Fast Design Methods for Suction Caisson Foundations

Stephen Suryasentana
Department of Engineering Science

Supervisors: Prof. Byron Byrne, Prof. Harvey Burd

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RENEWABLE ENERGY MARINE STRUCTURES

Scope

- Background
- Research Problem
- Proposed Solution
- oxCaisson design methods
- Case Study
- Conclusion

Source: Ørsted

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Background

- Piled foundations are currently the most commonly used foundations for offshore wind turbines
- Caisson-based (multi-legged) foundations may be more common in the future, as they may be more economical

Why?

- Larger wind turbines
  - Monopiles may get too large
- Deeper waters
  - Higher cost for installation
- Noise-regulated waters
  - Suction installation does not require costly, noise-isolating equipments (unlike pile driving)

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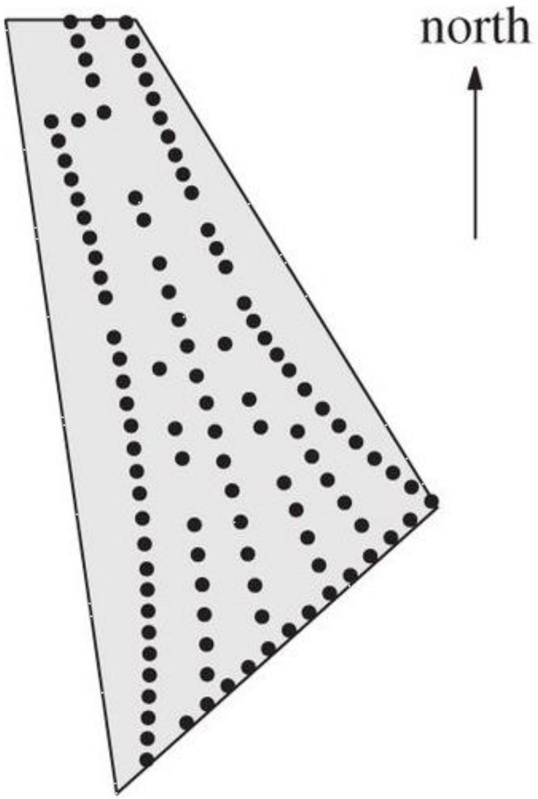
Background

- Current design methods for caisson foundations are less mature compared to their pile counterparts
- Pile design methods (i.e. Winkler models)
  - Fast
  - General (can be used in most soil profiles)
- Suction caisson design methods
  - Macro-element model
    Fast but not general
  - 3D Finite Element (3DFE) method
    Accurate, general but slow
    Most commonly used.
    Suitable for oil & gas projects (just a few structures).

Research Problem

- Optimisation of offshore wind farm is a large scale design project
- Hundreds of foundations
- Requires large number of calculations
- Current design methods are impractical (3DFE is too slow)
- Motivation: fast design methods for suction caisson foundations are needed to optimise large scale design



Optimised offshore wind farm layout (Kallehave et al., 2015)

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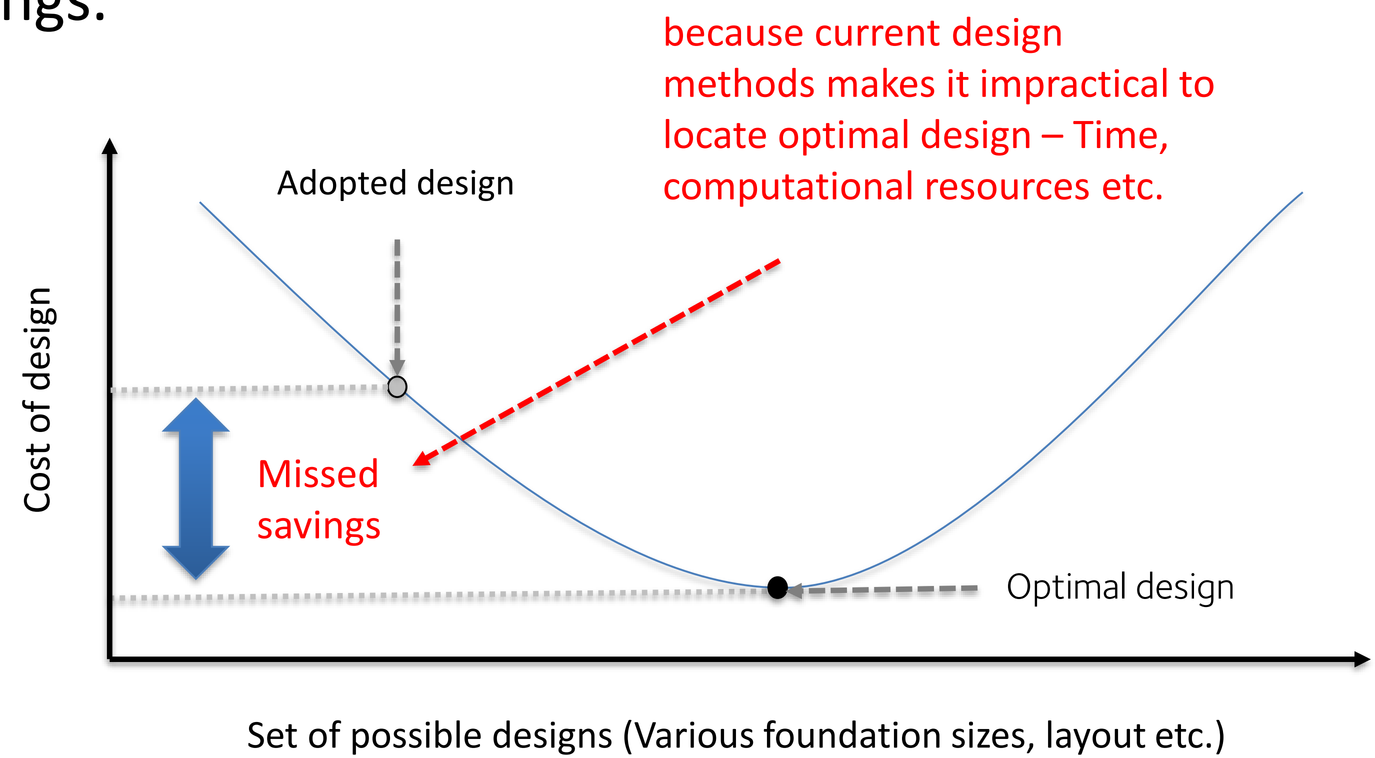
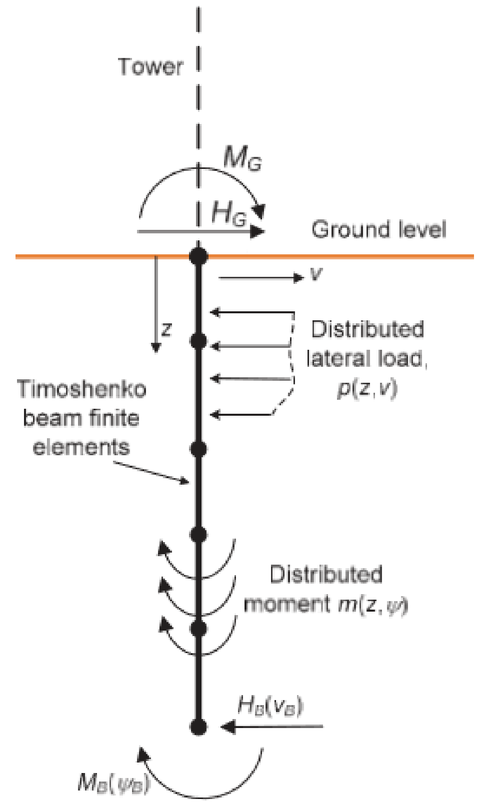
Why is it important?

