FOUNDATIONS FOR WIND TURBINES

ENGR 340 – Fall 2011

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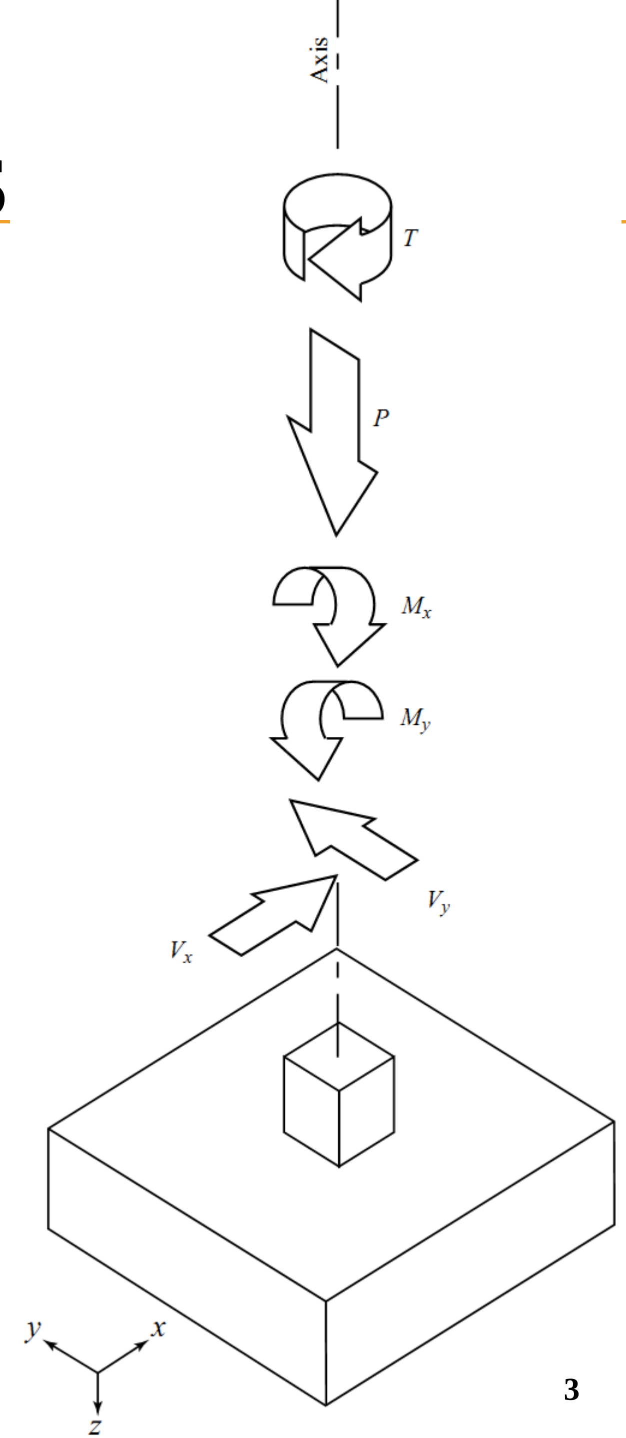
OUTLINE

Topics	**Lecture #**
Design requirements, Foundation types	1
Overview of geotechnical engineering • Soil mechanics • Site investigations • In-situ tests • Laboratory tests	1 & 2
Foundations for wind turbines, Design example	2

TURBINE FOUNDATION LOADS

- Vertical, shear forces and significant overturning moments are transmitted to foundation by tower
- Must be resisted within tolerances for foundation settlement and tilt
- Manufacturers typically specify horizontal and rotational foundation stiffness criteria
- Loading direction changes with wind direction and nacelle orientation
- Circular foundation shape is therefore optimal, but straight-sided (e.g. octagonal, hexagonal) is easier to construct
- Anchors can be used to add rotational strength



FOUNDATION CONTACT STRESS UNDER ECCENTRIC/MOMENT LOADS

To prevent loss of contact and uplift, the foundation is typically designed such that the eccentricity *e* of the resultant is *e* < *B/6*. In other words, *M*<*PB/6*.

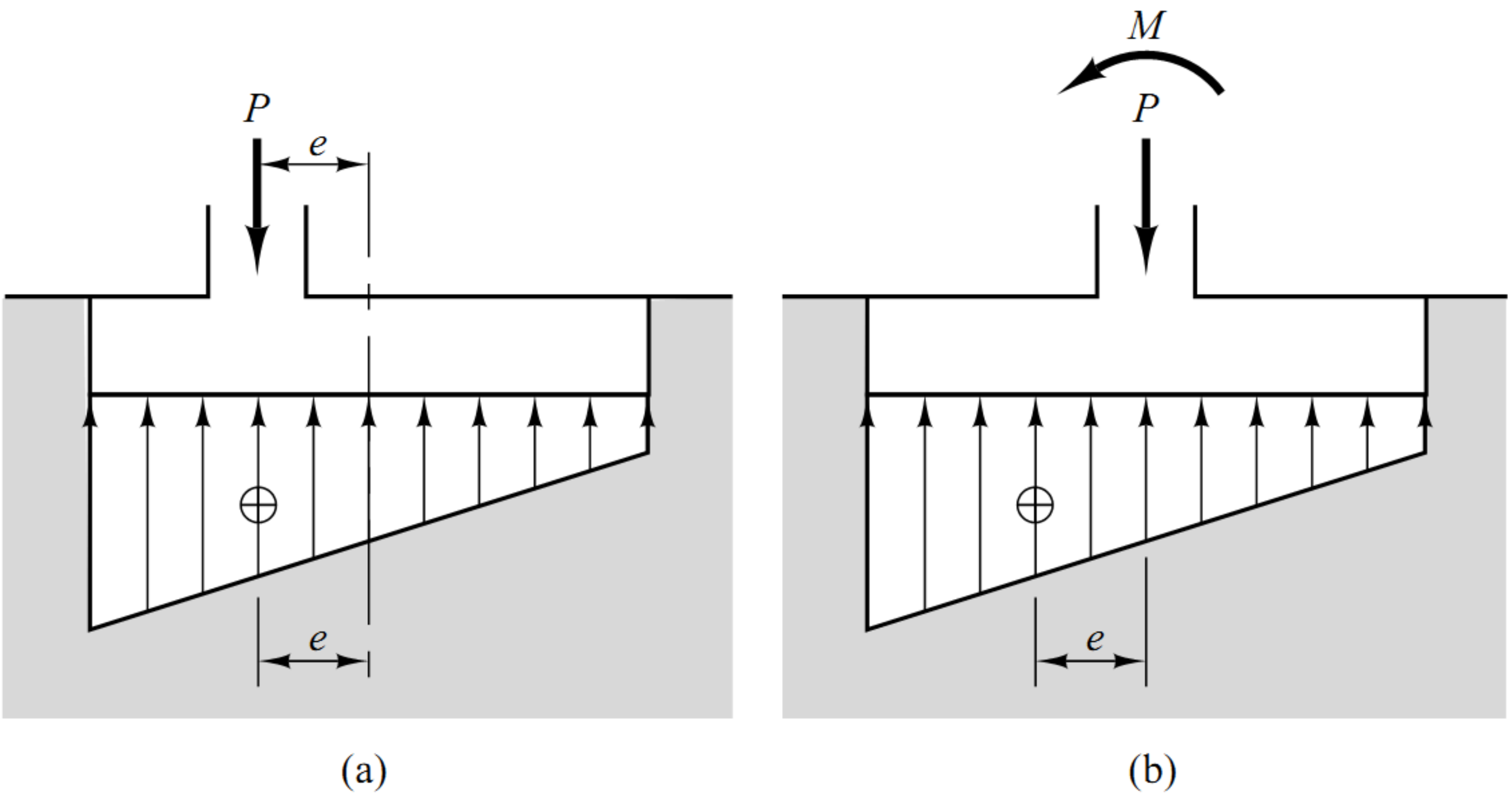
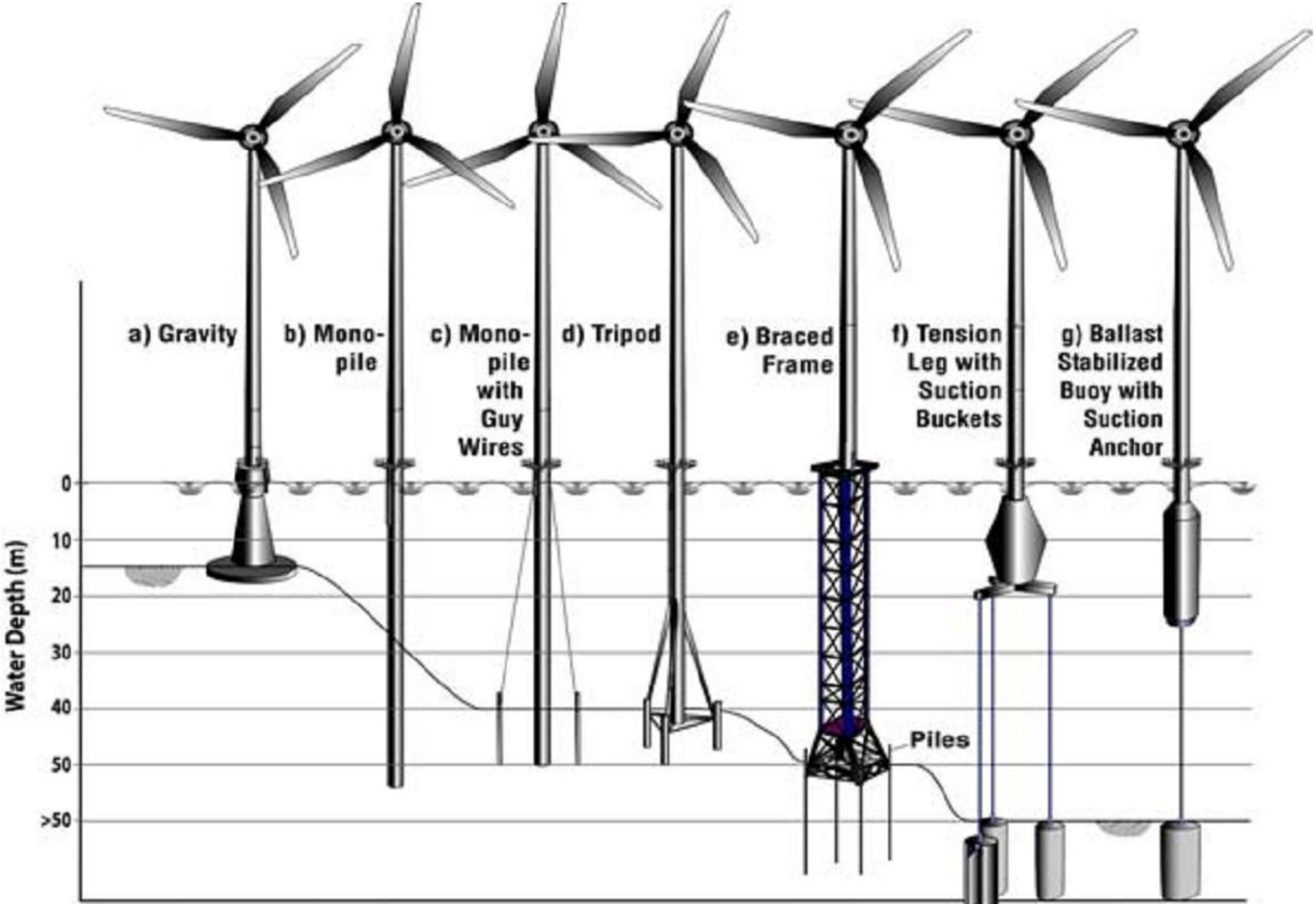


