Journée parrainée par

COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

Pieux d'ancrage, ancres à succion et ancres gravitaires

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Foundations of Floating Wind Turbines
Anchor piles, Suction Anchors, Gravity Anchors

Summary of the presentation

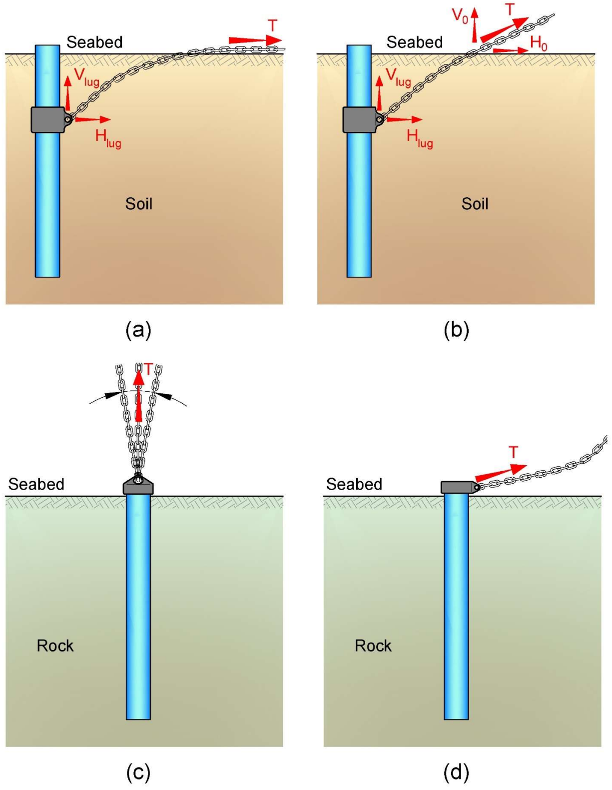
- Chapter 09 – Anchor Piles
  - driven piles;
  - drilled and grouted piles.
- Chapter 10 – Suction Anchors
- Chapter 11 – Gravity Anchors

This presentation aims at presenting a summary of the content of the Recommended Practice, highlighting the content and some of the main elements

Foundations of Floating Wind Turbines
Anchor piles, Suction Anchors, Gravity Anchors

Anchor Piles

- straight structural elements with length, penetration/diameter ratios approximately greater than 10 (D/B > 10).
- only usual offshore pile foundations (driven piles, drilled and grouted piles) are covered in the RP.
- geotechnical design of the anchor piles shall account for:
  - axial capacity (in tension);
  - lateral capacity;
  - structural integrity of the piles;
  - axial and lateral displacements;
  - interaction between axial and lateral responses;
  - effects of torque on axial capacity;
  - feasibility of installation.
- and:
  - scour (Chapter 12);
  - soil liquefaction due to earthquakes;
  - overall site stability.
- **two main pile types:**
  - driven piles ("soils", i.e. sand and clay, chalk);
  - drilled and grouted piles (rock).



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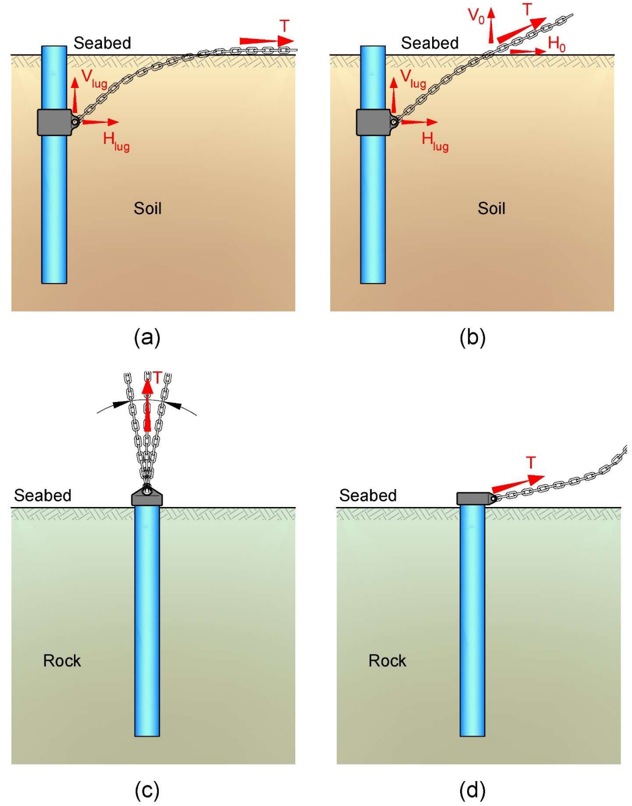
Driven anchor piles – Axial loading

- the main aspects to be taken into account are:
  - type of soil or rock;
  - degree of cementation;
  - pile axial flexibility, notably when materials undergo softening due to local displacements;
  - effect of cyclic degradation; and
  - effect of creep under sustained loading.

and in particular:

- ***siliceous sand***: conventional methods may be used; e.g. API RP2 GEO, DNV-RP-C212, ISO 19901- 4;
- ***non-cemented or weakly cemented carbonate sands and calcarenites***:
  - special attention required
  - driving → grains crushing → significant reduction in skin friction along the shaft;
  - axial capacity in tension → very low and difficult to predict reliably;
  - <u>the use of driven anchor piles in non-cemented or weakly cemented carbonate sands is strongly discouraged.</u>



