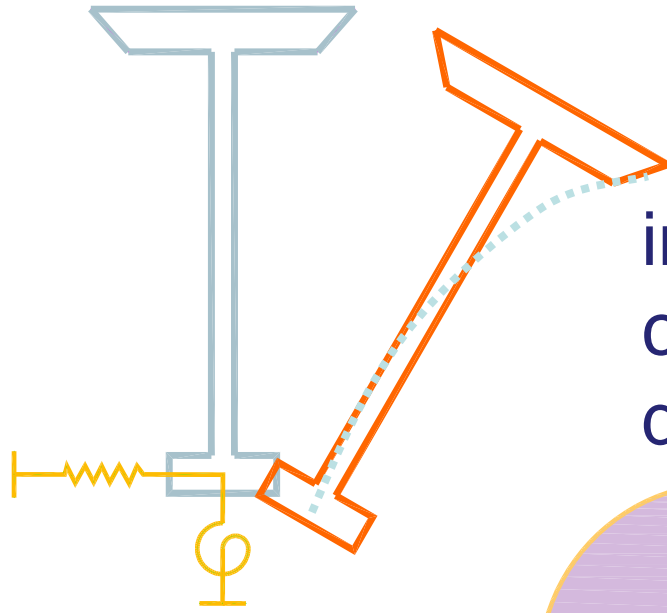


increased compliance & damping

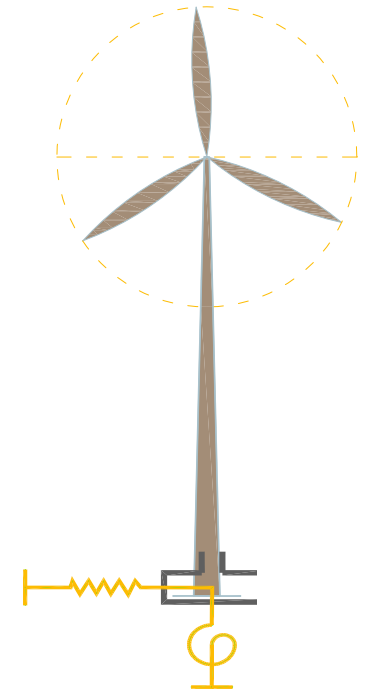
Nuclear Containment Structure



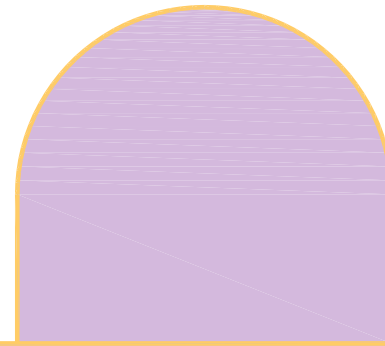
Bridge



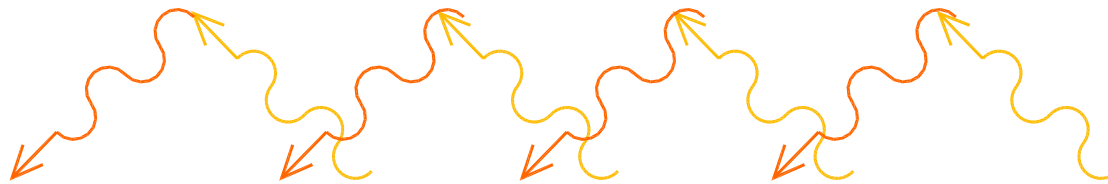
Wind Turbine



increased compliance & damping



Nuclear Containment Structure



wave scattering

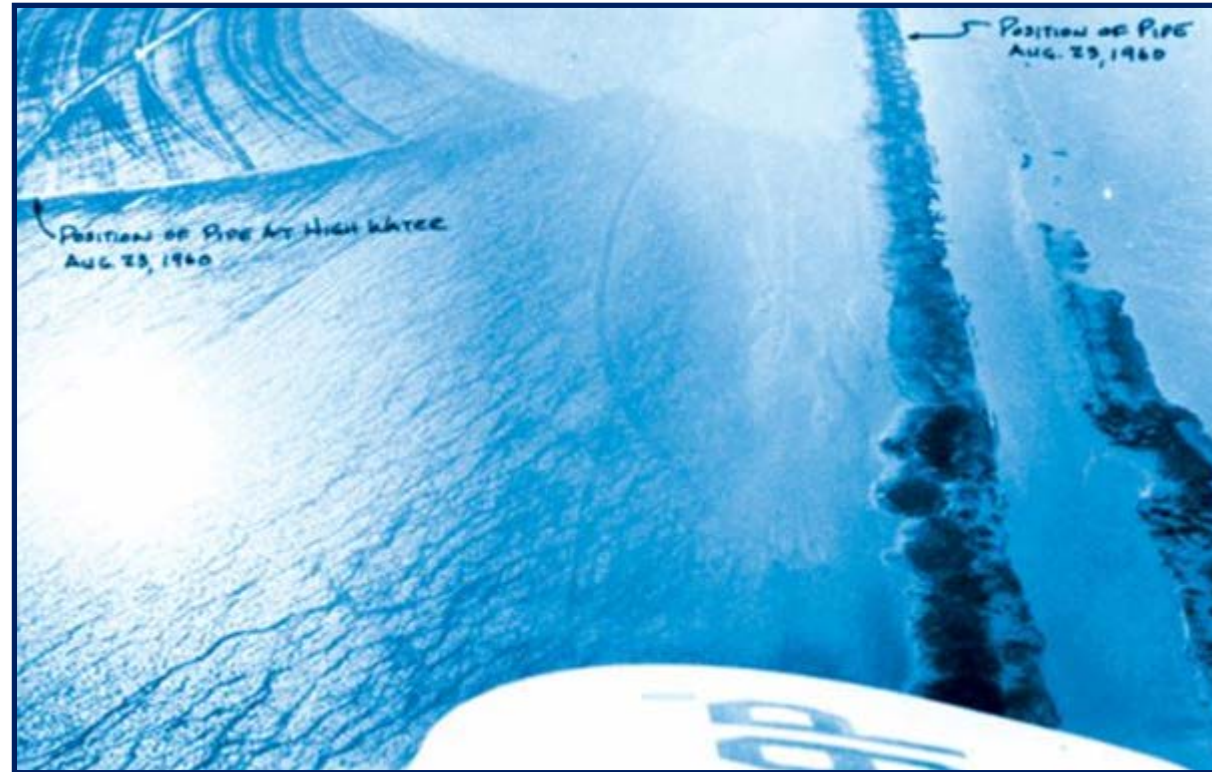
# Pilelines: some loading types

- Earthquake (dynamic) loading
- Slope instability / landslides
- Soil settlement/consolidation
- Soil Liquefaction
- Tectonic (fault) movement