Figure 5.14 (a) Eccentric and (b) moment loads on shallow foundations.

OFFSHORE FOUNDATION OPTIONS



Source: Malhothra, 2011

OFFSHORE FOUNDATIONS

Photos: NREL

TYPICAL TURBINE FOUNDATION OPTIONS

- On rock or competent soil:
  - Shallow concrete “inverted tee” mat foundations ($)
- On weak or soft soils (bearing capacity or stiffness too low, settlements too high):
  - Rammed Aggregate Piers or VibroPiers under footings or mats ($$)
  - Soil improvement such as deep soil mixing, compaction, over-excavation & replacement with compacted lifts of aggregate ($$$)
  - Deep foundations; piles, drilled shafts ($$$$)
  - Concrete-filled corrugated pipe with post-tensioned anchor bolts (proprietary design; $$?)

SHALLOW/SLAB FOUNDATION VARIANTS

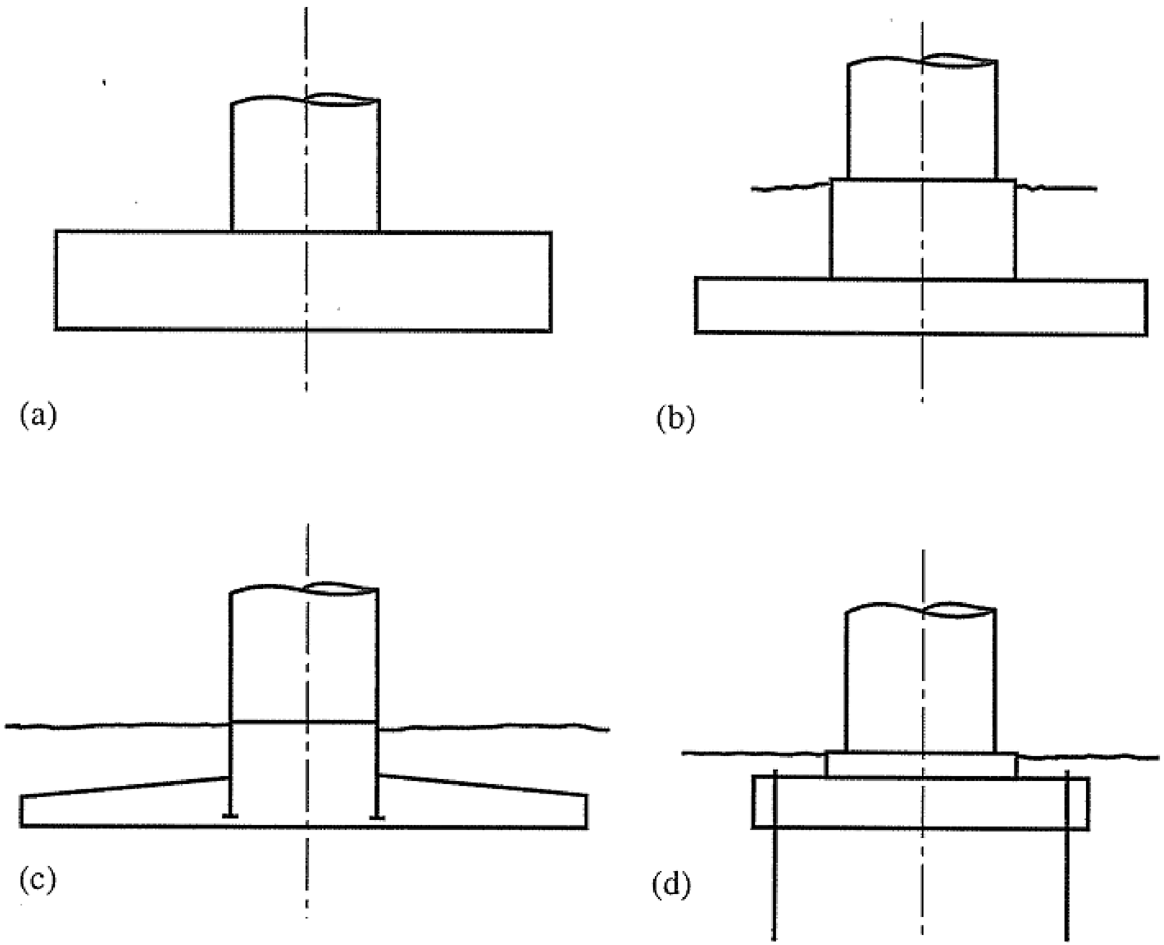


Figure 7.44 (a) Plain Slab; (b) Stub and Pedestal; (c) Stub Tower Embedded in Tapered Slab; (d) Slab Held Down by Rock Anchors

