ISSMGE TC209 Workshop
Challenges of Offshore Geotechnical Engineering

Challenges in Harvesting of Offshore Wind Energy in Turkey:
Analysis and Modeling of Soil-Foundation Interaction in OWT

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Bodrum - Turkey

Outline

1. **Wind energy in Turkey**
   - Overall look
   - Motivation
   - Current offshore potential in Europe
   - Issues and near future plans
2. **OWT foundations**
   - Types in terms of analysis perspective
3. **Numerical modeling aspects of OWT foundations**
   - Key issues
   - Monopile foundations
   - Modeling seabed-foundation interaction
   - Analysis of seabed soil as a two-phase material
   - Effects of soil constitutive modeling
4. **Summary**

Wind energy in Turkey

Overall look:

- Wind energy is an underrated renewable energy source in Turkey

- According to current wind atlas, coastal lines of Marmara and Ege regions have the highest potential both onshore and offshore

- Annual averages of wind speed at a 10m height are 4.5-5.6m/s along Ege coasts, and 3.4-4.6m/s inland. Bandırma district has the highest wave speed of 8.04m/s

- The first onshore harvest was in Çeşme/İzmir in 1986 with a 55kW turbine and the first wind farm was built in Alaçatı/İzmir in 1998 with 12 turbines

- The first largest wind power plant is the 10.2MW BORES built in Bozcaada having a capacity of 17 units of 600kW power

- 240 MW power in Soma/Manisa is the biggest onshore windfarm

What about the offshore wind energy?

Motivation:

- Offshore wind energy is indispensible among the nations with high wind potential.

- Numbers don't lie!

- **In Europe, wind power capacity increased from 3.2GW in 2000 to 142GW in 2018 with a combined growth rate of more than 10%**

- **Total power generation gets up to 8 MW/OWT across Europe and expected to reach 12 MW in 2025.**

- **Blade diameters are up to 164m, tower heights 113m**

What about the offshore wind energy?
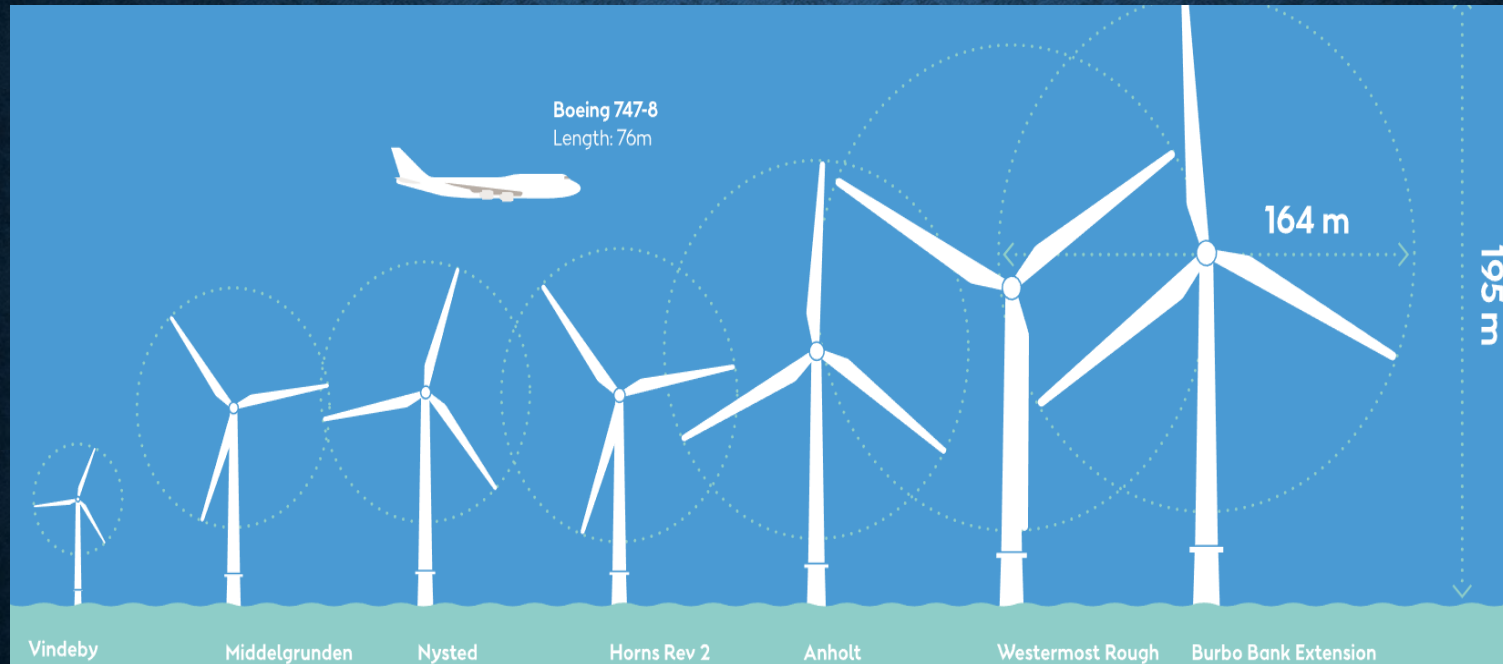
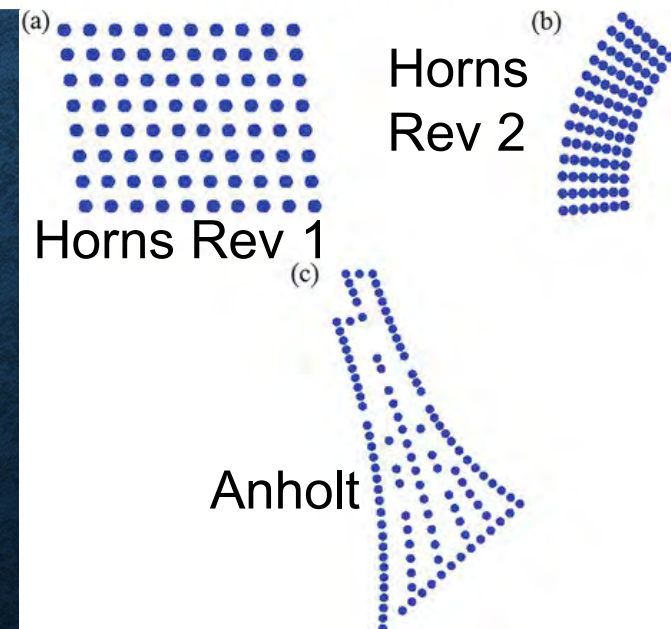| Year:	1991	2001	2003	2010	2013	2015	2017
D(m):	35	76	82	93	120	154	164
H(m):	35	64	69	68	82	102	113
Capacity (MW):	0.45	2.0	2.3	2.3	3.6	6.0	8.0

(Dong Energy, orsted.tw)

Wind farms in northearn Europe

Horns Rev 1 Offshore Wind Farm is located in the North Sea, 14-20 km off the southern part of Denmark's western coast.

Horns Rev 1

Horns Rev 2

Anholt

(Hansen, 2015)

	Horns Rev 1	Horns Rev 2	Horns Rev 3 (by 2020)
Capacity (MW)	160	209.3	406.7
Single Capacity (MW)	2.0	2.3	8.0
Number of Turbines	80	91	49
Turbine Heights (m)	110	114.5	187
Rotor Heights (m)	70	68	102
Blade D(m)	80	93	164
Foundation	Monopile	Monopile	Monopile
Pile length (m)	18	40	40-50
Pile D(m)	4.04	4.0	6.5
Project Costs (M Euro)	278	475	1000
Occupied Area (km^2)	21	33	144

Offshore wind energy in Turkey

Issues:

- OWT costs are still high

- Large tower and foundation sizes (6-8m) and their specialized materials

- Some local firms have the capacity to install monopiles but manufacturing of piles having large D is a problem

- Multi-physical analysis and design aspects and challenging installation stage at complex field conditions

- Dependence on the state/government support

- Potential economic downturns and unreliable local investment conditions

Offshore wind energy in Turkey

Near Future Plans:

- **1.2 GW power** is envisaged at about 30m near water depths.

- The Turkish Ministry of Energy and Natural Resources accepted applications for an offshore wind plant which would be the 'biggest' in the world and the first of its kind in the country in Oct. 23, 2018.

- However, no official submissions were received. So, near future plans seem to have been postponed indefinitely!

- Still 3 potential locations, Saroz, Gelibolu and Kıyıköy; **Kıyıköy** being a popular choice but may not be the most feasible one

- Various types of data will need to be gathered. **Oceanographic, meteorological, hydrological, seismological** data (water depths, currents, storms etc.)

- Detailed **reconnaissance study** will be performed

Offshore wind turbine foundations: Common types

Gravity Foundation

Monopile

Mono-caisson

Tripod

Multi-caisson

Very shallow water<20m

Shallow water 20-30m

Intermediate water 30-50m

Sharif Ahmed et al. (2015)
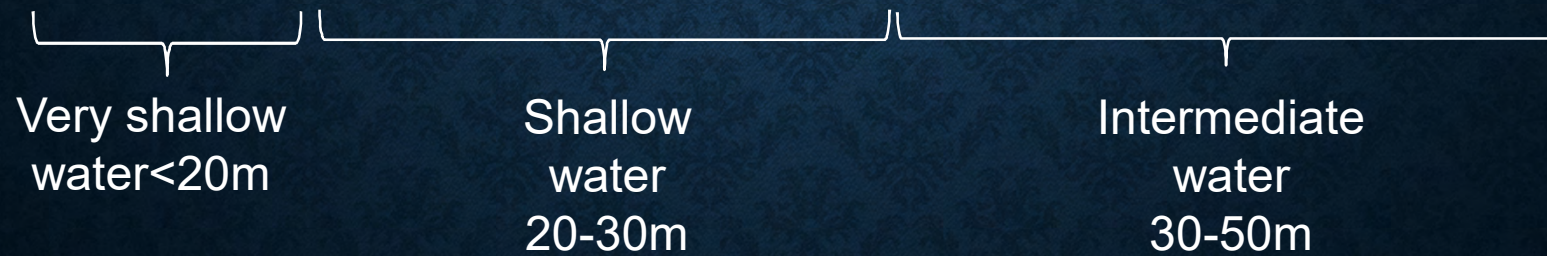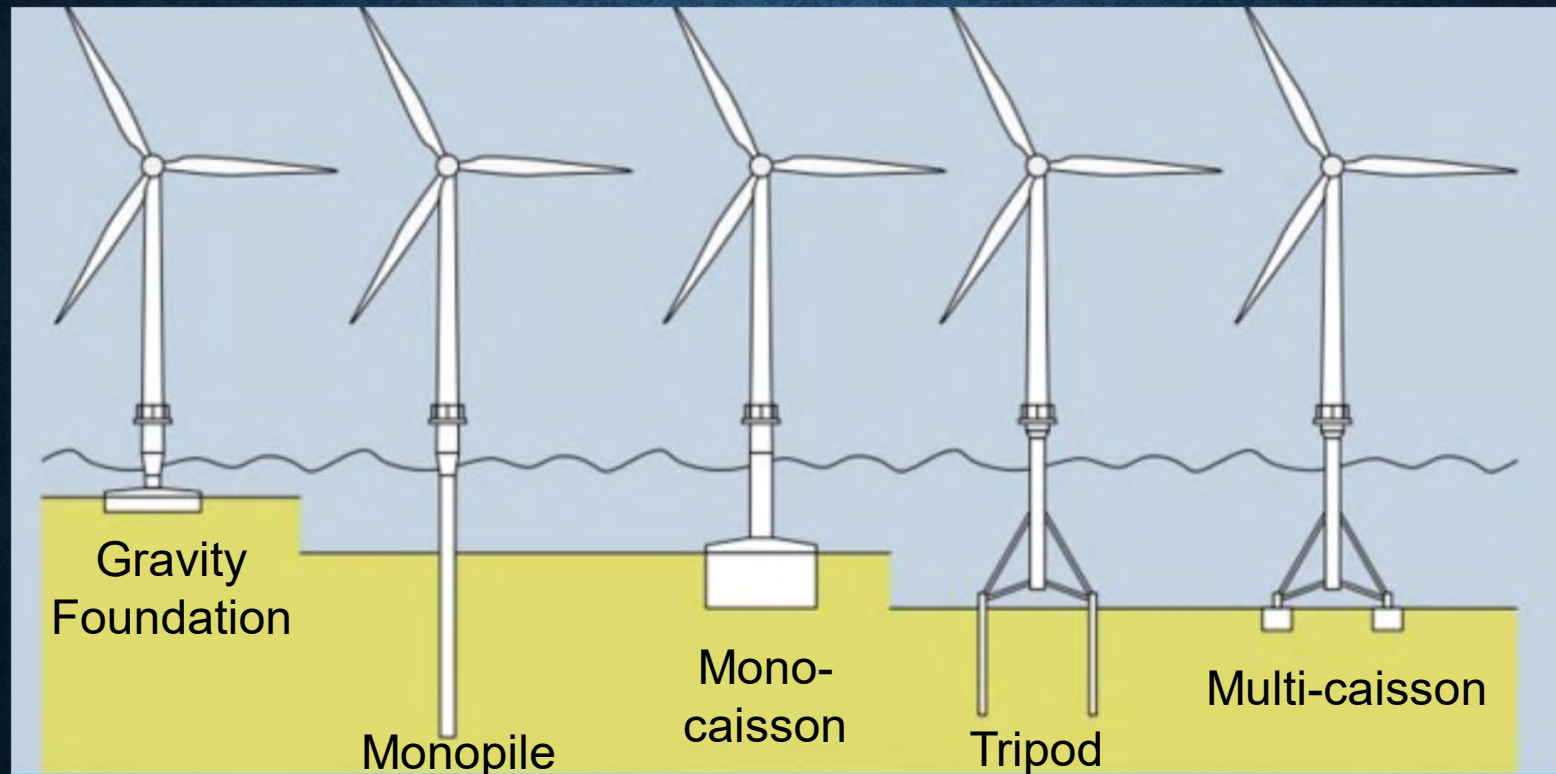
Offshore wind turbine foundations: Floating types