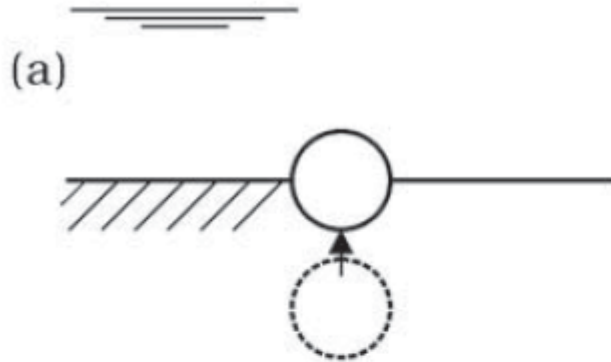
# Seabed liquefaction

**Pipeline flotation  
due to soil  
liquefaction  
(Damgaard et al.  
2006)**

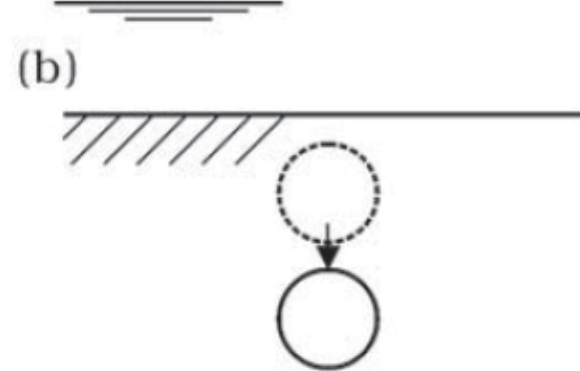


# 🔥 Possible liquefaction consequences

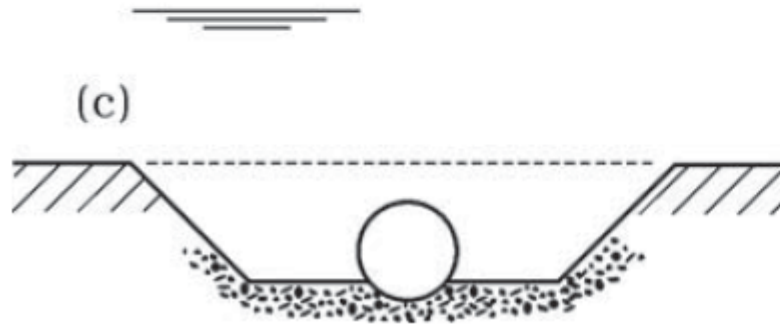
**Pipe floatation**



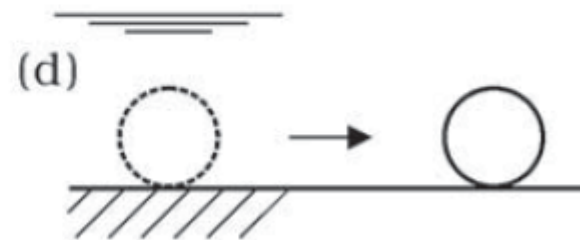
**Pipe settlement**



**Settlement of the surrounding soil**

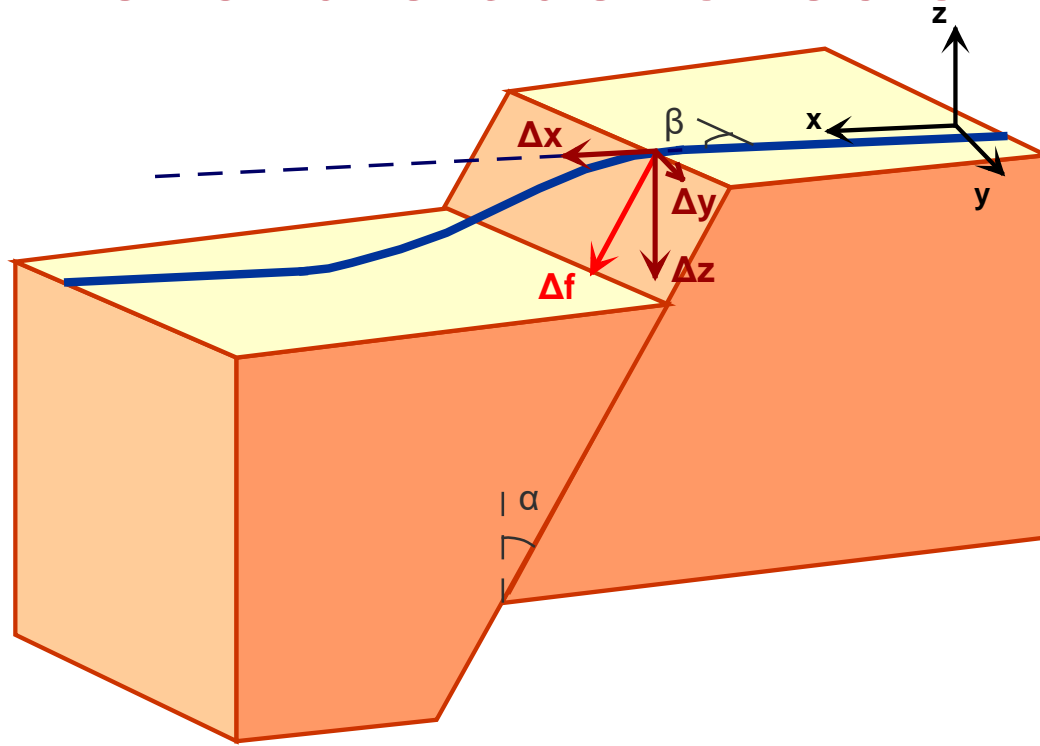


**Pipe displacement**

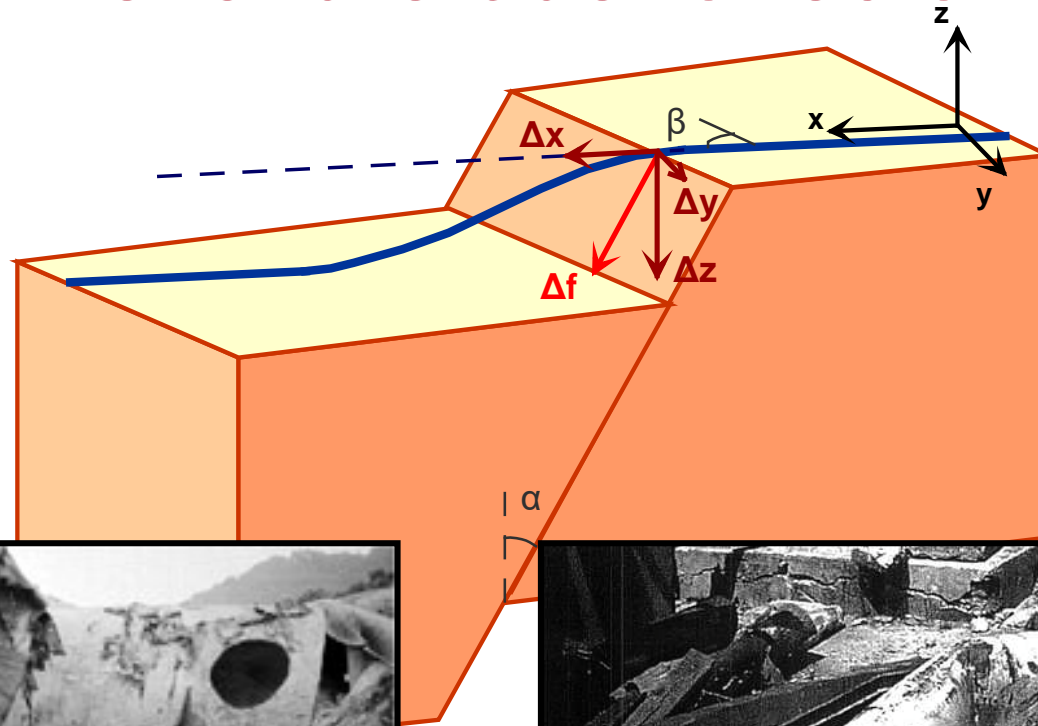


from Damgaard et al. 2006

# 🔥 Pipeline failure due to tectonic action



# 🔥 Pipeline failure due to tectonic action

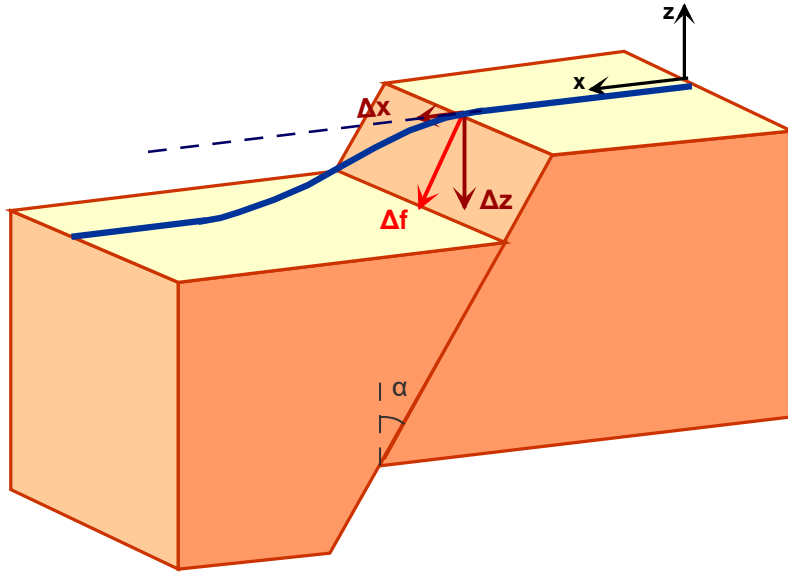


**Kocaeli, Turkey (1999)**

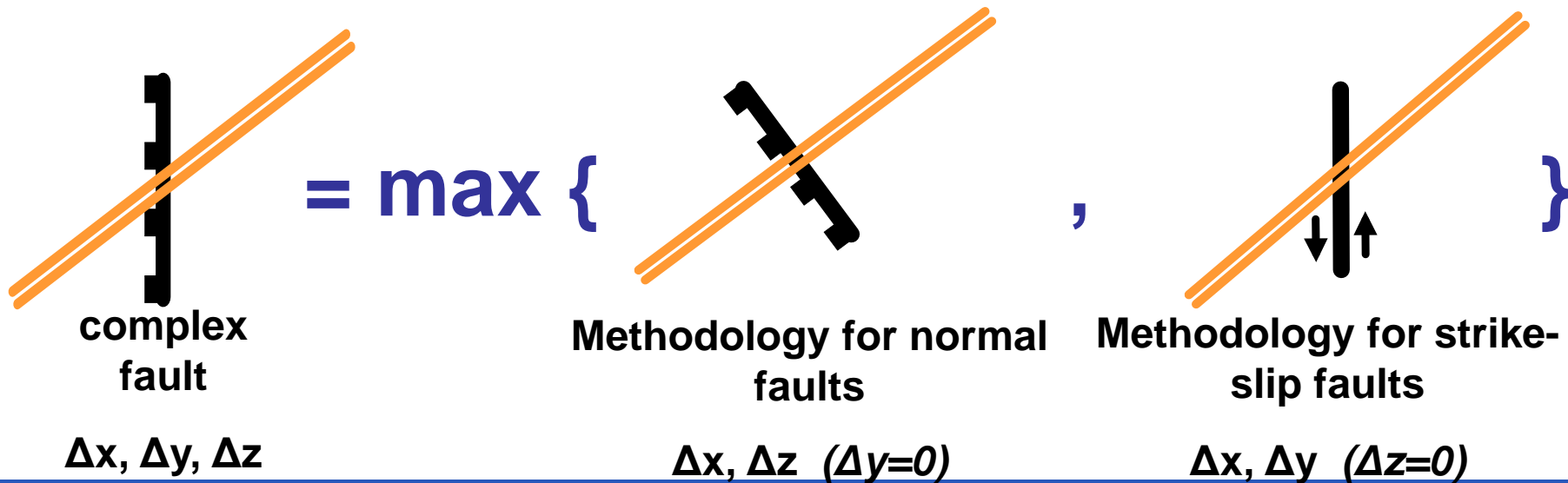
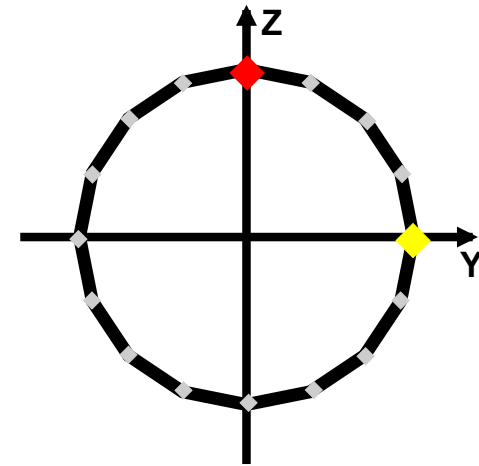


**Chi-Chi, Taiwan (1999)**

# 🌿 Pipeline failure due to tectonic action



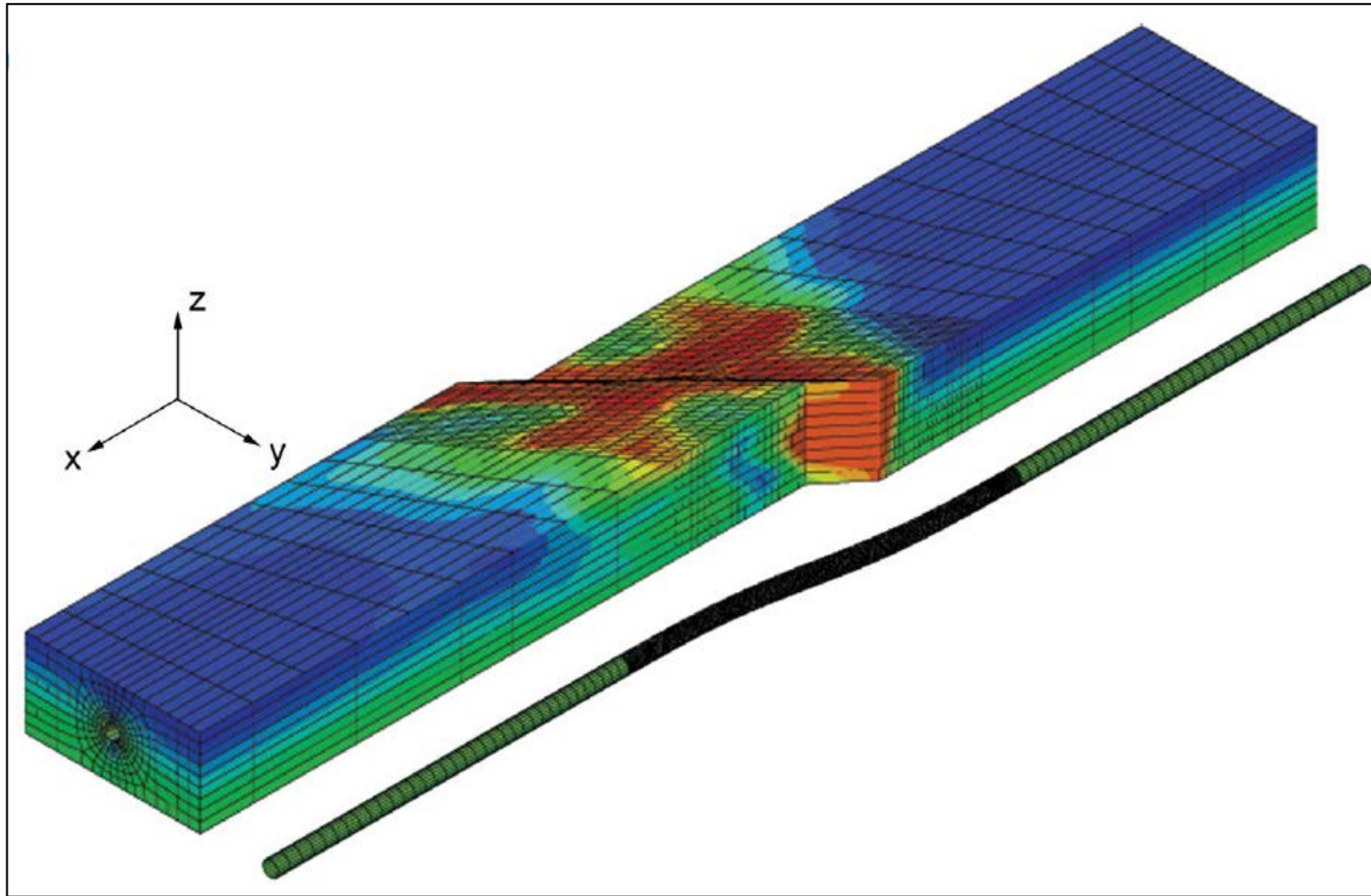
# 🔥 Pipeline failure due to tectonic action



# Common design approach

## Accurate models:

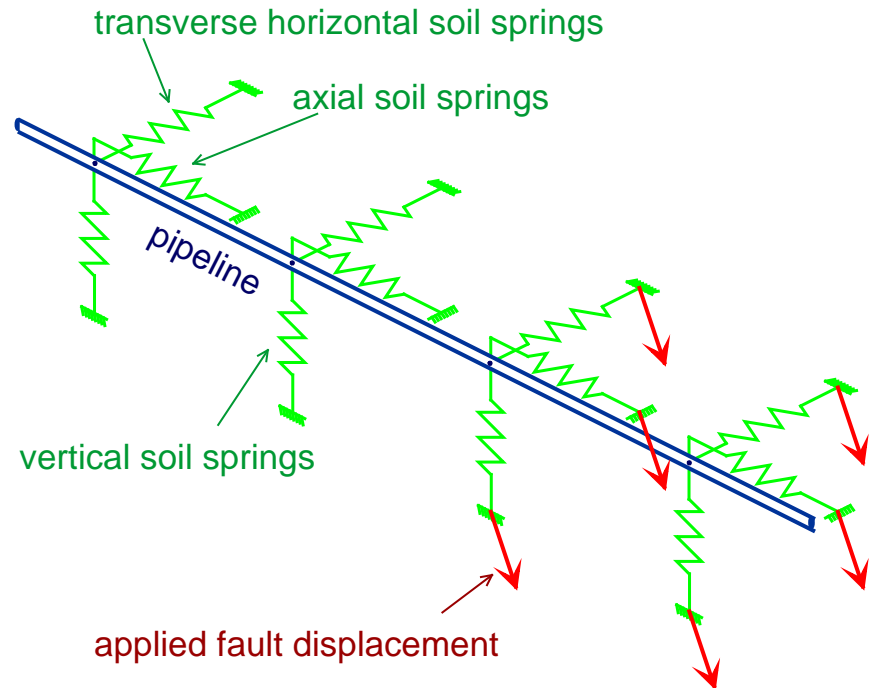
- ✓ Model soil as a continuum :



# Common design approach

## 3-D non linear analyses using FEM

- ✓ Model pipeline with beam elements
- ✓ Non linear behaviour of the steel
- ✓ Elastic– perfectly plastic soil strings
- ✓ Applied fault displacement
- ✓ Geometric non linearity due to large displacements