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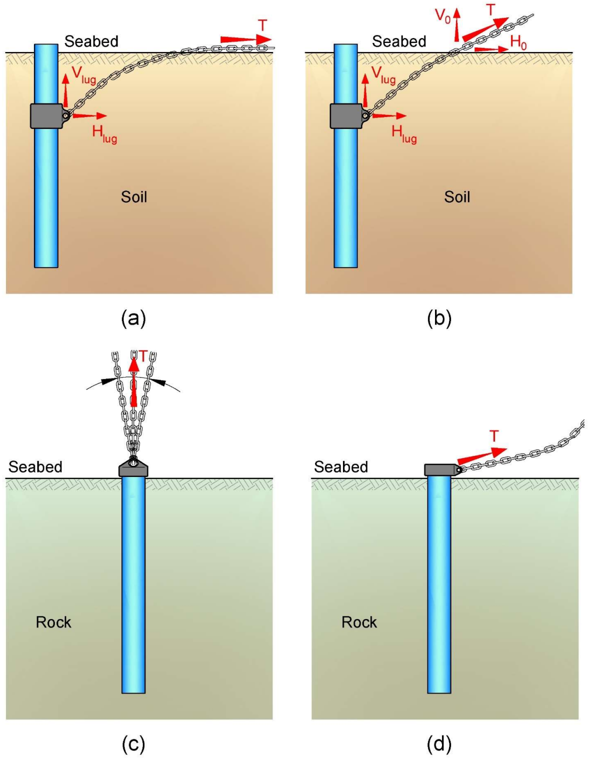
Driven anchor piles – Axial loading (continued):

- ***chalk***:
  - “complex” material: again, special attention required;
  - may offer very low resistance during driving, but can develop significant axial friction over time (“set-up”);
  - classification of chalk(s) → reference to CIRIA (2002):
    - good for classification;
    - recommended shaft friction (20kPa for low density, 120kPa for high density & Grade A) is based on limited data;
  - for specific engineering project involving chalk formations, it is recommended to conduct preliminary pile tests;
  - recent advancements provided by Carrington et al. (2011), Barbosa et al. (2015), and Jardine et al. (2018). These research works have contributed to a better understanding of the behaviour of piles driven into medium to high density saturated chalks in underwater conditions;
  - ***ALPACA JIP research*** (2019-2022, ongoing):
    - wide range of pile diameters;
    - robust methodology to predict the expected SRD;
    - long term capacity and pile behaviour (t-z).



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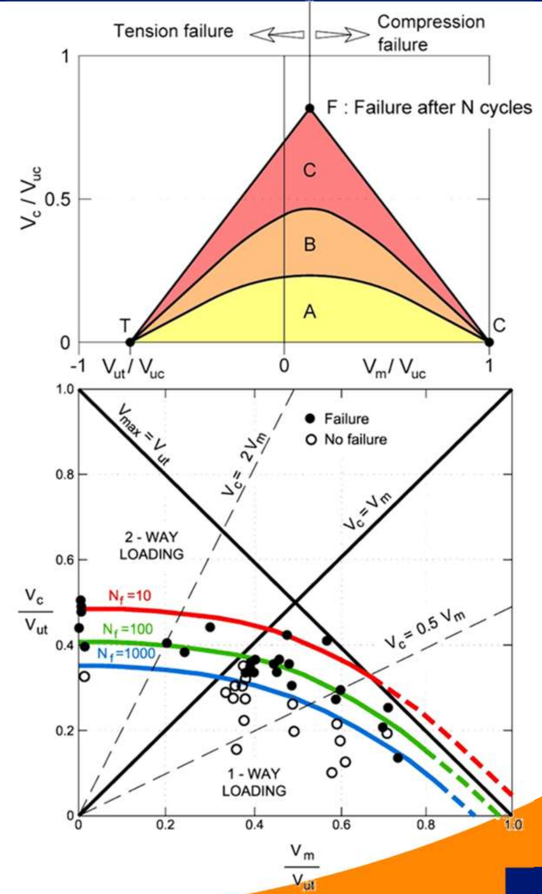
Driven anchor piles – Axial loading - cyclic loading

- potentially detrimental effect of cyclic loadings on the capacity (shaft friction);
- for taut moorings → large cyclic component with respect to the average;
- applied cyclic load separated in cyclic and average:
  - use of cyclic stability diagram: 3 zones, A (stable); B (meta-stable); C (unstable)
  - depends on pile stiffness;
  - ….
- SOLCYP (2017) recommendations present a comprehensive synthesis of all the currently available data on the behaviour of piles under cyclic loadings
- particular cases:
  - carbonate sands and calcarenites, strong cyclic degradation : use excluded;
  - chalk: extensive data from the ALPACA JIP (2018, ongoing).
- use of numerical tool possible and required for accurate predictions:
  - CYCLOPS (Erbrich et al., 2011); TZC (Burlon et al., 2013);
  - SOLCYP (2017) recommendations propose an original method based on the determination of degradation laws from CNS tests



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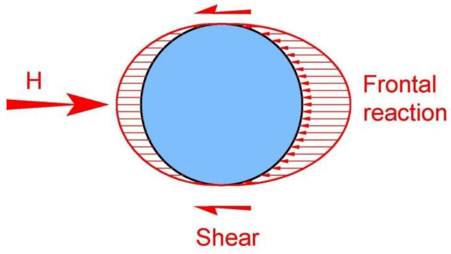
Driven anchor piles – Lateral loading