Spar-buoy   Semi-submersible   Tension-leg platform
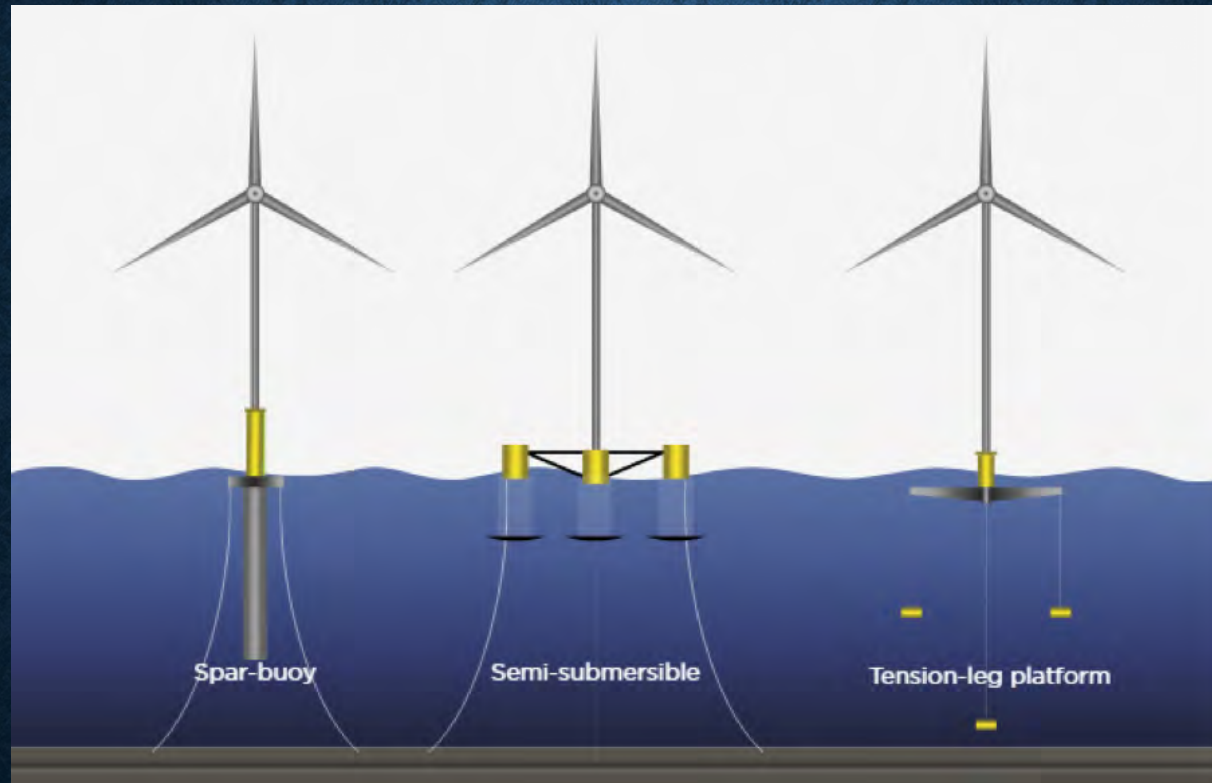
agci.org

Deep water
>50m

Numerical modeling aspects of OWT foundations

Key Issues: Forces and distributions

Challenge: How to determine the correct load distributions?
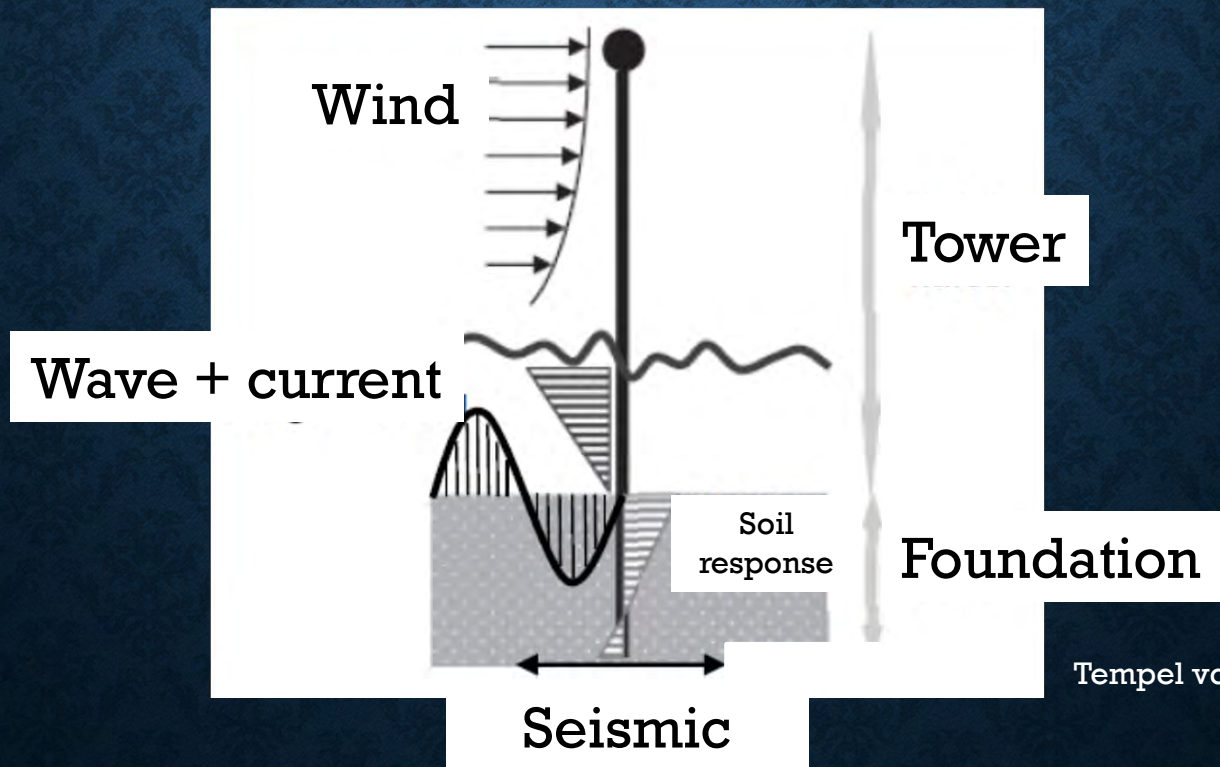
Tempel vd. 2010

Numerical modeling aspects of OWT foundations

Key Issues: Forces and distributions
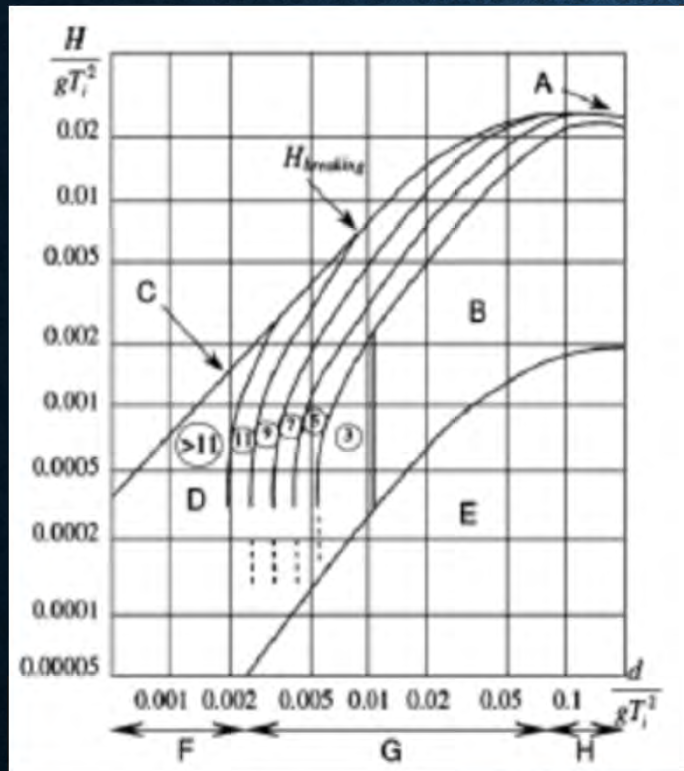
A: Deep water breaking, H/L=0.14

B: Stokes 5th order

C: Shallow water breaking, H/d=0.78

D: Stream function

E: Linear wave theory

F: Shallow water

G: Intermediate water

H: Deep water

Morrison equation

$$F(t) = \frac{\pi}{4} \rho_w C_M D^2 \ddot{u}(t) + \frac{1}{2} \rho_w D C_D \dot{u}(t)|\dot{u}(t)|$$

$$F(t) = \frac{\pi}{4} \rho_w C_M D^2 \ddot{u}_{da\lg a}(t) + \frac{1}{2} \rho_w D C_D \left(\dot{u}_{da\lg a}(t) + \dot{u}_{ak\iota nt\iota}(t) \right) \left| \left(\dot{u}_{da\lg a}(t) + \dot{u}_{ak\iota nt\iota}(t) \right) \right|$$

Current force

Tempel vd. 2010

Numerical modeling aspects of seabed-OWT foundation interaction

Monopile Foundations: Closer look
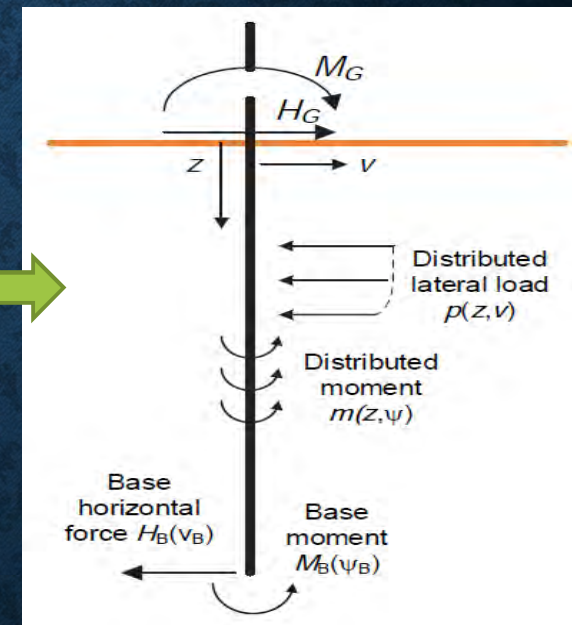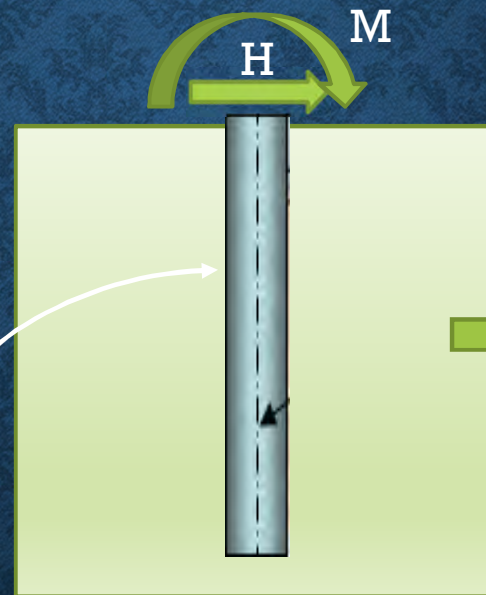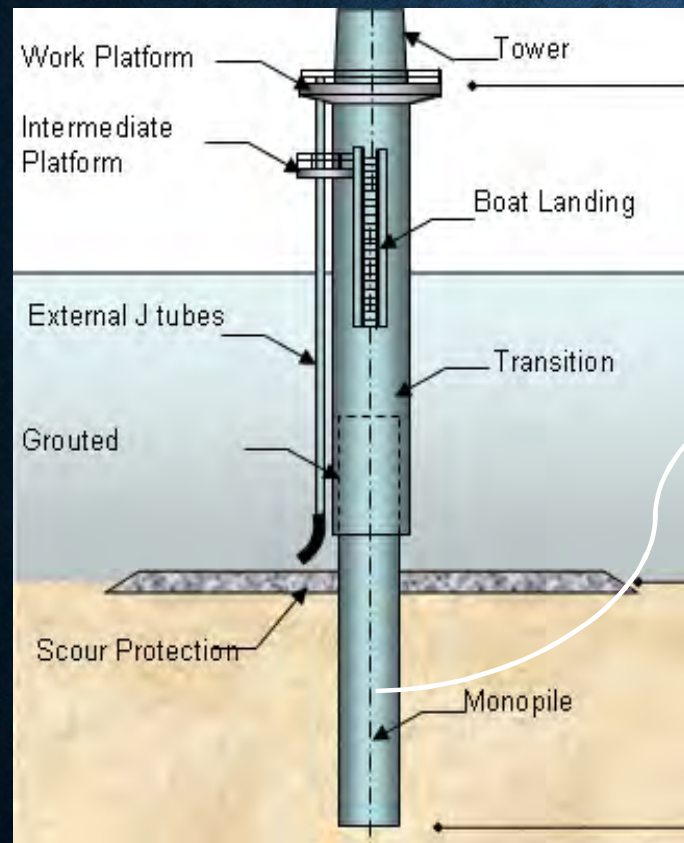
www.wind-energy-the-facts.org/offshore-support-structures.html)

Modeling seabed-OWT interaction

Nonlinear Winkler Springs:

- Laterally oriented **p-y springs** are used to represent the lateral resistance of the pile-soil interface,

- **t-z and q-z springs** to represent the frictional resistance along the length of the pile and the tip resistance at the base of the pile.