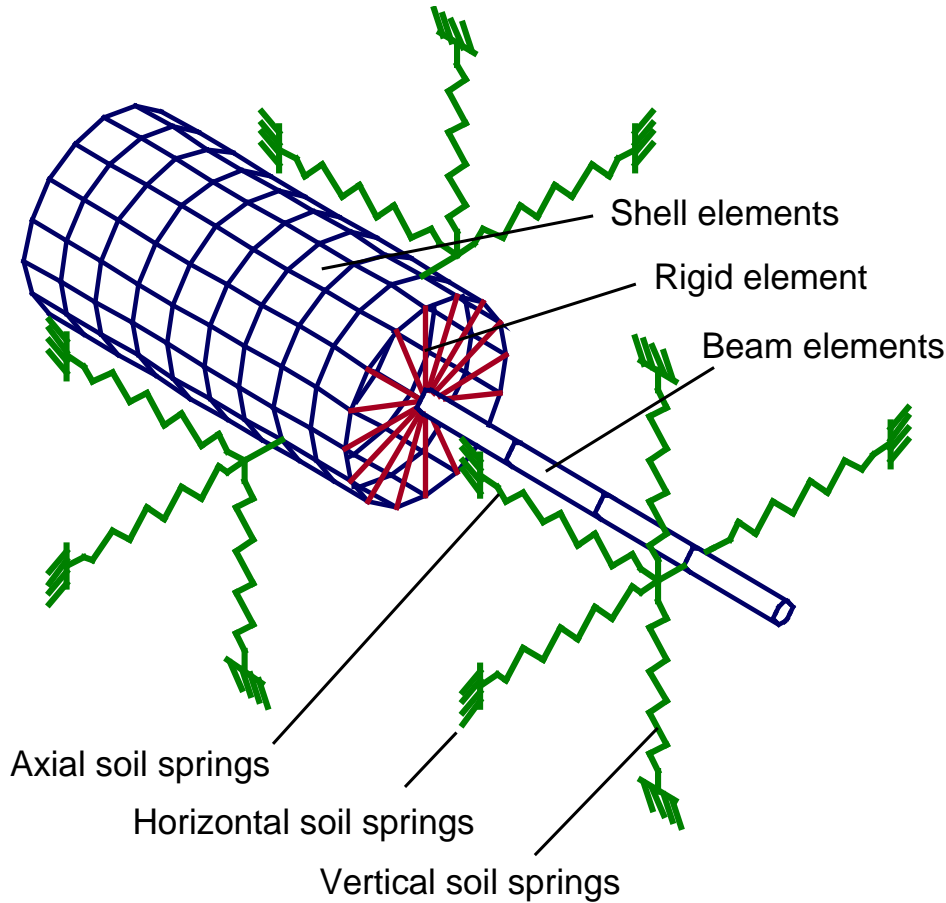


**American Lifelines  
Alliance – ASCE (2005)**

# Common design approach

## Accurate models:

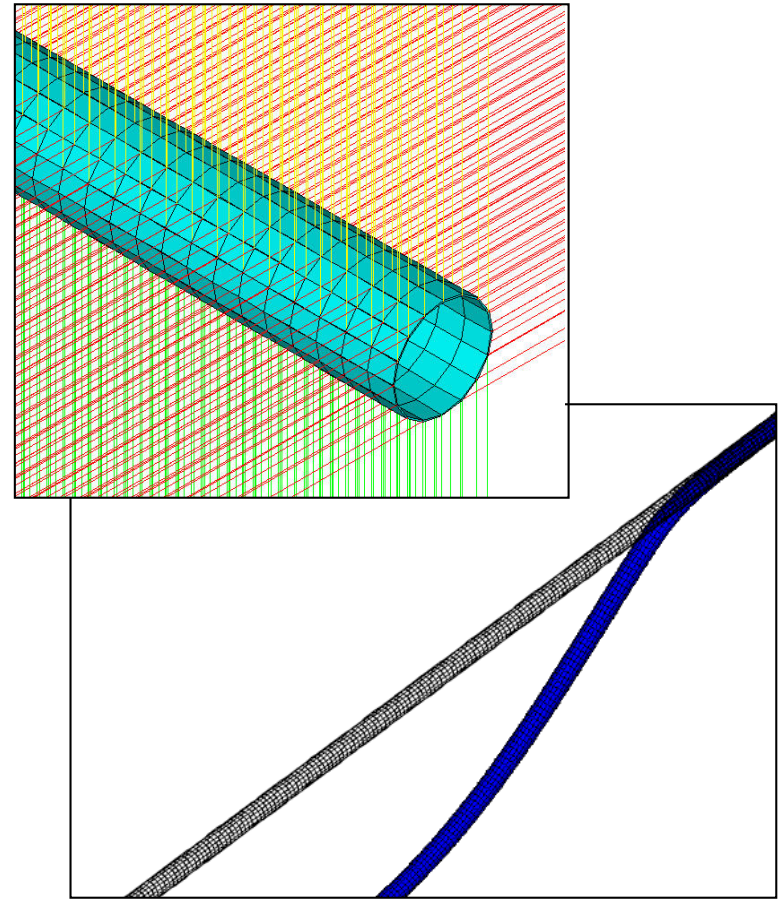
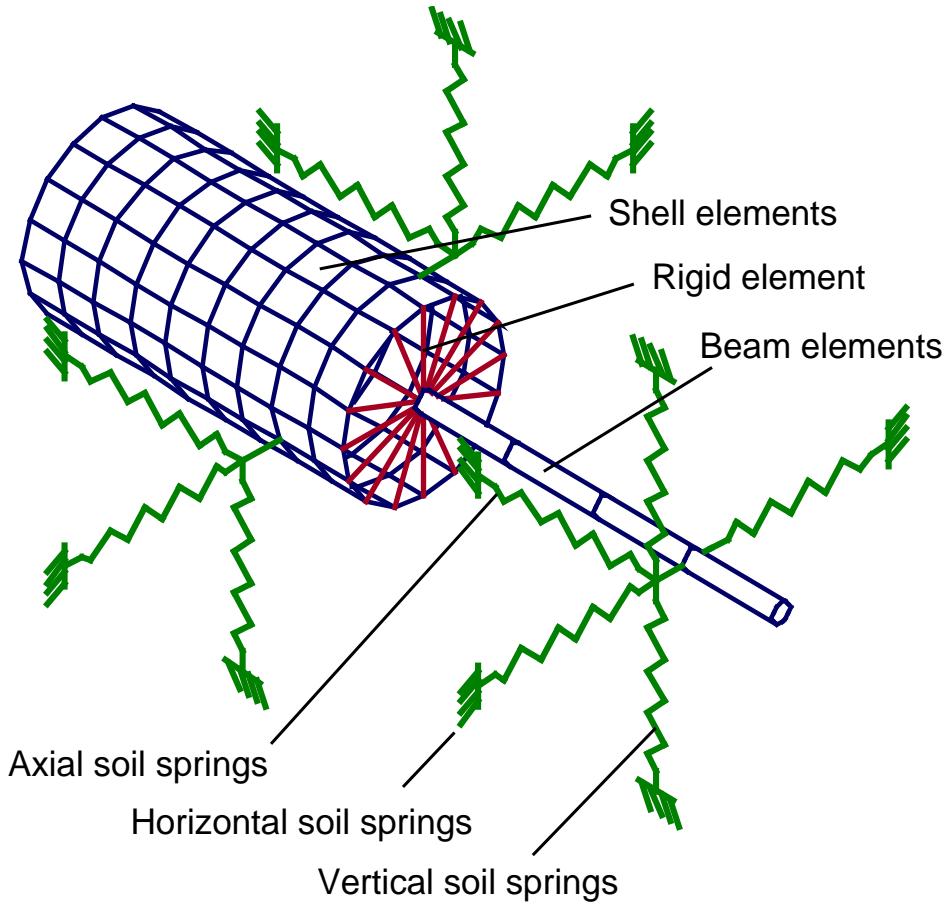
- ✓ Hybrid model (combination of beam and shell elements):



# Common design approach

## Accurate models:

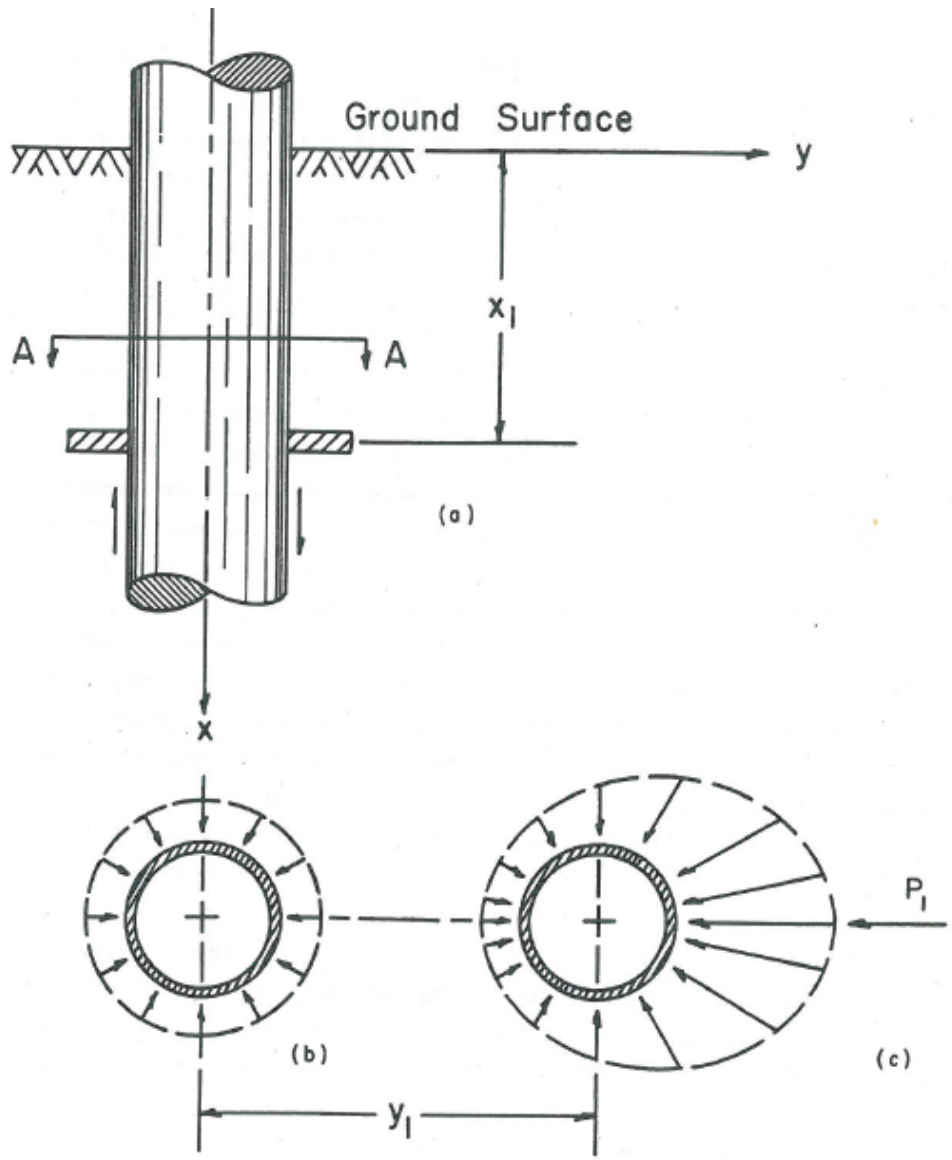
- ✓ Hybrid model (combination of beam and shell elements):



🌿 “spring theory”: p-y & t-z curves

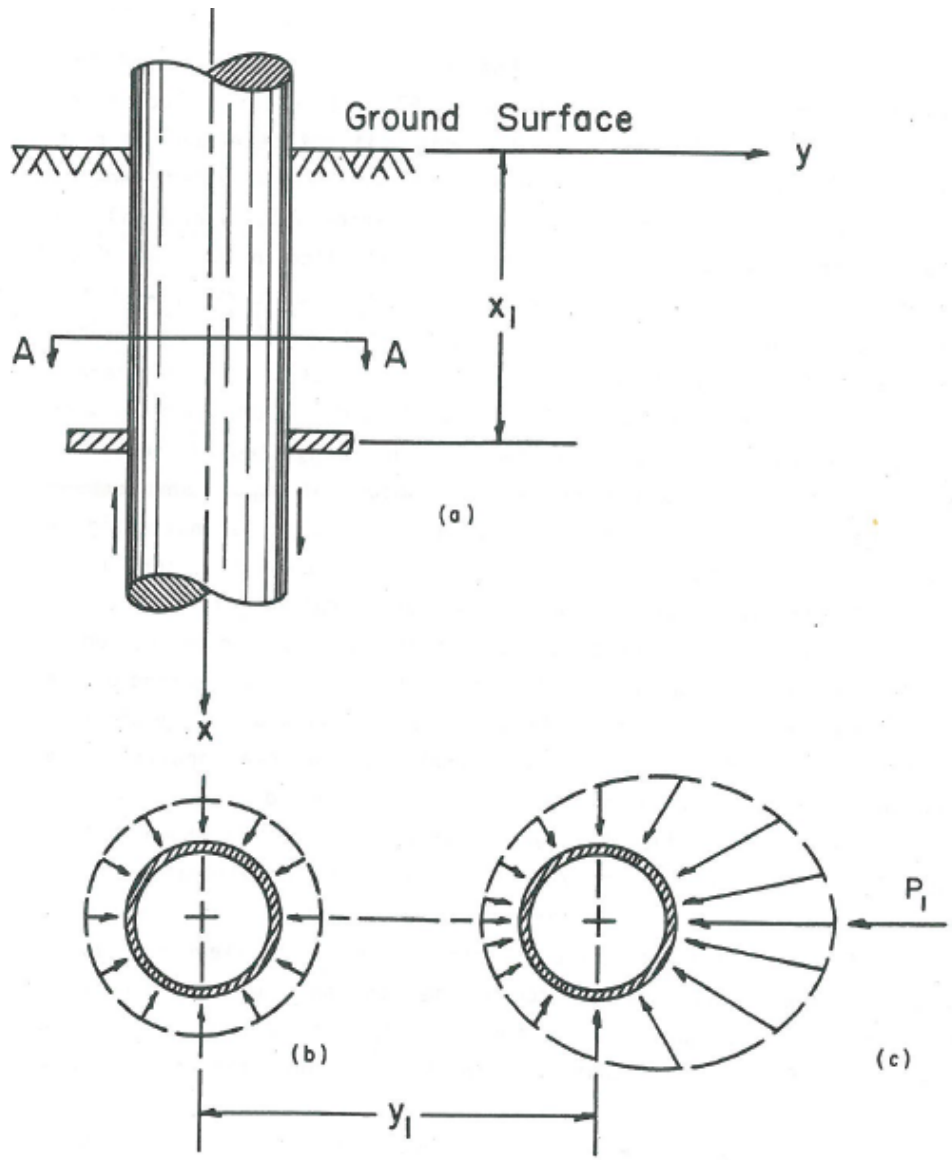


Lateral soil resistance  $p$  and the respective displacement  $y$ .



