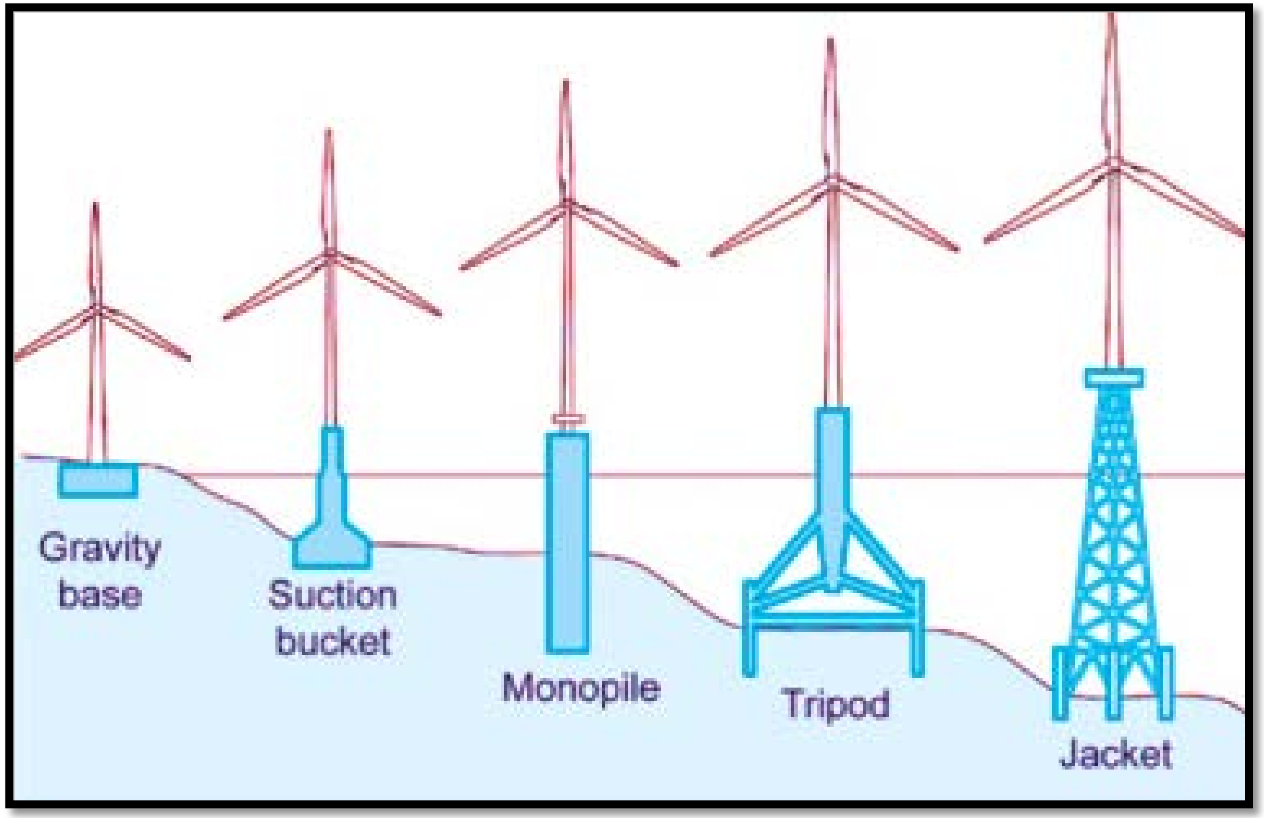
Workshop 2
Study of structural and foundation systems of Wind Turbines

Footing Design of Wind Turbines

Prof. Panagiotis Pelekis

Wind Turbine Foundation Systems



Most common types

- Gravity base (circular slab)
- Monopile or group of piles
- Both

Footing Design of Wind Turbines

A Roadmap for Safe Footing Design of Wind Turbines

Stability of the foundation system (ULS)

- Bearing capacity
- Slippage
- Overturning

Serviceability of the foundation system (SLS)

- Settlement
- Tilt

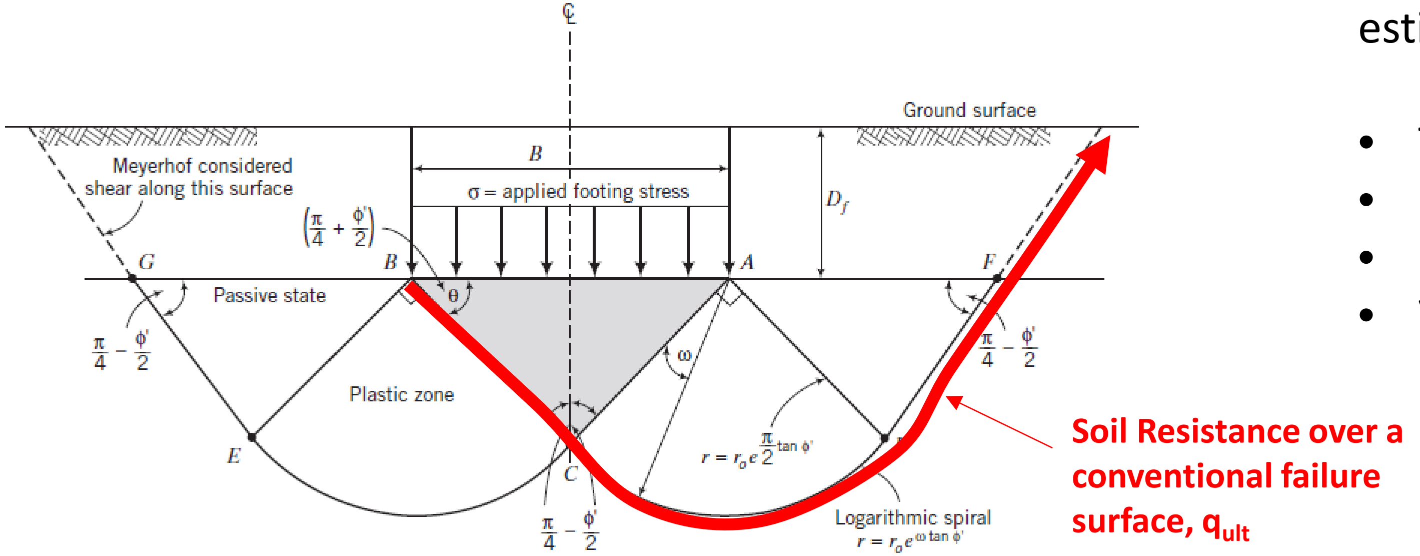
Loads from the turbine to the soil through a foundation system. An important task of a geotechnical engineer is to use the knowledge of the properties of soils and their response to loadings to design the foundation and must ensure that a foundation satisfies the following two stability conditions:

1. The foundation must not collapse or become unstable under any conceivable loading. **This is called ultimate limit state (ULS)**

2. Settlement of the structure must be within tolerable limits so as not to impair the design function of the structure. **This is called serviceability limit state (SLS)**.

Both requirements must be satisfied. Often, it is **settlement** that governs the design of shallow (turbine) foundations.

Bearing Capacity of Single Footing under Vertical Loading



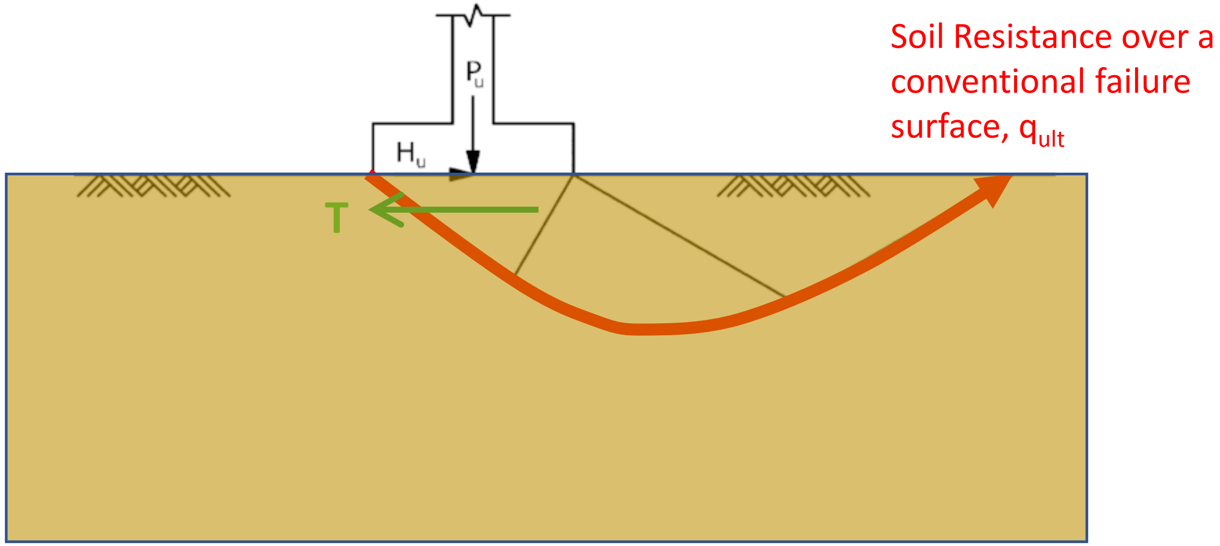
A plethora of bearing capacity equations, based on limiting equilibrium has been proposed for the estimation of ultimate bearing capacity

- Terzaghi, 1943;
- Meyerhof, 1963
- Hansen, 1970
- Vesic, 1973

Allowable Bearing Capacity

$$q_a = \frac{q_u}{FS} + \gamma D_f$$

Bearing Capacity of Single Footing under Inclined Loading



The failure surface is shallower and shorter i.e. less ultimate soil resistance is expected.