- **Added mass approach** for the pile-water interface due to induced acceleration into water as a result of structural vibration
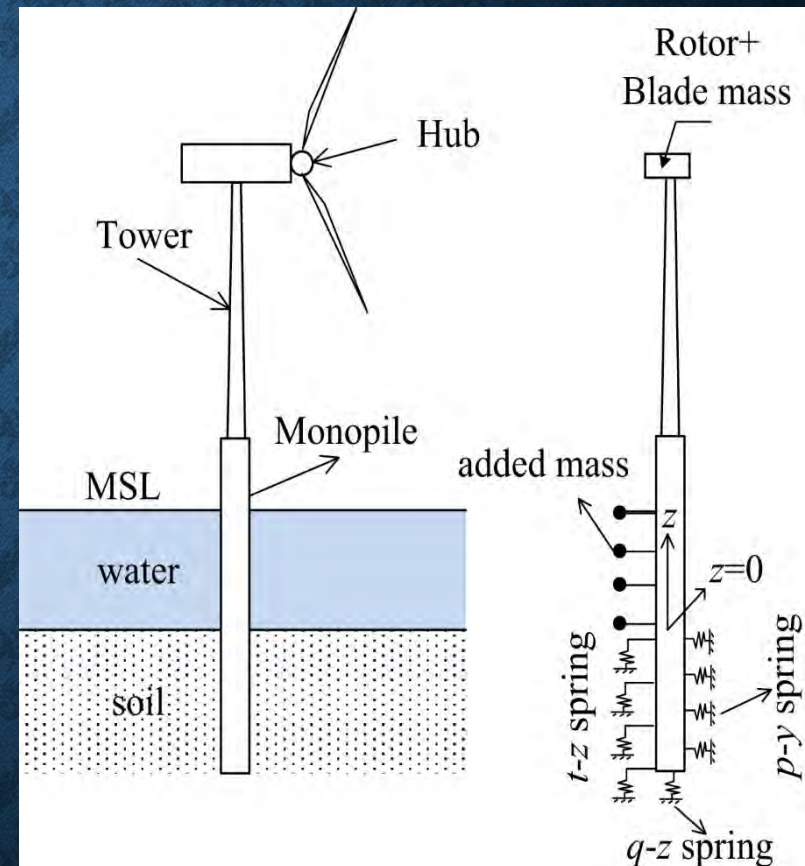
Modeling seabed-OWT interaction

3-D Finite Element Method:

- Boundary conditions (wave and current-induced loadings, ABCs)
- Seabed-foundation interaction (interface/contact elements)
- **Soil constitutive model !**
- Potential liquefaction or cyclic mobility of soil due to progressive build-up of pore pressure must be captured
- Plastic deformations of seabed need to be evaluated
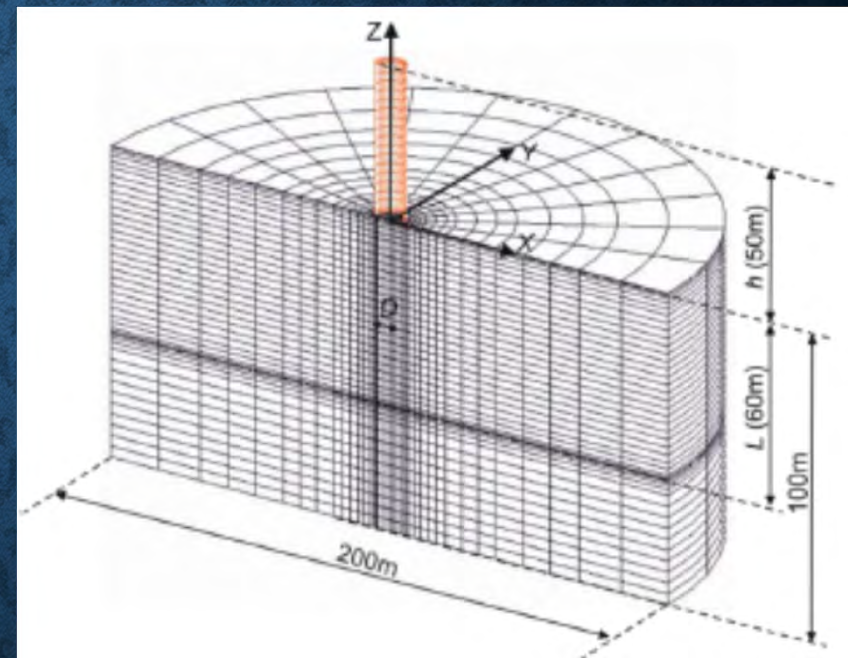
Burd et al., 2017

Modeling of OWT foundations: Monopile

- Boundary conditions

Absorbing boundary

Physical boundary

Absorbing boundary
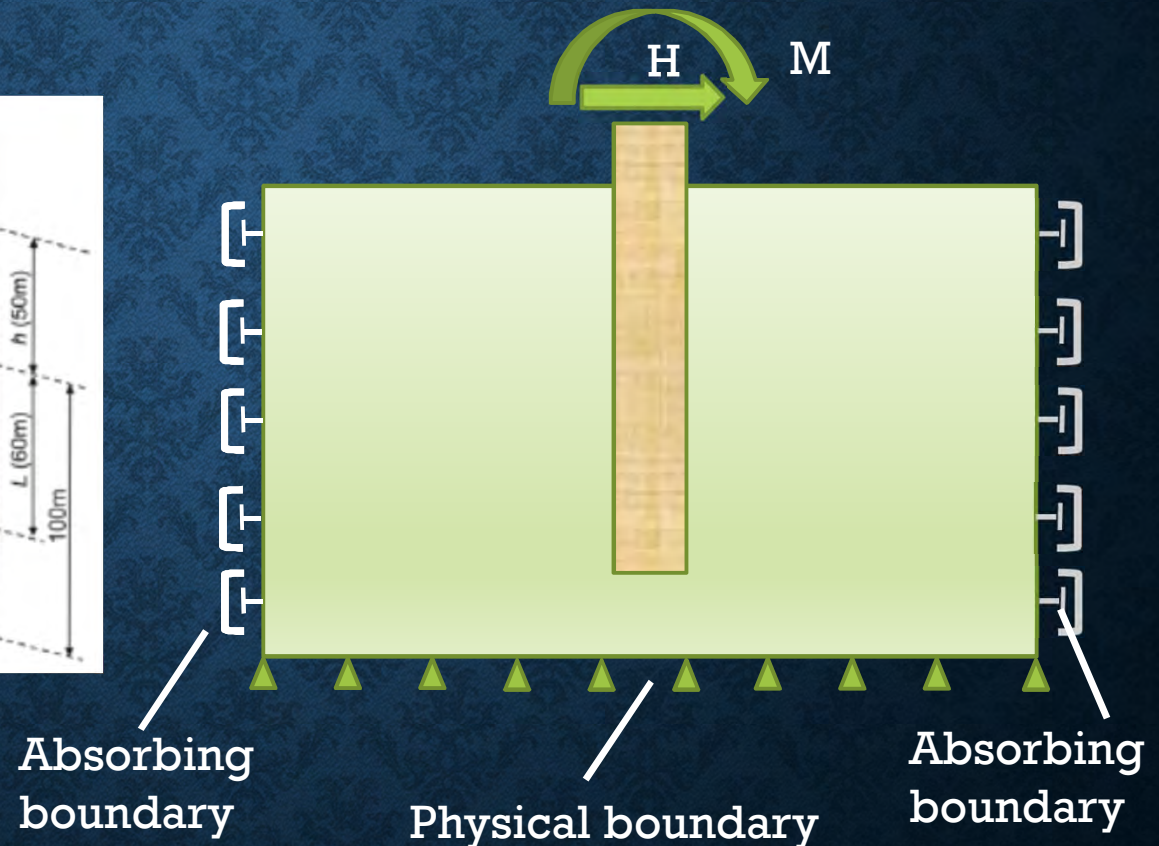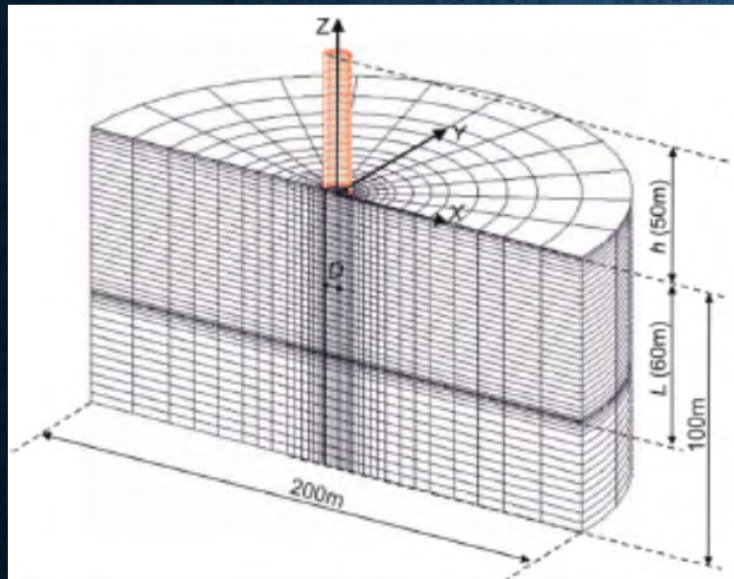
Combined FEM - *p-y* method

Burd et al. (2017) (**PISA** Project)

- Soil response is evaluated by 3-D nonlinear dynamic FE analyses (constitutive model of seabed is incorporated)

- Results are verified with field test data

  - 1-D design model of the pile is developed through *extended p-y method*

  - 1-D results are calibrated with FEM results
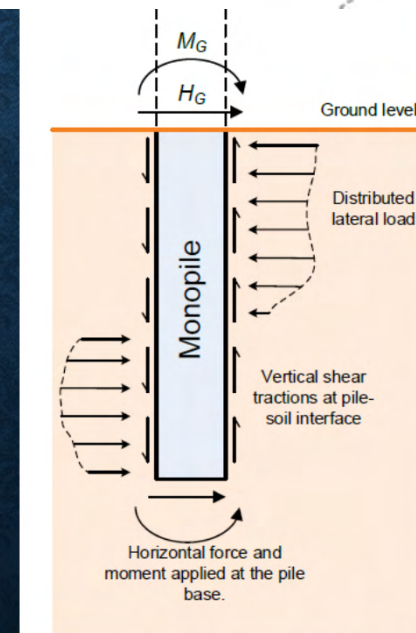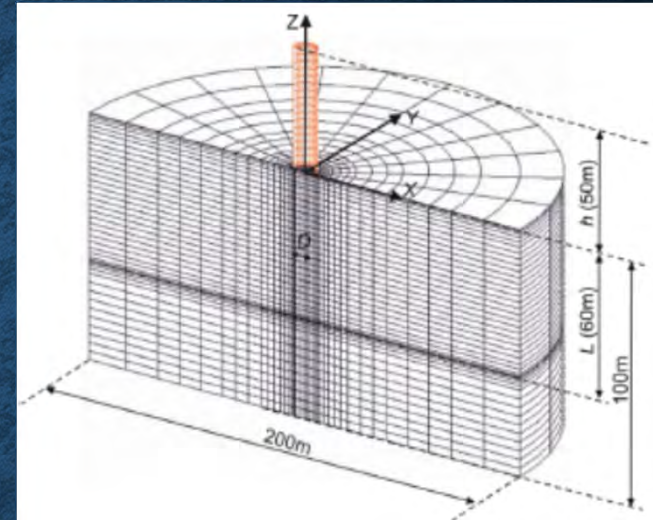
Burd et al., 2017

Combined method of seabed-pile interaction

- Four additional components of soil reaction are considered in the model

- Soil reactions are applied on the embedded beam based on Winkler assumption

- Functions relating the soil reactions and the local pile displacements (or rotations) are termed 'soil reaction curves'.