PILED FOUNDATION VARIANTS

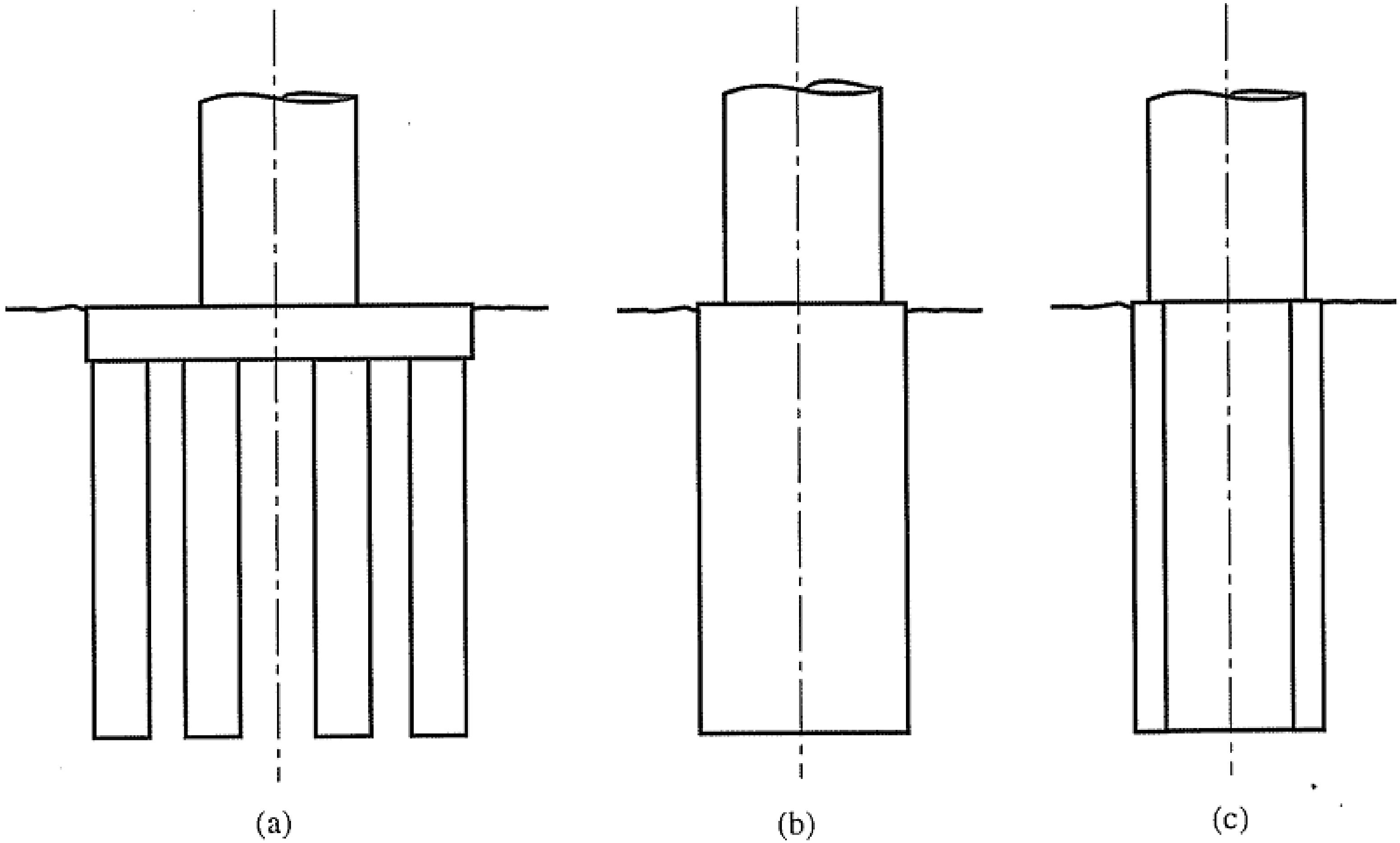


Figure 7.45 (a) Pile Group and Cap; (b) Solid Mono-pile; (c) Hollow Mono-pile

PILED FOUNDATION VARIANTS

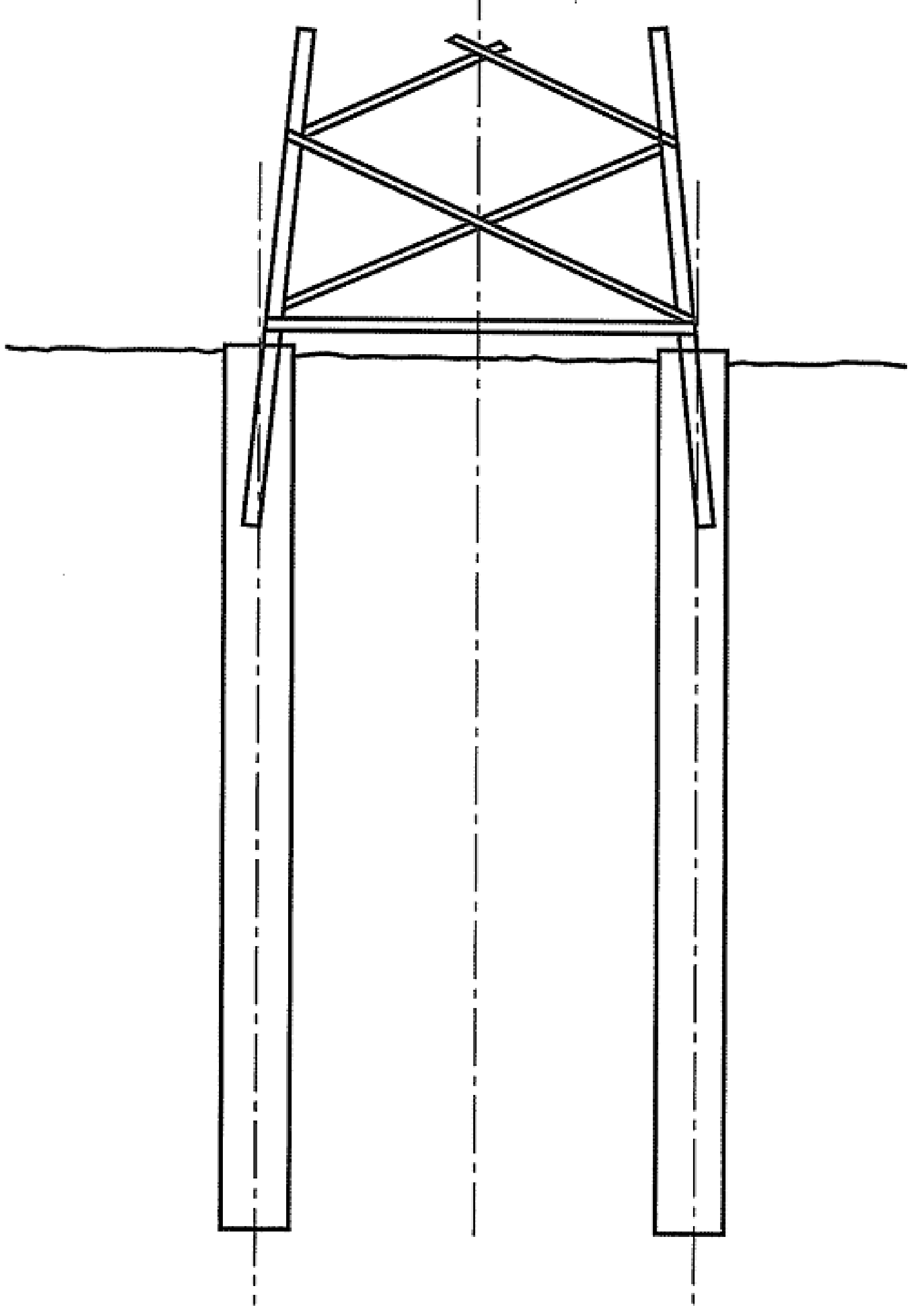


Figure 7.46 Piled Foundation for Steel Lattice Tower

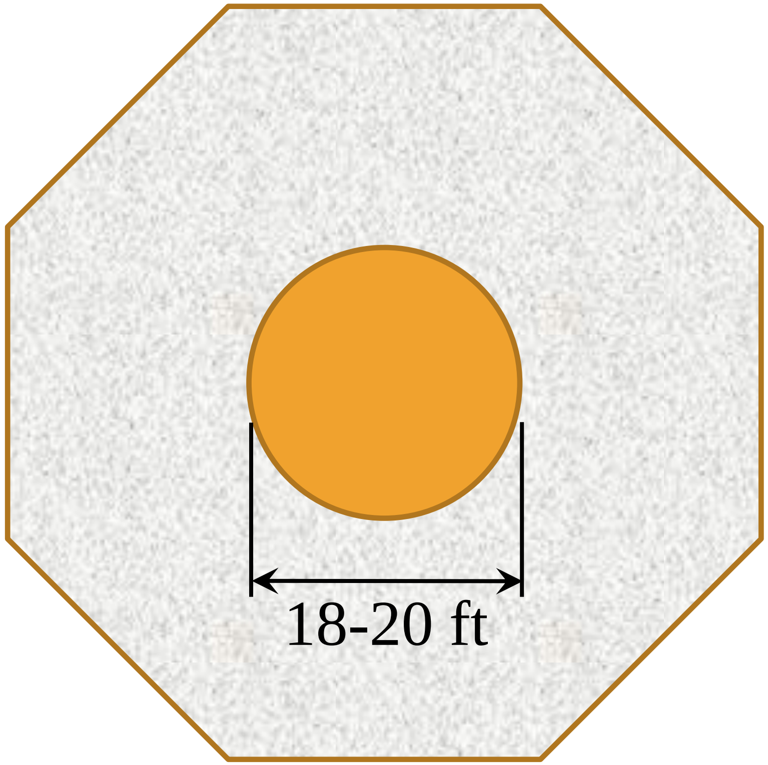
OCTAGONAL SHALLOW MAT FOUNDATIONS

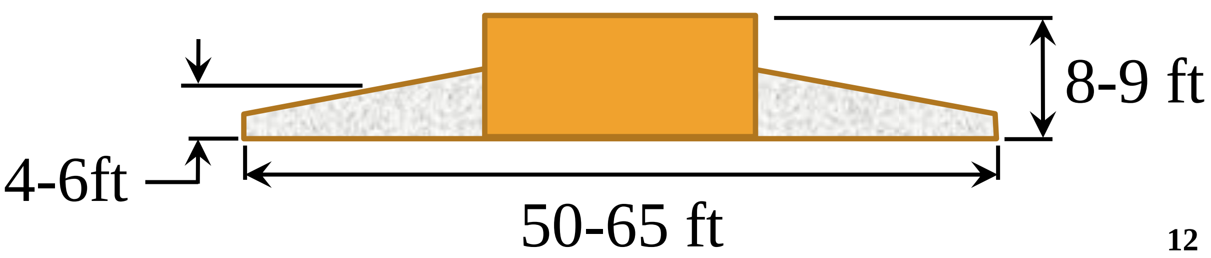
Source: GeoPier / http://www.windsystemsmag.com/view/article.php?articleID=97

OCTAGONAL SHALLOW MAT FOUNDATIONS

Typical dimensions:

- Footing
  - width: 50-65 ft
  - avg. depth: 4-6 ft
- Pedestal
  - diameter: 18-20 ft