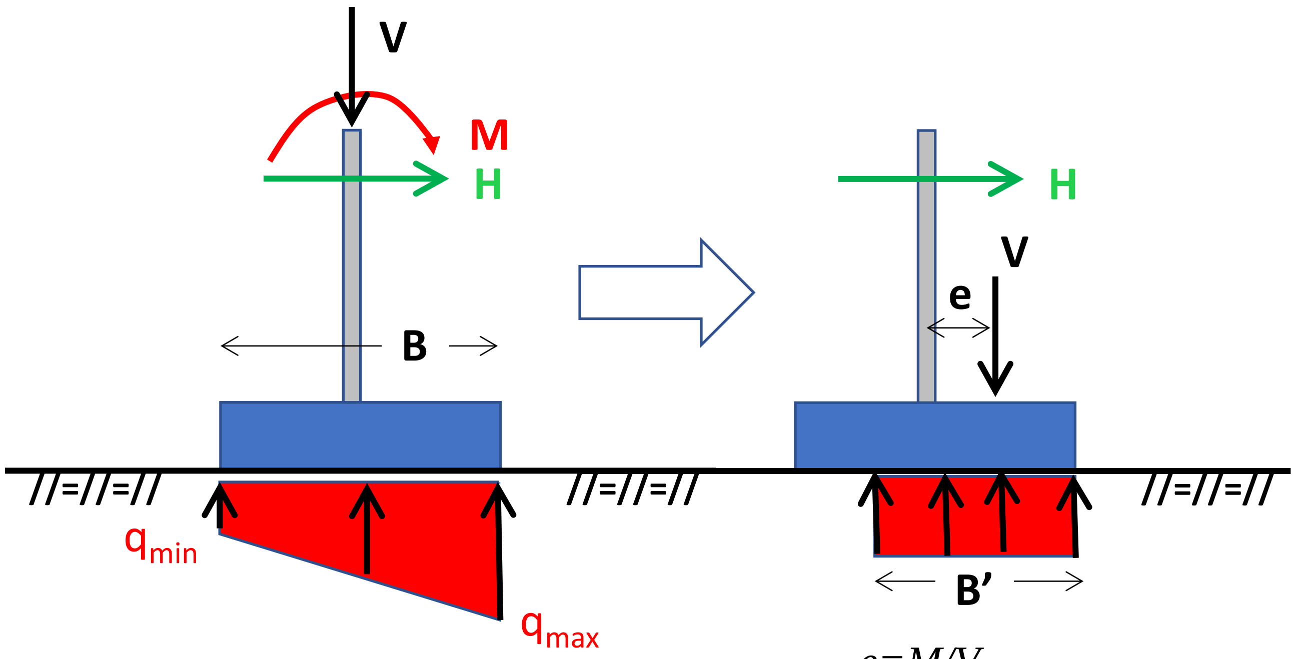
Reduction factors are induced in the bearing capacity equation.

When horizontal loads are present a Safety Factor against Slippage must be calculated:

$FS = T / H_u$

Where T= the friction resistance over the area of the footing (interface resistance).

Bearing Capacity of Single Footing under eccentric loads



$e = M/V$

$B' = B - 2e$

$$A' = \frac{D^2}{2}\left[\cos^{-1}\frac{2e}{D} - \frac{2e}{D}\sqrt{1-\left(\frac{2e}{D}\right)^2}\right]$$

Area of circular footing

When the location of the resultant load (load center) is not coincident with the centroid (center of area) of the footing, the footing dimensions are theoretically adjusted to align the load center with the centroid. The distances from the center of the area to the location of the vertical component of the resultant load are eccentricities. Applied moments can be converted to a vertical resultant load at eccentricities.

The vertical load is now distributed to less area (effective contact area) and the **applied stress is increased**.

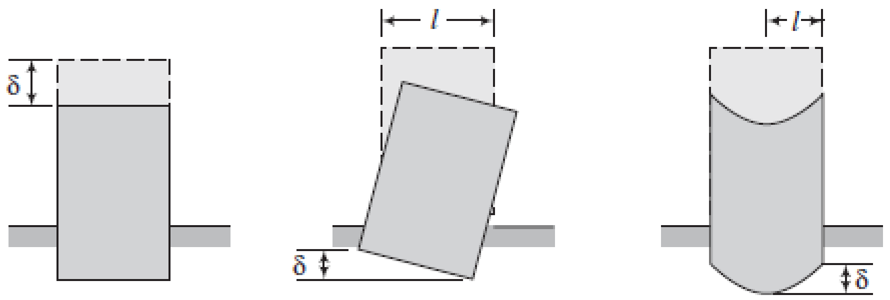
Overturning when e > D/2 (D= diameter)

Danger for permanent deformations at the corners due to rocking

Settlements of a single footing

Foundation settlement can be divided into three basic types:

- rigid body or uniform settlement
- tilt or distortion and
- nonuniform settlement



(a) Uniform settlement (b) Tilt or distortion (c) Nonuniform settlement

It is practically impossible to prevent settlement of shallow foundations. At least, elastic settlement will occur. Our task is to prevent the foundation system from reaching a serviceability limit state.

Maximum acceptable permanent deviations from the ideal vertical configuration of the axis of the unloaded support structure shall be specified in the design basis, including those that develop during the operational phase.

Realistically, it may be required that the foundation/substructure is installed and the tower is constructed with a total tolerance for the tower axis tilt of 0.25°.

Then, when limiting the total and permanent tilt rotation to say 0.50°, this allows for permanent deformations in the soil to develop and implicate a nominal additional tilt rotation of the tower axis of 0.25°. Plastic soil deformations are typically associated with settlement gradients (for example between individually arranged direct foundations of the feet of a lattice tower) and/or ultimate loads on the support structure.