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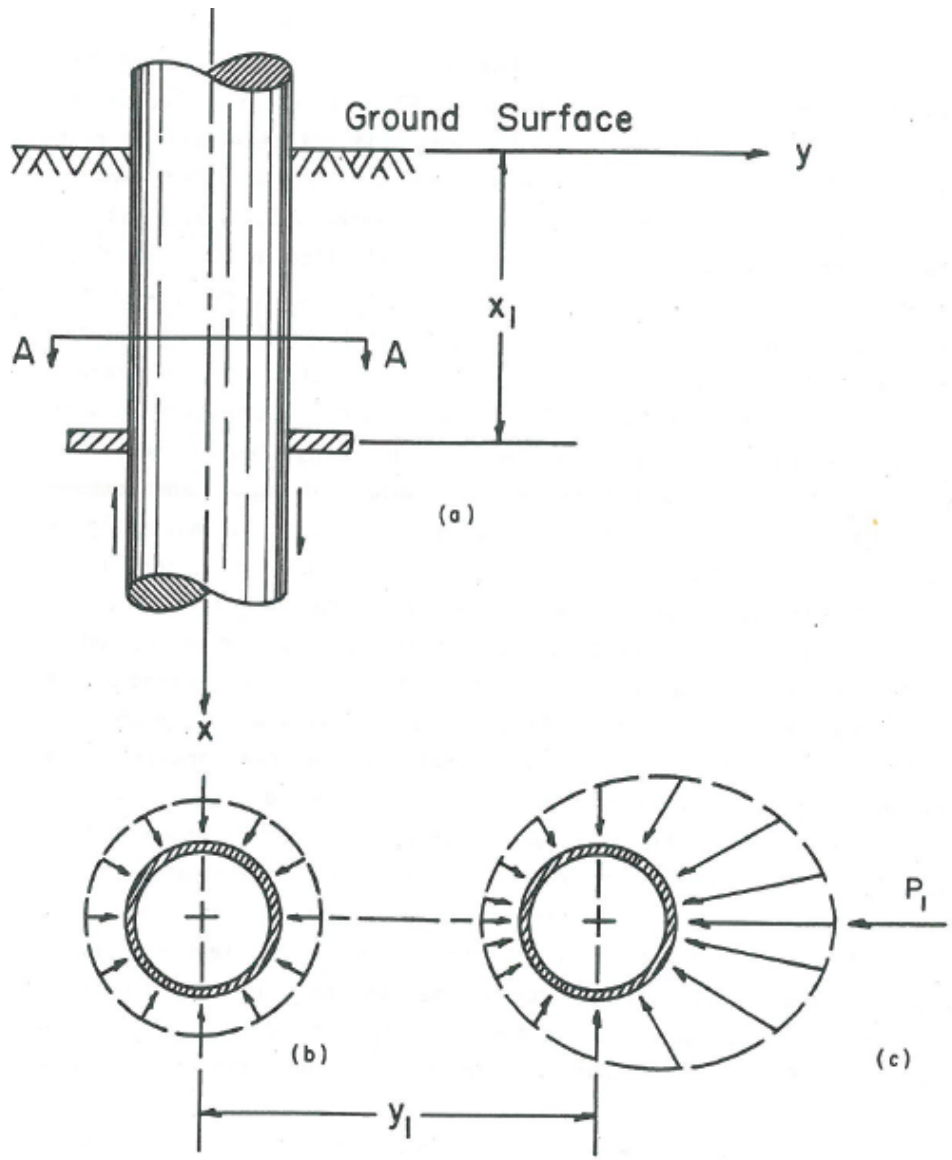
Cut A-A parallel to pile diameter



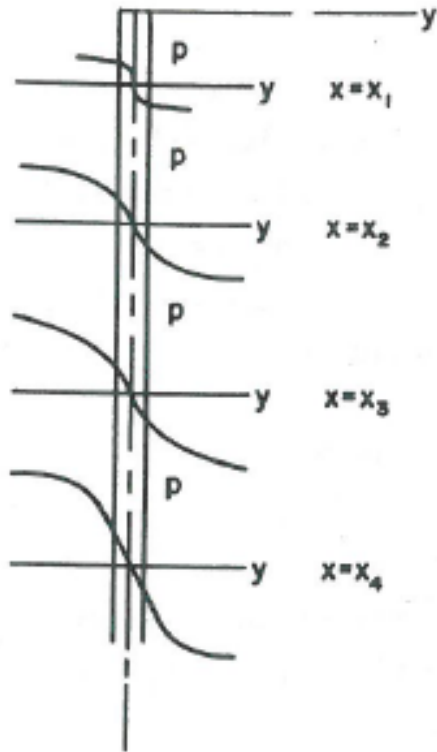
Lateral soil resistance  $p$  and the respective displacement  $y$ .

Cut A-A parallel to pile diameter

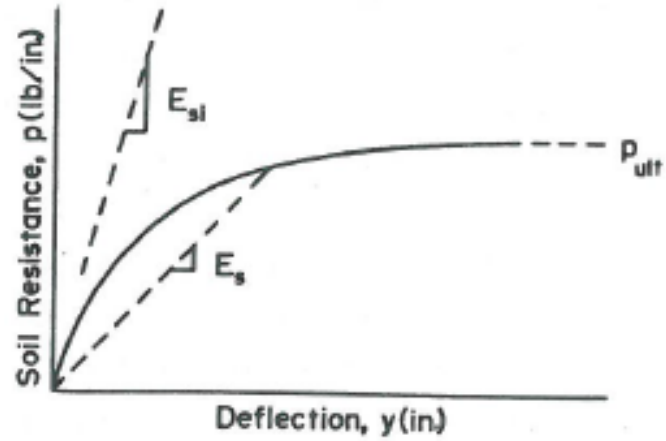
Soil stresses distribution before and after lateral loading



# 🔥 p-y curves



$p - y$  curves



Shape of  $p - y$  curves



# p-y theory

## McLeland & Focht (1958)

- Curvature

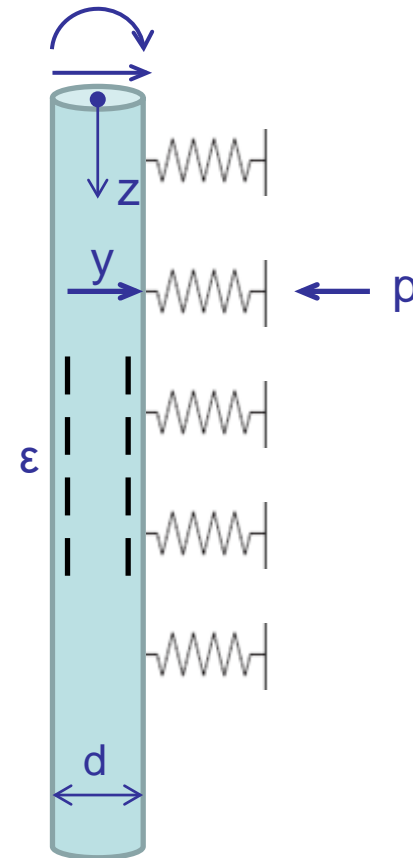
$$\left(\frac{1}{R}\right) \cong \varepsilon \frac{2}{d}$$