  - height: 8-9 ft





RAMMED AGGREGATE PIERS (RAPs) UNDER FOOTINGS OR MATS

Source: GeoPier / http://www.windsystemsmag.com/view/article.php?articleID=97

RAPs UNDER FOOTINGS OR MATS

RAPs are used for

- Decreased settlements
- Improved bearing capacity in weak or compressible soils
- Increased rotational stiffness
- Uplift resistance

Alternative solutions for uplift resistance:

helical anchors or helical piles

ANCHORS FOR UPLIFT RESISTANCE

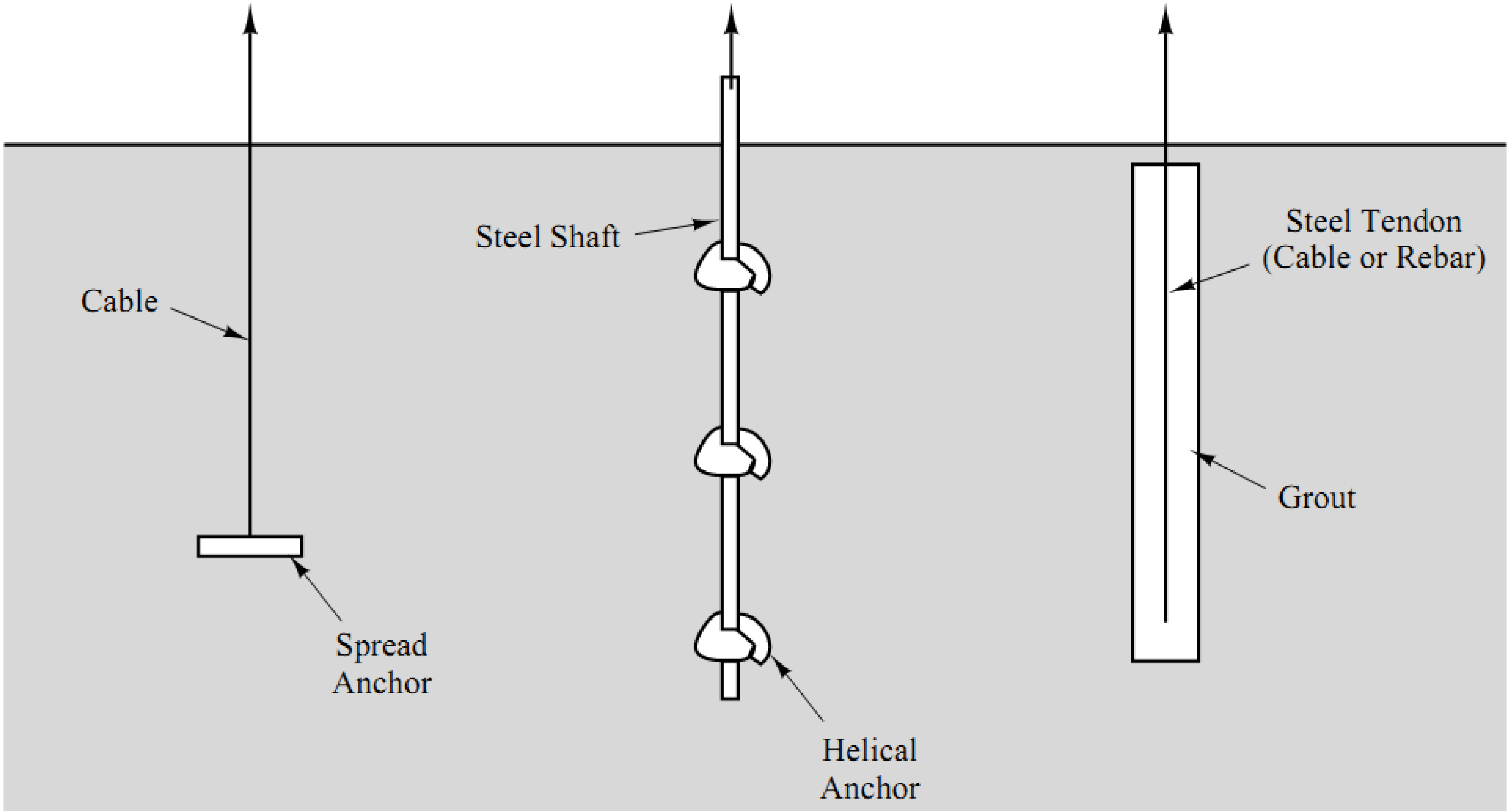
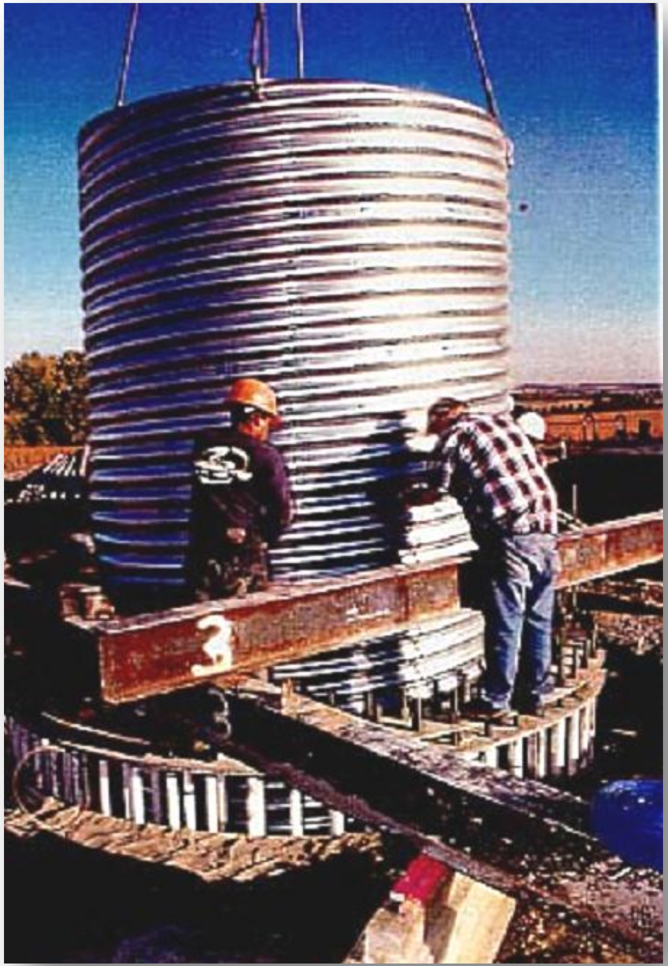


Figure 11.51 Types of anchors (Adapted from Kulhawy, 1985; Used with permission of ASCE).