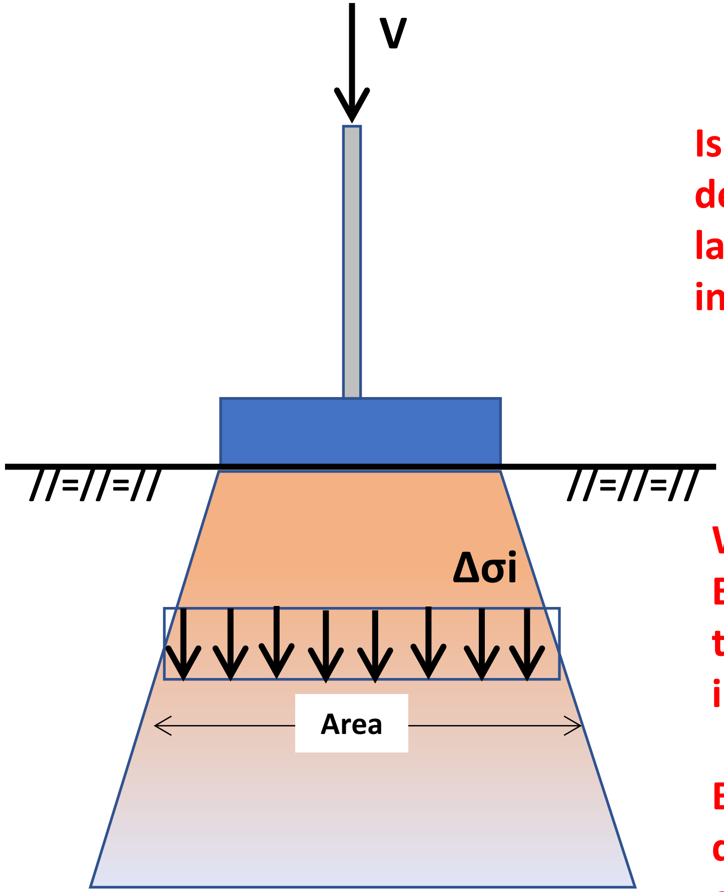
Settlements of a single footing, S

Immediate or elastic

- Rocks
- Very stiff clays
- Dense Sand & Gravels

Consolidation & Creep

Normally or slightly consolidated **Clays (time depended)**



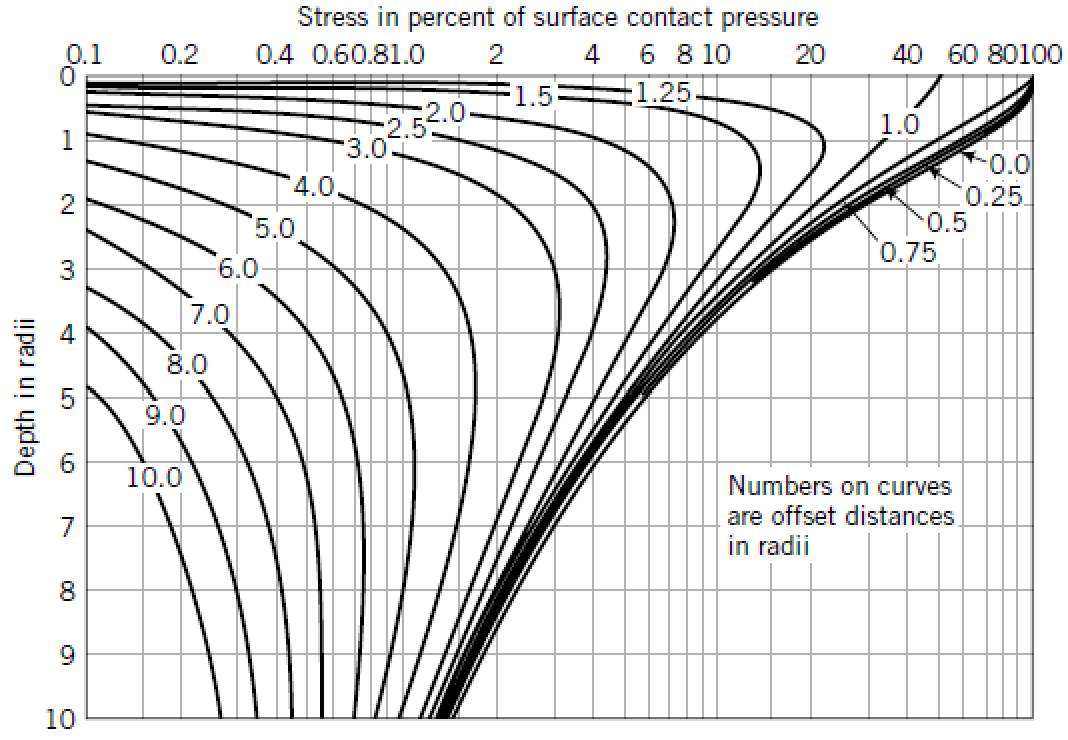
$\Delta\sigma_i$ x Area = V

Is the cumulative vertical deformation, Δh_i, of each layer, due to vertical stress increment, $\Delta\sigma_i$

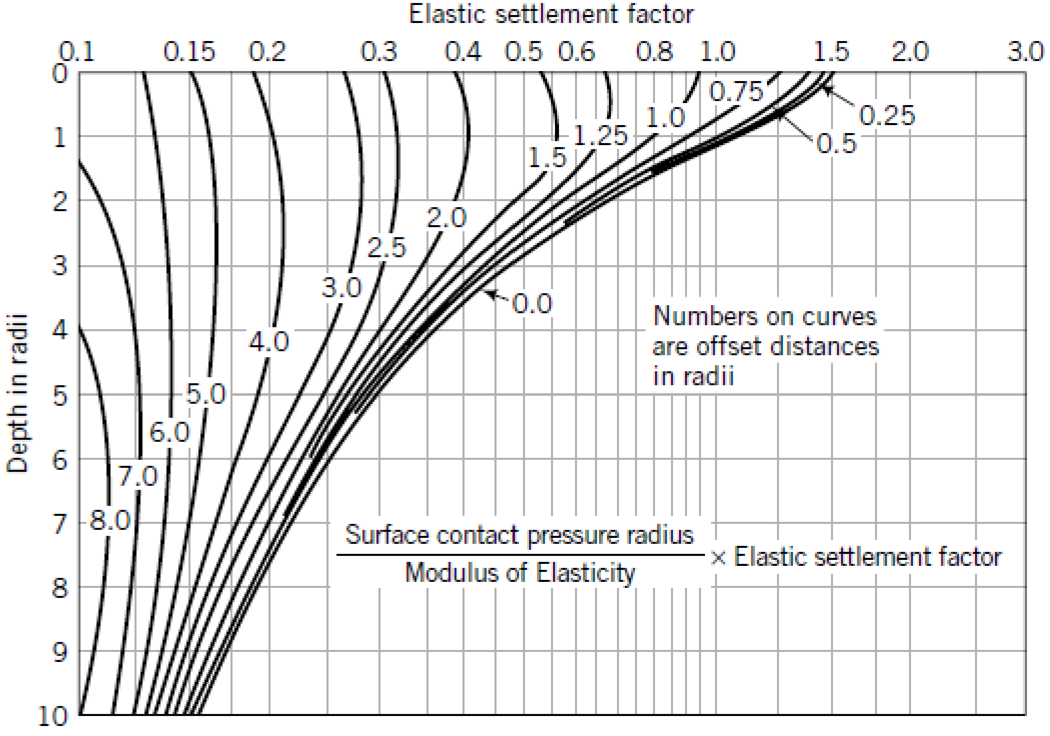
We tend to underestimate the Elastic moduli and to neglect the fact that the moduli is increasing with depth.