- Lateral Resistance

$$p = -E_p I \left(\frac{1}{R}\right)''$$

- Lateral displacement

$$y \cong \int_0^z \int_0^z \left(\frac{1}{R}\right) dz + c_1 z + c_2$$



# t-z theory

- Bending strain

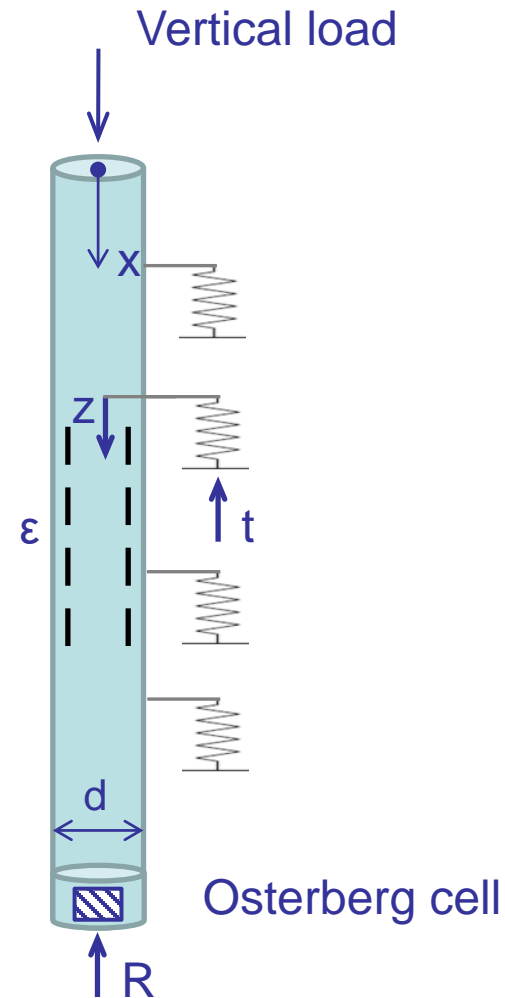
$$z' \equiv \varepsilon$$

- Lateral skin friction

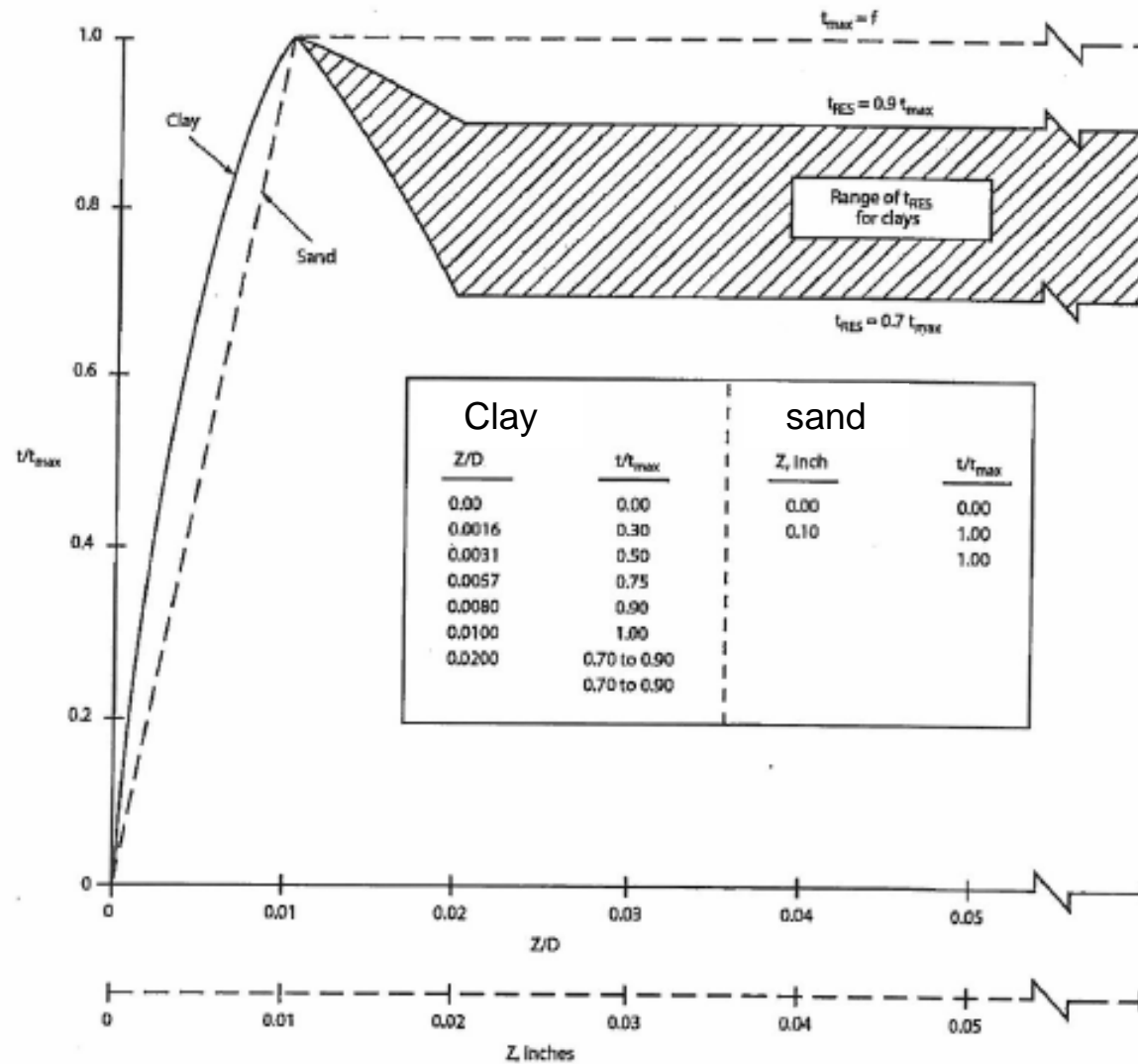
$$t = E_p A (\varepsilon)'$$

- Settlement

$$z = \int_0^z \varepsilon dx + c$$

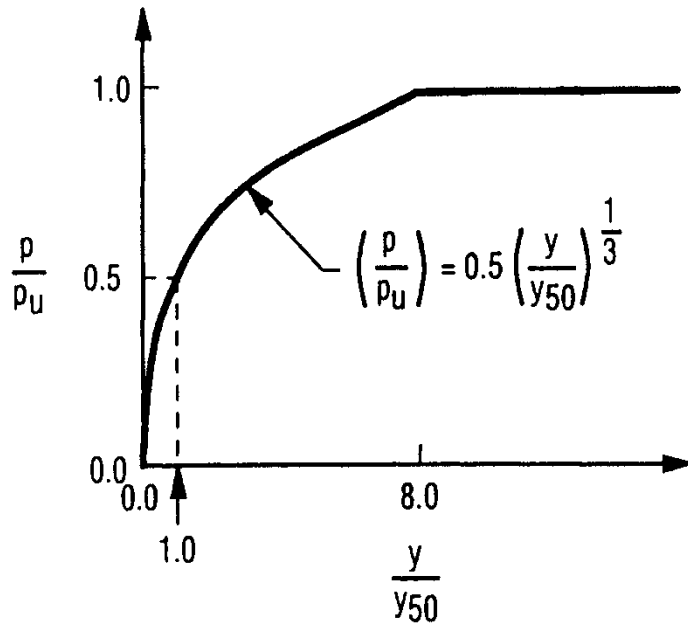


# t-z curves

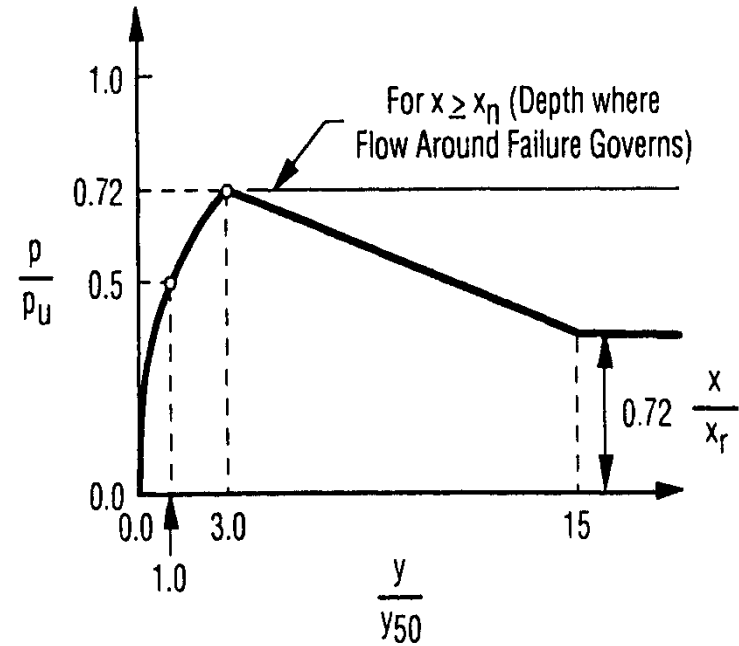


# p-y curves

- Soft Clay



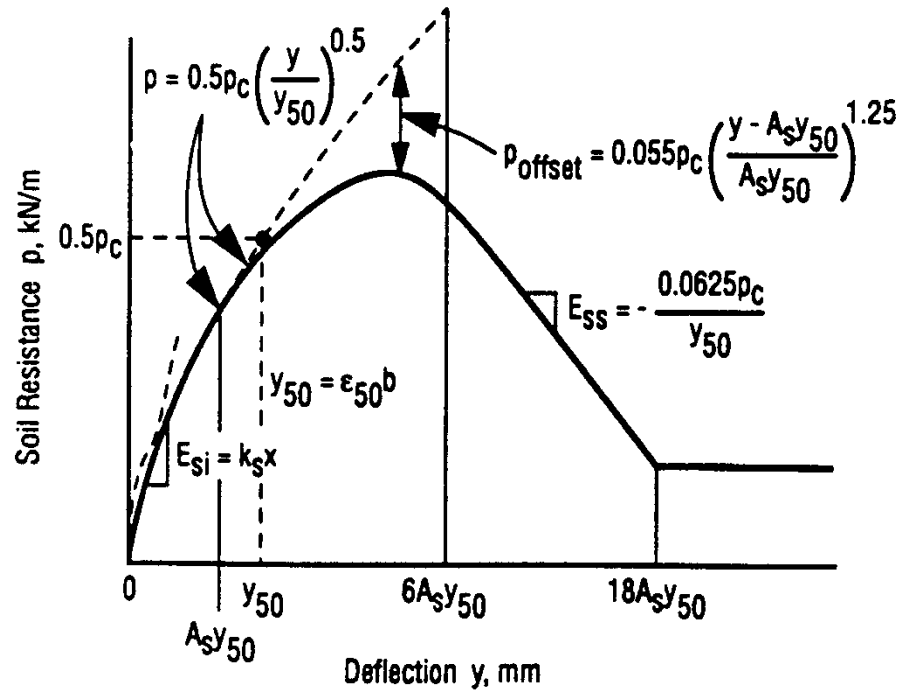
Static loading



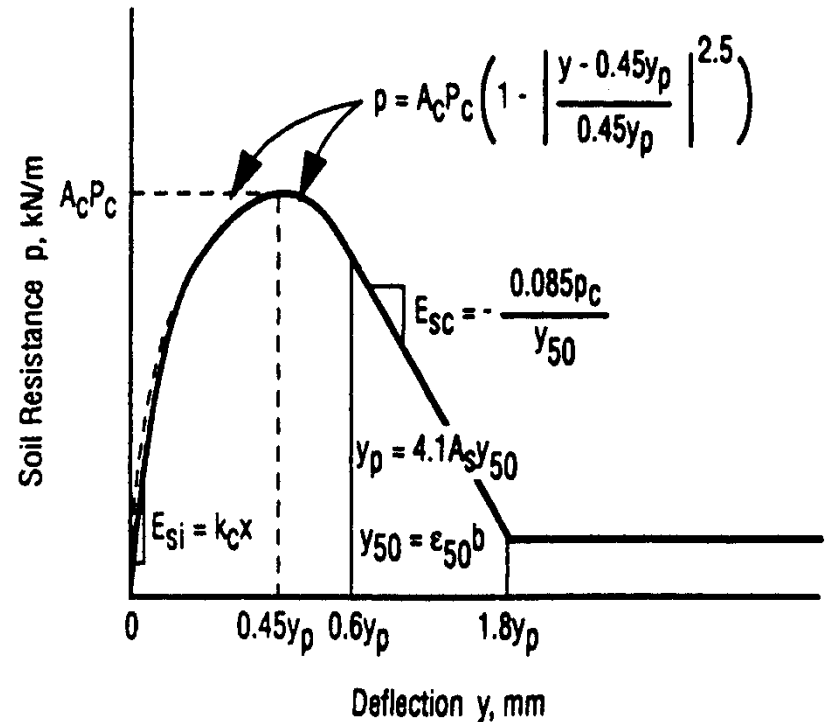
Cyclic loading

# p-y curves

- Stiff clay below the water table



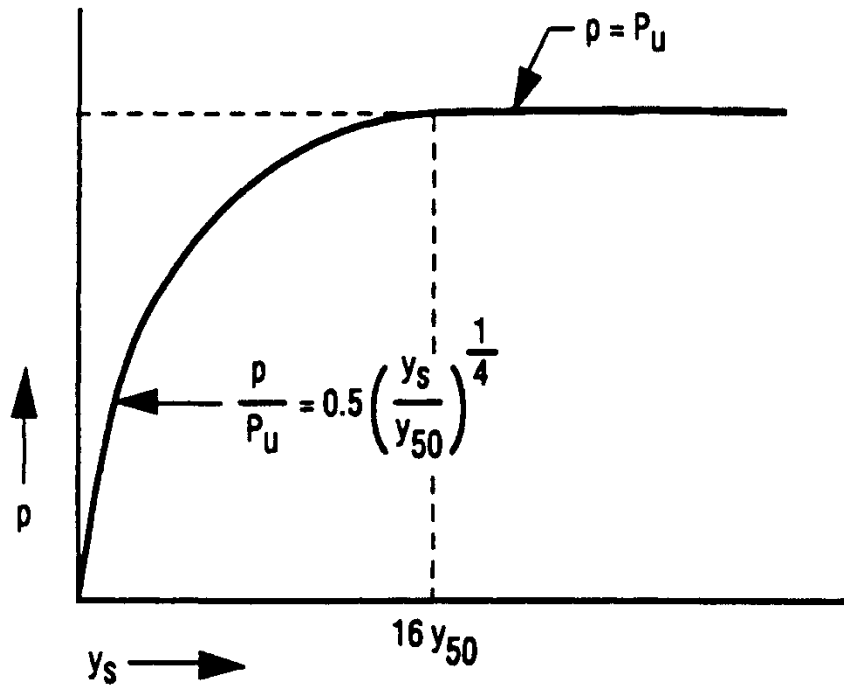
Static loading



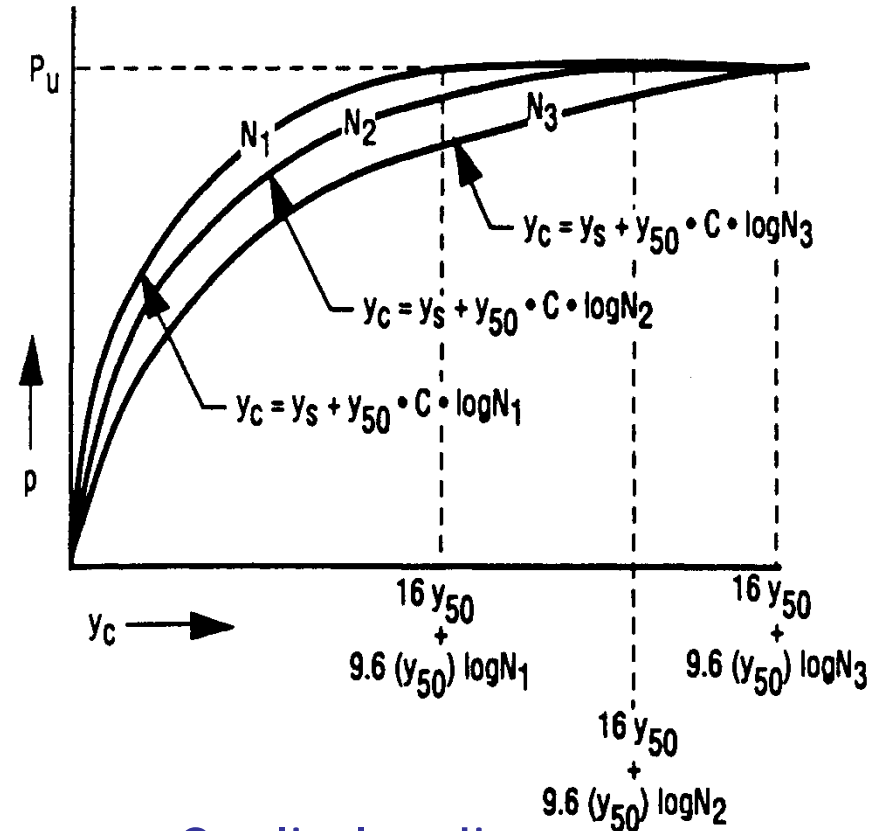
Cyclic loading

# p-y curves

- Stiff clay above the water table



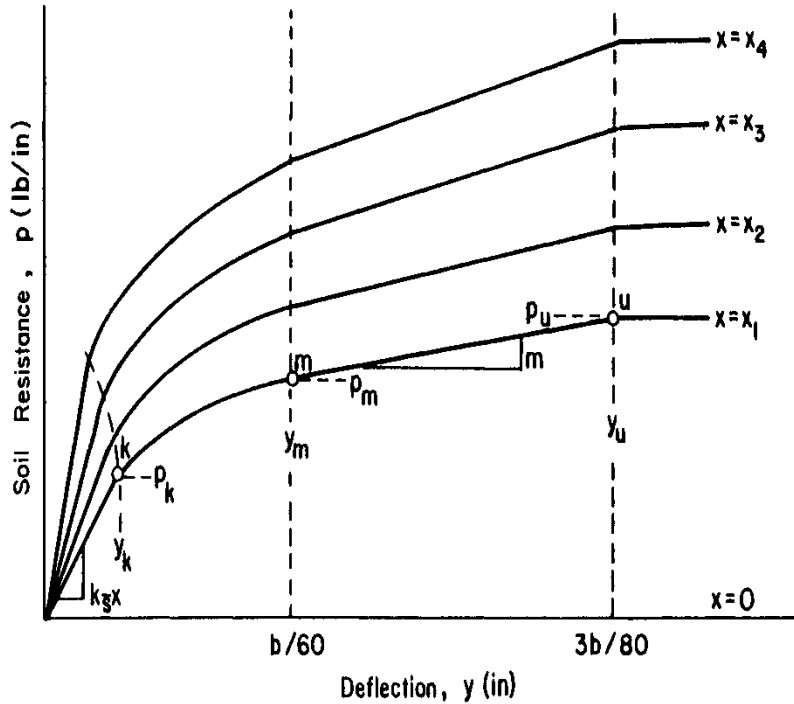
Static loading



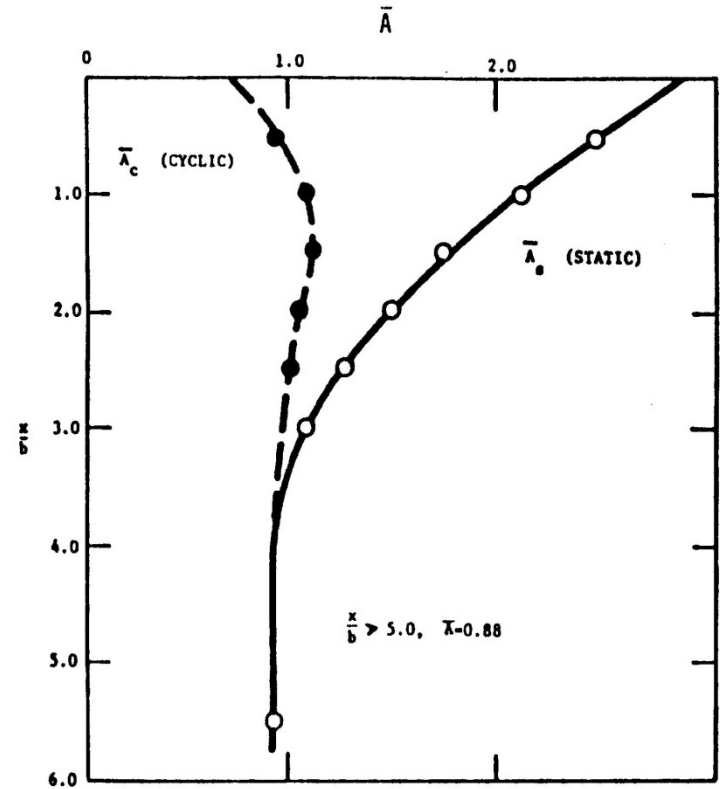
Cyclic loading

# p-y curves

- Sand (Reese Criteria)



Static loading



Cyclic loading

# p-y curves for sand

$$P = A \times P_u \times \tanh \left( \frac{\kappa H}{AP_u} y \right)$$

where

- $A = 0.9$  for cyclic loading  
( $3 - 0.8 H/D$ )  $\geq 0.9$  for static loading
- $P_u$  = lateral bearing capacity (kN/m)
- $\kappa$  = initial Winkler modulus (kN/m<sup>3</sup>)
- $y$  = lateral displacement(m)
- $H$  = depth(m)