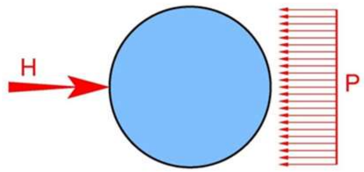
- loads are applied or at the pile head or at some depth below the mudline, typically at the lug level;

- in flexible piles, the lateral behaviour is governed the first few meters below the sea floor;

- lateral “capacity” is defined by:
  - lateral displacements under the effect of monotonic and cyclic loadings;
  - pile integrity, specifically the bending resistance of the pile structure;

- lateral behaviour → p-y curves method used mostly:
  - ground response schematized by non-linear springs represented each by a p-y curve;
    - siliceous sands and clays → ISO 19901-4 (2016)
    - clays monotonic (and cyclic p-y curves), proposed in Draft ISO DIS 19901-4 (Feb. 2022);
    - chalk: improvements expected from ALPACA and ALPACA+
  - lateral behaviour under cyclic loading:
    - siliceous sands and clays → ISO 19901-4 (2016 & Draft 2022);
    - CFMS (2020) Recommendations for planning and designing foundations of offshore wind turbines





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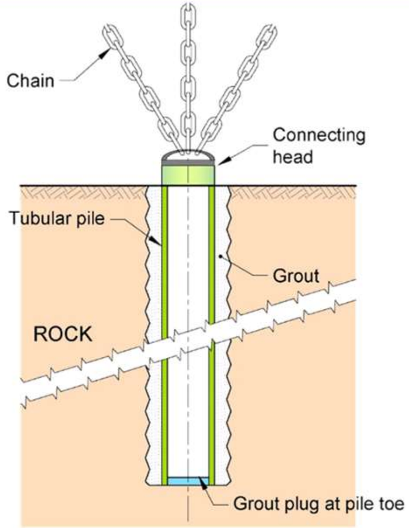
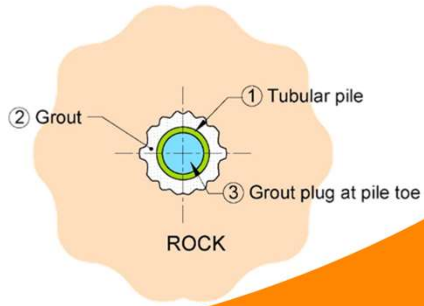
Drilled anchor piles – Axial loading – Main elements

- preferred in:
  - very hard soils, rock or cemented soils;
  - soils where driving could significantly reduce the shaft friction.
- construction:
  - drilling of an open borehole;
  - lowering of a metallic pipe pile, with centralizers;
  - grouting.
- installation process impacts the pile behaviour, thus the design process of the piles as compared to driven steel piles:
  - soil decompression: drilling the borehole decompresses the surrounding soil, as opposed to driving which leads to a partial soil displacement. In self-standing rocks or soils, the effective stress shall be considered zero at the borehole..
  - grouting; careful procedure to be followed;
  - drilling mud to be considered with care, as formation of a “cake” on the borehole affect the final axial capacity: the RP discourages the use of drilling mud
  - borehole stability; to be granted from end of drilling to grout curing.





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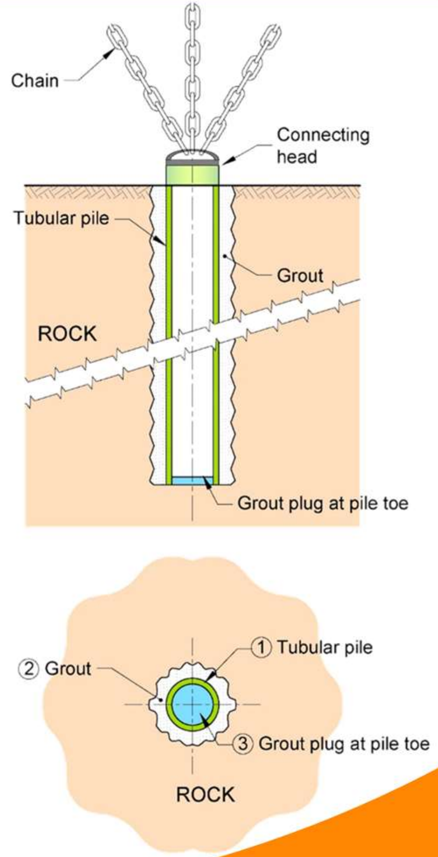
Drilled anchor piles – Axial loading – Methods

- estimate of rock-grout shear strength and pile-grout shear strength;

- pile-grout shear strength depends on:
  - grout unconfined resistance;
  - presence of shear keys;
  - rock-mass stiffness (confinement);
  - reference in DNV ST 0126 (2021), ISO 19902;

- rock-grout shear strength depends on:
  - the roughness of the borehole surface; usually estimated based on rock UCS (Seidel & Colingwood);
  - to improve knowledge for future projects, borehole roughness measurement is recommended (not easy!);
  - rock-mass stiffness (confinement); measurement of such stiffness recommended during site investigation (CFMS (2020), §6.4.5).
  - comprehensive elements in CFMS (2020), §9.4.2.1.