Based on EC7 the maximum depth for settlement calculation is that where $\Delta\sigma_i$ =20% of the initial vertical stress at the same depth.

DISTRIBUTION OF VERTICAL STRESS AND ELASTIC DISPLACEMENT UNDER A UNIFORM CIRCULAR LOAD



(a) Vertical stress increase



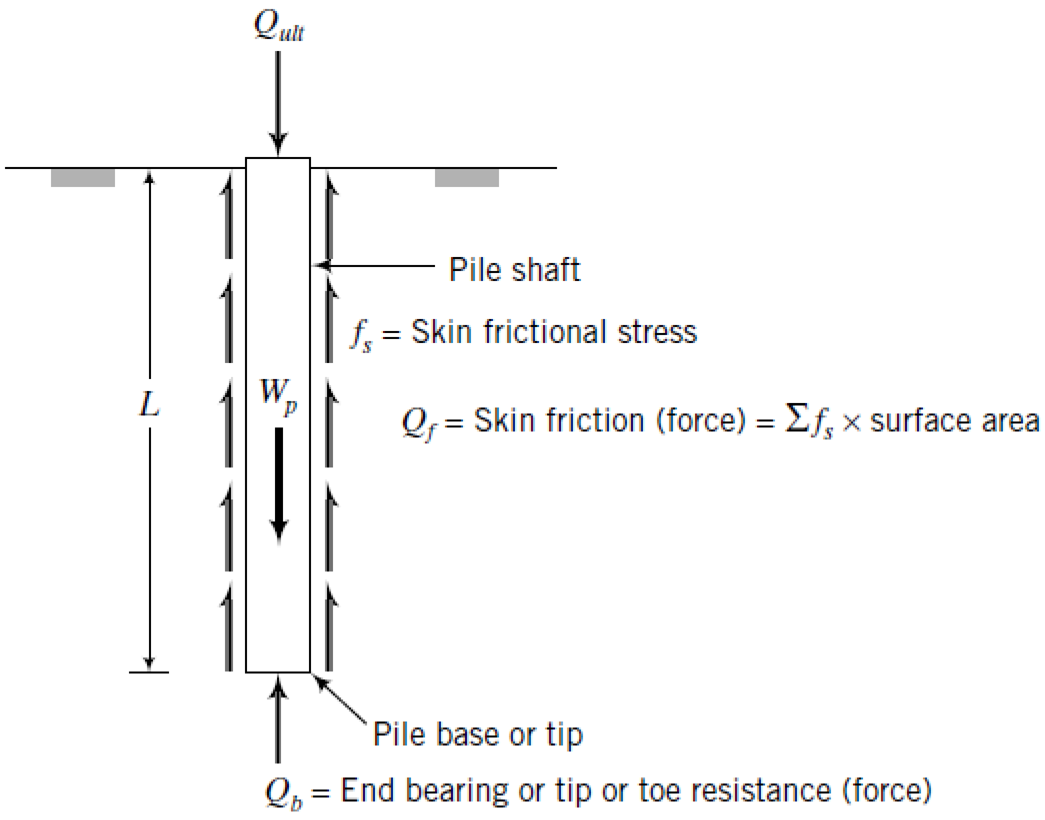
(b) Elastic settlement

SOURCES: Foster and Alvin (1954); Poulos and Davis (1974).

Piles under vertical loading

A pile is a slender, structural member installed in the ground to transfer the structural loads to soils at some significant depth below the base of the structure. Structural loads include axial loads, lateral loads, and moments.
Structures that cannot be supported economically on shallow foundations are normally supported by pile foundations. Pile foundations are used when:

- The soil near the surface does not have sufficient bearing capacity to support the structural loads.
- The estimated settlement of the soil exceeds tolerable limits (i.e., settlement greater than the serviceability limit state).
- Differential settlement due to soil variability or nonuniform structural loads is excessive.
- The structural loads consist of lateral loads, moments, and uplift forces, singly or in combination.
- Excavations to construct a shallow foundation on a firm soil layer are difficult or expensive.