- Lack of efficient design tool will inhibit increased cost savings.



Proposed Solution

- Winkler model (called oxCaisson)
  - Fast but fairly accurate solution
- Similar to OxPile
  - 2 types of soil reactions – distributed + base
  - Calibrate the soil reactions using 3DFE analyses
- Different from OxPile
  - OxPile: Lateral and moment loads
  - oxCaisson: 6DoF loading
    (i.e. axial, lateral, moment, torsional loads)

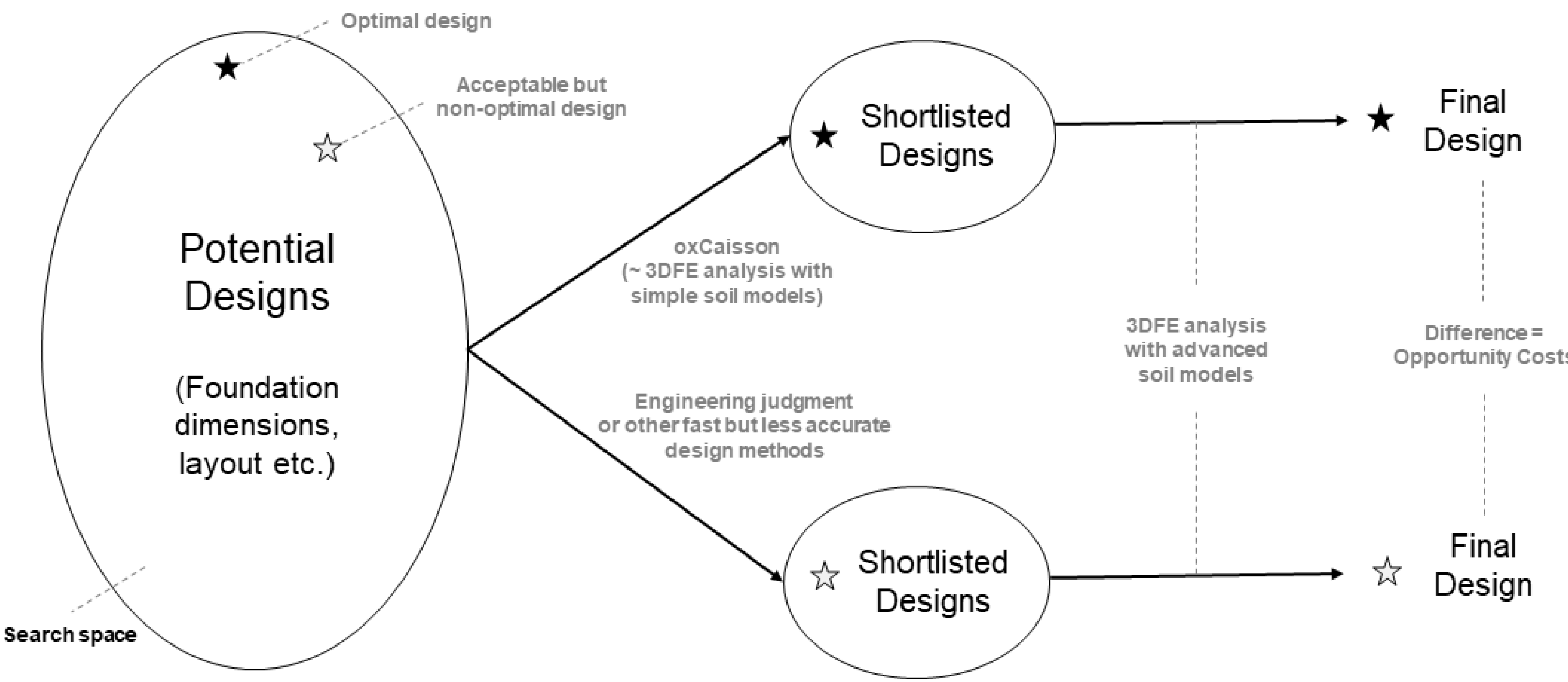


OxPile (Byrne et al. 2017)