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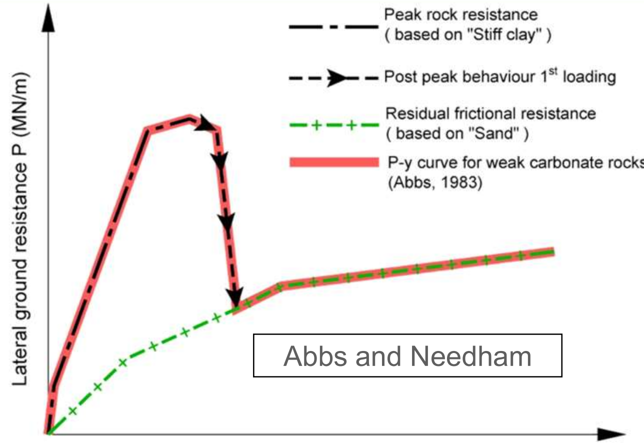
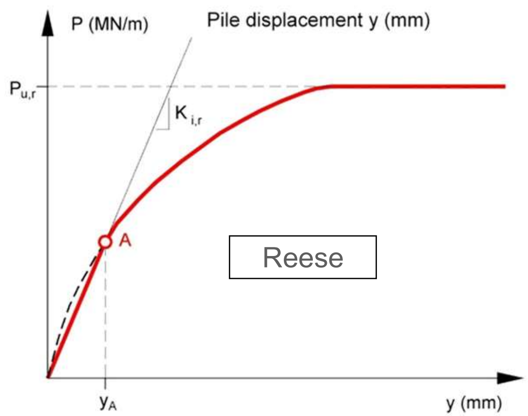
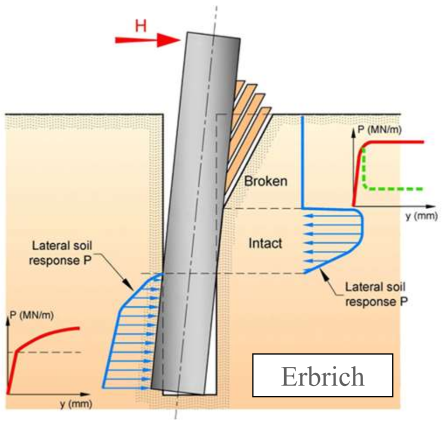
Drilled anchor piles – Lateral loading

- again, lateral behaviour → p-y curves method used mostly
- representative of brittle behaviour of rocks (as mostly used for..)
- carbonate sands, specifically calcarenites:
  - Abbs and Needham, combining:
    - before failure: Reese;
    - after failure: Murchison and O'Neill's model (for sands).
- non-carbonate rock....
  - Reese....
  - ultimate resistance, P_{ur} calculated by UCS of intact rock, and α_r (RQD);
  - α_r (RQD) relationship subject to criticism;
  - CFMS proposes to use the rock mass compressive strength $q_{u,rm}$ and rock mass stiffness $E_{i,rm}$ instead of the α_r ;
- cyclic loading:
  - Abbs (1983) for soft carbonate rocks;
  - Fragio et al. (1995) for hard marls;
  - Novello (1989) for calcarenites; and,
  - Erbrich (2004) for calcarenites







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Driven anchor piles – Installation

- Driven anchor piles → usually installed by impact hammers;
  - pile driving analyses shall ensure:
    - installation at the required target depth + the hammer(s) required for the installation;
    - integrity of the metallic tube (stress control) + adequate remedial procedures (e.g. drilling).
  - prediction of driveability:
    - determine the static component of the Soil Resistance to Driving (SRD);
    - simulate the dynamic behaviour of the hammer-pile-soil system (wave equation).
  - procedures for the SRD are not indicated by Standards:
    - experience in the geographical area → improve the reliability of SRD;
    - guidance in CFMS (2020) *Recommendations for planning and designing foundations of offshore wind turbines*
    - in chalk → ALPACA and related publications;
    - attention to damage to pile toe in dense sand or hard materials (cemented soils or rocks).
  - dynamic impact testing:
  - vibro-driving:
    - effective, but: effects of vibrations on pile wall friction are not yet fully understood, and no proven calculation methods are available for axial capacity after installation;
    - not recommended for anchor piles subjected to significant tensile loads;
    - specifically discouraged for taut moorings unless pile design can be substantiated through dedicated and representative pile tests, or by driving the pile for most of the penetration after stabbed in the soil by vibration.

https://acteon.com/products-services/noise-mitigation-systems/

after: https://iqip.com/products/pile-driving-equipment/hydrohammer/

Foundations of Floating Wind Turbines
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Drilled and Grouted anchor piles – Installation

- construction and installation requires to account for:
  - drilling:
    - borehole stability shall be ensured in all phases of the construction; otherwise casing required;
    - drilling tool to be selected depending on rock type and strength;
    - use of drilling mud discouraged;
  - grouting:
    - grouting of the annulus is performed by pumping the grout by means of pipes;
    - from the bottom of the pile;
    - if raising of pipes necessary, to be done in steps granting pipe bottom stays below top grout level.

after www.Seacore.com

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Suction Anchors (in soft clays)