$$Q_{ult} = Q_f + Q_b - W_p$$

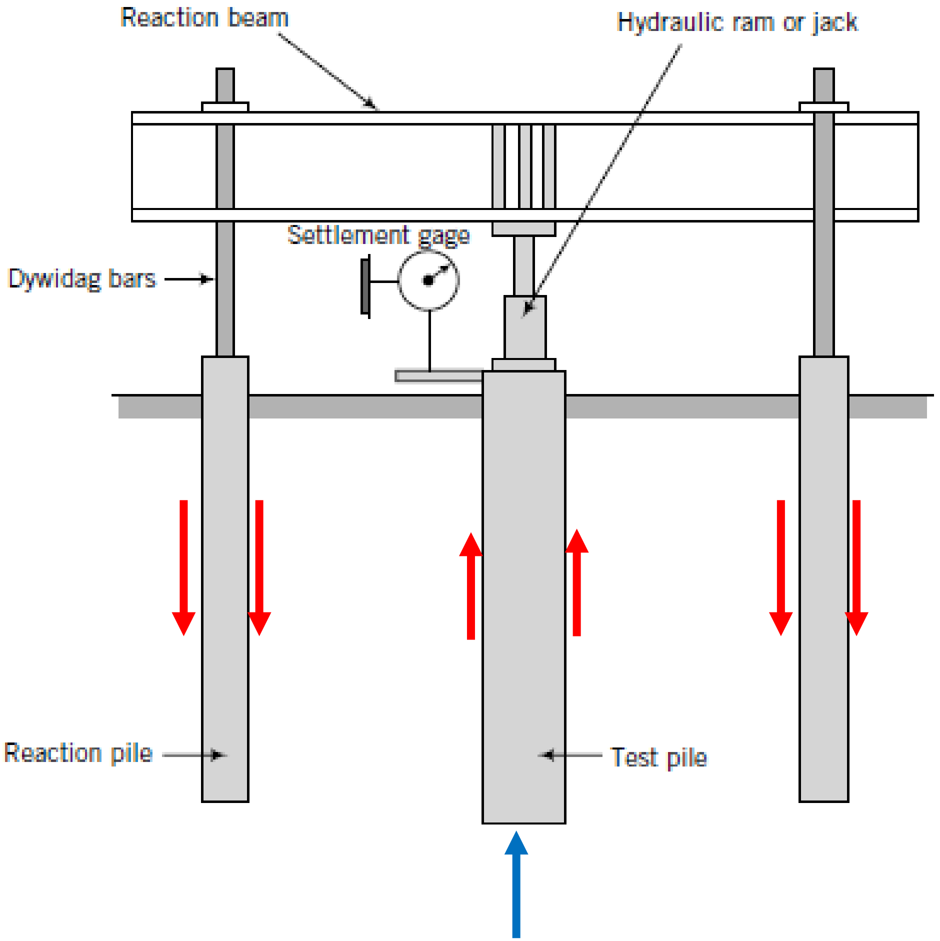
$$Q_a = \frac{Q_{ult}}{FS}$$

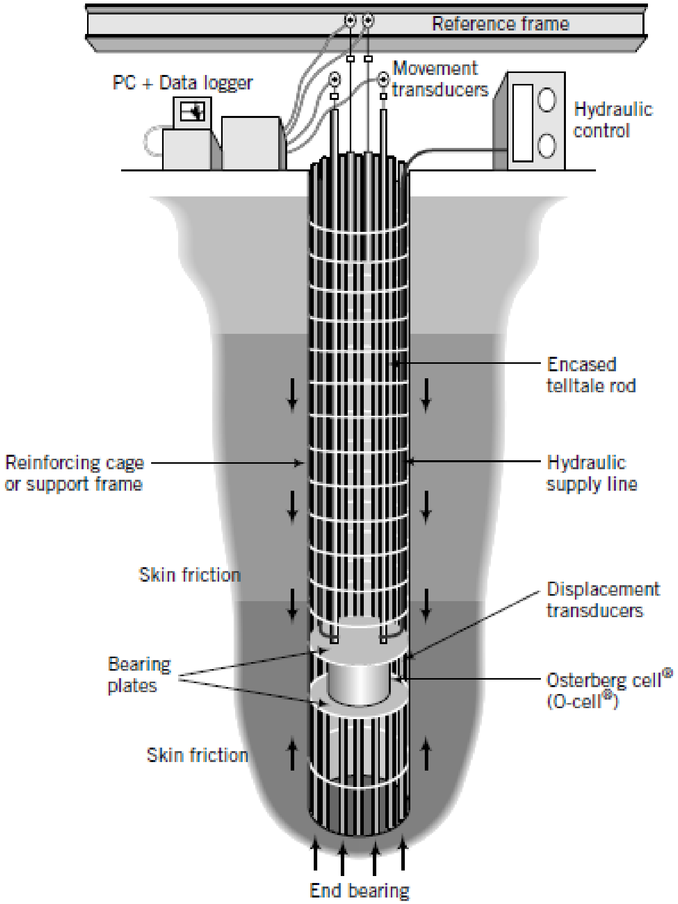
Some issues…

- Pile installation has significant effects on pile load capacity.
- The stresses imposed on the soil mass during pile installation and the application of structural loads are complex.
- Around the shaft, the soil is compressed by the displacement of the soil to accommodate the pile and sheared by interface friction at the pile–soil interface. A cylindrical volume of soil around the pile is
- disturbed or remolded, and may reach critical state. The minimum thickness of the disturbed soil is <40% of the pile radius. In normally and lightly overconsolidated fine grained soils, and loose coarse grained soils, positive excess porewater pressures would develop, while in highly overconsolidated fine grained soils, and dense coarse grained soils, negative excess porewater pressure would develop, at least in the disturbed soil mass. These excess porewater pressures would dissipate, leading to soil settlement during the design life of the foundation.
- Highly overconsolidated fine grained soils, and dense coarse-grained soils, can develop negative excess porewater pressures and cause the soil strength to increase temporarily. This could lead to the overestimation of the pile load capacity.
- The stress state of the soil is very different from the original soil state and is practically indeterminate.