Benefits of oxCaisson

- Easy to couple with structural analysis programs
- Easy to deploy (Winkler model software already used for pile designs)
- Easy to understand (similar to pile design methods)
- Offers '3DFE equivalent' accuracy at much higher efficiency. (reduce design cycle times by enabling rapid analysis of alternative designs)
- Works for multi-layered soil profiles
  (problematic for macro-element models)

Use Case of oxCaisson



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Requirements of oxCaisson

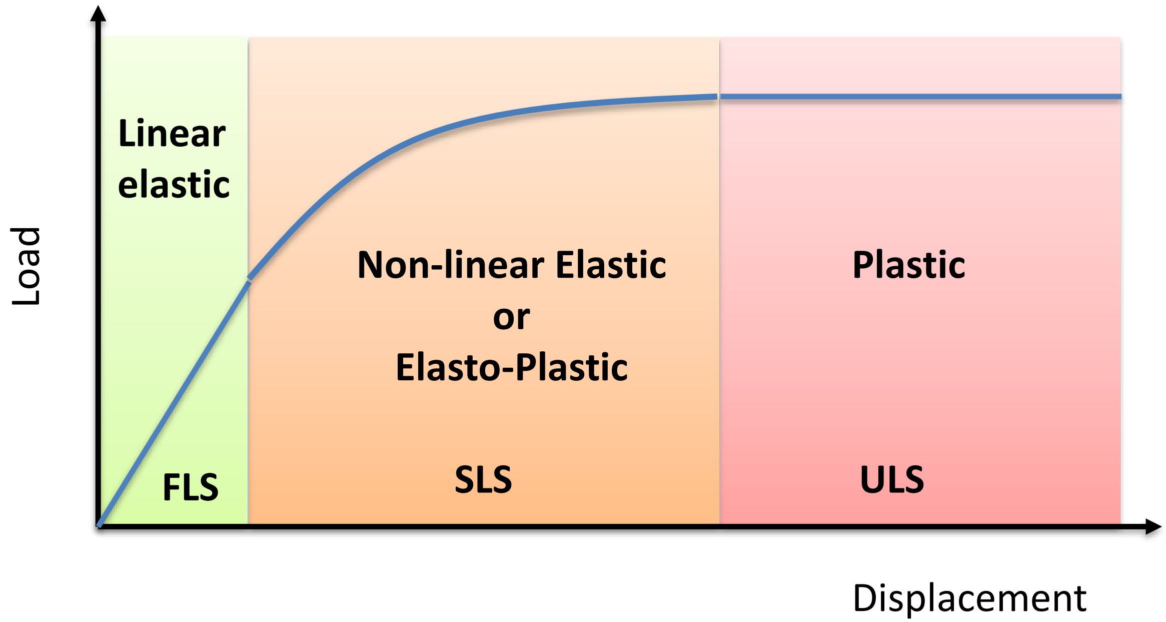
- Design method need to be able to account for FLS, SLS, ULS

Soil
- Stability
  - Ultimate failure (excessive deformation) — **ULS**
- Deformation
  - Under small working loads — **FLS**
  - Under higher working loads — **SLS**

1. **Predict maximum loads that can be applied before failure occurred (ULS)**
2. **Predict soil displacement under small working loads (FLS)**
3. **Predict soil displacements under higher working loads (SLS)**

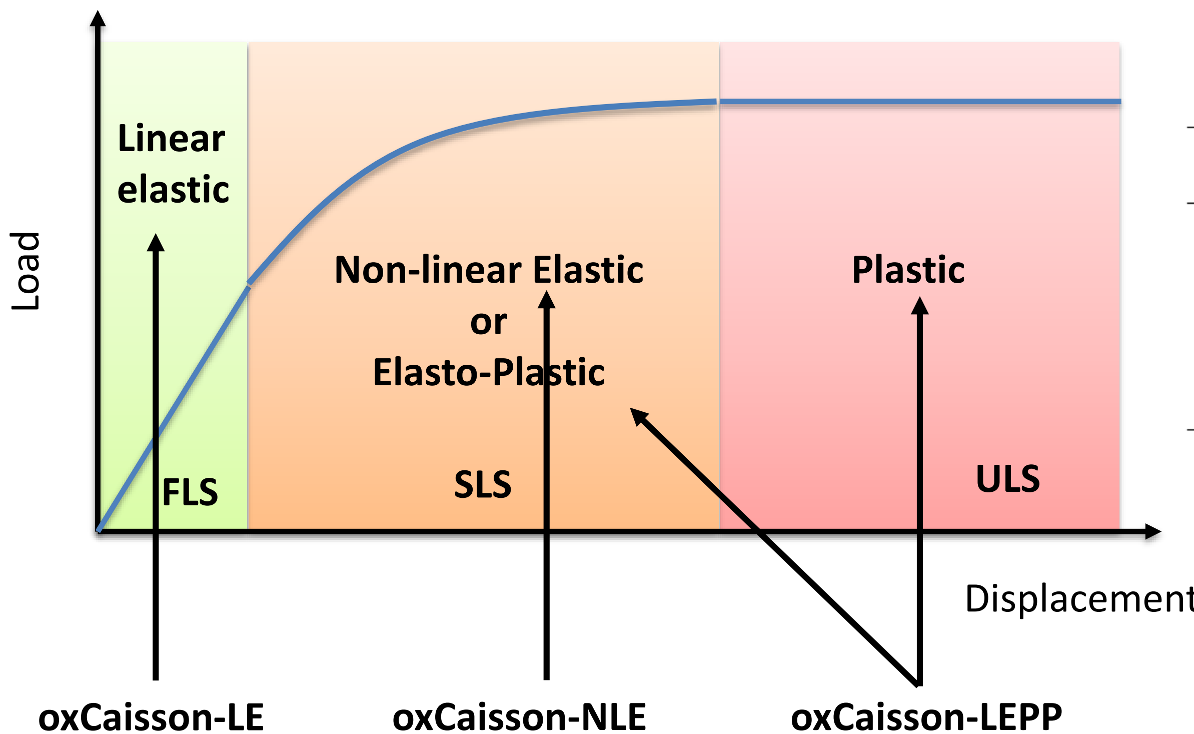
oxCaisson

- Idealise caisson behaviour in each limit state



oxCaisson

- oxCaisson is a family of design methods



	FLS	SLS	ULS
oxCaisson-LE	✓	-	-
oxCaisson-NLE	✓	✓	-
oxCaisson-LEPP	✓	✓	✓

oxCaisson-LE (Linear Elastic)

