Ancres draguées et ancre plaques

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Floating Wind Farm
Drag Anchors and Plate Anchors
Recommendations

Topics:

- Type of Anchors – General description
  - Plate Anchors – Drag Embedded anchors
- Penetration predictions – Drag Embedded anchors
- Anchor line equations
- Drag Embedded Anchors kinematic
- Drag Embedded Anchors in sand and high strength Clays
- Characteristic resistance of Fluke anchors
- Post Installation effects
- Installation tension and proof tests
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Type of anchors

- Anchor Piles:
  - Driven/vibro Piles
  - Drilled and Grouted Piles
  - Dynamically installed piles (Torpedos)

Vibrotry driven piles
Torpedo Pile - T120
Subsea Drilling

Courtesy of Fugro drilling services
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Recommendations

Type of anchors

- **Suction Anchors**

- **Gravity Anchors**

Source: Offshore wind design AS
Type of anchors

Plate Anchors:
- Push-in Plate Anchors
- Suction Embedded Plate Anchor (SEPLA)
- Dynamically Embedded Plate Anchor (DEPLA)
Drag – Embedment Anchors (DEA)

- **Fluke Anchors**
  - HHP anchors
  - 3x4 to 6x9m – 5t to 50t (i.e. ballasted)
  - Limited uplift resistance

- **Vertical Loaded Anchors (VLA)**
  - Tension on the line is redirected to be perpendicular to the plate
  - Shear Pin
  - Require deep burial
  - 5 to 30m² fluke area
The penetration and self-burial of a fluke anchor into the seabed is a complex soil structure interaction mechanism.

The initial angle during anchor setting is a governing parameter.

Trajectory & UHC prediction methods:
- Empirical (Based on manufacturer charts)
- Analytical approaches (i.e. limit equilibrium and Plasticity)

Predictions are particularly challenging in layered soils.

Chain forerunner / soil interaction influences the anchor trajectory.
Drag Embedment Anchor – Penetration/trajectory predictions

- **Effect of the initial angle into the anchor trajectory**
  - Optimal initial fluke angle for setting stage

![Graph showing effect of initial fluke angle in clay]

- 48% of more drag needed

![Diagram of a scale model anchor in a sand bed (α=40°). Effect of fluke angle]
Empirical predictions

- Based on anchor manufacturer charts
- Recommendations from codes
  - ISO, API, (Based on NEL)
- Charts are provided for generic soil conditions and not site specific

BS-EN-ISO 19901-7: Station keeping systems for floating offshore structures and mobile offshore units – Estimated Maximum fluke tip penetration

Example of Vryhof chart for drag/embedment predictions

NEL: (Naval Civil Engineering Laboratory)
Empirical predictions

- Based on anchor manufacturer charts
- Recommendations from codes
  - ISO, API, (Based on NEL)
- Charts are provided for generic soil conditions and not site specific
- General practice is to consider:
  - A penetration not exceeding 60% of the maximum penetration; or
  - A resistance not exceeding 60% of the ultimate resistance.

NEL: (Naval Civil Engineering Laboratory)

UHC: Ultimate Holding Capacity
Analytical approaches

- Based on Limit Equilibrium:
  - Neubecker and Randolph*
  - DNV (DIGIN software): (DNV-RP-E301)
- Based on Plasticity limit models
  - O’Neil et al.
  - Aubeny and Chi*

Anchor line equations

- Integration of DEA trajectory & Anchor line equation

* General principles for drag anchors in Clay provided in “Recommendations for planning and designing anchor foundations of floating wind turbines Appendix D” CFMS (2024)
Anchor line equations - Clay

- **Anchor line on the seabed (lying line)**
  - No uplift during installation
  - Seabed friction
    \[ f = \mu \cdot W/l_z \]
    - coefficient of seabed friction
    - seabed friction per unit length of the line [kN/m]
    - submerged weight per unit length of anchor line [kN/m]
    - length of the slack portion of the line on the seabed [m]