PILE LOAD TEST (ASTM D 1143)

- To determine the load capacity of a single pile or a pile group, especially when the design requires methods that are outside of accepted practice.
- To determine the settlement of a single pile at working loads.
- To verify estimated load capacity.
- To obtain information on load transfer in skin friction and in end bearing.
- To satisfy regulatory agencies.


Reaction beam
Hydraulic ram or jack
Settlement gage
Dywidag bars
Reaction pile
Test pile


Reference frame
PC + Data logger
Movement transducers
Hydraulic control
Encased telltale rod
Reinforcing cage or support frame
Hydraulic supply line
Skin friction
Displacement transducers
Bearing plates
Osterberg cell®
(O-cell®)
Skin friction
End bearing

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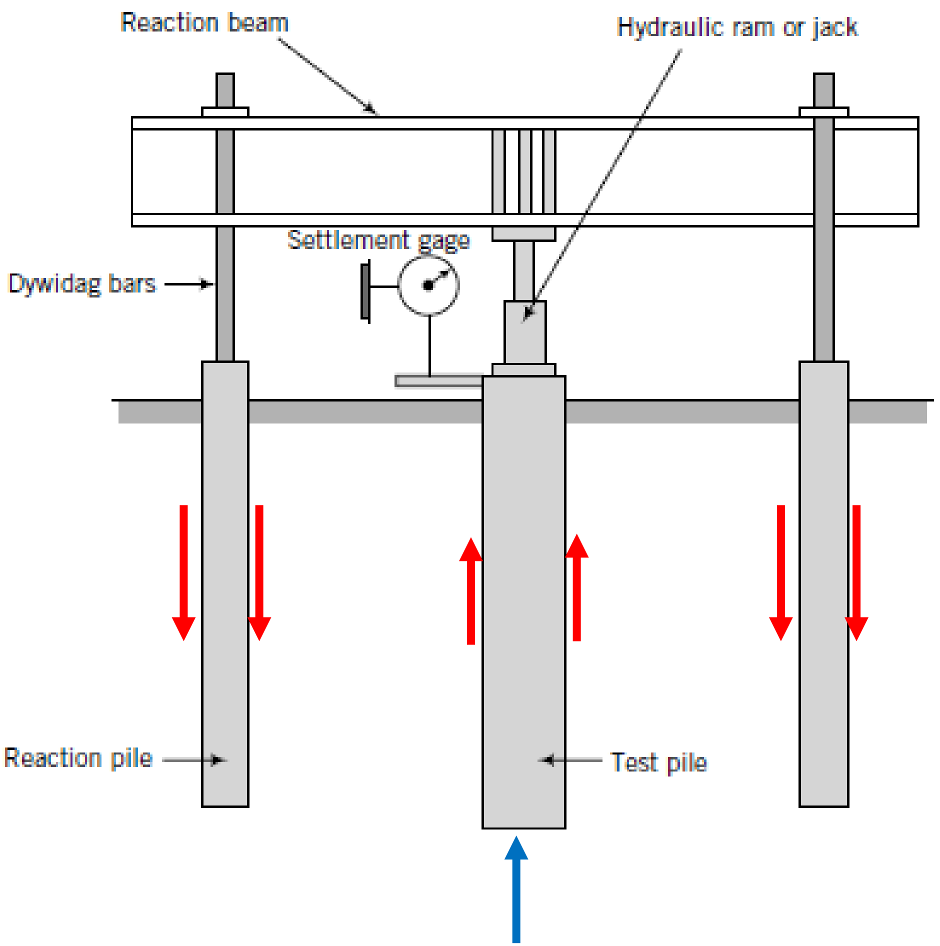
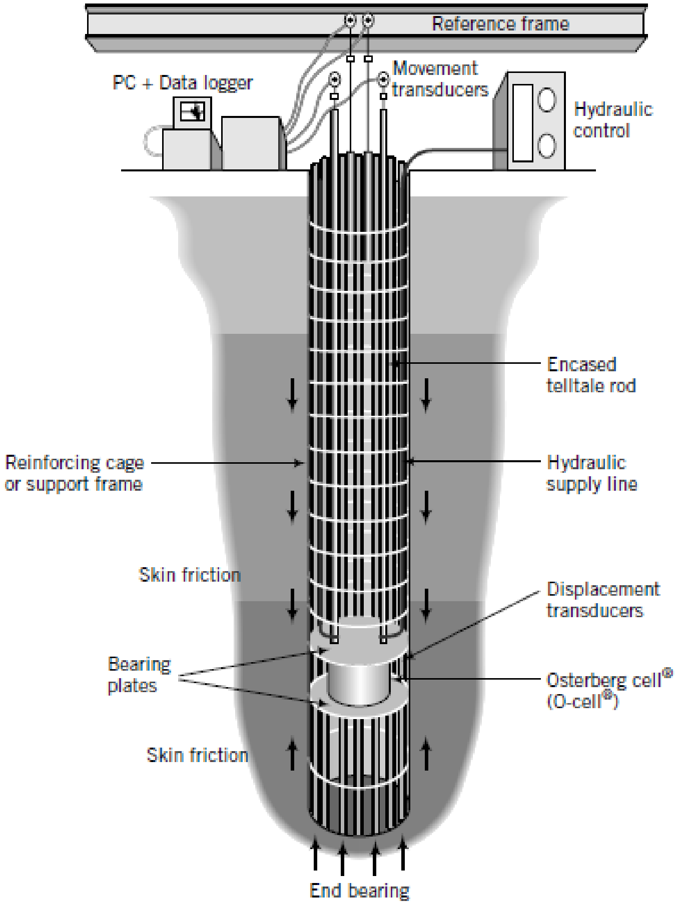