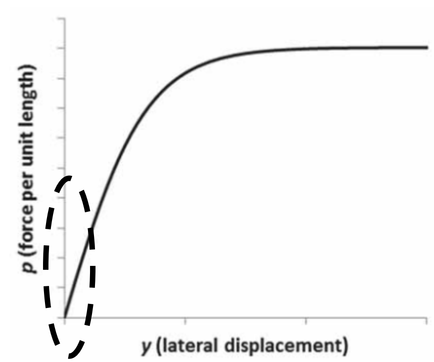
- Soil reactions are linear functions of displacements
- Corresponds to the initial stiffness of non-linear Winkler models for pile designs

oxCaisson-LE

API p-y

p = k y

where y can be any of 6DoF



$$P = A \times p_u \times \tanh\left[\frac{k \times H}{A \times p_u} \times y\right]$$

$$\frac{\partial p}{\partial y} = k$$

$$\frac{\partial p}{\partial y} = kH\ \mathrm{sech}^2(kHy/Apu)$$

$$\frac{\partial p}{\partial y} = kH \quad at \quad y = 0$$

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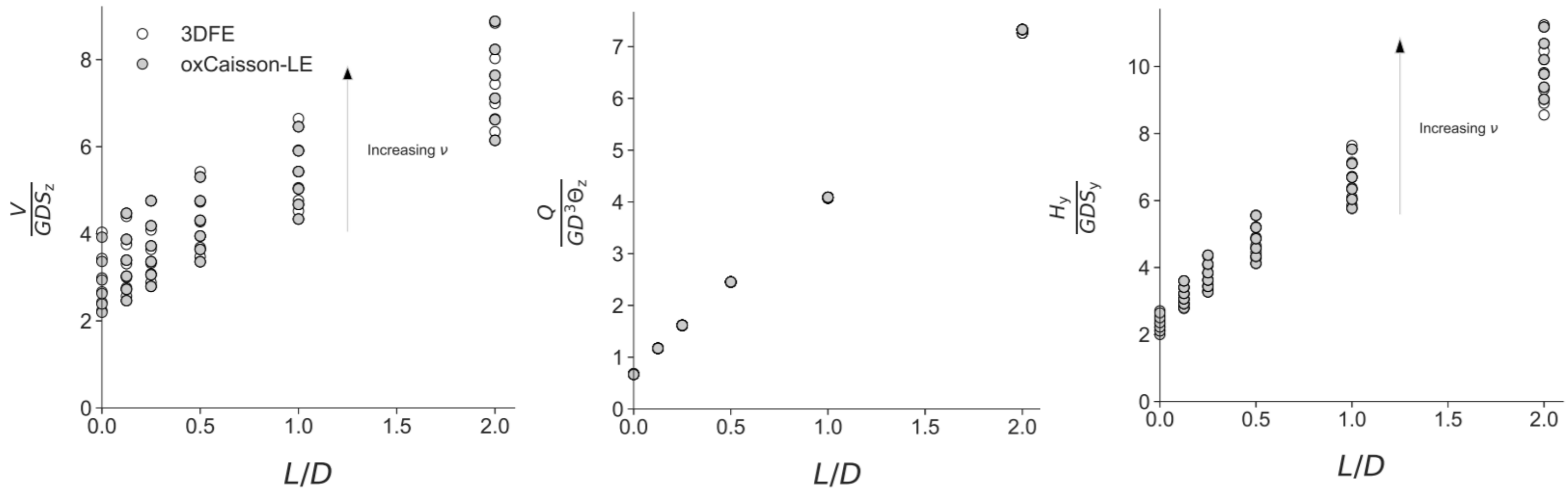
oxCaisson-LE (Linear Elastic)

- Approximates 3DFE analyses using linear elastic soil
- Very efficient
  - Time for 144 analyses: 3DFE **(36 hours)** vs oxCaisson-LE **(1 sec)**



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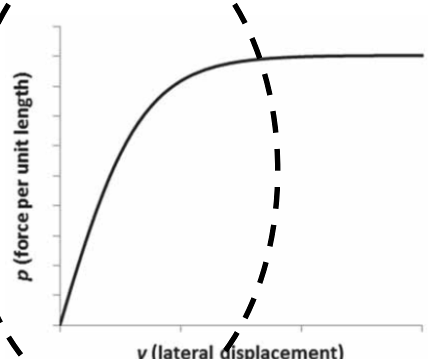
oxCaisson-NLE (Non-linear Elastic)

- Soil reactions are non-linear functions of displacements
- Corresponds to the non-linear Winkler models for pile designs (but no ultimate response)

oxCaisson-NLE

p = f(y)

where f is a non-linear function



API p-y (Sand)

$$P = A \times p_u \times \tanh\left[\frac{k \times H}{A \times p_u} \times y\right]$$

What is f(y)?