# p-y curves for sand

- Estimation of  $\kappa$  as a function of  $\phi$

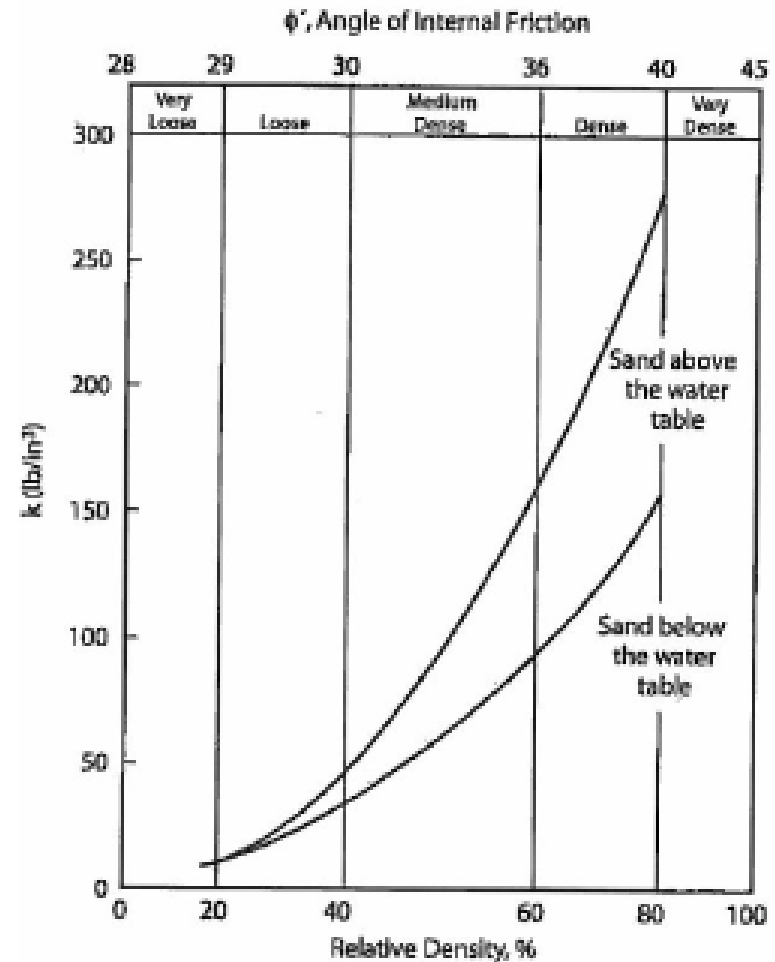
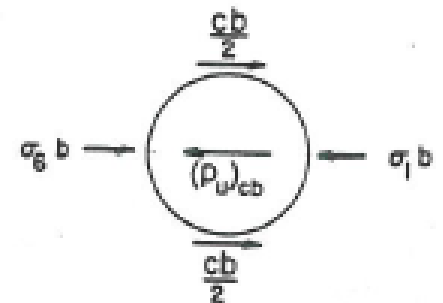
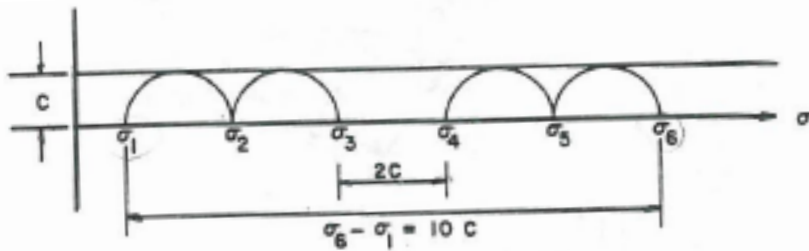
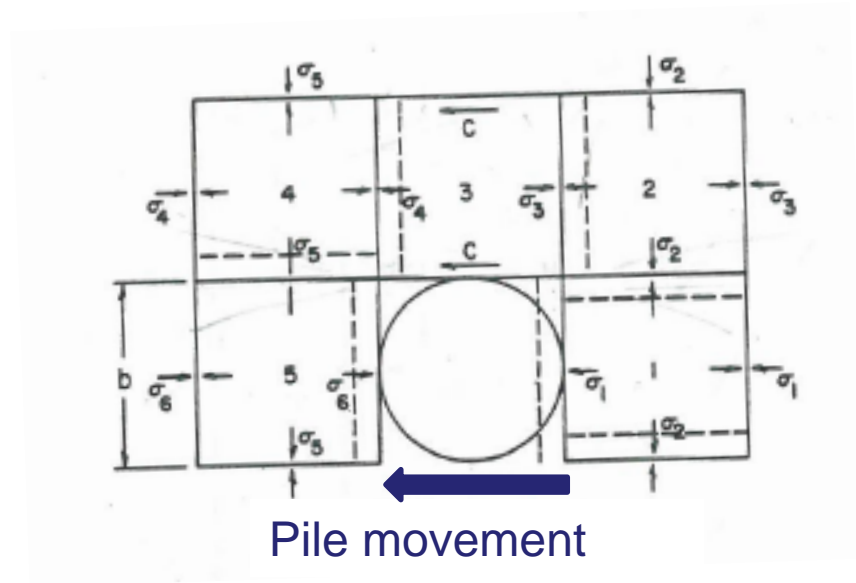


Figure 6.8.7-1—Relative Density, %

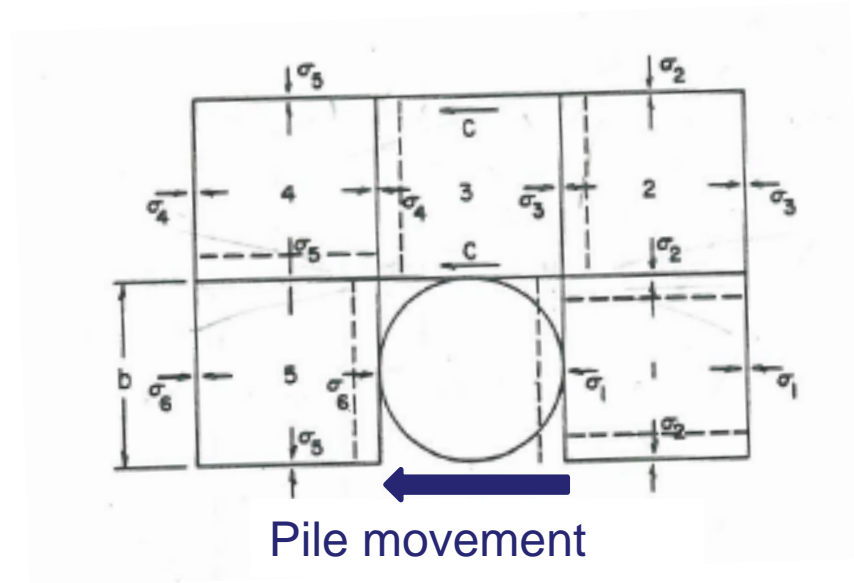
# 🔥 Flow-around type pile failure in clay

Cut of the pile and the surrounding soil

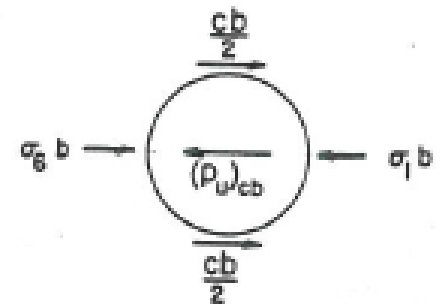
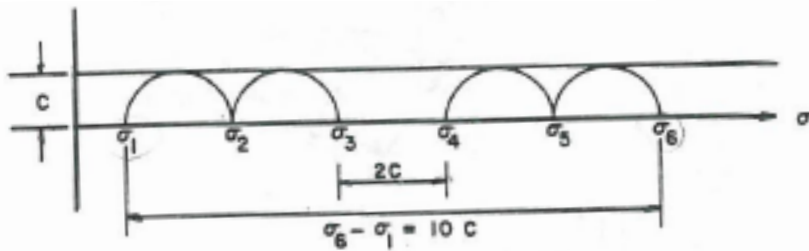


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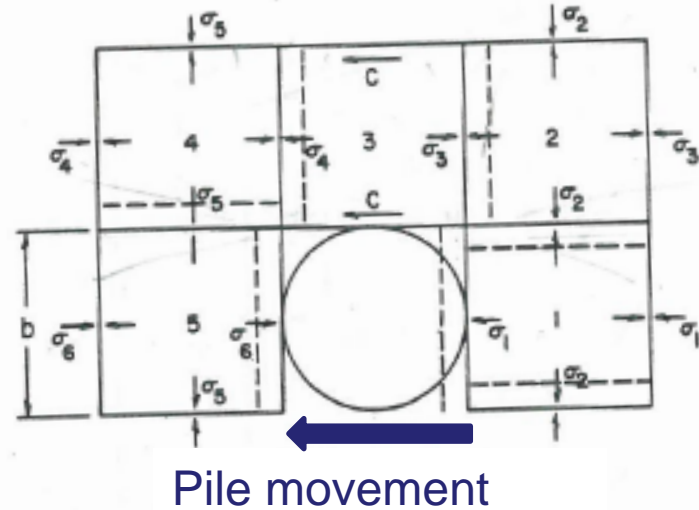


Mohr – Coulomb diagram

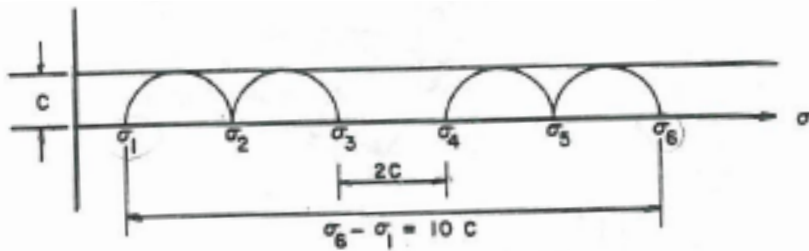


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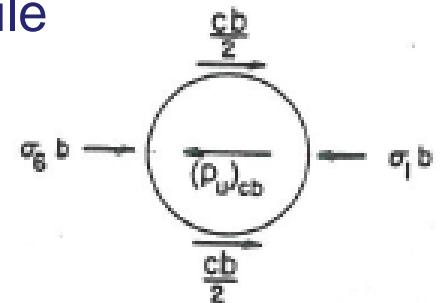
Cut of the pile and the surrounding soil



Mohr – Coulomb diagram

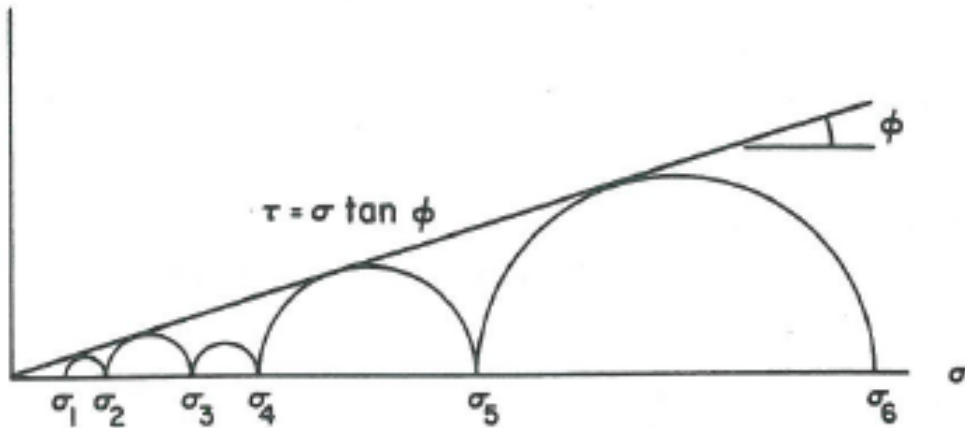
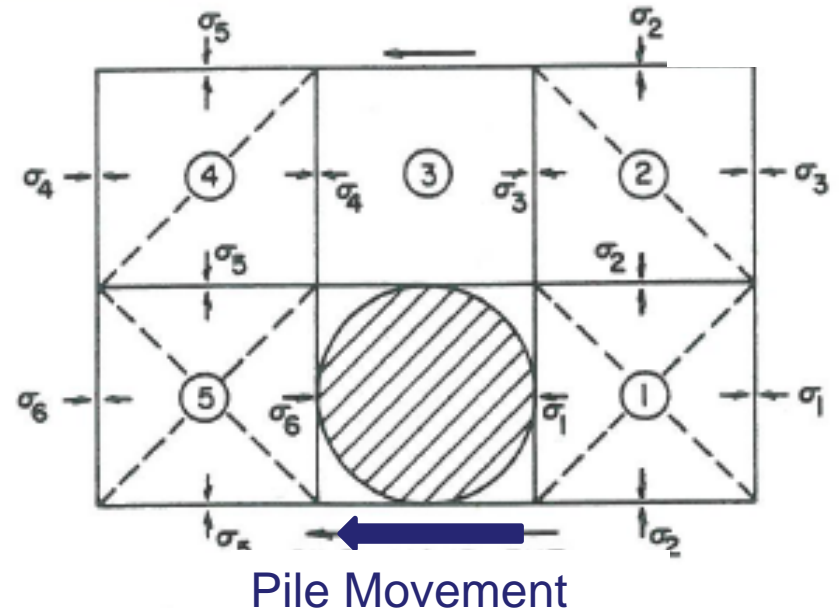


Forces on the pile



# 🌟 Flow-around type pile failure in sand

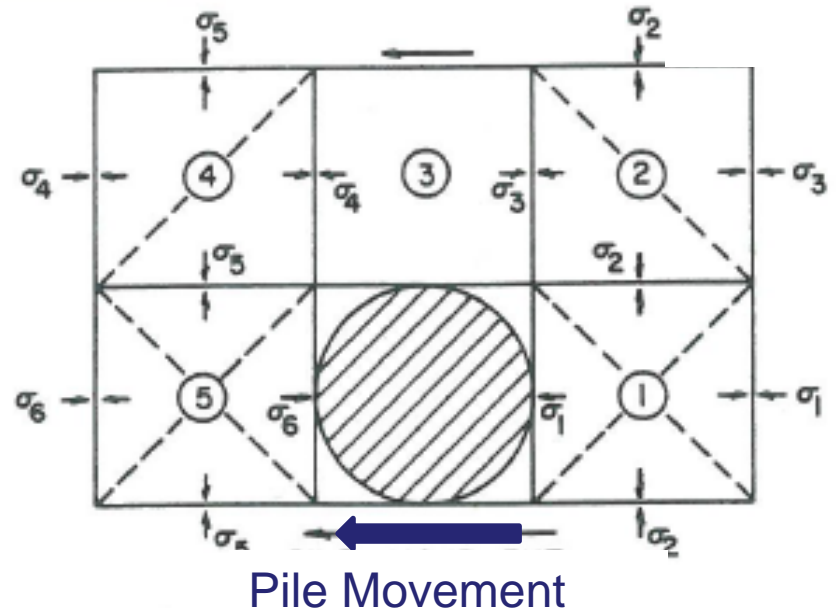
Cut of the pile and the surrounding soil