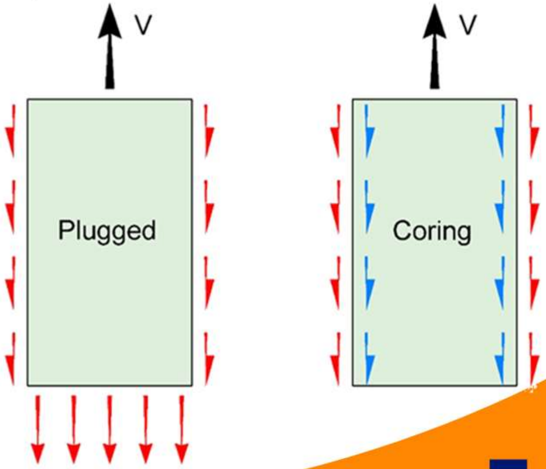
- vertical cylindrical caissons
- typical size:
  - diameters (B) ranging from 4 to 10 meters;
  - length-to-diameter ratios (L/B) between 3 and 6;

- installed by self-weight penetration + under-pressure (“suction”) ;
- can be installed in soft clays and in sands;
- this CFMS Recommendation addresses only suction anchor in soft clays.

- geotechnical design of a suction anchor should prioritize the determination of the:
  - axial uplift capacity.
  - maximum horizontal capacity corresponding to the optimum lug depth.
  - failure envelope to verify capacity under combined V-H loading (for a determined application point).
  - distribution of normal and shear stresses applied by the soil on the caisson wall for the structural design;
  - impact of torsion, misalignment, etc.;
  - installation and retrieval.

https://www.hit-gh.com/

adapted after https://www.esubsea.com/



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Suction Anchors (in soft clays)

Axial capacity

- minimum between:
  - plugged (eternal shaft friction + reverse end bearing); $V_u = Q_{out} + Q_{base} + W'_p$
  - coring (external + internal shaft friction); $V_u = Q_{out} + Q_{inn} + W'_p$

- reverse end bearing capacity factor:
  - $N_{cr} = 6.2 \{1 + 0.34 \arctan (z_i / B)\} < 9$; for $z_i / B < 4.5$
  - S_u average over a depth of 0.5B below the tip level;

- shaft friction:
  - $\tau_{shaft} = \alpha\, S_u^{DSS}$ with S_u^{DSS} accounting for cyclic effects;
- selection of α :
  - API RP 2A (part penetrated by self-weight) + 0.65 (for part penetration by suction pressure); guidance in DNV-RP-E303, 2021 ;

- internal shaft friction depends on presence or not of ring stiffeners (DNV-RP-E303, 2021);
- possible detachment of soil from pile ("tension crack") to be taken into account.


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adapted after https://www.esubsea.com/

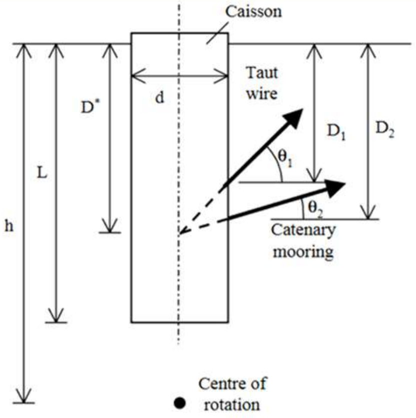
$= Q_{out} + Q_{base} + W$

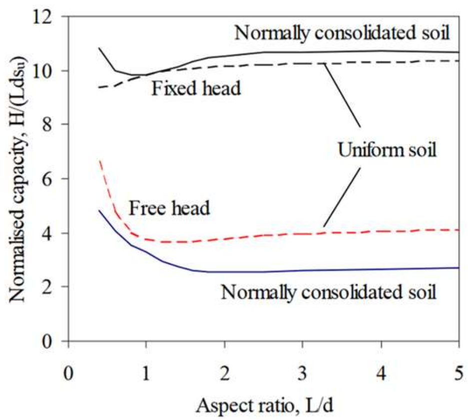
Suction Anchors (in soft clays)

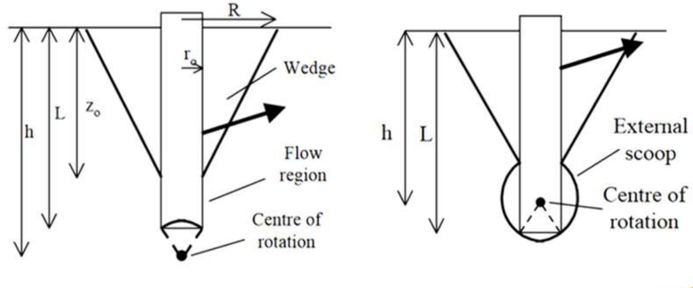
Horizontal capacity

- depends on the position of the point of load application;
- maximum H obtained if load is applied to obtain pure translation without rotation;
- the caisson's movement is determined by the position of the centre-line intersection of the loads line of action…..
- optimization of the application point required to obtain max H possible.