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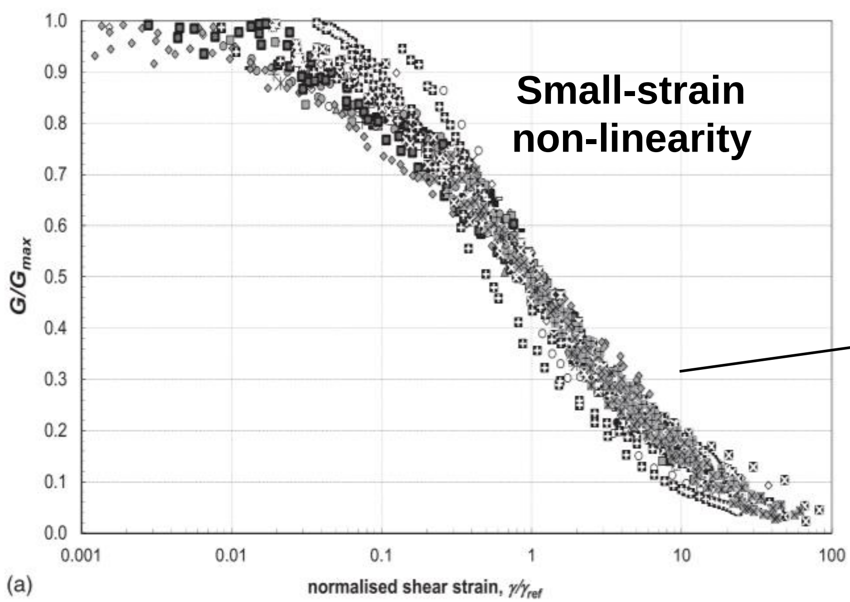
oxCaisson-NLE (Non-linear Elastic)

- Small-strain, non-linear behavior of soil commonly described in terms of secant stiffness degradation curve
- f(y) calibrated against 3DFE analyses using a custom, small-strain, non-linear elastic soil model



Vardanega, P. J. & Bolton, M. D. (2013), 'Stiffness of Clays and Silts : Normalizing Shear Modulus and Shear Strain',

$$\frac{G}{G_0} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_{\mathrm{ref}}}\right)^{\alpha}}$$

Common formulation to describe small strain behaviour of sand, clay, silt etc.

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oxCaisson-NLE (Non-linear Elastic)

- f(y) requires the inputs: G_0, γ_{ref}, α

$$\frac{G}{G_0} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_{ref}}\right)^{\alpha}}$$

- These are obtained from the soil sample stress-strain results (from triaxial test or simple shear test)

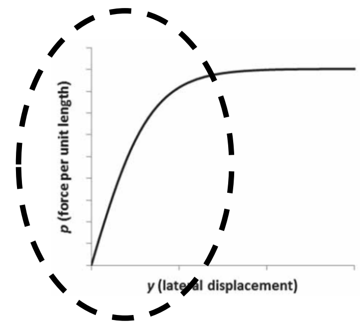
- No extra work required since most people already have this info (as the above equation is widely adopted)

oxCaisson-NLE (Non-linear Elastic)

- Site-specific soil reactions that better correspond to soil sample behaviour

- Focuses on the small-strain, non-linear behaviour

- Unified formulation for sand & clay (Convenient)



oxCaisson-NLE (Sand & Clay)

p = f(G_0, γ_{ref}, α, y)

API p-y (Sand)

$$P = A \times p_u \times \tanh\left[\frac{k \times H}{A \times p_u} \times y\right]$$

API p-y (Soft Clay)

p/p_u	y/y_c
0.00	0.0
0.50	1.0
0.72	3.0
1.00	8.0
1.00	∞

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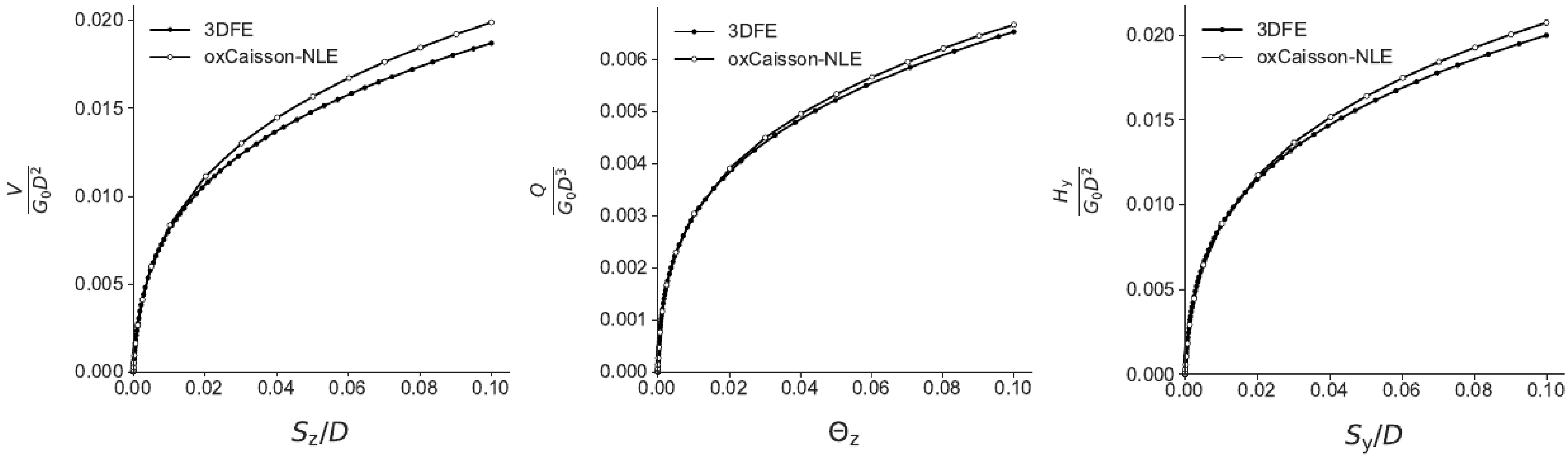
oxCaisson-NLE (Non-linear Elastic)