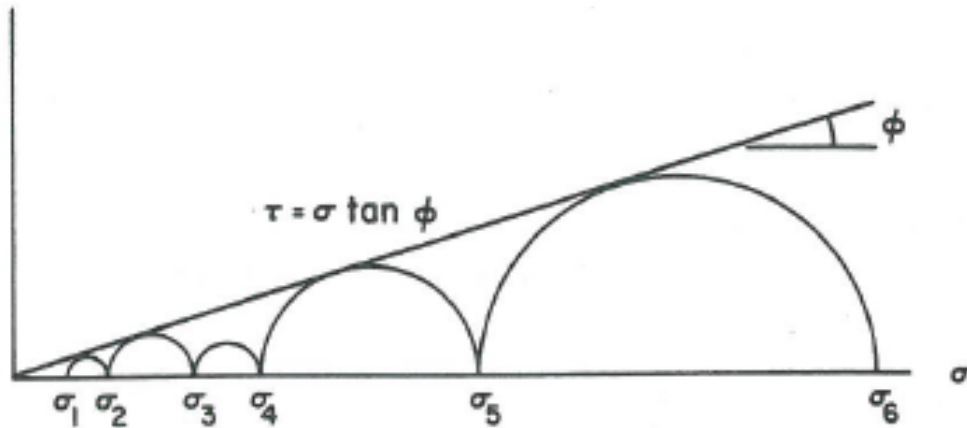
(b)

# 🌟 Flow-around type pile failure in sand

Cut of the pile and the surrounding soil



Mohr – Coulomb diagram



(b)

# Lateral bearing capacity

## ➤ Lateral resistance in soft clays

$$p_u = 3c + \gamma X + J \frac{cX}{D} \quad , \quad X < X_R$$

$$p_u = 9c \quad , \quad X \geq X_R$$

where

- $p_u$  = lateral bearing capacity (kPa)
- $c$  = undrained shear strength (kPa)
- $D$  = pile diameter (m)
- $\gamma$  = unit weight (kN/m<sup>3</sup>)
- $J$  = dimensionless coefficient ranging between 0.25 – 0.5
- $X$  = depth (m)
- $X_R$  = thickness of soft clay (m)  $\left( \sigma_D / \frac{\gamma D}{c} + J \geq 2D \right)$



# 🔥 Lateral bearing capacity

- Lateral resistance in stiff clay

$$p_u \cong 8c - 12c$$

- Lateral resistance in sand

$$p_{us} \cong (C_1 \times H + C_2 \times D) \gamma H$$

$$p_{ud} \cong C_3 D \gamma H$$

where

- $p_u$  = lateral bearing capacity (kN/m)
- $D$  = pile diameter (m)
- $\gamma$  = unit weight (kN/m<sup>3</sup>)
- $\phi$  = friction angle (°)
- $H$  = depth (m)
- $C_1, C_2, C_3$  = coefficients from Fig.6.8.6-1 as function of  $\phi$



# 🔥 Lateral bearing capacity

- Coefficients  $C_1$ ,  $C_2$ ,  $C_3$  as a function of friction angle

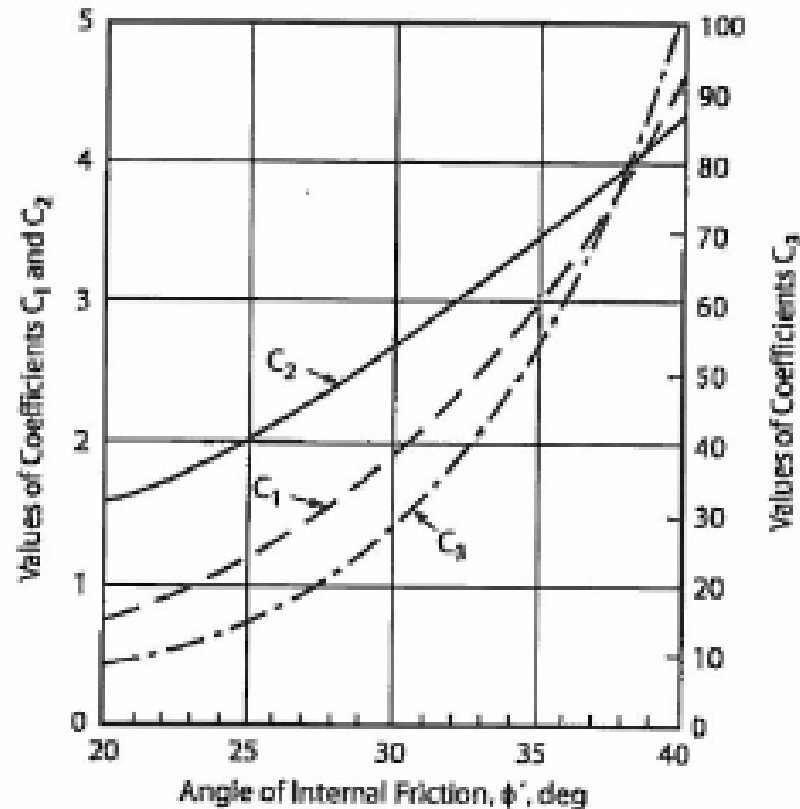


Figure 6.8.6-1—Coefficients as Function of  $\phi'$

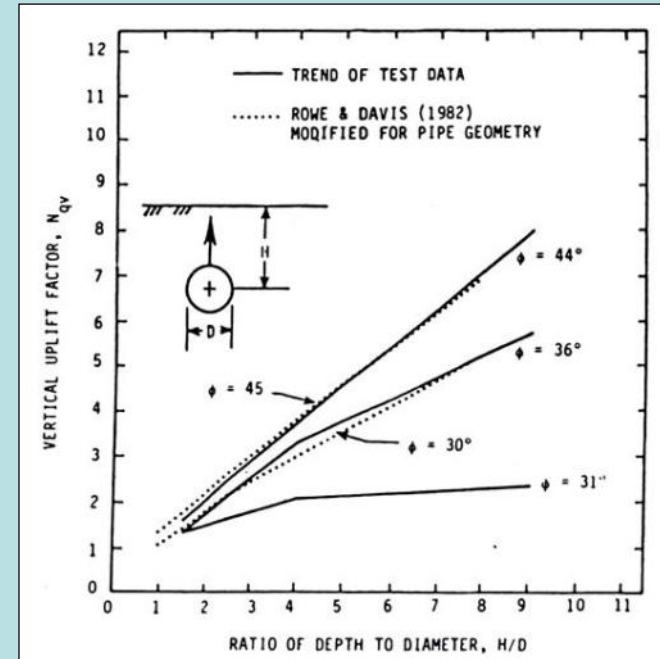
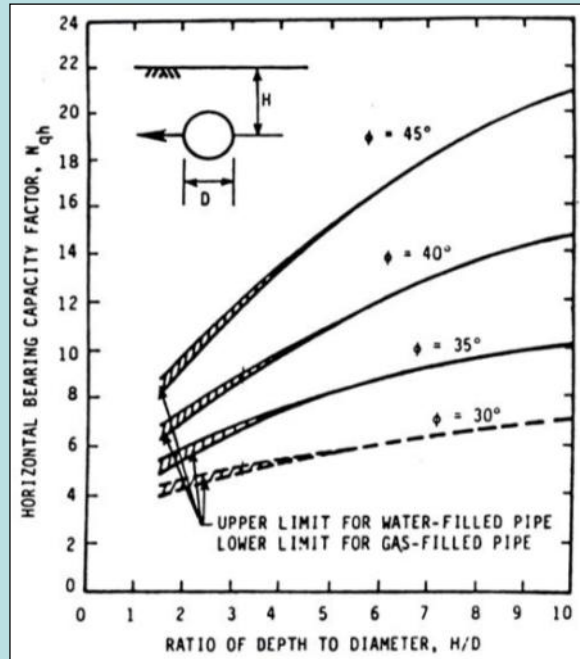


 elastic spring stiffness  $\kappa$



# elastic spring stiffness $k$

## Soil springs



**What is the shape of the curves p-y?**

- Experimental investigation
- Numerical analyses with constitutive models

# Summary

Research needs for pipeline-specific p-y curves:

- elastic Winkler constants for (1) three principal directions, (2) kinematic & inertial loads
- ultimate loads in three principal directions
- macro-modelling to couple responses along different directions
- development of pertinent loading-unloading rules



## Summary (cont.)

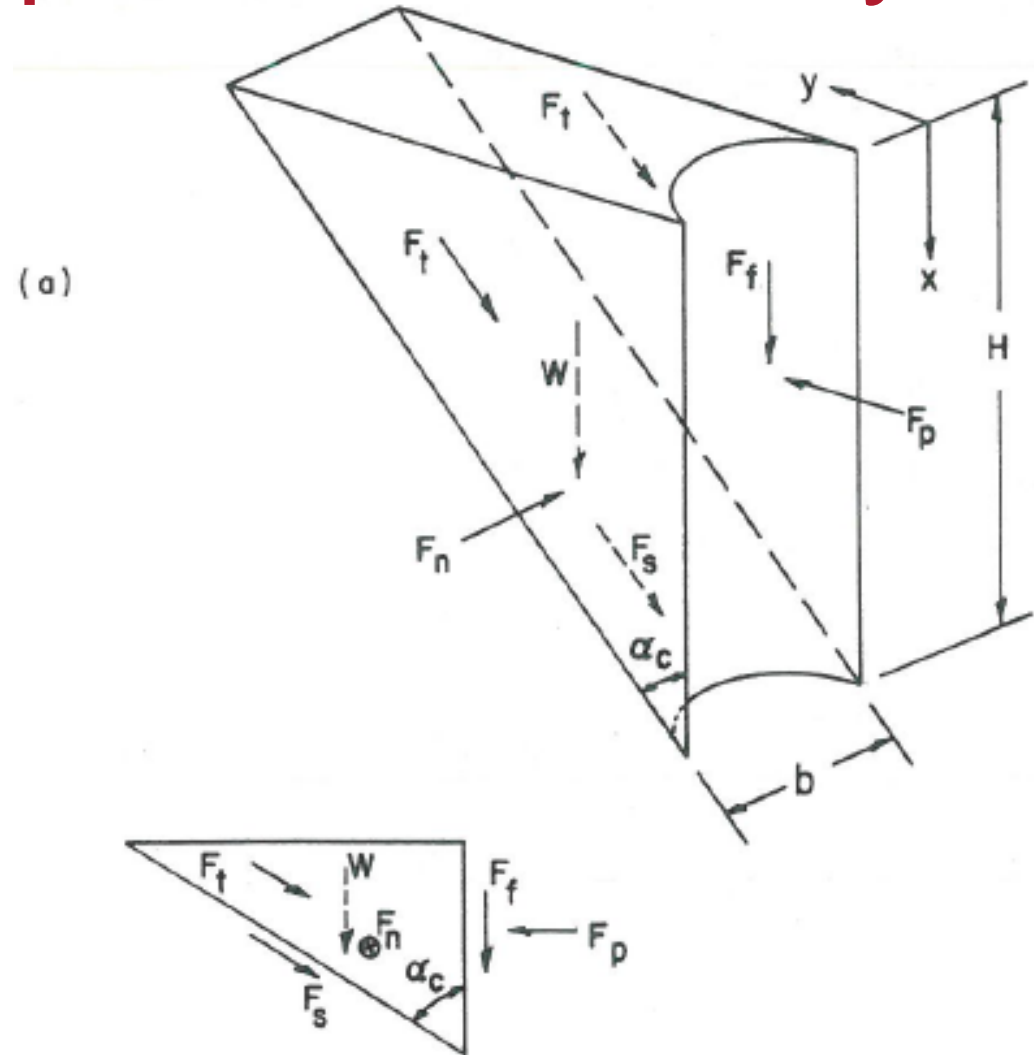
- proper calibration using experimental results
- comparisons against current state of practice
  
- conceptual developments (e.g. negative soil mass vs inclusion effects)