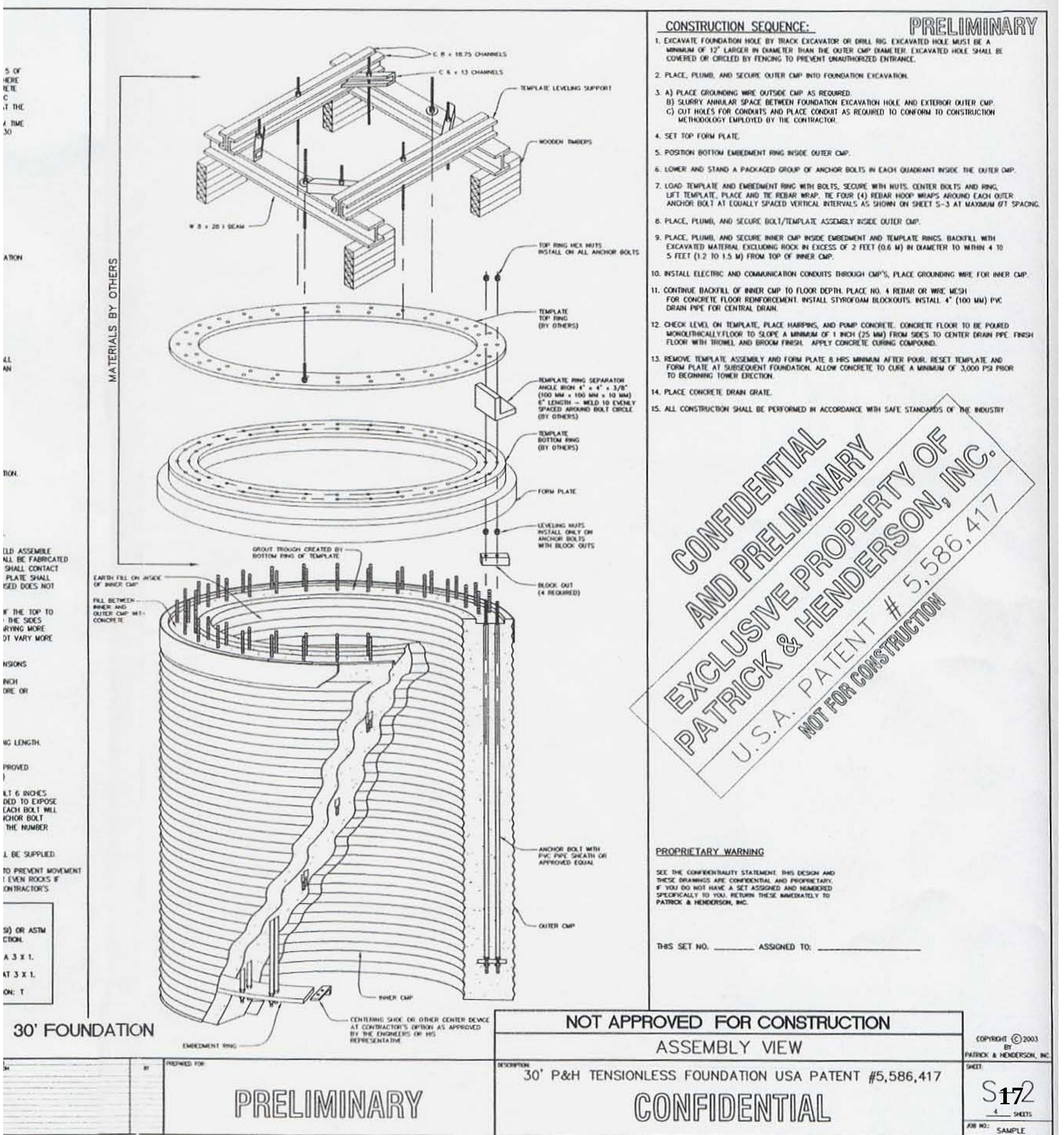
P&H TENSIONLESS FOUNDATION DESIGN

- Proprietary design of Patrick & Henderson, Inc.
  - concentric corrugated metal pipes filled with concrete that is compressed by post-tensioned rods



http://www.maine.gov/doc/lurc/projects/redington/Click_to_Start.htm

For more info, see Patent # 5586417 patents.google.com



FOUNDATIONS MUST BE DESIGNED FOR THE SITE CONDITIONS OF EACH PROJECT, NOT JUST SELECTED

"Using site-specific design loads and carrying out site-specific wind turbine designs is somewhat in contrast with the current trend within the wind turbine industry. In order to keep down manufacturing costs, the current trend is not to site-optimise wind turbines, but rather to produce a selection of standard wind turbines. The task is then to choose a standard wind turbine from this selection and verify that it is suitable for a given location. The tower and the foundation may still be site-optimised if desirable, and site-specific loads will be required for this purpose. ***The foundation design will always have to be site-specific in that it needs to be designed for the prevailing local soil conditions****."*

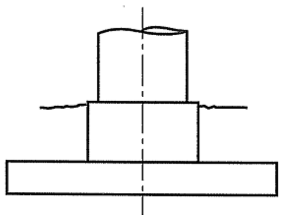
Guidelines for Design of Wind Turbines, 2nd ed. – DNV/Risø

FOUNDATIONS MUST BE DESIGNED FOR THE SITE CONDITIONS OF EACH PROJECT, NOT JUST SELECTED

"Foundation designs are integrated into the type certification for some turbines. Where this is the case, the ***foundation design must be evaluated for the external conditions for which it is intended****.* ***Poor geotechnical investigation and foundation design have led to delays and cost overruns*** *at European wind farms (Gerdes et al. 2006)."*

Structural Integrity of Offshore Turbines – Oversight of Design, Fabrication and Installation, TRB Special Report 305, 2011

DESIGN STEPS/CHECKS FOR SHALLOW FOUNDATIONS



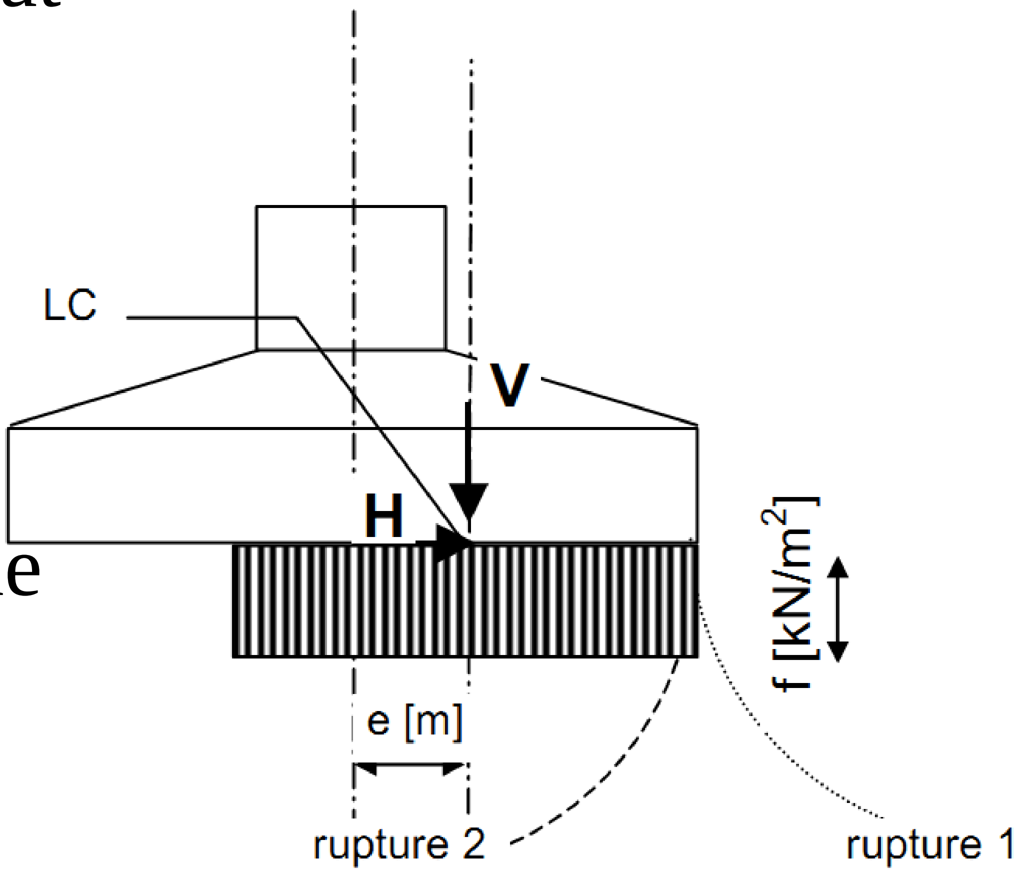
1. Minimum embedment below frost depth
2. Bearing capacity
3. Settlements: Elastic, Consolidation and Differential
4. FS against sliding and overturning
5. Structural design of foundation (typ. reinforced concrete)
6. Drainage
7. Foundation stiffness accounting for modulus degradation due to cyclic loading
8. Dynamic analysis for avoiding resonance of soil-foundation-structure system
9. Scour and erosion (for offshore foundations)