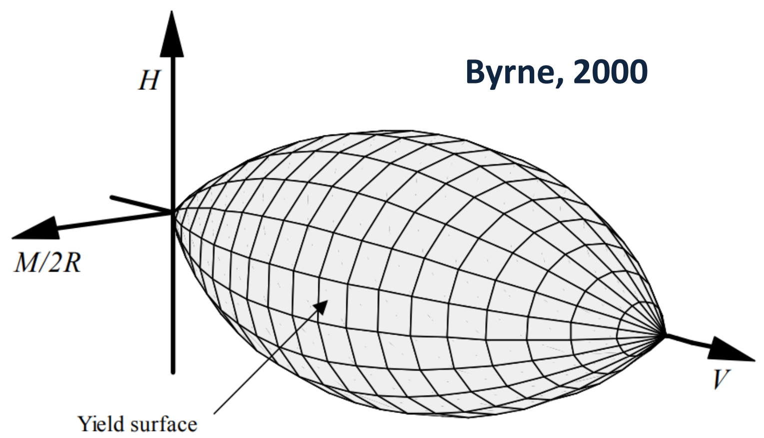
- Approximates 3DFE analyses using small-strain, non-linear elastic soil
- Very efficient
  - Time for 4 analyses: 3DFE **(5 hours)** vs oxCaisson-NLE **(2 secs)**



oxCaisson-LEPP (Linear Elastic, Perfectly Plastic)

- Elasto-plastic Winkler model

- Recall failure envelopes for shallow foundations
  Capture interaction between combined loading at failure



- ‘Local failure envelopes’ for the Winkler soil reactions

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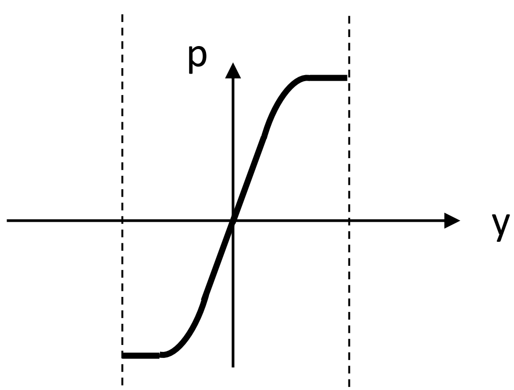
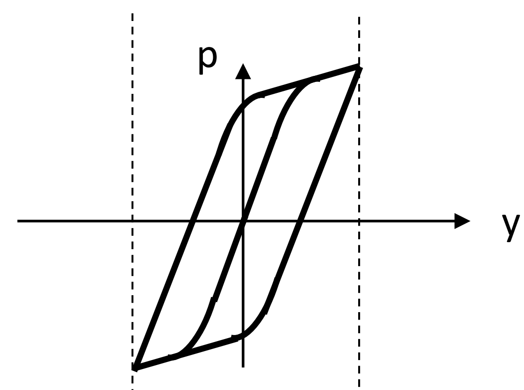
oxCaisson-LEPP (Linear Elastic, Perfectly Plastic)

- Calibrated against 3DFE analyses using von Mises soil (Clay)
- Overcome shortcomings of non-linear elastic Winkler models
  - Captures interaction effects of combined loading at failure.
    (Most Winkler models assume no interaction between vertical or lateral loading i.e. p-y & t-z soil reactions behave independently)
  - Simulate permanent displacement
  - Can be extended to support cyclic loading

API p-y

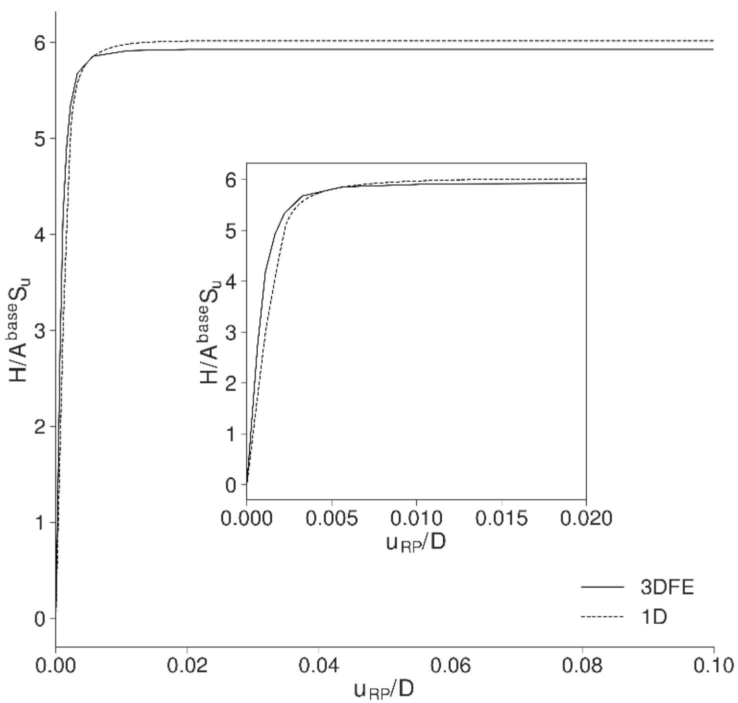


True cyclic response

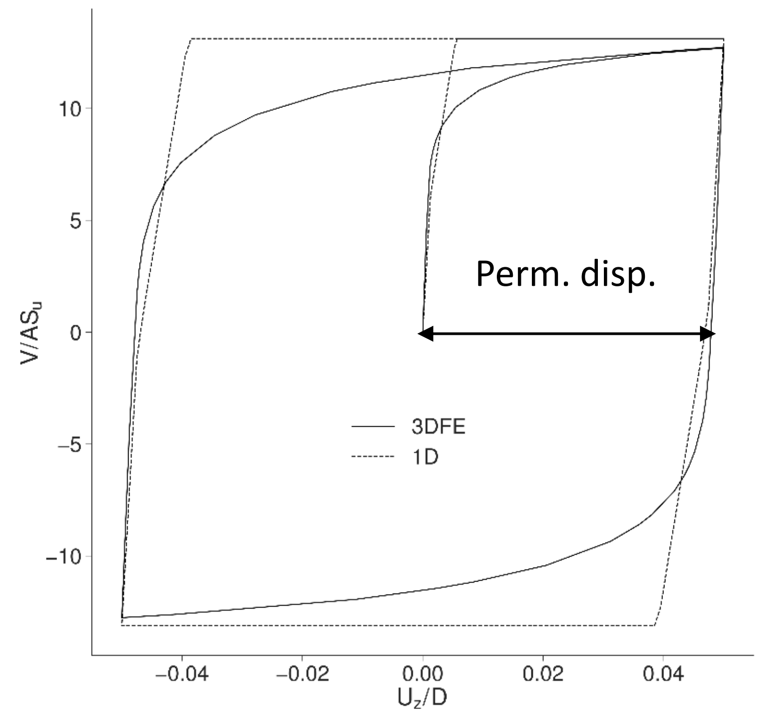


oxCaisson-LEPP (Linear Elastic, Perfectly Plastic)