- Although the Winkler approach neglects the coupling between adjacent soil layers, *p-y* method is quite commonly used.
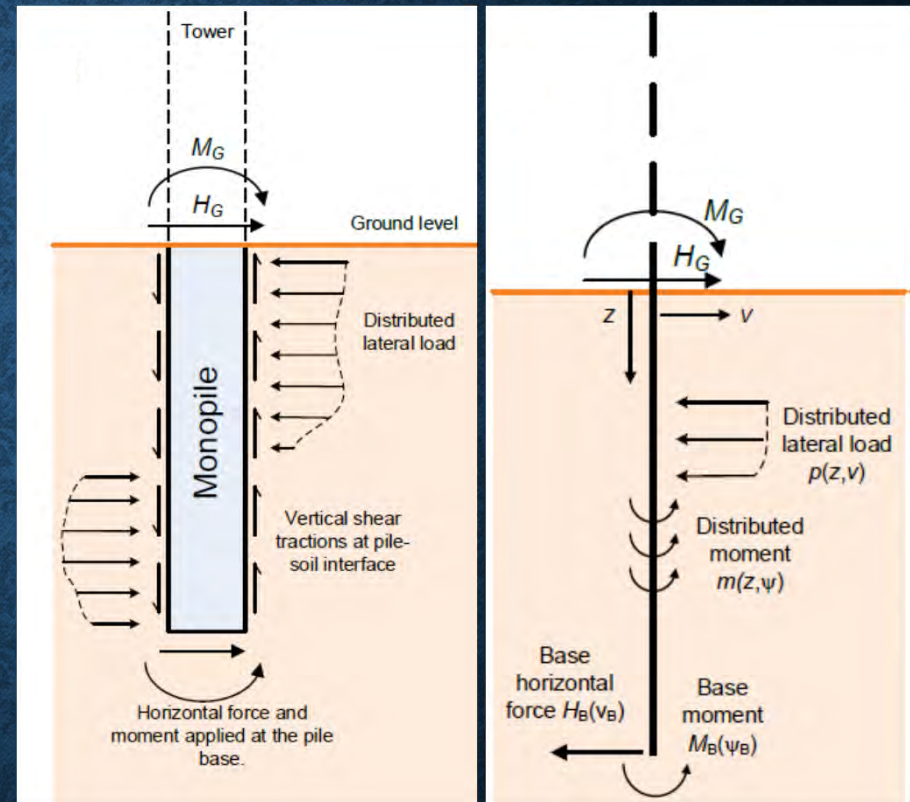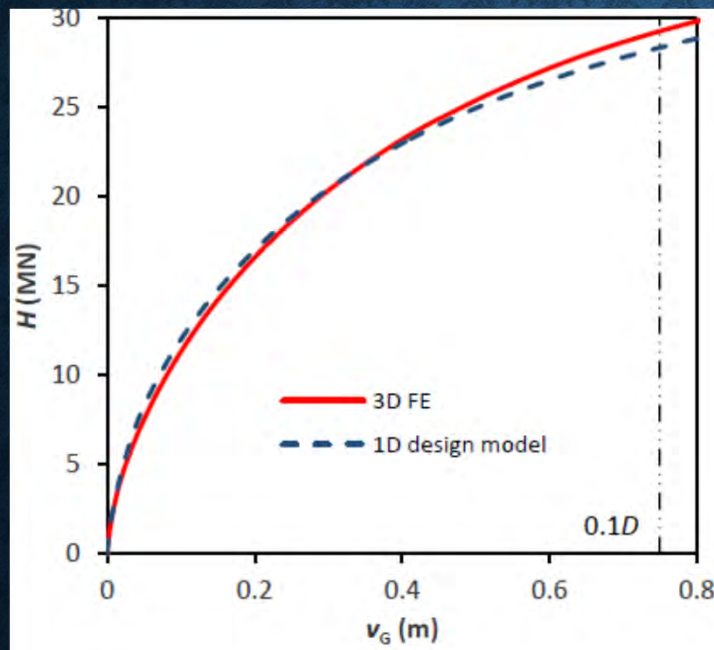

Burd et al., 2017

Combined method of seabed-pile interaction
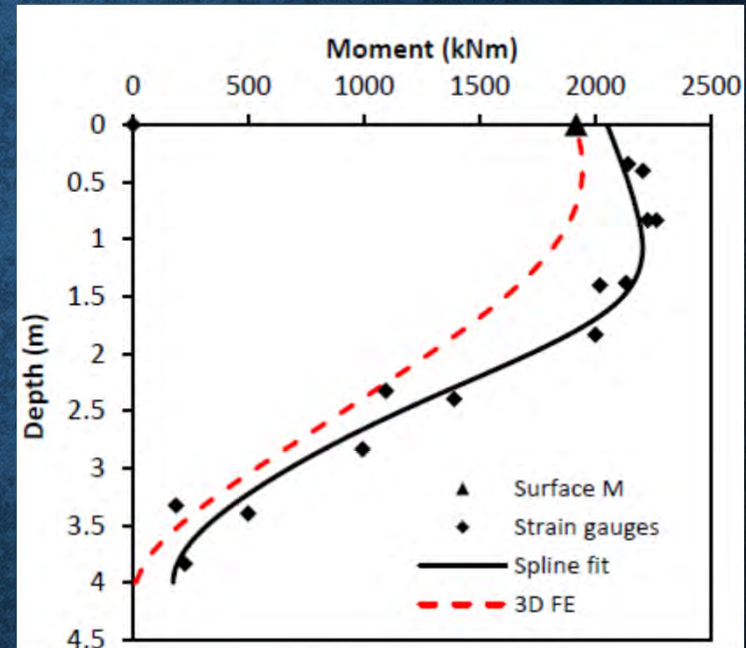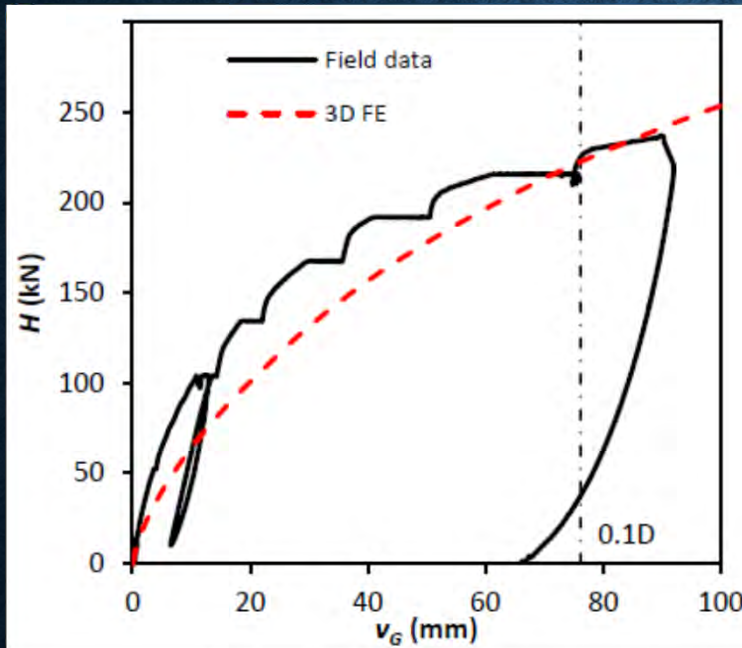
Burd et al., 2017

Calibration with 3-D FEM Results
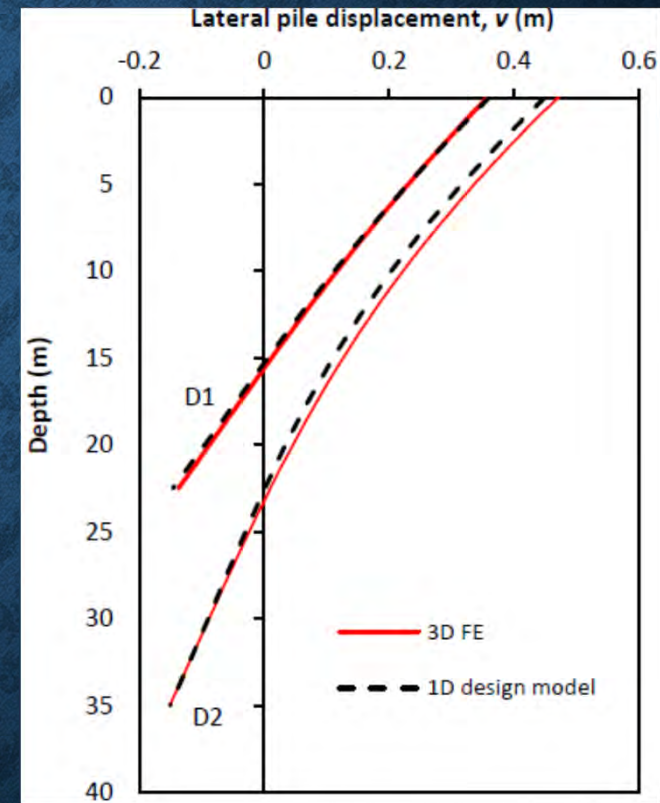
Burd et al., 2017

Modeling seabed as a 2-phase material

- Coupled flow and deformation problem

- Governing equations (Biot 1941, 1955, 1962)

Physical laws:

Constitutive Law $\longrightarrow$ Stress-Strain Relationship

+

Momentum Conservation $\longrightarrow$ Momentum Balance

+

Mass Conservation $\longrightarrow$ Mass Balance
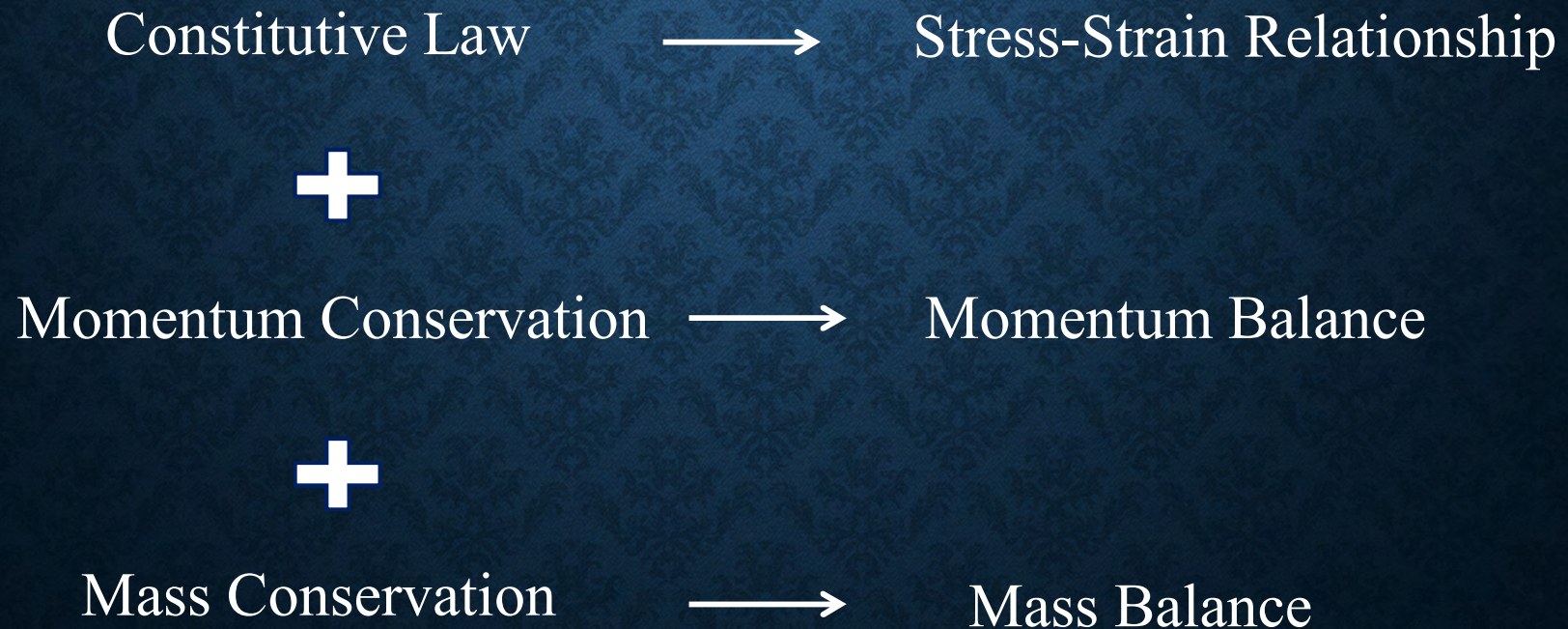
Poro-inelasticity

Total Equilibrium

$$\sigma_{ij,j} + \rho g_i - \rho \ddot{u}_i - \rho_f \ddot{w}_i = 0$$

Equilibrium of Pore Water

$$-p_{,i} - \frac{\rho_f g_i}{k_i} \dot{w}_i - \rho_f \ddot{u}_i - \frac{\rho_f}{n} \ddot{w}_i + \rho_f g_i = 0$$

Mass Conservation

$$\dot{u}_{i,i} + \dot{w}_{i,i} + \frac{n}{K_f} \dot{p} = 0$$

Poro-inelasticity

Constitutive relations and stress state

$$\sigma_{ij} = \sigma_{ij}' - \delta_{ij} p$$

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right)$$

$$\sigma_{ij}' = D_{ijkl}\left(\varepsilon_{kl} - \varepsilon_{kl}^{0}\right)$$

$$\beta = \frac{1}{K_f} = \frac{1}{K_w} + \frac{1-S}{p_0}$$

Various formulations

Partially Dynamic Formulation (PD / u-w-p form)

$$\sigma_{ij,j} + \rho g_i - \rho \ddot{u}_i = 0$$

$$-p_{,i} - \frac{\rho_f g_i}{k_i} \dot{w}_i - \rho_f \ddot{u}_i + \rho_f g_i = 0$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} + \frac{n}{K_f} \dot{p} = 0$$

Partially Dynamic Formulation (PD / u-p form)

$$D_{ijkl} u_{k,l} - \delta_{ij} p_{,j} = \rho \ddot{u}_i$$

$$\dot{u}_{i,j} + \left(\frac{-k_i}{\rho_f g_i} p_{,j} - \frac{k_i}{g_i} \ddot{u}_i \right)_{,i} = -\frac{n}{K_f} \dot{p}$$