**Thank you!**  
**Grazie!**  
**Ευχαριστώ!**  
**Merci!**  
**Danke!**



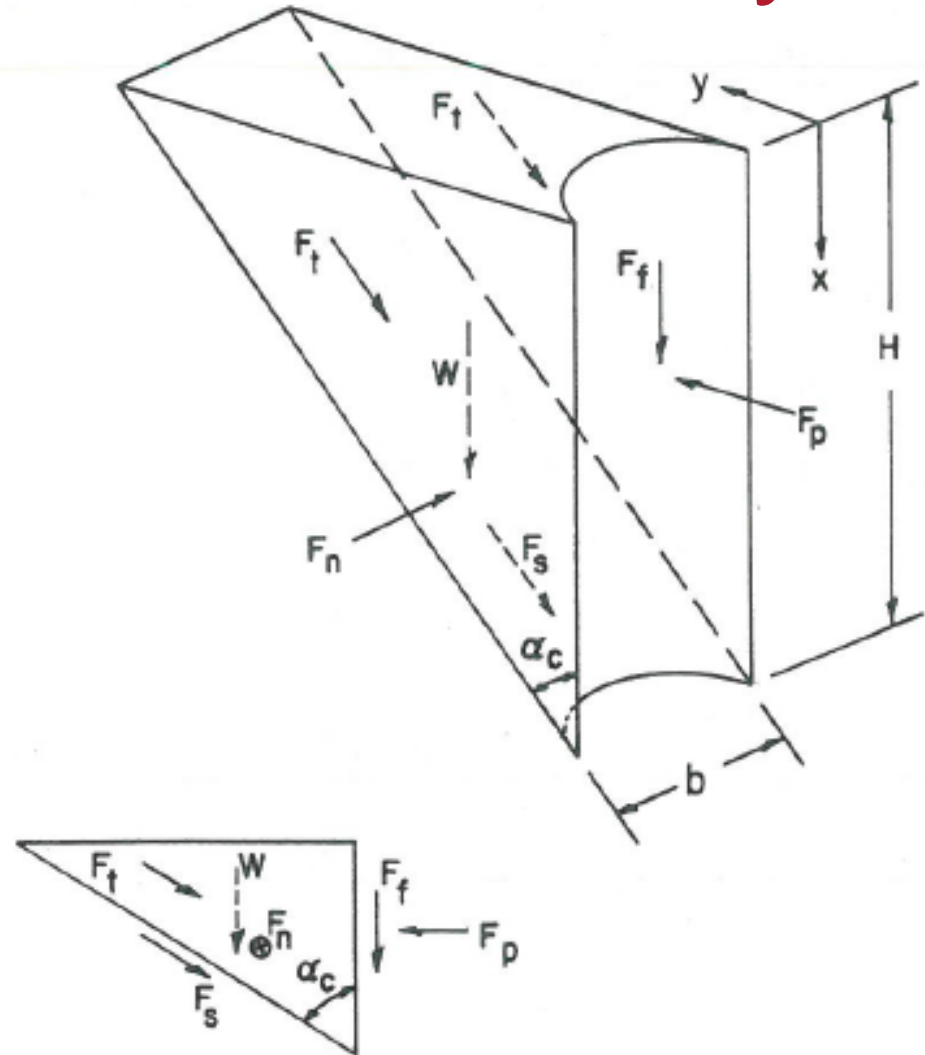
# 🔥 Wedge type pile failure in clay



# 🔥 Wedge type pile failure in clay

Wedge shape

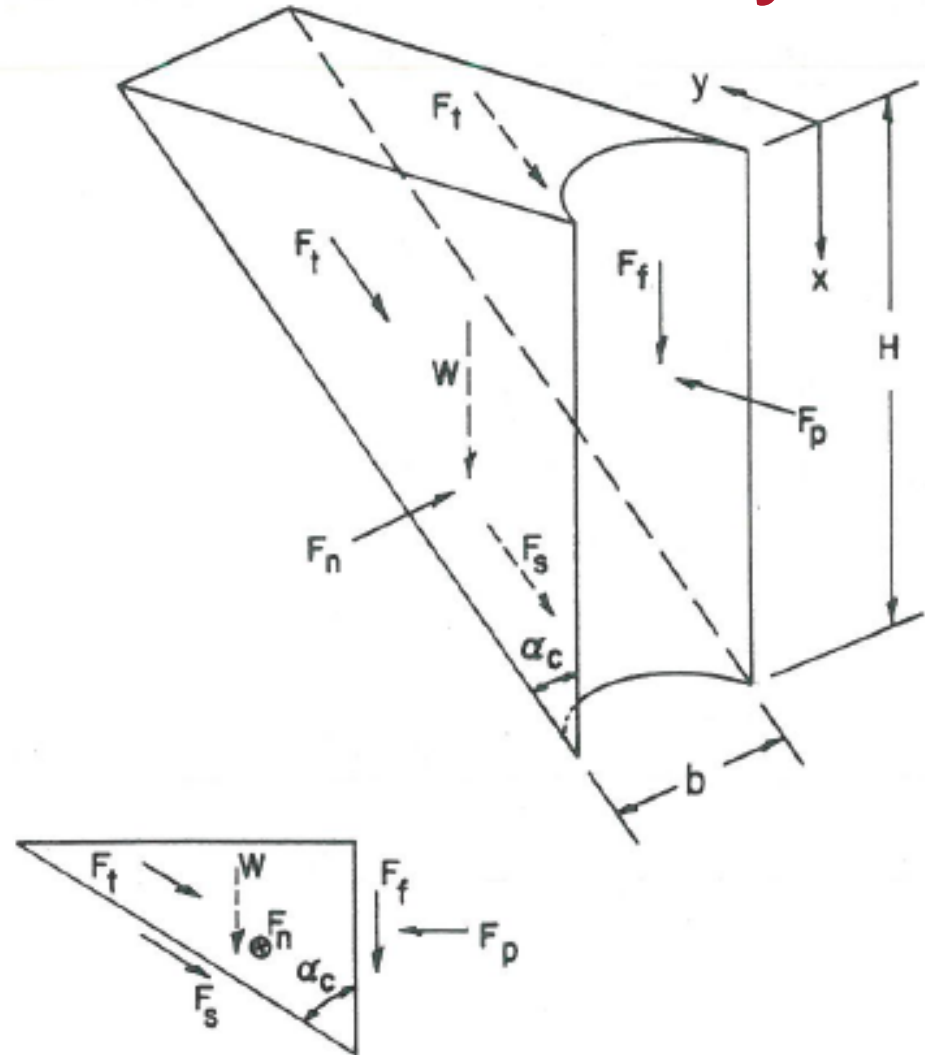
(a)



# 🔥 Wedge type pile failure in clay

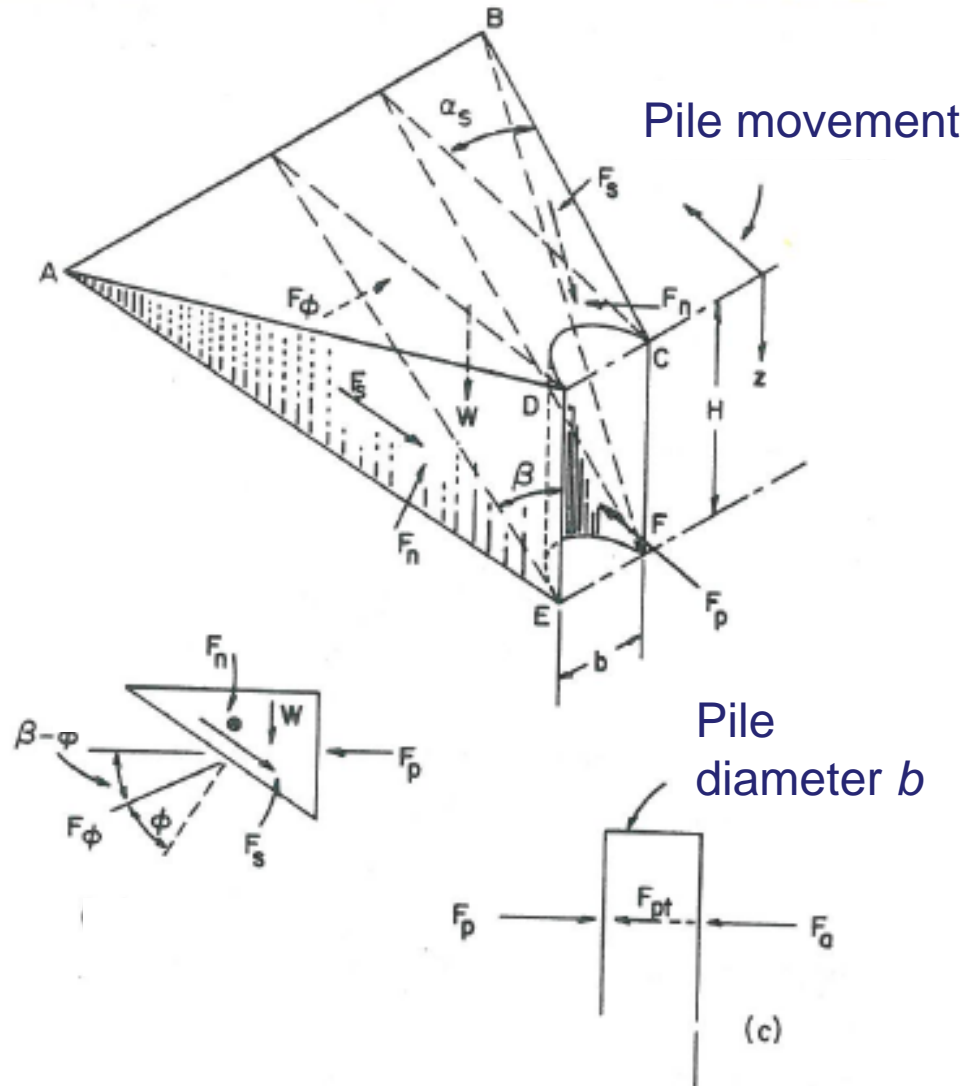
(a)

Wedge shape



Forces on the wedge

# 🔥 Wedge type pile failure in sand

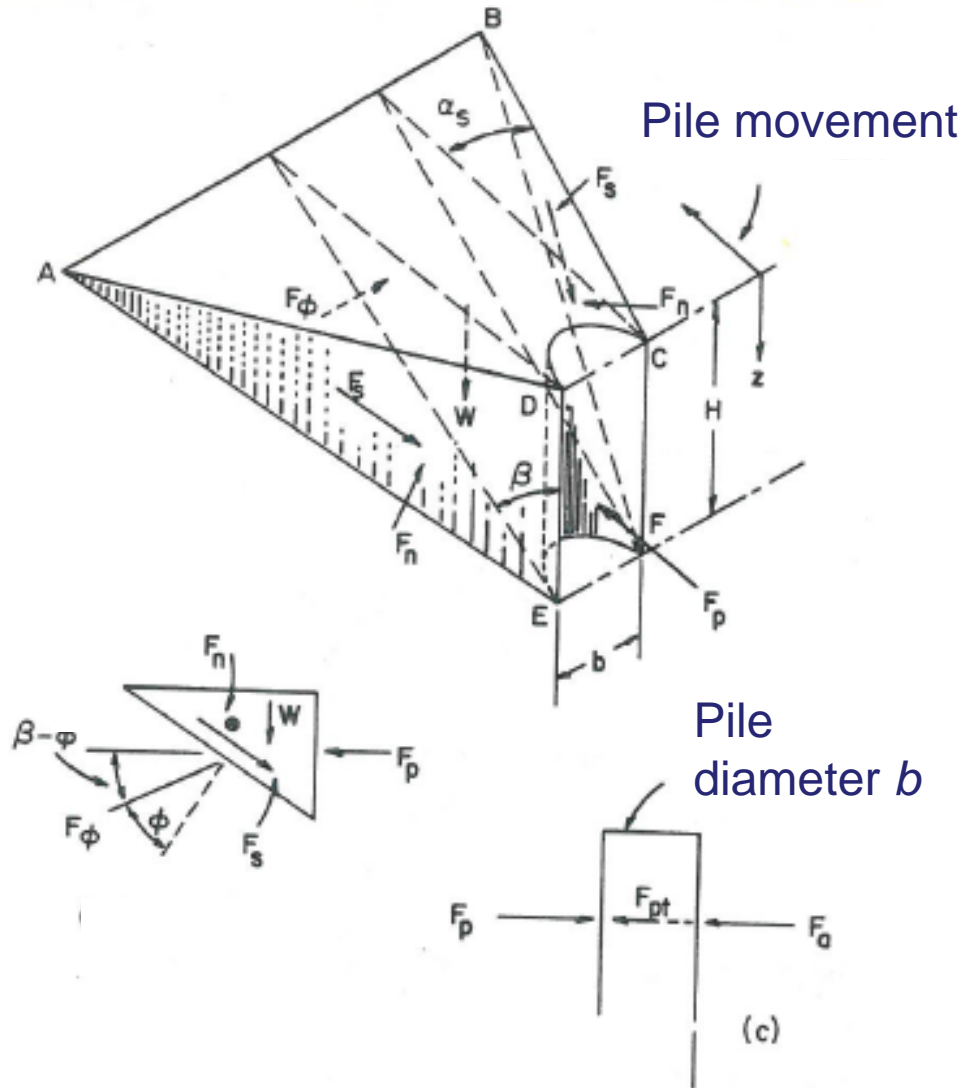




# 🔥 Wedge type pile failure in sand

Wedge shape

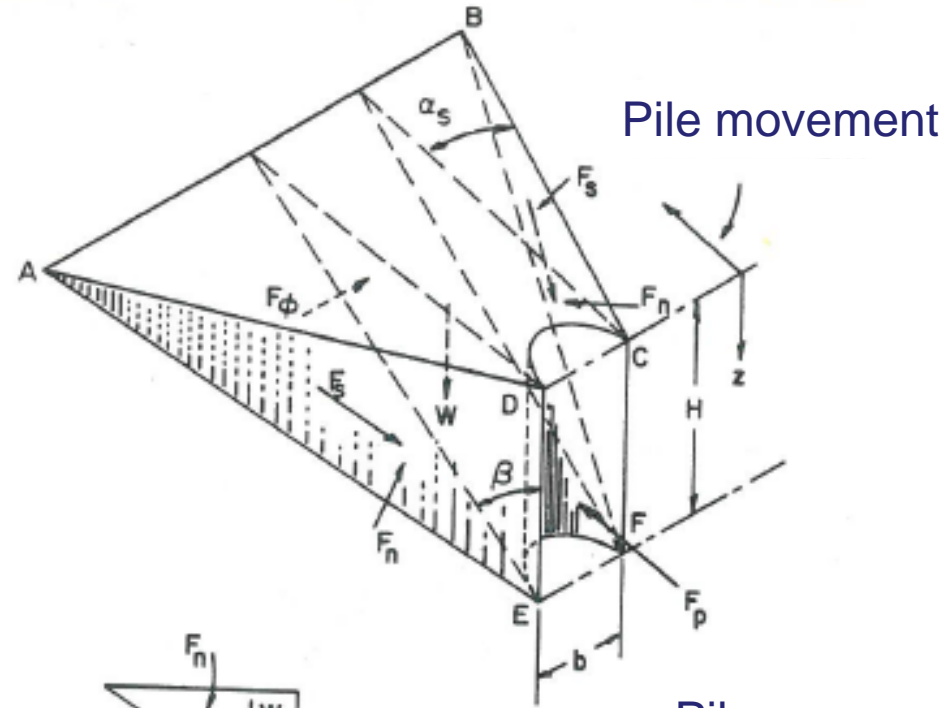
Forces acting on the wedge



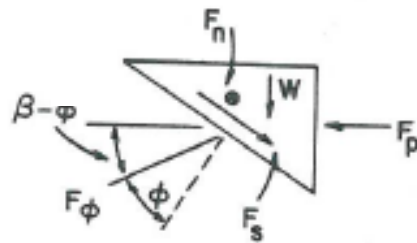
Pile diameter  $b$

# 🔥 Wedge type pile failure in sand

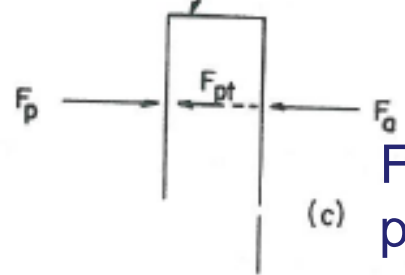
Wedge shape



Forces acting on the wedge



Pile diameter  $b$



Forces acting on the pile