- $H_u = 10\ D\ B\ S_{u\ mean}$ for pure translation







(a) Conical wedge and flow region (b) External base rotational scoop

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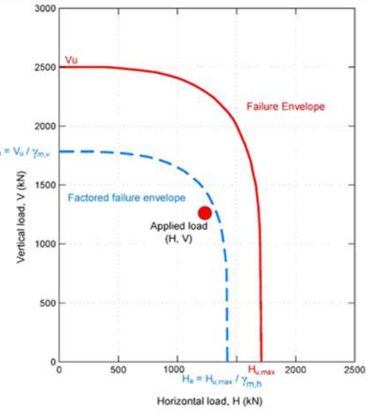
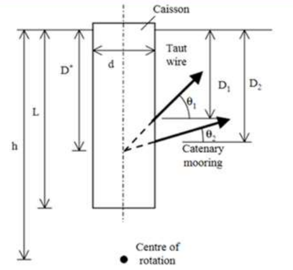
Suction Anchors (in soft clays)

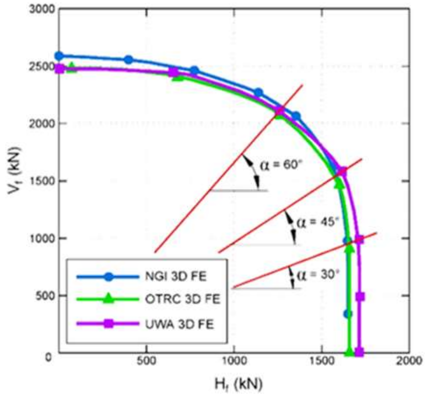
- Combined V - H:
  - depends on max H_u (function of the point of load application, with V =0);
  - depends on max V_u (pure vertical load, i.e. for H=0);
  - analytical shape of the V_u-H_u interaction domain can be used.
- finite element analysis can be used to construct the failure envelope by varying the loading angle at the padeye
- several Authors have developed useful analytical equations, calibrated us-ing 3D FEA, to describe vertical-horizontal-moment (VHM) failure envelopes for caisson capacity in clay:

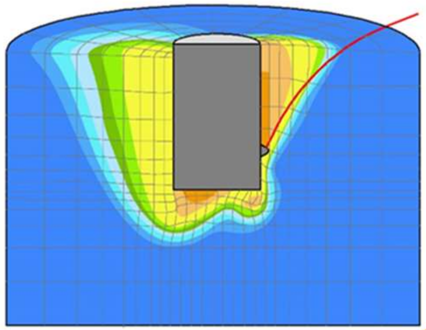
$$\left(\frac{V}{V_u}\right)^n + \left(\frac{H}{H_{u,max}}\right)^m = 1$$

- $H_{u,max}$: H_u for the optimal padeye depth, i.e. with defined load application point.









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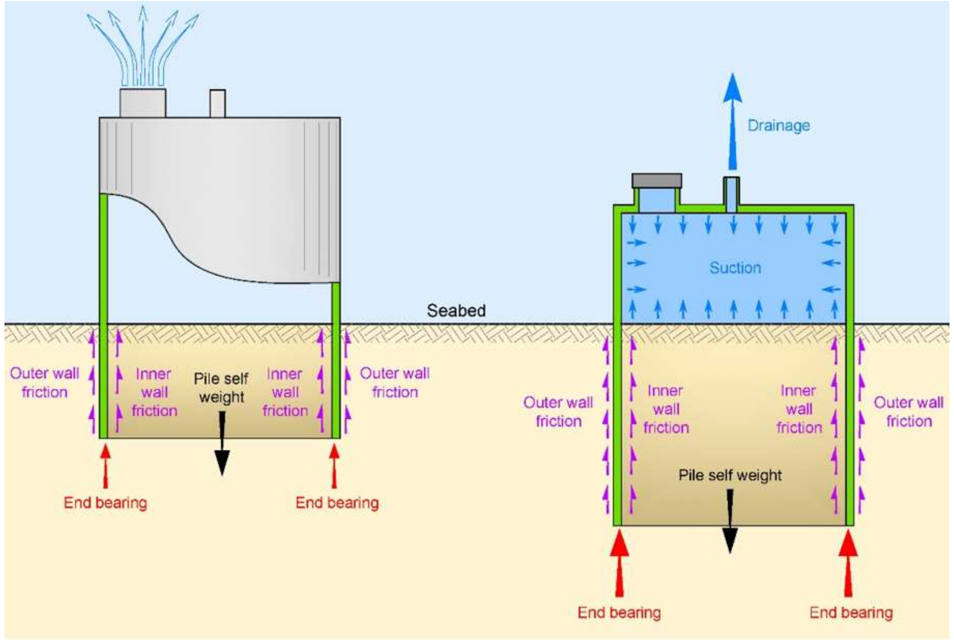
Suction Anchors (in soft clays)

- Installation:
  - the soil penetration resistance , Q_{tot}, during self-weight embedment and assisted pumping is computed as the sum of:
    - the frictional resistance at the pile-soil interface (inside and outside);
    - the pile tip bearing resistance.

$$Q_{tot} = Q_{tip} + Q_{side}$$

  - Q_{tip} ----> based on bearing capacity of annular base;
  - Q_{side} ----> based on $\alpha = 1 / S_t$
  - effect of internal stiffeners to be taken into account ---> DNV-RP-E303 (2021)
  - required underpressure: $\Delta u_n = (Q_{tot} - W') \; / \; A_{base}$
  - plug heave to be considered as well.