Various formulations

Quasi-Static Formulation (QS / u-w-p form)

$$\sigma_{ij,j} + \rho g_i = 0$$

$$-p_{,i} - \frac{\rho_f g_i}{k_i} \dot{w}_i + \rho_f g_i = 0$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} + \frac{n}{K_f} \dot{p} = 0$$

Quasi-Static Formulation (QS / u-p form)

$$D_{ijkl} u_{k,l} - \delta_{ij} p_{,j} = 0$$

$$\dot{u}_{i,j} + \left(\frac{-k_i}{\rho_f g_i} p_{,j} \right)_{,i} = -\frac{n}{K_f} \dot{p}$$

Challenge: What formulation to use and when?
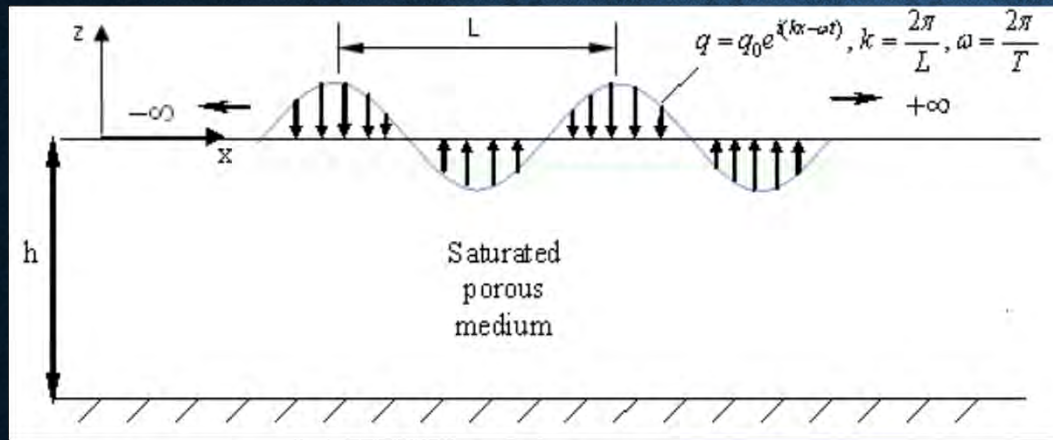
$$\left(u, w, \sigma_{xx}', \sigma_{zz}', \tau_{xz}, p\right) = \left(U, W, S_{xx}, S_{zz}, T_{xz}, P\right) e^{i(kx - \alpha t)}$$

$f(\mathbf{x}, \mathbf{z}, t)$ $\qquad$ $f(\mathbf{z})$

$$\Pi_1 = \frac{k V_c^2}{g \beta \omega h^2} \qquad \Pi_2 = \frac{\omega^2 h^2}{V_c^2} \qquad m = 2\pi \frac{h}{L}$$

- Under harmonic wave loading, response is also harmonic

- Closed form solution is in the form below

- Several non-dimensional parameters with physical meanings are introduced,

  $\Pi_1, \Pi_2, \mathbf{m}$

Domain of formulations

$m=0.01$

$m=0.1$
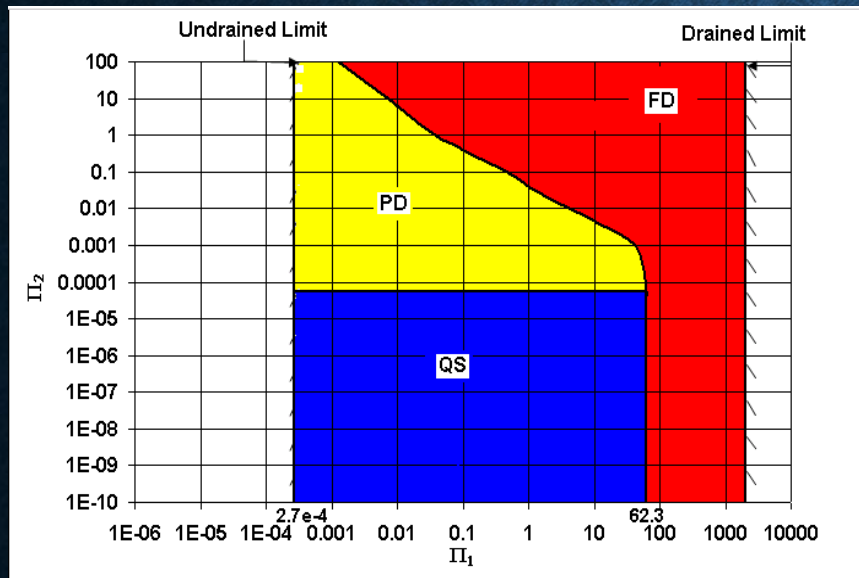
Error PD-QS<3% (blue)

Error PD-QS>3%
Error FD-PD<3% (yellow)

Error FD-PD>3% (red)
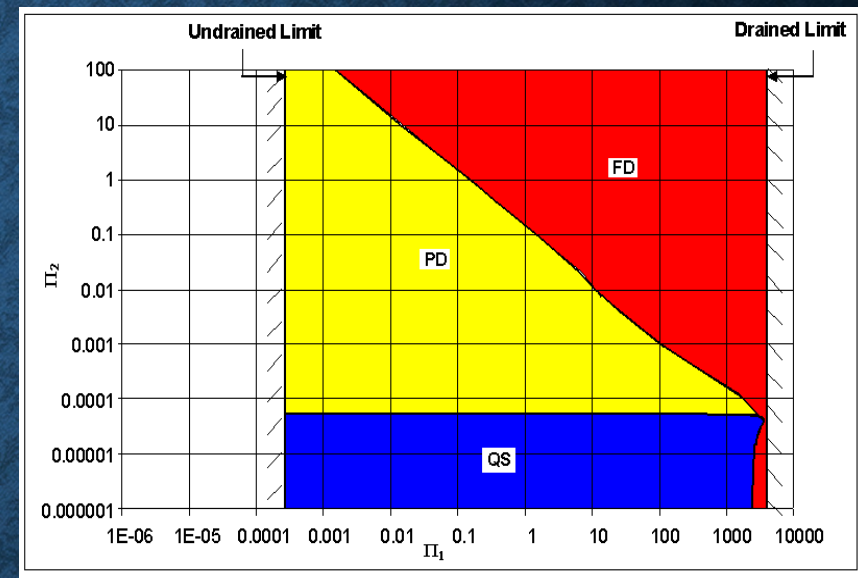
Ülker and Rahman, (2019)

Applicability of domains

Where does a problem fall on the non-dimensional space?

$$0.05 \leq T \leq 2\,s$$

$$\text{Here } T=0.3\,s \rightarrow m=2\pi\,\frac{100}{2000 \times 0.3} \approx 1$$

$$2 \leq T \leq 15\,s$$

$$\text{Here } T=5\,s$$

$$0.15 \leq \frac{h}{L} \leq 1.5$$

$$1 \leq m \leq 10$$

$$\text{Here } m=10$$
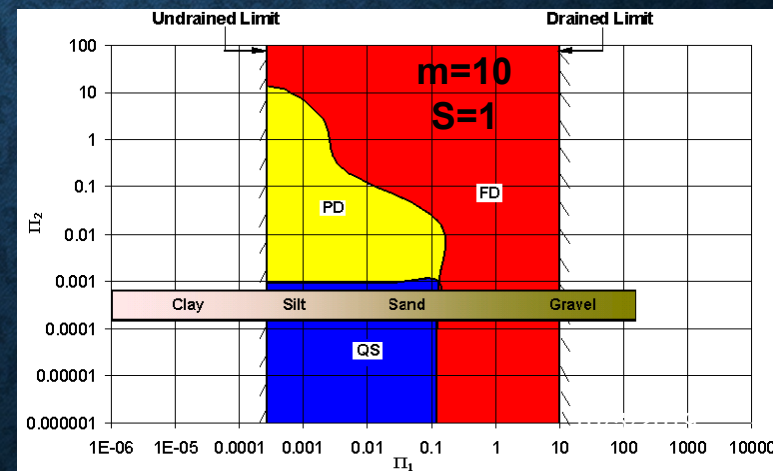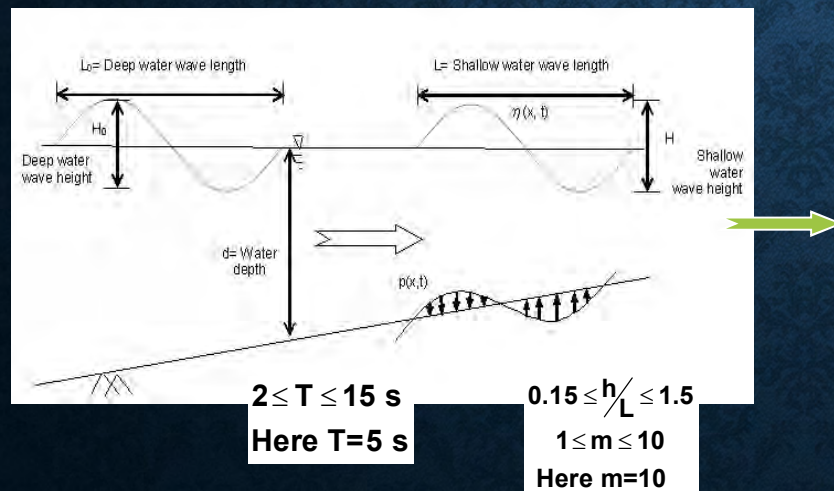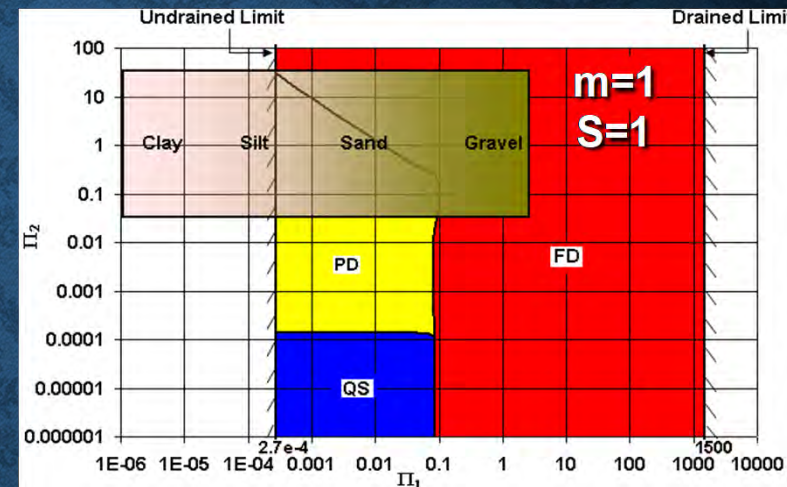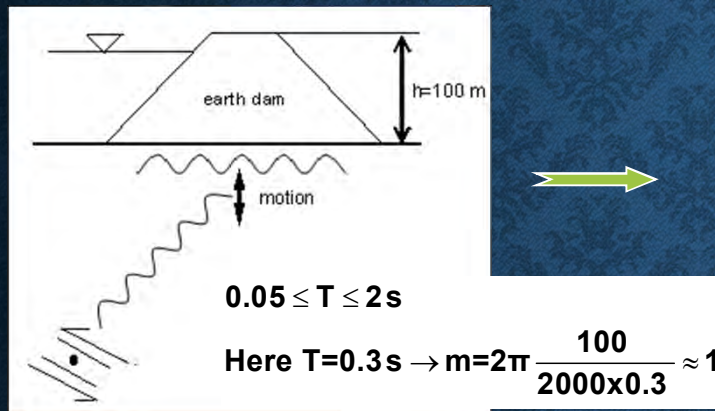
Ülker and Rahman, (2019)

Applicability of domains
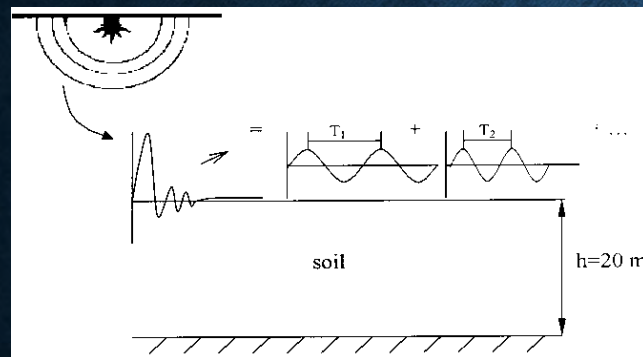
$0.005 \leq T \leq 0.02$ s

Here T=0.08 s $\rightarrow$ m=2$\pi \dfrac{h}{(V.T)} \approx 1$
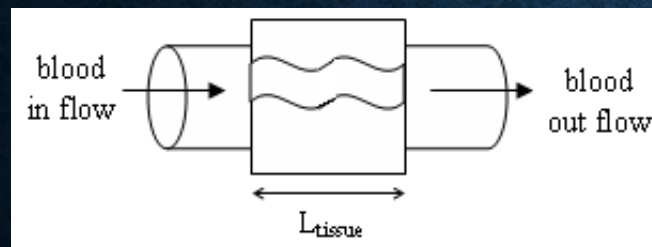
$0.3 \leq T \leq 1$ s
Here T=1s