BEARING CAPACITY: ECCENTRICITY OF LOAD

- Design loads V, H act at the foundation base

- Eccentricity e = M/V

- H is reduced if a torque M_z acts about vertical axis (see DNV/Risø Guidelines)

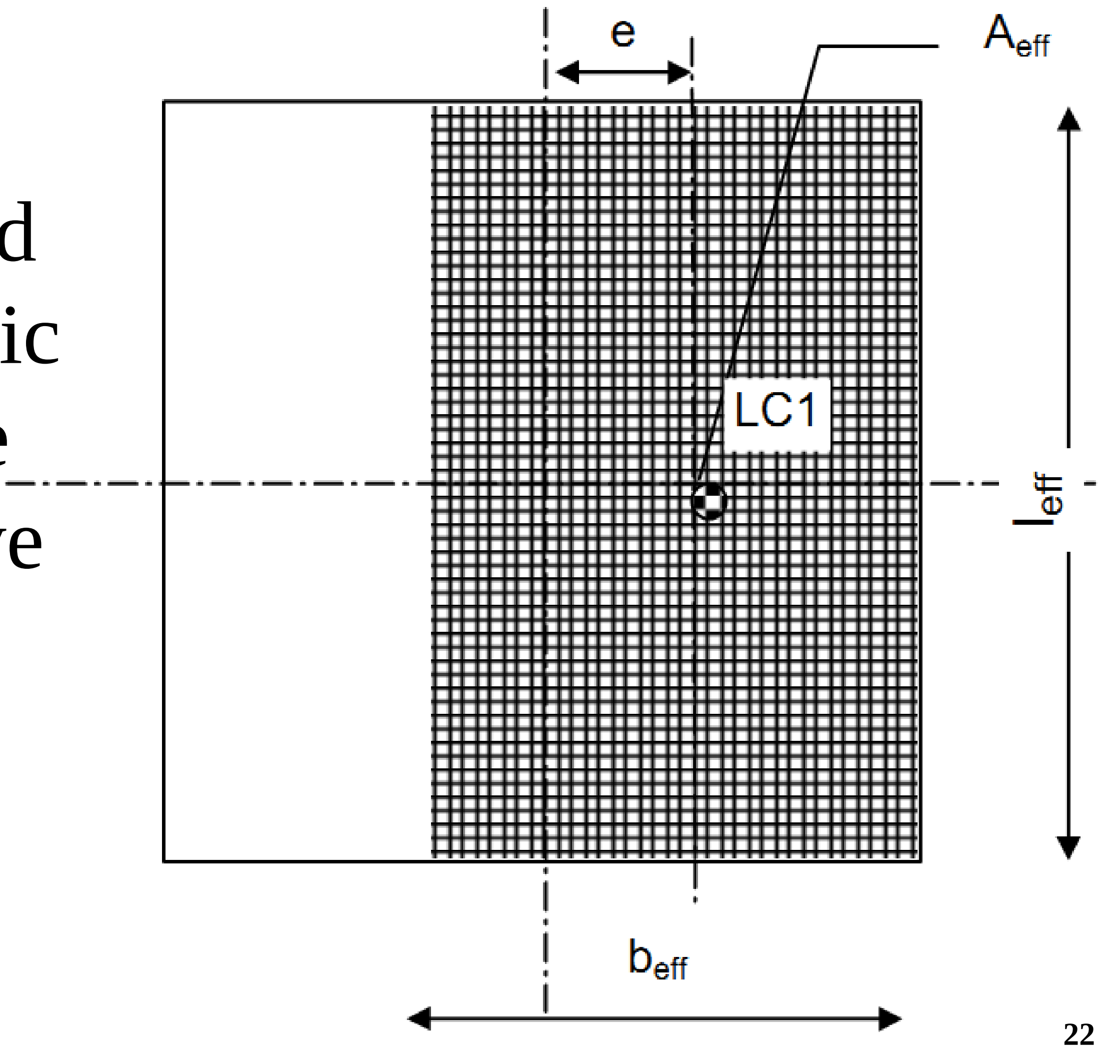


BEARING CAPACITY:
EFFECTIVE AREA FOR ECCENTRIC LOAD

Reduced effective foundation area $A_{eff} = b_{eff}\, l_{eff}$ is defined such that the eccentric vertical load is at the center of the effective area:

$$b_{eff} = b - 2e$$

$$l_{eff} = b$$

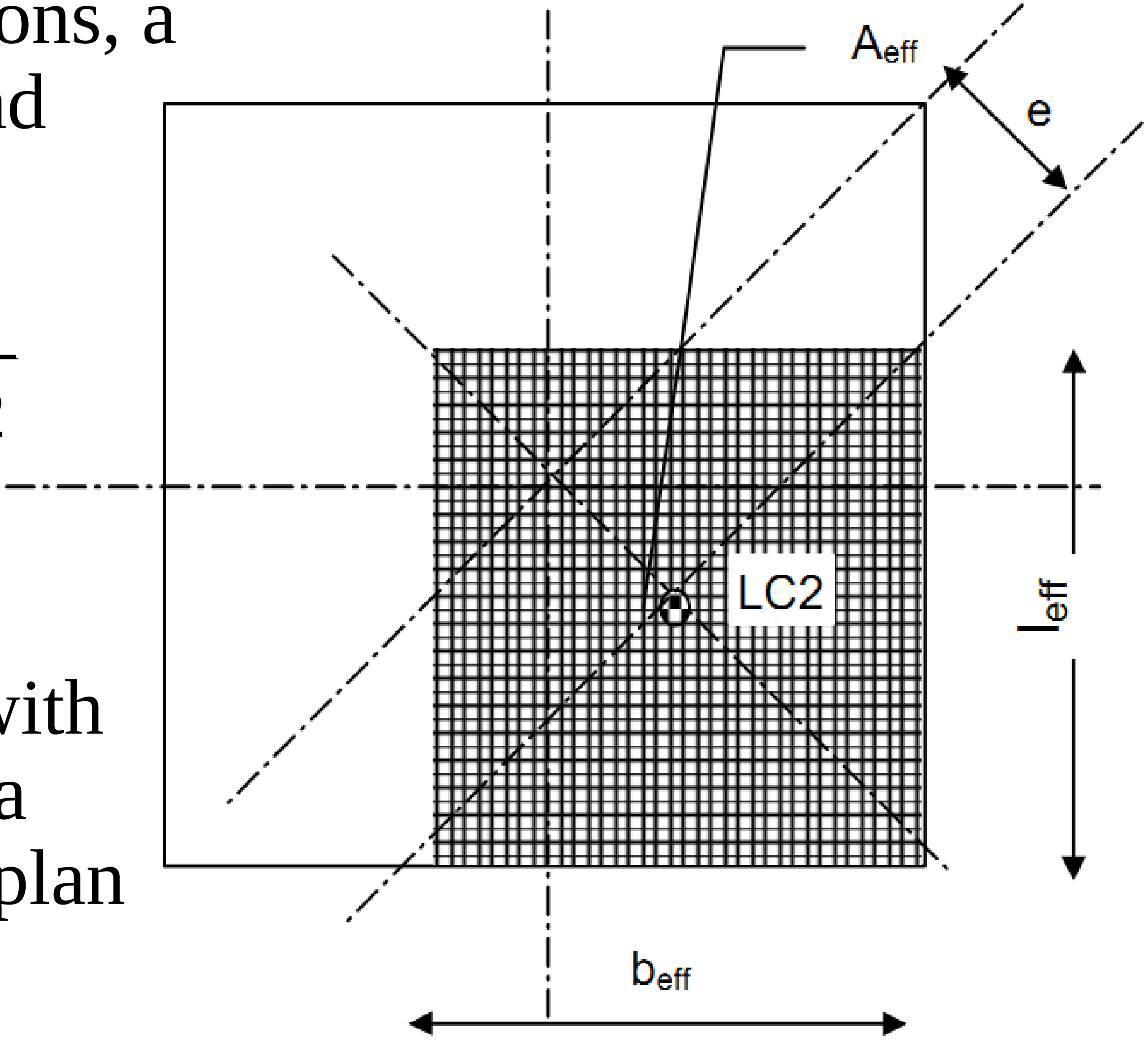


BEARING CAPACITY: EFFECTIVE AREA FOR DOUBLY ECCENTRIC LOAD

- For square foundations, a doubly eccentric load further reduces the effective area:

$$b_{eff} = l_{eff} = b - e\sqrt{2}$$

- Since direction of eccentricity varies with nacelle orientation, a circular foundation plan is the most efficient