<table>
<thead>
<tr>
<th>Seabed friction</th>
<th>Lower bound</th>
<th>Default value</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Chain</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- **Anchor line embedded in the soil**
  - From dip-Down point to anchor shackle
  - Reverse catenary shape: Numerical iteration – Boundary conditions (known T at Dip-down, shackle z (m))
  - Recommended values of En, Et, Nc & \( \alpha \) (DNV-RP-E301) for wire/chain
  - Simplified method proposed by Neubecker & Randolph (\( W' \) neglected)

\[ T \left( \theta^2 - \theta_0^2 \right) = 2zE_aN_b \left( s_{u0} + k \frac{z}{2} \right) \]

Force equilibrium element of chain – Vivarat et al
Anchor line equations – Non-Cohesive soils

**Mortensen (2015)**

\[ F = N \cdot \alpha_{\text{sand}} \quad N = d \cdot L \cdot A_{\text{sand}} \cdot (0.5 \gamma' \cdot d \cdot A_{\text{sand}} + N_{q'} \cdot z) \] (Bearing capacity strip foundation)

<table>
<thead>
<tr>
<th>Line</th>
<th>( A_{\text{sand}} )</th>
<th>( \alpha_{\text{sand}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>1.0</td>
<td>( \tan \psi' )</td>
</tr>
<tr>
<td>Chain</td>
<td>( b/d (\sim 3.4) )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Inverse catenary shape: Numerical iteration – Boundary conditions (known T at Dip-down, shackle z (m))

**Neubecker & Randolph (1995)**:

- Exponential relationship to derive the reverse catenary

\[ z^* = e^{-x \cdot \alpha} \]

- Good approximation for soils with proportional bearing resistance to depth

**Neubecker & Randolph – Centrifuge Test data D=2m to 3m \( \phi' = 34 \text{ to } 45^\circ \) versus proposed equation**
Aubeny and Chi (2010)

Kinematic of the anchor:

Angular velocity of the fluke: \( \dot{\theta} = \frac{\partial \theta}{\partial N_i} \)

Tangential velocity: \( v_t = \frac{\partial \theta}{\partial N_i} \)

Normal velocity: \( v_n = \frac{\partial \theta}{\partial N_n} \)

Anchor holding capacity

\[
f = \left( \frac{|c_1| N_e}{N_{n,\text{max}}} \right)^m + \left( \frac{|c_2| N_e}{N_{t,\text{max}}} \right)^n + \left( \frac{|c_3| N_e}{N_{m,\text{max}}} \right)^p - 1 = 0
\]

- \( N_n = N_{e_0}C_1 \)
- \( N_t = N_{e_0}C_2 \)
- \( N_m = N_{e_0}C_3 \)

 urbN euro calibrated from field measurements (ranges 4.4 to 9)

interaction coefficients considered as \( m = 1.56, n = 4.19, p = 1.5 \) and \( q = 4.43 \) (Murff et al. 2005)

Ratio Normal / tangential translation

\[
R_{nt} = \frac{v_n}{v_t} = \frac{\left( \frac{|N_{n,\text{max}}|}{N_{n,\text{max}}} \right)^m \left( \frac{|N_{t,\text{max}}|}{N_{t,\text{max}}} \right)^n \left( \frac{|N_{m,\text{max}}|}{N_{m,\text{max}}} \right)^p - 1}{\left( \frac{|N_{n,\text{max}}|}{N_{n,\text{max}}} \right)^m + \left( \frac{|N_{t,\text{max}}|}{N_{t,\text{max}}} \right)^n + \left( \frac{|N_{m,\text{max}}|}{N_{m,\text{max}}} \right)^p - 1}
\]

Anchor line equation (Neubecker & Randolph)

\[
T_o \left( \theta_o^2 - \theta_o \right) = 2zE_oN_o \left( s_{u_0} + k \frac{z}{2} \right)
\]

Equilibrium tension at anchor shackle (0° rotation)

\[
T_o = N_{e_0} s_{u_0} A_f
\]

Key equation anchor rotation / padeye angle line

\[
\frac{d\theta_o}{dz} = \frac{1}{\theta_o} \left( E_o N_o c_b - \frac{k \theta_o^2}{2 s_{u_0}} \right)
\]
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DEA kinematic and holding capacity - Clay