$\rightarrow$ m=2$\pi \dfrac{L_{tissue}}{L} \approx 0.1$

Ülker and Rahman, (2019)
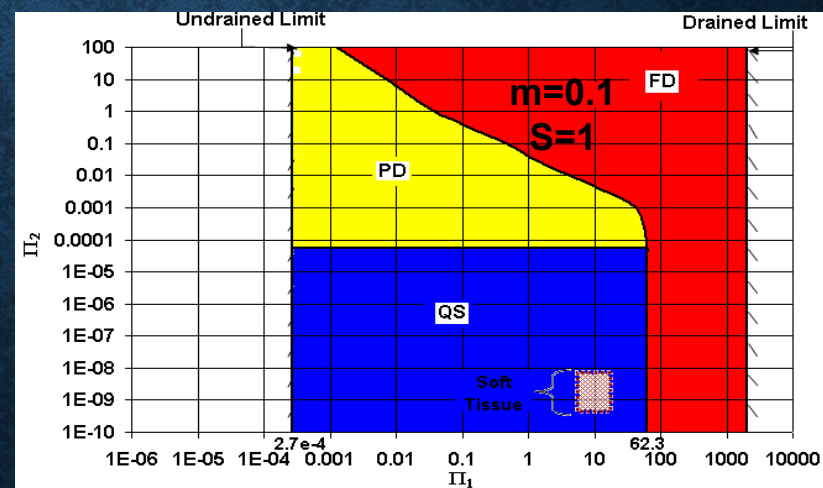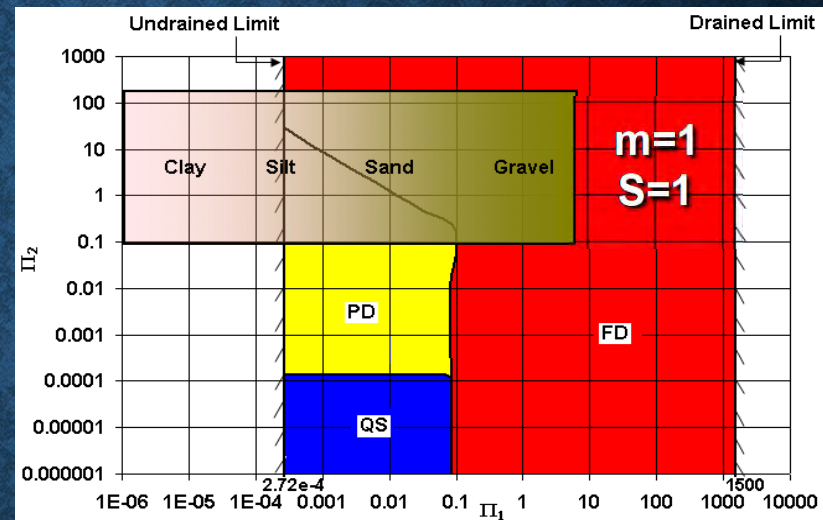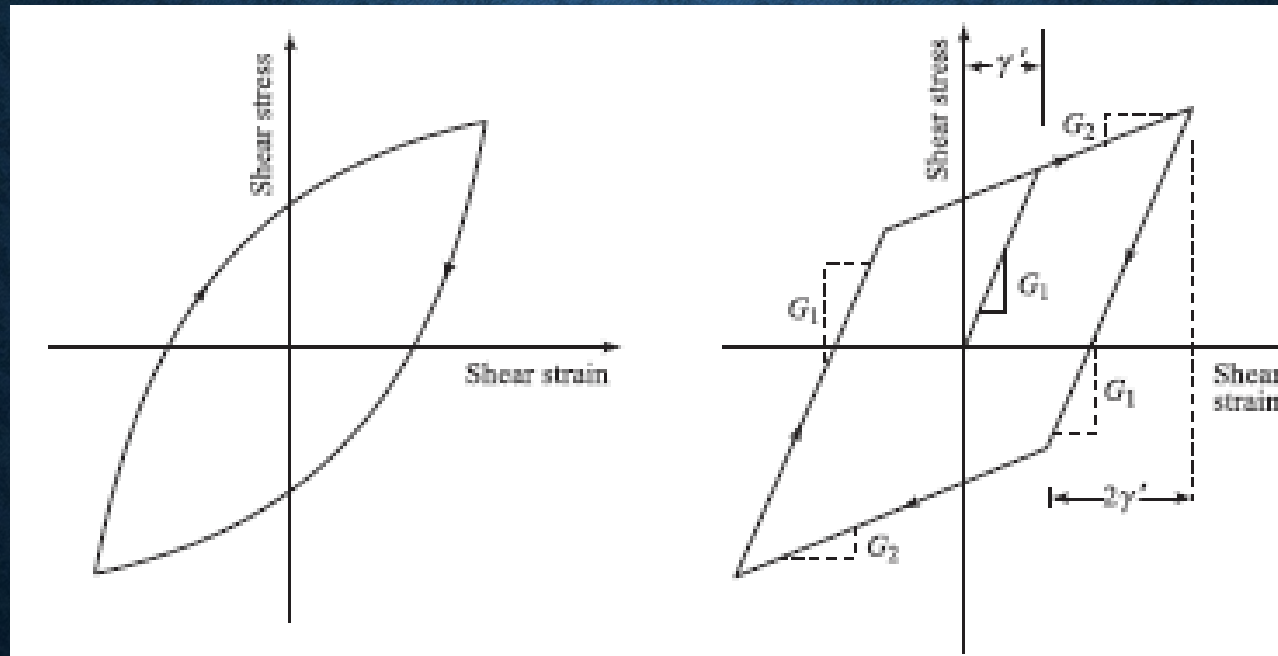
Seabed constitutive modeling

- Elasto-plastic behavior of seabed
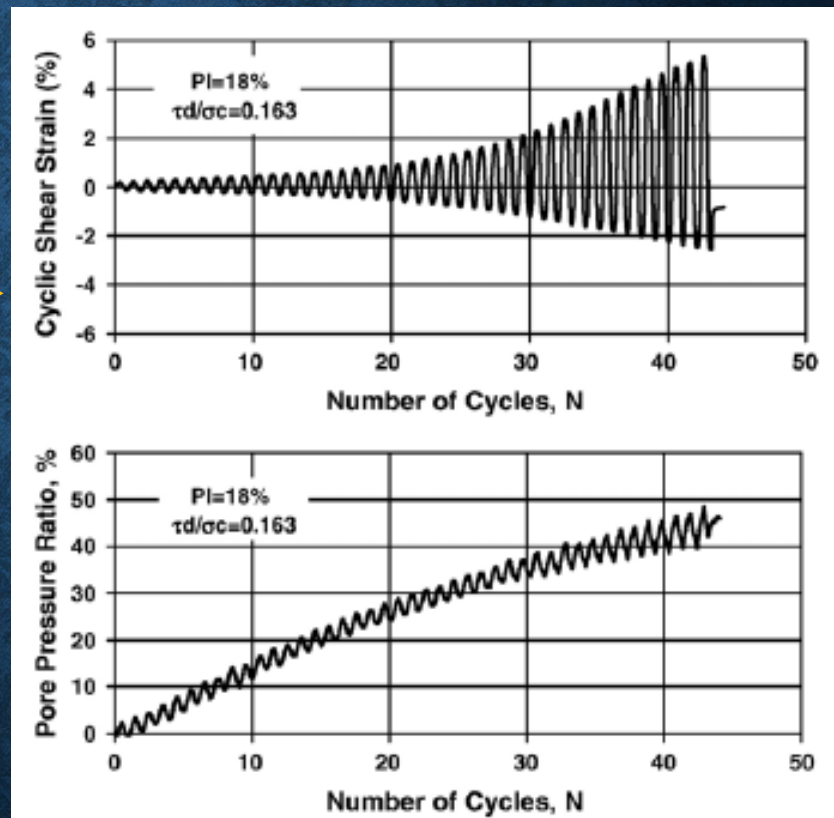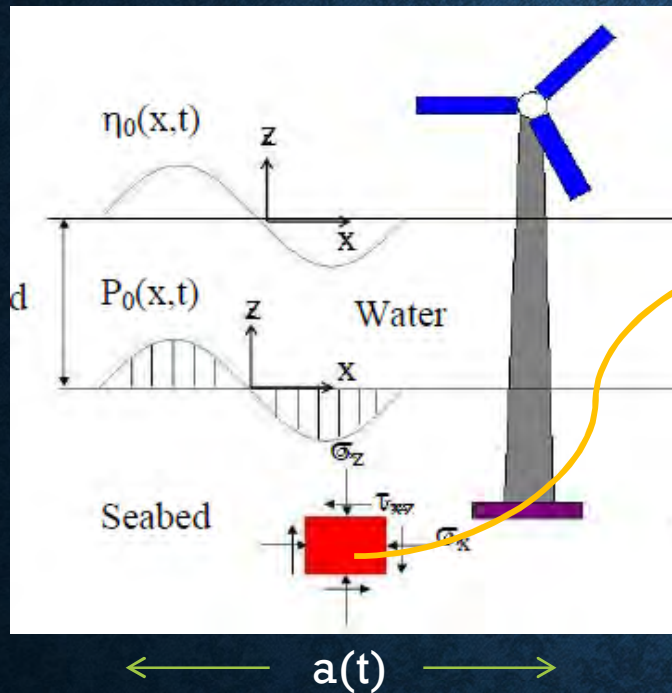
$$\sigma_{ij}{}' = D_{ijkl}^{ep}\varepsilon_{kl}$$

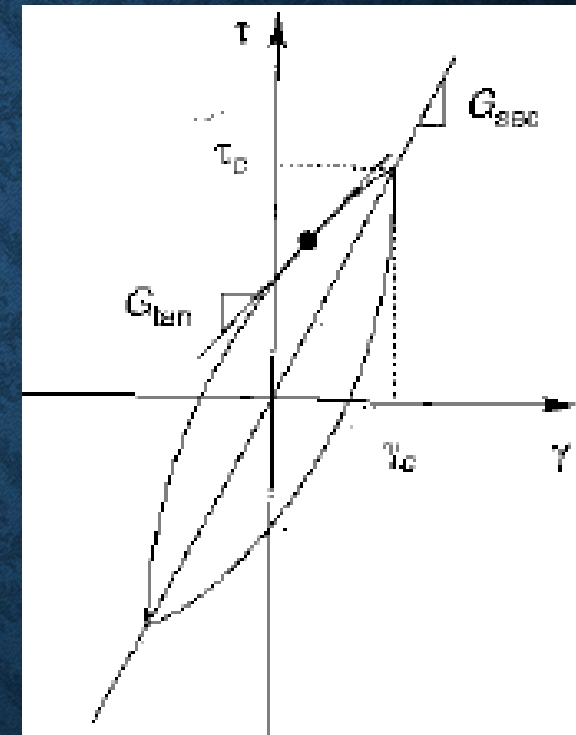# Challenge: How to tackle such constitutive modeling in offshore soils?

- Option 1: Simplified procedures
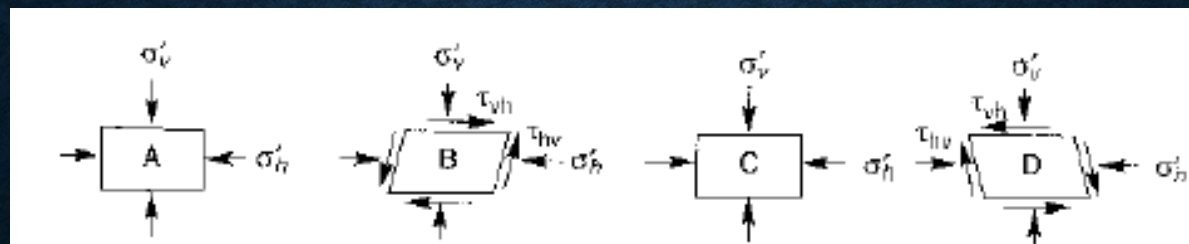
Challenge: How to tackle such constitutive modeling in offshore soils?

Option 1: Simplified procedures

- Secant and tangent shear moduli and damping ratio are calculated.

- Away from the structures, a hysteresis loop seen could be the soil's response to cyclic shear.

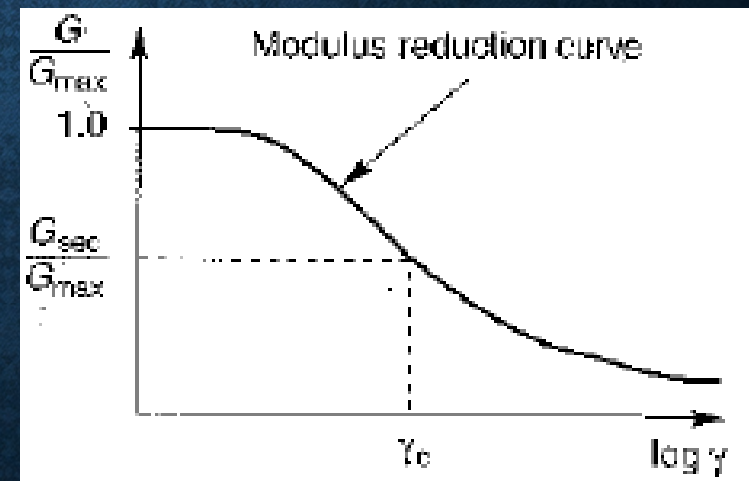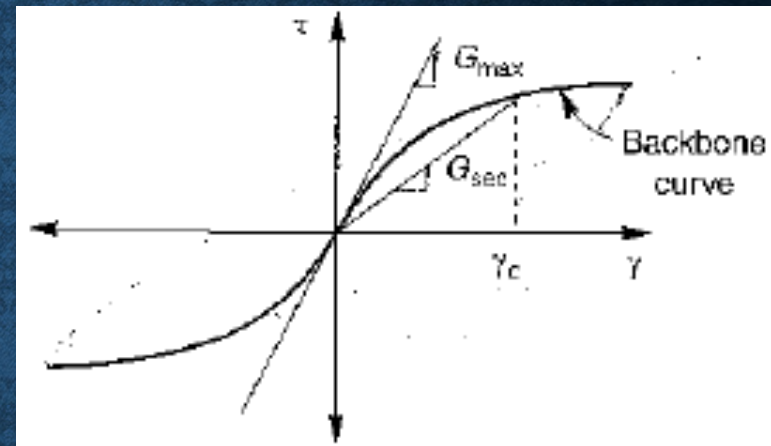- Equivalent **G**$_{sec}$ represents the average stiffness of the soil.

$$G = \frac{\tau}{\gamma}$$

$$\xi = \frac{W_D}{4\pi W_s} = \frac{1}{2\pi} \frac{A_{loop}}{G_s \gamma_c^2}$$

Challenge: How to tackle such constitutive modeling in offshore soils?