BEARING CAPACITY: EFFECTIVE AREA FOR ECCENTRIC LOAD ON OCTAGONAL/CIRCULAR FOUNDATIONS

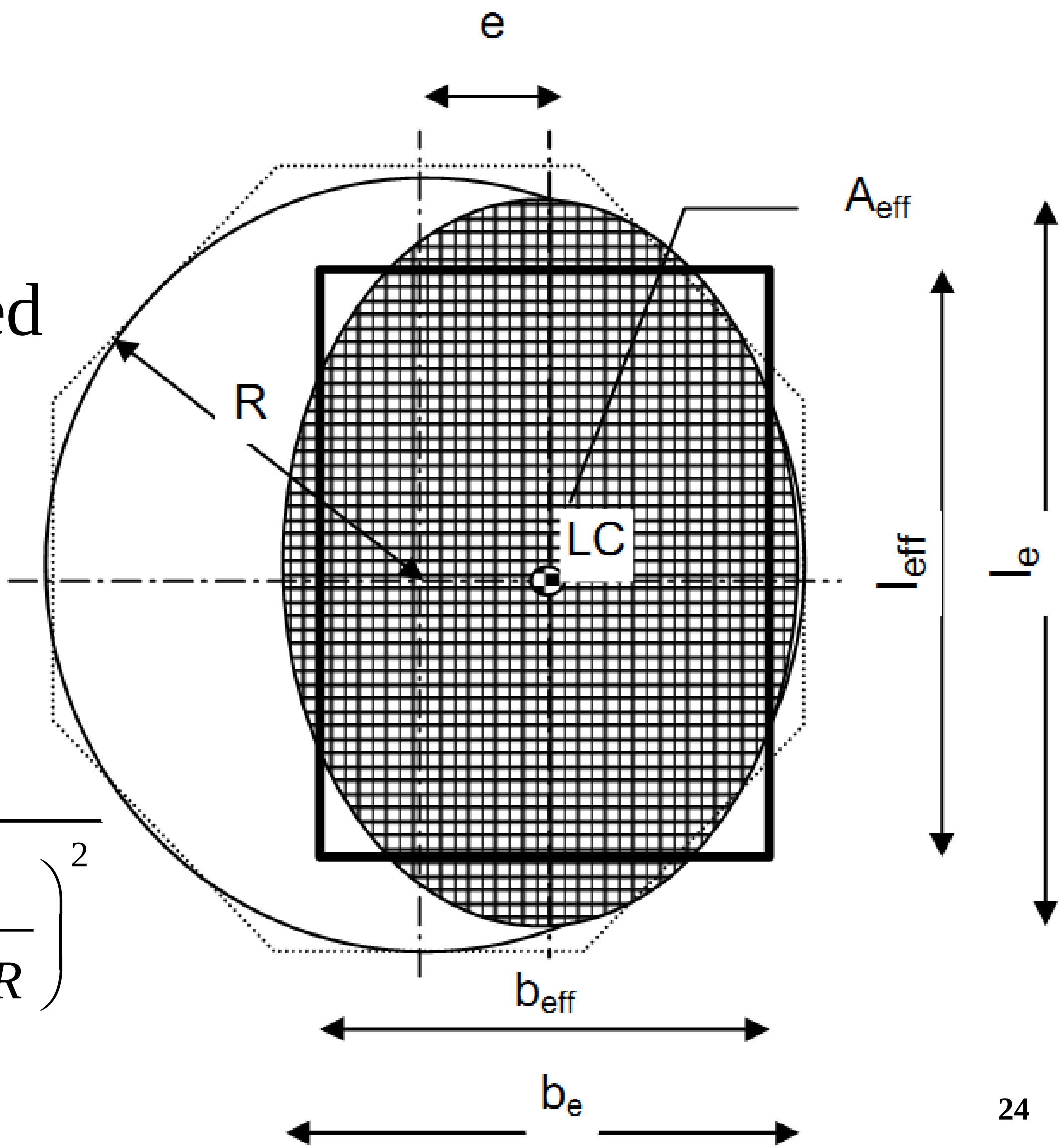
- Octagonal foundation is more practical for construction

- Ellipse is used for reduced area:

$$A_{eff} = 2\left[R^2 \cos^{-1}\left(\frac{e}{R}\right) - e\sqrt{R^2 - e^2}\right]$$

Major axis: $l_e = 2R\sqrt{1-\left(1-\frac{b}{2R}\right)^2}$

Minor axis: $b_e = 2(R-e)$



BEARING CAPACITY: EFFECTIVE AREA FOR ECCENTRIC LOAD ON OCTAGONAL/CIRCULAR FOUNDATIONS

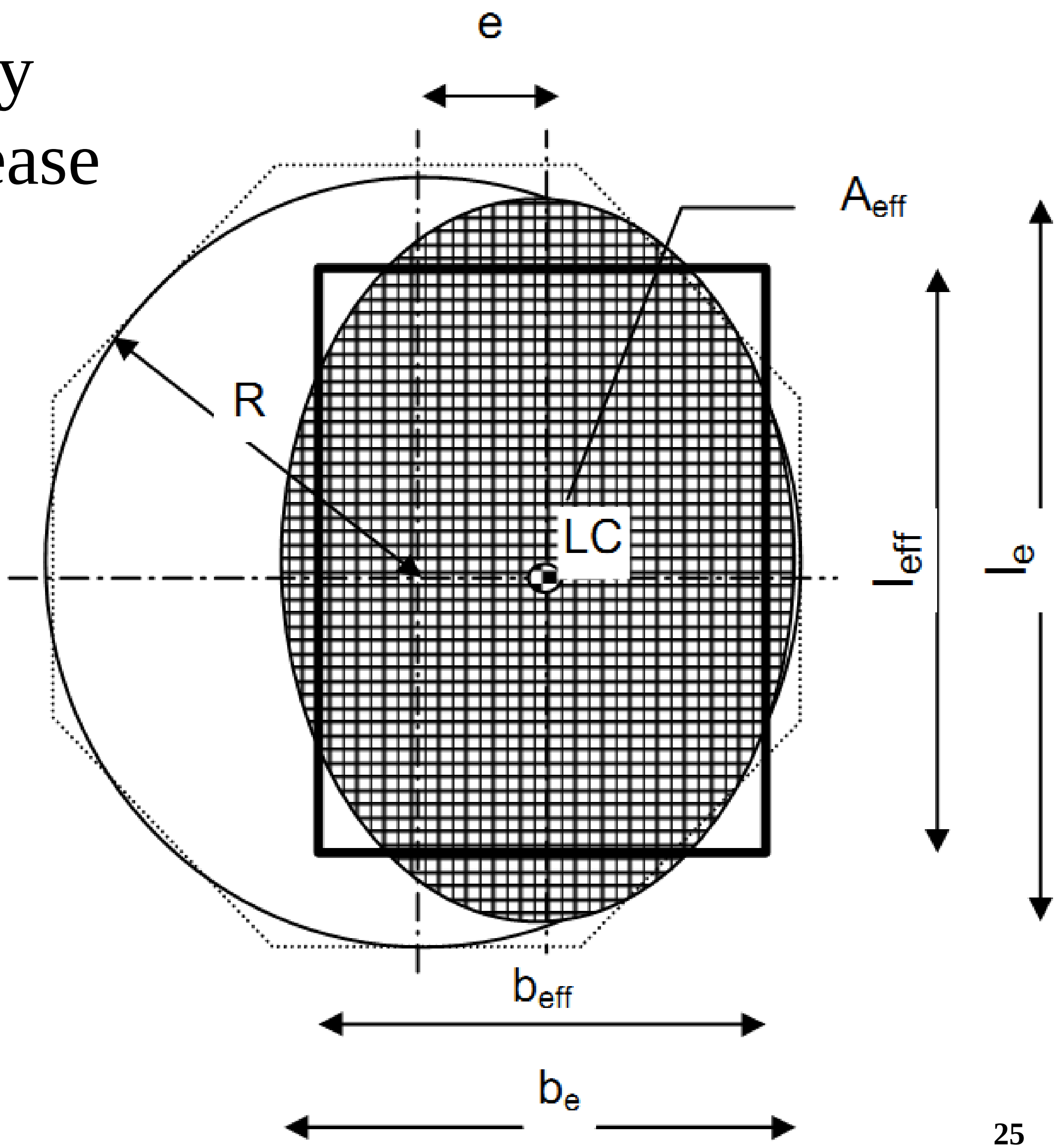
- Ellipse can be replaced by equivalent rectangle for ease of design calculations:

Take

$$b_{eff} = l_{eff} \frac{b_e}{l_e}$$

then

$$l_{eff} = \sqrt{A_{eff} \frac{l_e}{b_e}}$$



BEARING CAPACITY

- Fully drained (long-term) conditions:

$$\boxed{q_{ult} = c'N_c + q'N_q + \frac{1}{2}\gamma' b_{eff} N_\gamma}$$

- Undrained (short-term or rapid loading) conditions in clay:

$$\phi_u = 0,\ N_\gamma = 0,\ N_q = 1,$$

$$\boxed{q_{ult} = c_u N_c + q}$$

- Generally need to apply shape, depth, & inclination factors as well

SETTLEMENT

- Total settlement $S_T = S_e + S_c + S_s$
  - S_e = Elastic settlement (immediate). Most important for sands.
  - S_c = Consolidation settlement; due to squeezing out of water and air from pore space. Most important for clays, small for sands. Can take years to complete. <u>Rate</u> and <u>amount</u> of settlement determined from consolidation theory combined with lab tests.
  - S_s = Secondary settlement; long-term rearrangement of soil structure under constant effective stress. Magnitude depends on mineral types present in soil

FS AGAINST SLIDING

$$F_s = \frac{\Sigma(\text{hor. resisting forces})}{\Sigma(\text{hor. driving forces})} = \frac{c_b \cdot A_{eff} + V \tan \delta_b}{H} \geq 1.5$$

- c_b = adhesion between soil and foundation, often taken as 1/2 to 2/3 of the soil's cohesion
- δ_b = angle of interface friction between soil & base, often taken as 1/2 to 2/3 of ϕ
- For Undrained conditions in clay, $\phi_u = 0$;

$$F_s = \frac{c_b \cdot A_{eff}}{H} \geq 1.5$$

FS AGAINST OVERTURNING

- Similar to the case of sliding, we can take the ratio of restoring moments to overturning moments:

$$F_s = \frac{\Sigma(\text{restoring moments})}{\Sigma(\text{overturning moments})} \geq 1.5,$$

Loss of contact is usually ensured by keeping e<B/6

FACTOR OF SAFETY AGAINST OVERTURNING

$$F_S < 1.0$$

noturbinesin.saddleworth.net

DRAINAGE

- Needed to maintain the design bearing capacity as calculated based on the assumed maximum water table elevation

- Can be provided by using drainage “tiles”, free-draining backfill, and sloping the finished grade away from foundation to prevent ponding

- Excessive wetting of clay soils can cause expansion → differential settlements

- Excessive drying of clay soils (e.g. from nearby vegetation) can cause shrinking →settlements

DYNAMIC ANALYSIS: COUPLED SOIL-STRUCTURE INTERACTION

"A complete natural frequency analysis shall be performed for the <u>combined structure consisting of turbine, tower, tripod and piles"</u> ***[and soil]***. *For this purpose, the non-linear soil must be linearized. It is to be verified that the lowest frequencies differ from at least ±10% of the 1P and 3P rotor frequencies at nominal power."*

Guidelines for Design of Wind Turbines, 2nd ed. − DNV/Risø

DYNAMIC ANALYSIS: COUPLED SOIL-STRUCTURE INTERACTION

"The dynamics and relative stiffness of the supporting structural and foundation components, commonly envisaged as a monotower in shallow water (but which could be a vertical axis system, a floating system, etc.), have an ***interrelationship with the stiffness and rotation frequency and loads of the blades that must be carefully addressed in the design for long-term performance.****"*

Structural Integrity of Offshore Turbines – Oversight of Design, Fabrication and Installation, TRB Special Report 305, 2011

DYNAMIC FOUNDATION STIFFNESS

- Dynamic Soil-Structure Interaction (SSI): dynamic soil response affects response of structure and vice-versa
- Stiffness of soil is generally nonlinear and frequency dependent, but often simplified in terms of springs and dashpots
- Stiffness (shear modulus G) and damping (ξ) depend nonlinearly on cyclic shear strain γ_c
- As γ_c increases, G decreases from small-strain value G_{max} while ξ increases
- Design: must use a reduced G based on anticipated shear strain level (typically 10^{-2} to 10^{-3} for wind turbines) in dynamic analysis of soil-foundation-turbine system
- G can then be used to obtain an "equivalent elastic" Young's modulus E for calculating elastic settlements using the reduced foundation area (see Mayne et al. 2002)

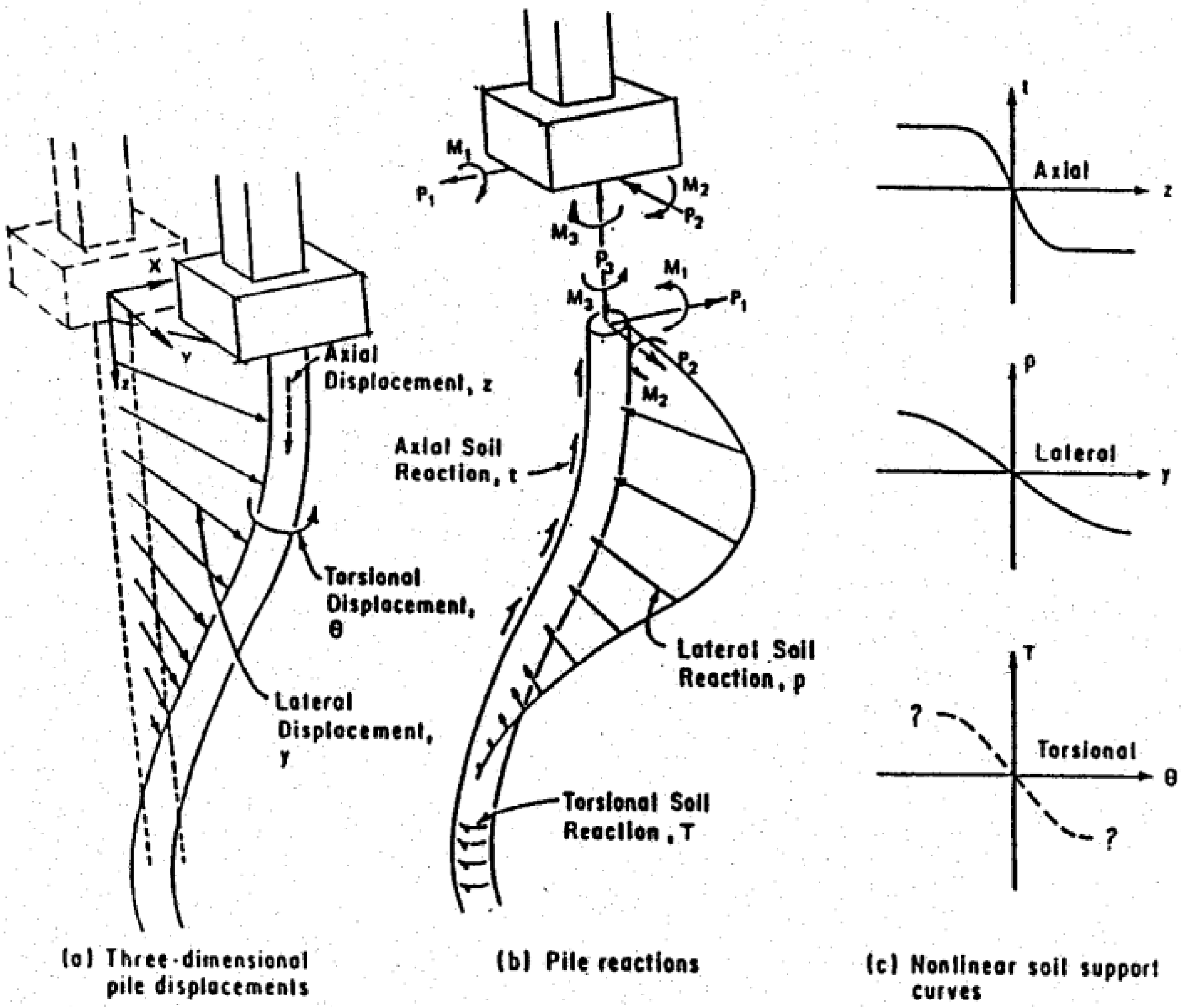
Mayne, P.W. et al., "Subsurface Exploration-Geotechnical Characterization", FHWA Publication NHI-01-031, May 2002.

DESIGN OF PILE FOUNDATIONS

More complicated than shallow foundations

Covered in

CE 561



Ensoft (1996), *Computer Program Group 4.0 User's Manual*

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