- Elasto-plastic load displacement behaviour for SLS
- Unlike oxCaisson-NLE, oxCaisson-LEPP has ultimate response



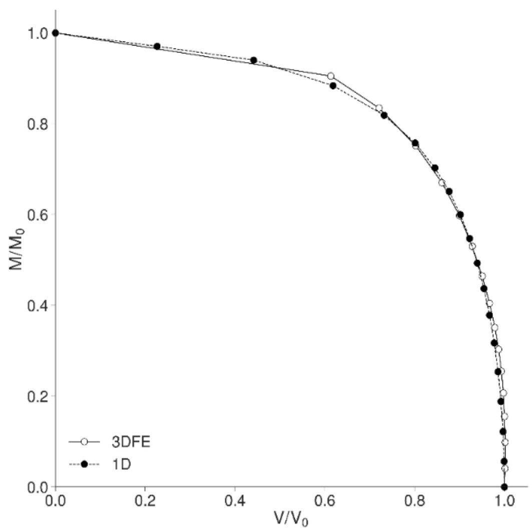
Monotonic Loading

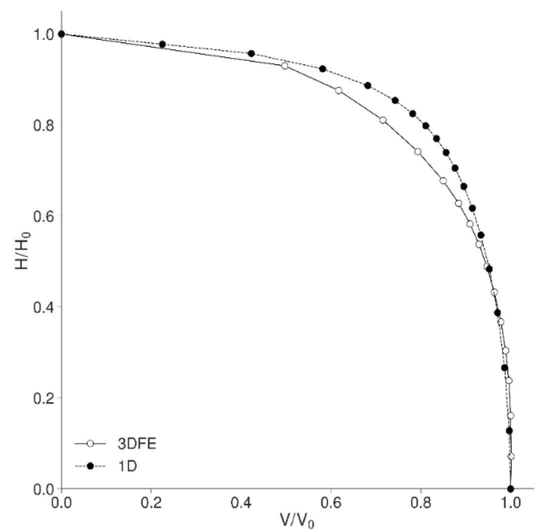


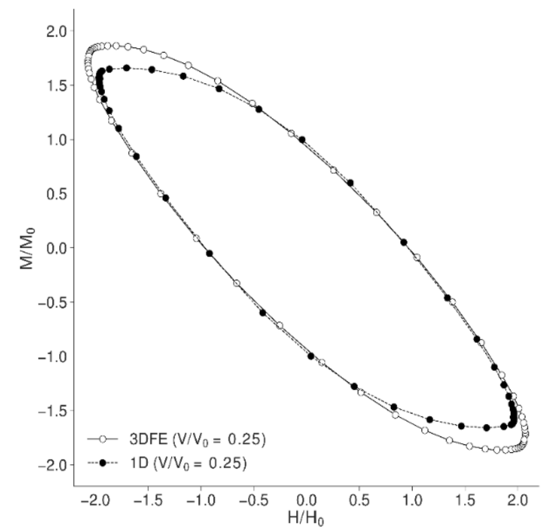
Cyclic Loading

oxCaisson-LEPP (Linear Elastic, Perfectly Plastic)

- Approximates 3DFE analyses using linear elastic, perfectly plastic soil with von Mises yield criterion (Undrained Clay)
- Determine global failure envelopes for ULS
- High Efficiency
  - Time for 3 envelopes: 3DFE **(4 hours)** vs oxCaisson-LEPP **(16 mins)**







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Case Study

- Find the **optimal dimensions** for a mono-suction caisson foundation (i.e. single caisson)
- Optimal dimensions = lowest cost design (i.e. minimum caisson steel volume) that satisfy the limit states conditions
- Assume $t_{skirt}/D = 0.005$ and $t_{lid}/D = 0.05$
- Unknowns to solve for: **D** and **L**
- Consider only lateral and moment loads

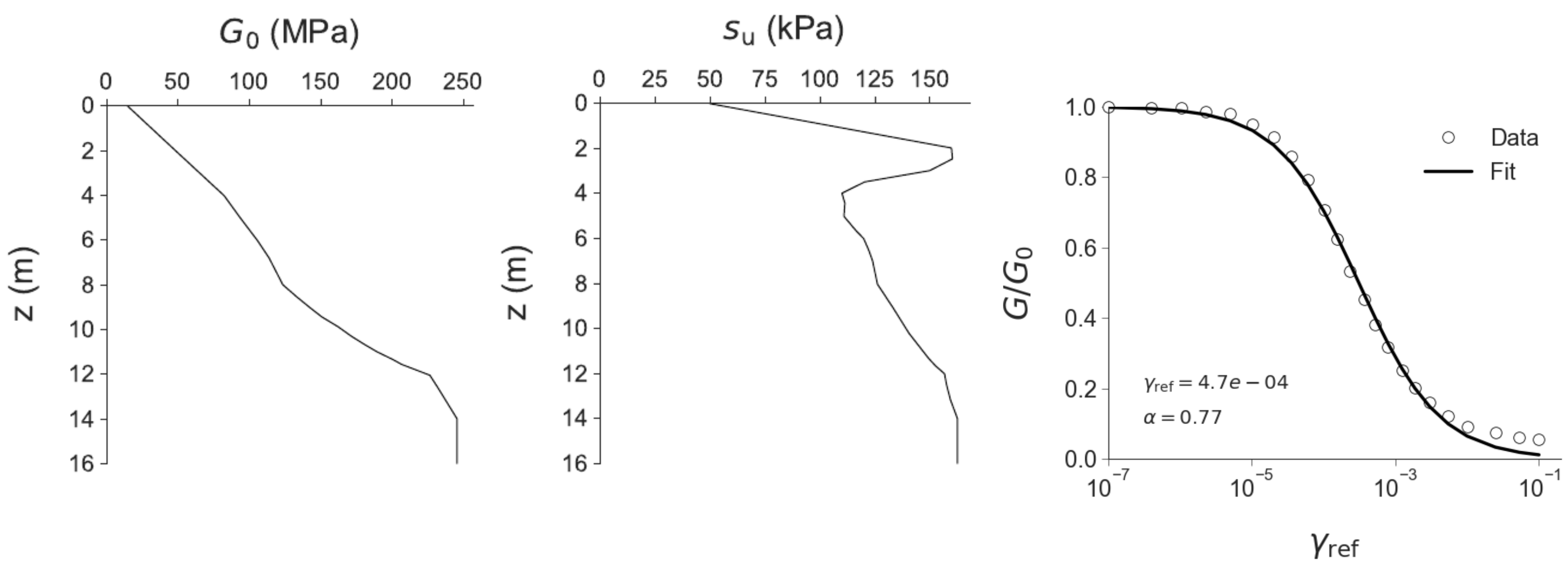
Table 10.1: SLS and ULS design loads for the London Array wind farm (Doherty & Lehane 2017).