Option 1: Simplified procedures

- Representative of reduction in stiffness

- Typical behavior of different soil types

- Measured at dynamic soil tests

Challenge: How to tackle such constitutive modeling in offshore soils?

Option 2: Complex but robust procedures

- Theory of plasticity

- Elasto-plastic response of seabed soils is formulated using a number of theories; Classical Plasticity, Bounding Surface Plasticity, Generalized Plasticity, Hypoplasticity etc.

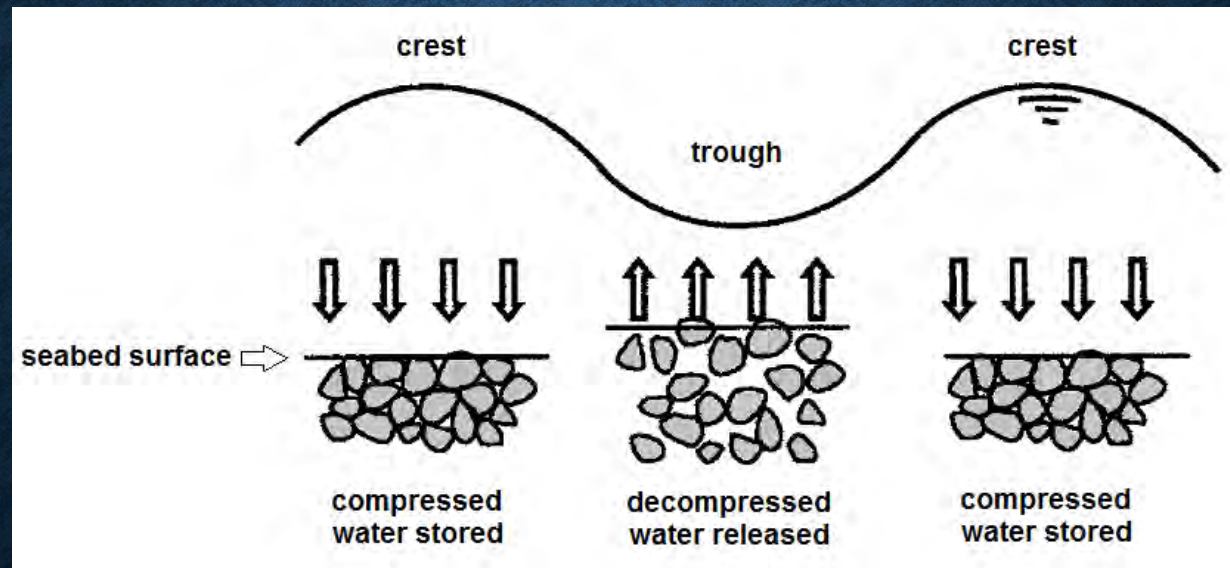- **Objective: Capture wave-induced instabilites of seabed around offshore structures !**
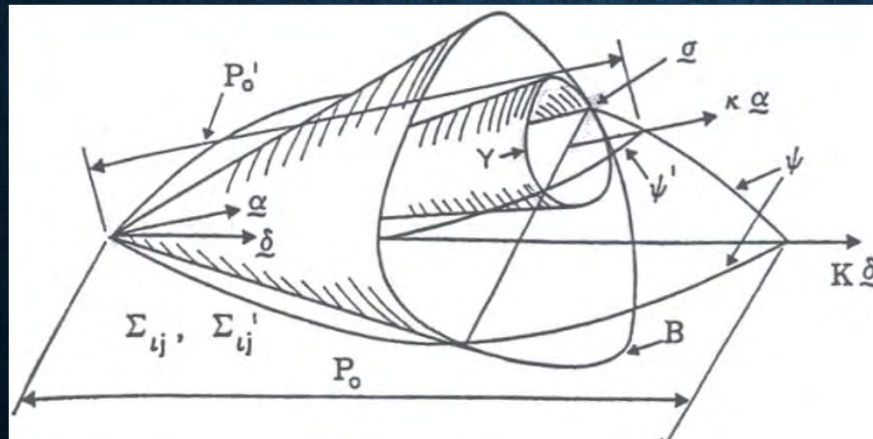
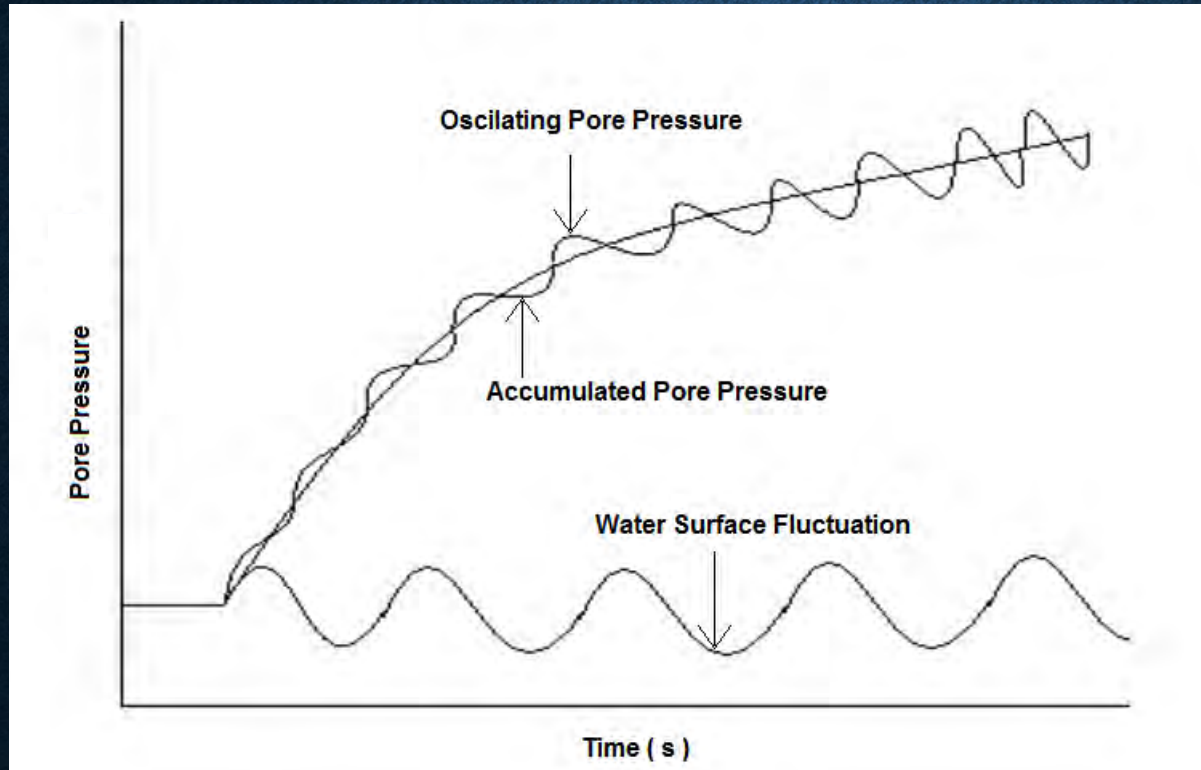
$$F = \bar{\sigma} - \eta g(\theta) I = 0$$

Poorooshasb and Pietruszczak, (1986)

Challenge: How to model instability of offshore soil-structure systems?

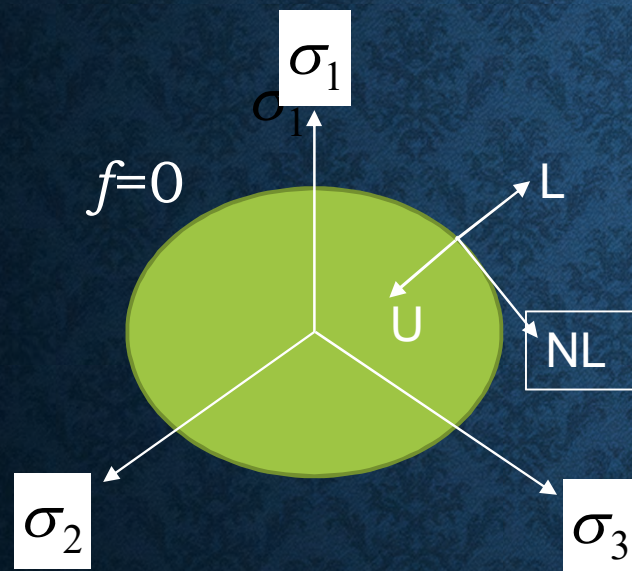Wave-induced upward seepage flow causing liquefaction

Dynamics of saturated porous seabed

Residual liquefaction

Instantaneous liquefaction

Challenge: How to accurately identify loading, unloading distinction?

$$d\sigma_{kl}' : n > 0 \rightarrow \text{Loading}$$

$$d\sigma_{kl}' : n < 0 \rightarrow \text{Unloading}$$

$$d\sigma_{kl}' : n = 0 \rightarrow \text{Neutral loading}$$

$$n = \frac{\dfrac{\partial f}{\partial \sigma}}{\sqrt{\left(\dfrac{\partial f}{\partial \sigma}\right)^{T} \dfrac{\partial f}{\partial \sigma}}}$$

Calculate σ'−ε relationship

Strain Controlled

$$d\sigma_{ij}' = D^{ep}_{ijkl} d\varepsilon_{kl}$$

$$d\varepsilon_{ij} = C^{ep}_{ijkl} d\sigma_{kl}'$$

$$C^{ep}_{ijkl} = C^{e}_{ijkl} + \frac{1}{H_{L/U}} n_g^{L/U} \otimes n = \left(D^{ep}_{ijkl} \right)^{-1}$$

$$d\sigma' = \underbrace{\left[D^e - \frac{D^e n_g^{L/U} n^T D^e}{H_{L/U} + n^T D^e n_g^{L/U}} \right]}_{D^{ep}_{ijkl}} d\varepsilon$$

Stress Controlled

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{\,e} + d\varepsilon_{ij}^{\,p}$$

$$d\varepsilon_{ij}^{\,e} = C^{e}_{ijkl} d\sigma_{kl}'$$

$$d\varepsilon_{ij}^{\,p} = \frac{1}{H_{L/U}} \left[n_g^{L/U} \otimes n \right] : d\sigma_{ij}'$$
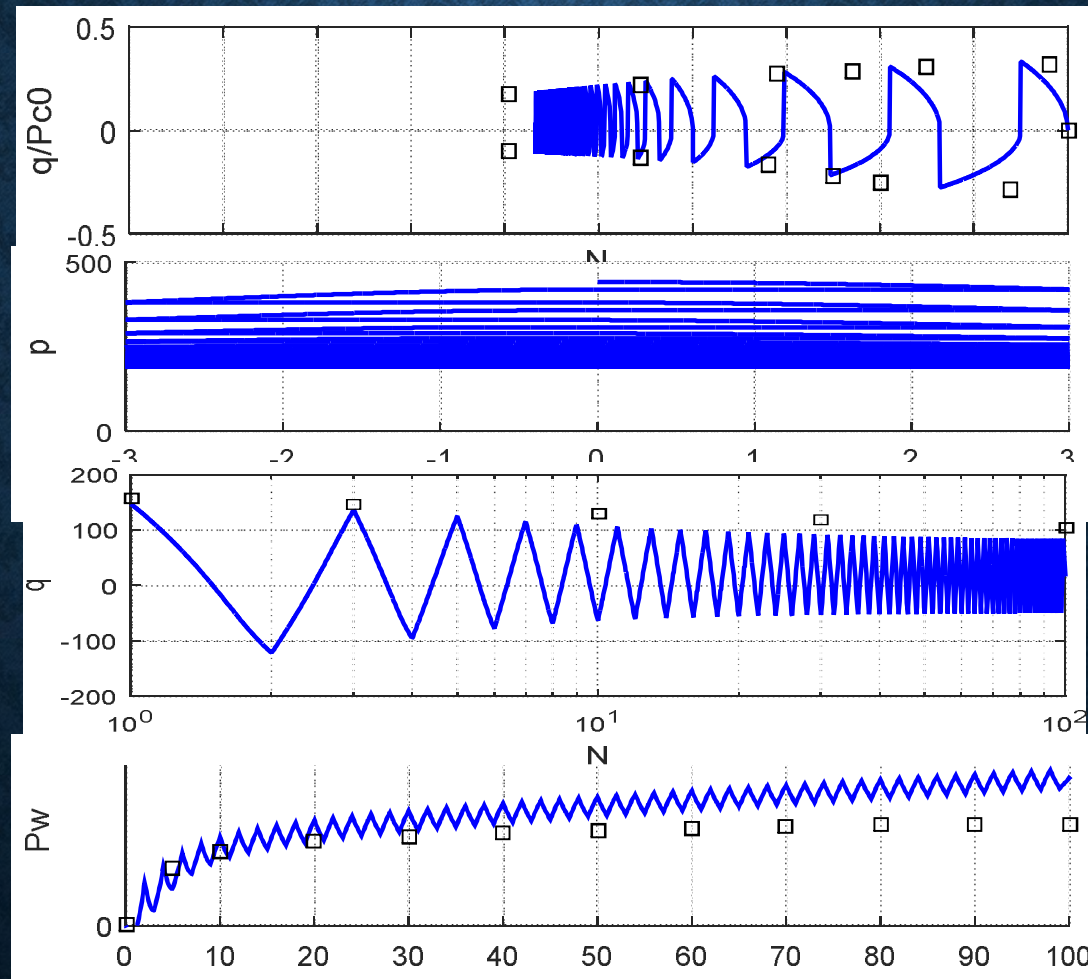
$$d\varepsilon_{ij} = C^{e}_{ijkl} d\sigma_{kl}' + \frac{1}{H_{L/U}} \left[n_g^{L/U} \otimes n \right] : d\sigma_{ij}'$$