- **Aubeny and Chi (2010)**
  - Full drag distance & penetration prediction
  - Ultimate anchor holding capacity at 0° fluke rotation
  - Prediction for additional drag distance at operation
  - Relatively complex
  - Homogenous soft Clay $S_u = S_{u0} + K \cdot z$
  - $N_{e0}$ bearing factor requires site correlation & depends on multiple variables:
    - Shank thickness, Fluke thickness, fluke shank angle

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Example using $Su=2+1.5z$, $N_{e0}=5.8$, Fluke area 6m², Initial angle $\theta_i=45^\circ$, line diameter=0.076m
DEA in Sand and High strength Clay – General recommendations

- **Sand**
  - Analytical predictions similar to clay provided in (Neubecker and Randolph (1996), Miedema et al (2001) and Liu et al (2010))
  - Shallow penetration expected, fluke ballast is in some cases required
  - In very dense sand, penetration = 1 x fluke length and loose sand 2 x fluke length
  - General recommendation is at least one fluke penetration to dump scouring effects
  - Drag distances are short: ~8 x Fluke length

- **High strength clays**
  - Poorly documented
  - Adopt a lower fluke shank angle than the one recommended for soft clays

- **Layered soils**
  - Sand/Hard clay transitions or soft Clay / Hard clay transitions (slippage risk)
The characteristic resistance of DEA at the dip down point is defined as:

\[ \text{RC} = \text{R}_{\text{ic}} + \Delta R_{\text{post}} + \Delta R_{\text{fric}} \]

- **R** \(_{\text{ic}}\) : Characteristic installation resistance at dip down point
- **\Delta R_{\text{post}}** : Post installation effects (cyclic effects, set-up, additional drag)
- **\Delta R_{\text{fric}}** : Frictional resistance chain/seabed along L\(_s\) (if no uplift)

- The characteristic installation resistance is equal to the installation tension (T\(_i\)) since measurable and maintained during a sufficient time lapse.
- The characteristic resistance with post installation effects are:
  - **With additional drag**
    \[ \text{RC} = \text{R}_{\text{ic}} + \Delta R_{\text{dr}} + \Delta R_{\text{cy}} + (\Delta R_{\text{fric}}) \]
  - **With no additional drag**
    \[ \text{RC} = \text{R}_{\text{ic}} + \Delta R_{\text{setup}} + \Delta R_{\text{cy}} + (\Delta R_{\text{fric}}) \]
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Post Installation effects

- **Additional drag**
  - Allows for lower $T_i$
  - Anchor allowed to penetrate/drag for a design event
  - Additional drag mobilizes further resistance (however set-up effects are lost)
  - Depending on the project constrains and consequences (soil type & ground uncertainties, mooring configuration, floating wind turbine tolerances)

- **Cyclic loading effect**
  - Variation in resistance: combination of rate of loading effects (+) and cyclic degradation effects (-)
  - For one way loading the above cumulated effect is (+)
  - Special care in highly compressible soils or highly sensitive to cyclic degradation (i.e. carbonate soils) whose effect can be (-) (Neubecker et al (2005))

- **Set-up effects (in clay)**
  - In the direction of the fluke
  - Partial remolding (uneven disturbance): Disturbance Ratio DR=0.5
  - Set-up factor $U_{\text{setup}} = f(S_t, DR, t_{\text{setup}}, \text{geometry, depth, orientation})$

\[ R_{\text{cy}} = R_{i,c} \cdot U_{\text{setup}} \cdot U_{\text{cy}} = R_{i,c} + \Delta R_{\text{setup}} + \Delta R_{\text{cy}} \]
Minimum Installation tension $T_{i,\text{min}}$

$$T_{i,\text{min}} = T_i + \gamma_R \cdot \Delta R_{f,i}$$

- Minimum tension required at installation to reach the design capacity
- should be applied and maintained for a designated holding period.
- The holding period, influenced by soil type, should not be shorter than 15 minutes
- holding period, any relaxation (i.e. additional drag) should be compensated, and the tension maintained as constant as possible.

Example of proof test – courtesy of Subsea7