1 - Self weight penetration

2 - Suction assisted penetration

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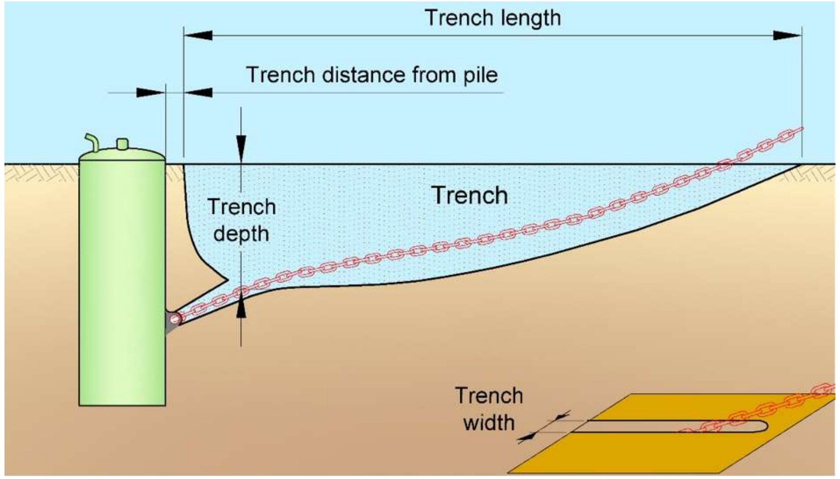
Suction Anchors (in soft clays)

Trenches induced by mooring chains



- instances of seabed trenches in the vicinity of suction piles have been discovered;
- limited published information available on this subject;

- possible causes:
  - large movements of the mooring chains under semi-taut or taut mooring conditions;
  - presence of structured, low unit weight clays.

- potential consequences of a trench formation include:
  - loss in horizontal capacity;
  - modification of anchor kinematics;
  - loss in reverse end bearing (REB) capacity due to the formation of channeling below the lug level.

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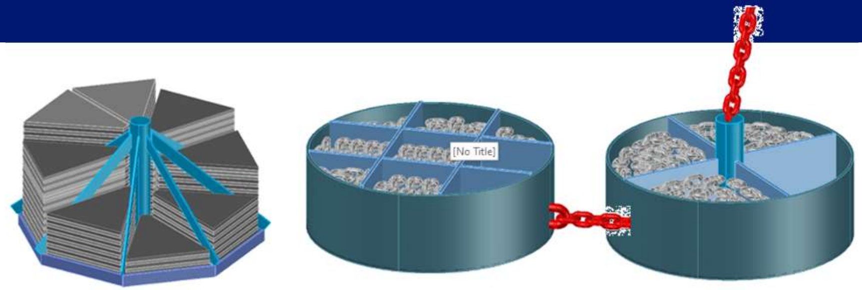
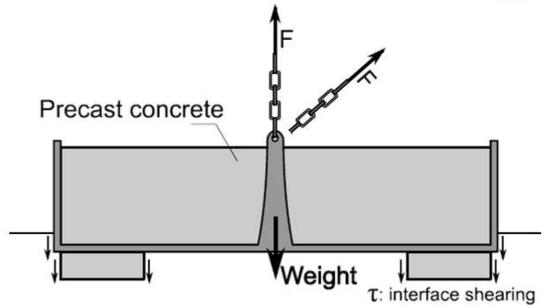
Gravity Anchors

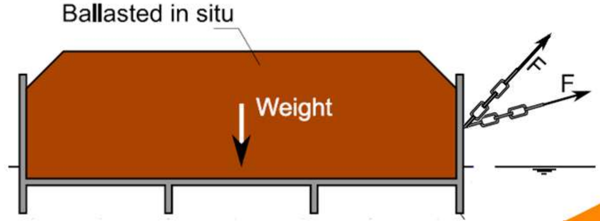
- Basic principles
  - gravity anchors derive their holding capacity from their self-weight;
  - typically have minimal or no embedment into the ground;
  - can be provided with skirts;
  - commonly used in areas with competent soils:
    - sands;
    - medium to very high strength clays;
    - and rocks;
  - various forms:
    - rigid, “monoblock”;
    - deformable or articulated structures

- <u>only Monoblock gravity anchor are treated in the Recommendations</u>





after B. Cerfontaine et al., 2023



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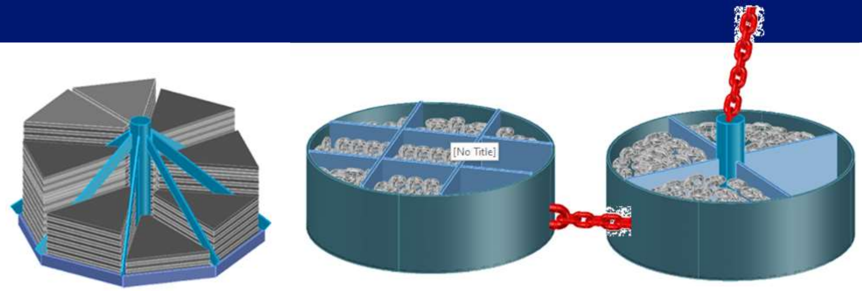

Gravity Anchors (monoblock)

- ULS and ALS are primarily affecting the design;
  - design to account for:
    - resistance to sliding;
    - bearing capacity (under V, H, M);
    - torque effects may be considered in certain cases;
    - cyclic loads;
    - uplift capacity;
    - overall stability with regards to overturning of extreme load cases; and
    - the hydraulic stability.
- SLS concerns the:
  - vertical displacements (settlements and rotations of the gravity bases);
  - horizontal displacements (irreversible sliding);
  - their order of magnitude shall not impact:
    - the floater response;
    - the structural integrity of the anchor.
- for ULS, ALS and SLS, cyclic loads effect shall be taken into account:
  - ULS, ALS: the accumulation of pore pressures and/or deformations of soils may lead to a decrease of the soil resistance;
  - SLS: cyclic loading can lead to an accumulation of permanent deformations and to changes in soil stiffness.