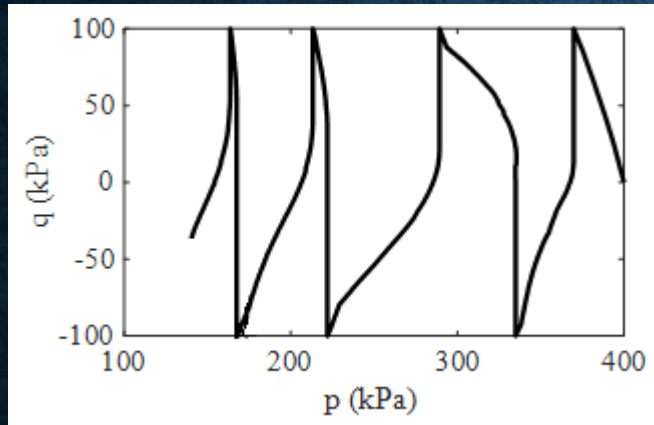# Dynamics of saturated porous seabed
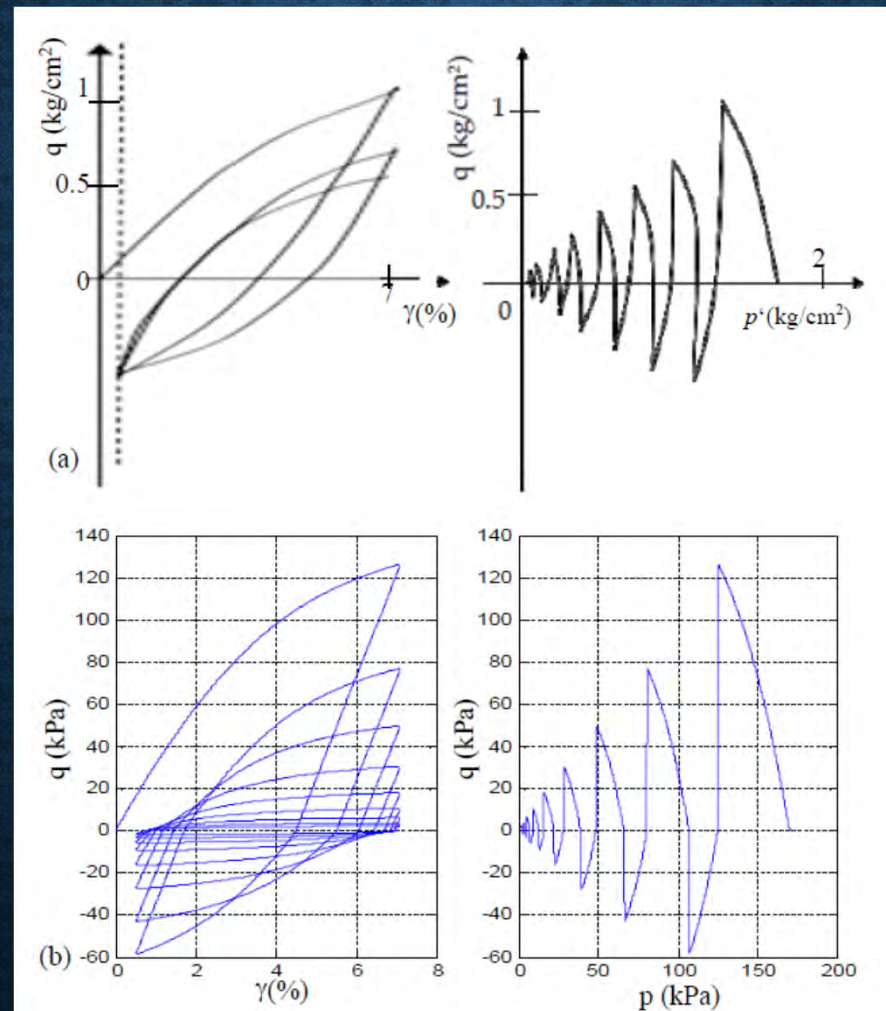
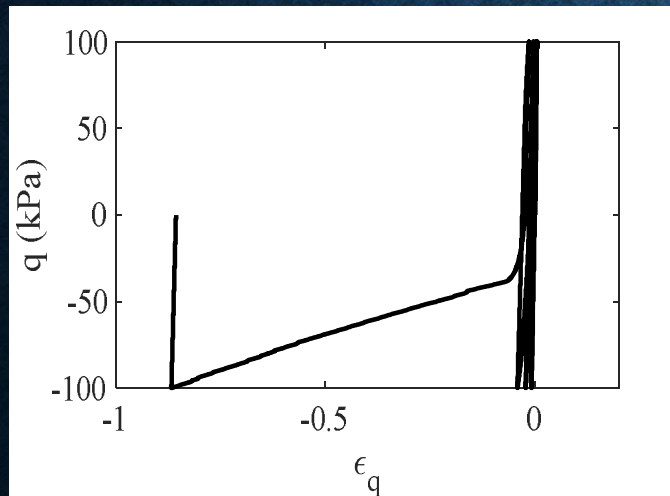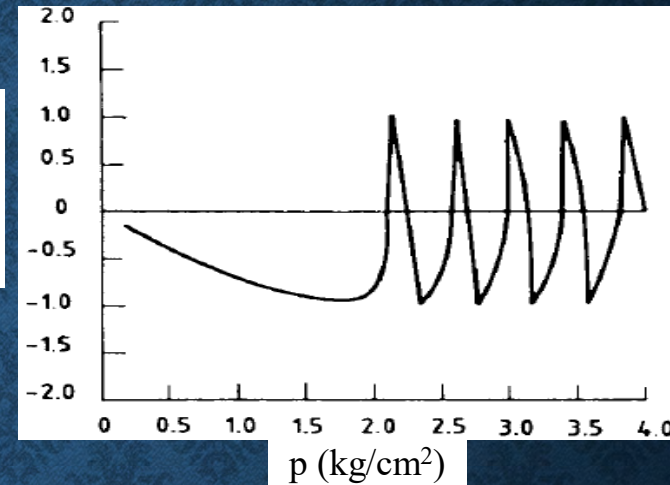Ülker, (2019)

Dynamics of saturated porous seabed
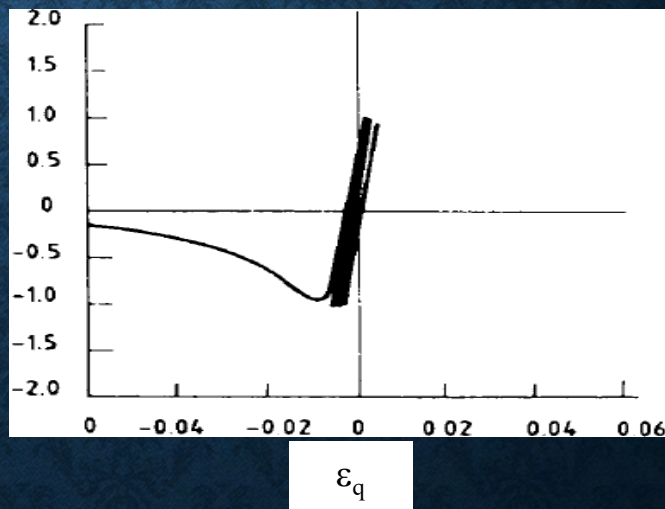

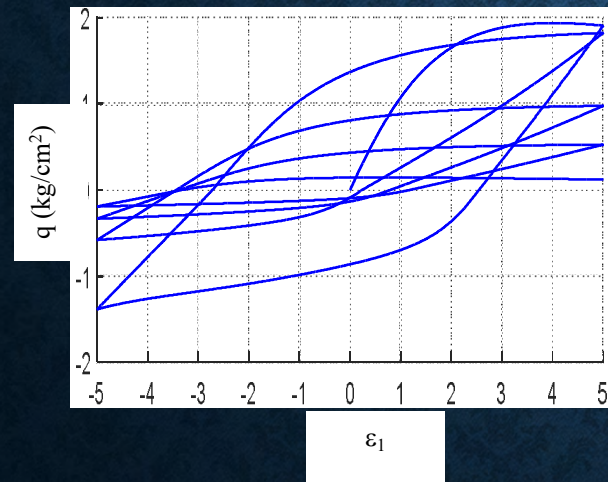Ülker, (2019)

Sands: Two-way stress-controlled test
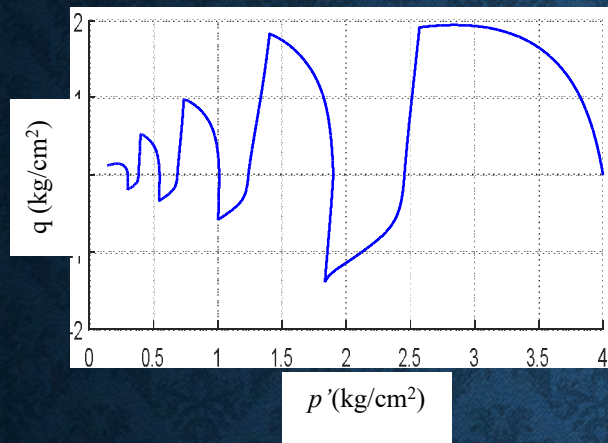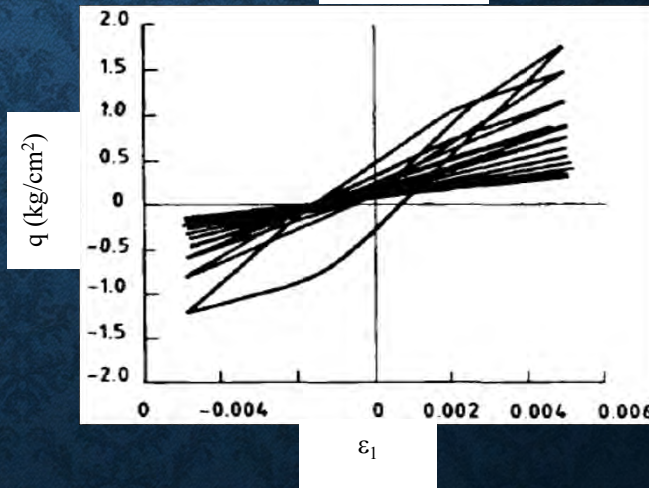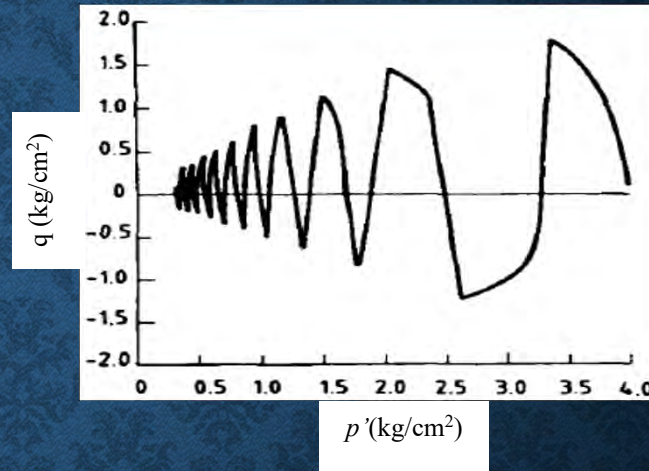

Tatlıoğlu and Ülker, (2019)

Pastor-Zienkiewicz Model (PZ-III)

Sands: Two-way strain-controlled test

Tatlıoğlu and Ülker, (2019)

Pastor-Zienkiewicz Model (PZ-III)

Summary

- It is too luxurious not to make use of offshore wind energy, especially for a country like Turkey surrounded by seas
- Challenges of Turkey in harvesting offshore wind is of two fold: Technical and political
- This was said for onshore wind at the time so sooner or later hopefully Turkey will produce power through offshore wind

Provided that these challenges are addressed:

- Reliable field data are gathered : Meteorological, oceanographic, geological, geotechnical etc.
- Relevant field and lab testing is performed
- Mathematical models are formulated
- Accurate numerical analyses are conducted to solve the appropriate governing equations along with;
- Seabed-foundation-water interaction is accurately handled
- Sophisticated soil constitutive models are incorporated
- Results are verified with tests
- The outcomes are fed into the design

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Thanks for listening

Questions/comments