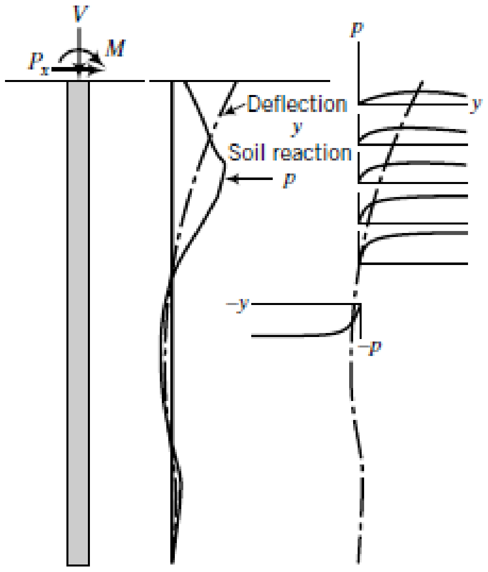


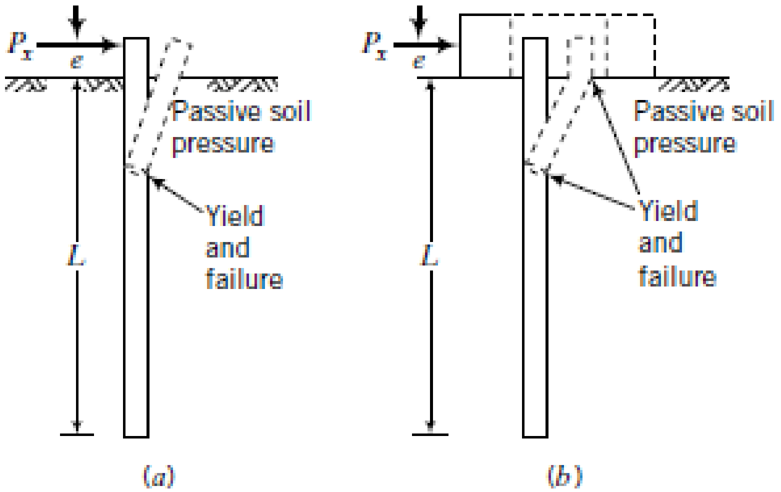
Piles under lateral loading

Wind Turbines founded on piles are subjected to lateral loads and moments in addition to vertical loads. Lateral loads may come from wind, seismic events, waves, docking ships, etc.

When a pile is subjected to lateral forces and moments, the pile tends to bend or deflect. The deflection of the pile causes strains in the soil mass. To satisfy equilibrium, the soil must provide reactions along the length of the pile to balance the applied loads and moments.
Because soil is a nonlinear material, the soil reaction is not linearly related to the pile deflection.

In designing laterally loaded piles, we need to know the pile deflection, particularly the pile head deflection, to satisfy serviceability requirements and the bending moments for sizing the pile. A pile that is attached to the pile cap such that no rotation occurs is called a fixed head pile. A pile that is attached to the pile cap such that rotation is unrestricted is called a free head pile.



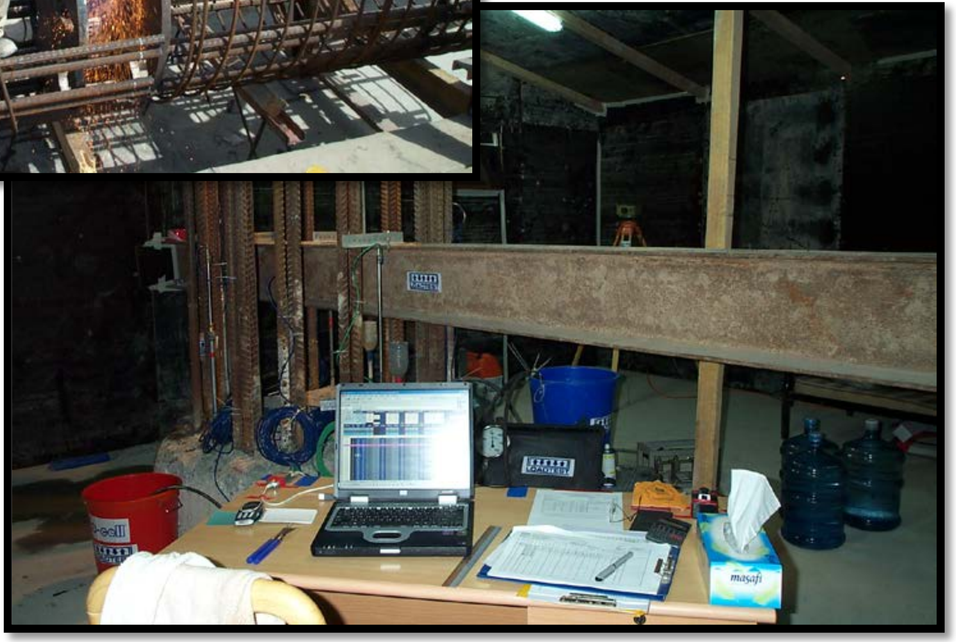


If testing is not feasible then analysis only with FEM.

Pile Load Test to Vertical loading with reaction ground anchors

Two Piles Load Test to Lateral Loading

O-cell Load Test



Thank you for your attention