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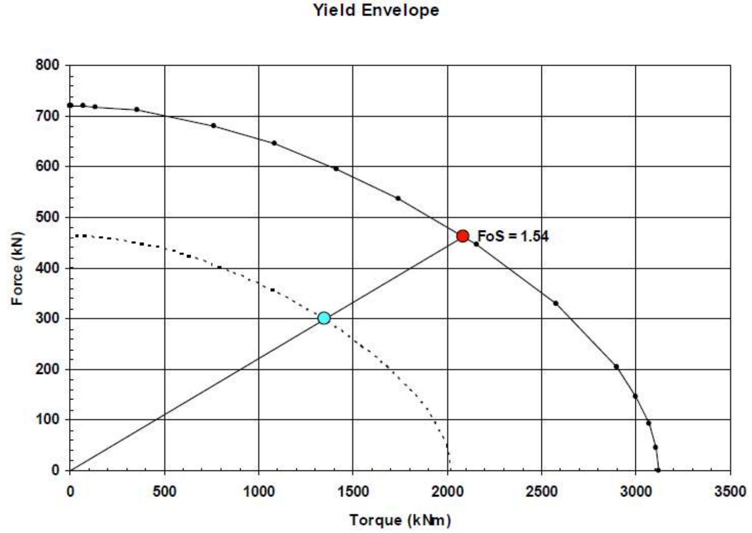
Gravity Anchors (monoblock)

- drainage
  - to calculate the behaviour of the ground under specific loadings for foundation design, it is essential to determine whether the conditions are drained or undrained;
  - gravity anchors of considerable size mobilise a significant volume of soil ----> the bearing capacity mechanism typically operates in undrained conditions;

- sliding resistance (essential !!) :
  - resistance mainly governed by nature of interface and strength of weak shallow layers;
  - seabed preparation (engineered gravel bed layer):
    - according to Pederstad et al. (2015), full drainage not guaranteed;
    - potential generation of pore pressure to be checked ---> e.g. DNV-RP-C212 (2021), § 5.2.3.

  - analytical methods ---> DNVGL-ST-0126 (2016) and ISO 19901-4 (2016);
  - effect of torsion:
    - can reduce the sliding resistance,
    - equivalent horizontal loading ---> DNV-RP-212 (2021), §5.4.3 ;
    - H-T interaction envelopes curves ---> Finnie and Morgan (2004) or Yun et al. (2009) .



H – T yield envelope - after Finnie & Morgan (2004)

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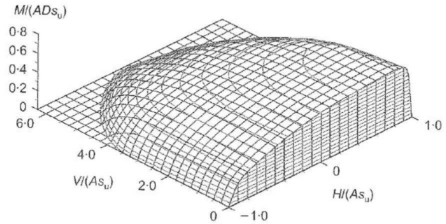
Gravity Anchors (monoblock)

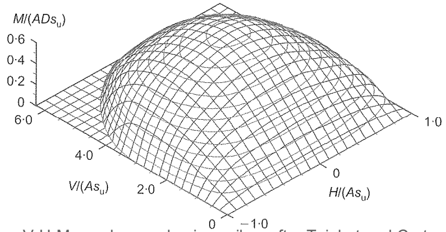
- <u>bearing capacity</u>
  - depends on M and H;
  - V-H-M envelopes used, effect of combined loading to be taken into account;
  - M can be removed if M negligible or if effective area concept is used;

- <u>uplift capacity</u>
  - shall not be taken larger than the submerged unit weight of the anchor.

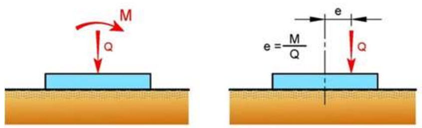
- <u>SLS verifications</u>:
- evaluate permanent displacements throughout anchor operational life;
- and that displacements do not :
  - change loads;
  - compromise the anchor structure;
  - deteriorate the anchor-seabed contact:
    - gapping not allowed for SLS loading;
    - can be allowed for ULS to max the centre of gravity.

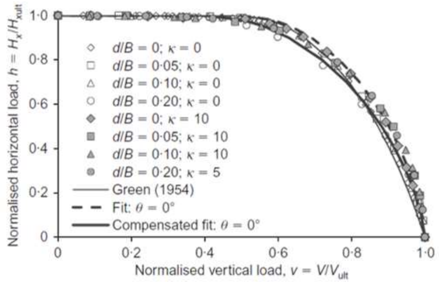


V-H-M envelope, cohesive soils, full adhesion– after Taiebat and Carter (2010)



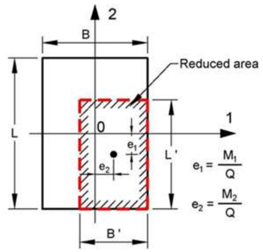
V-H-M envelope, cohesive soils – after Taiebat and Carter (2010)





V-H-M envelope, cohesive soils, – after Feng et al. (2014)

Equivalent loading



Foundations of Floating Wind Turbines
Anchor piles, Suction Anchors, Gravity Anchors

Gravity Anchors (monoblock)

- other subjects treated in the Recommendations
  - vertical stresses distribution;
  - resistance to skirt penetration;
  - installation;
  - decommissioning;
  - ground preparation.

Thank you !

Merci !

Grazie !