	SLS	ULS
Max lateral load at ground level	5.33 MN	7.20 MN
Max bending moment at ground level	219 MNm	295.65 MNm

Doherty, J. P. & Lehane, B. M. (2017), An Automated Approach for Designing Monopiles Subjected to Lateral Loads, *in* 'Proceedings of 36th International Conference on Ocean, Offshore Arctic Engineering OMAE 2-17', number June, Trondheim, Norway.

Case Study (Soil Properties)

- Assume Cowden Clay (PISA project) profile

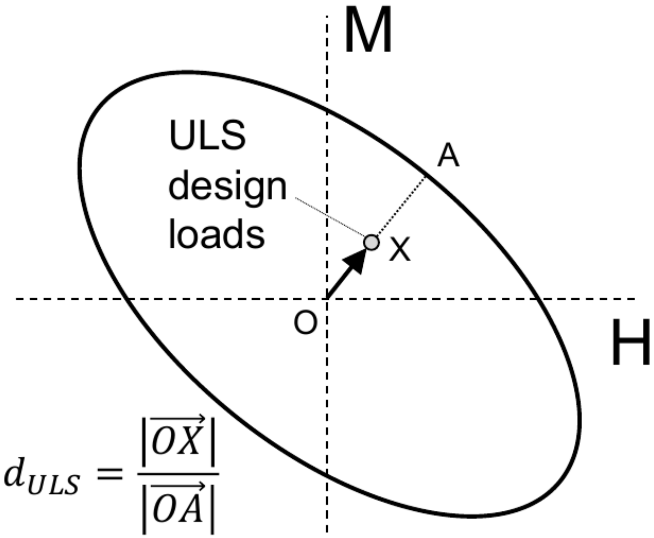


Byrne, B. W., McAdam, R., Burd, H. J., Houlsby, G. T., Martin, C. M., Beuckelaers, W. J. A. P., Zdravkovic, L., Taborda, D. M. G., Potts, D. M., Jardine, R. J., Ushev, E., Liu, T., Abadias, D., Gavin, K., Igoe, D., Doherty, P., Gretlund, J. S., Andrade, M. P., Wood, A. M., Schroeder, F. C., Turner, S. & Plummer, M. A. L. (2017), PISA: New Design Methods for Offshore Wind Turbine Monopiles, *in* 'Proceedings of the 8th International Conference for Offshore Site Investigation and Geotechnics', London.

Case Study (SLS and ULS conditions)

- For simplicity, consider only SLS and ULS here
- **SLS condition**: Rotation at ground level under SLS design loads < 0.5 degrees
- **ULS condition**: ULS design loads must not exceed capacity (structural capacity not considered here, caisson assumed to be linear elastic)

  i.e. ULS condition: $d_{uls} \leq 1$



$$d_{ULS} = \frac{|\overrightarrow{OX}|}{|\overrightarrow{OA}|}$$

- Design methods for assessments:
  oxCaisson-NLE for SLS
  oxCaisson-LEPP for ULS

Case Study (oxCaisson example code)

all vectors

z (m)	G (Pa)	su (Pa)
0	14925373	49850.3
1.990338	48056506	159880.2
1.995013	48134328	159884.6
2.47343	56226302	160329.3
2.995169	65051036	150000
3.497585	73548928	120359.3
4	82046820	110029.9
4.024587	82462687	110104.5
4.444444	87230106	111377.2
5.010424	93656716	110938.8
5.024155	93819929	110928.1
5.700483	1.02E+08	116766.5
6.009662	1.06E+08	119910.2
6.01496	1.06E+08	119933.9
6.512077	1.11E+08	122155.7
6.796066	1.14E+08	123211.7
6.995169	1.15E+08	123952.1
8.004363	1.24E+08	126123.8
8.038647	1.24E+08	126197.6

```
% define frame/structural properties (all scalars)
frame = struct('L', 10, 'D', 10, 'E', 200e9, 'v', 0.25, 't', 0.05);
% define soil properties (all are vectors of same size)
soil = struct('G', G, 'z', z, 'v', v, 'su', su, 'ss_ref', ss_ref, 'ss_a' = ss_a);

% select oxCaisson-NLE
o = oxCaisson(frame, soil);
o = o.set_soil('nle'); % o.set_soil('lepp') for oxCaisson-LEPP
o.nel = 20; % optional. by default, no. of finite elements is 20.
o = o.init();

% prescribe SLS design loads
o = o.prescribe_load('Hy', 5.33e6);
o = o.prescribe_load('Mx', 219e6);
o = o.solve();

% get rotation at ground level for the final step
urx = o.results.global.URx(end);
```

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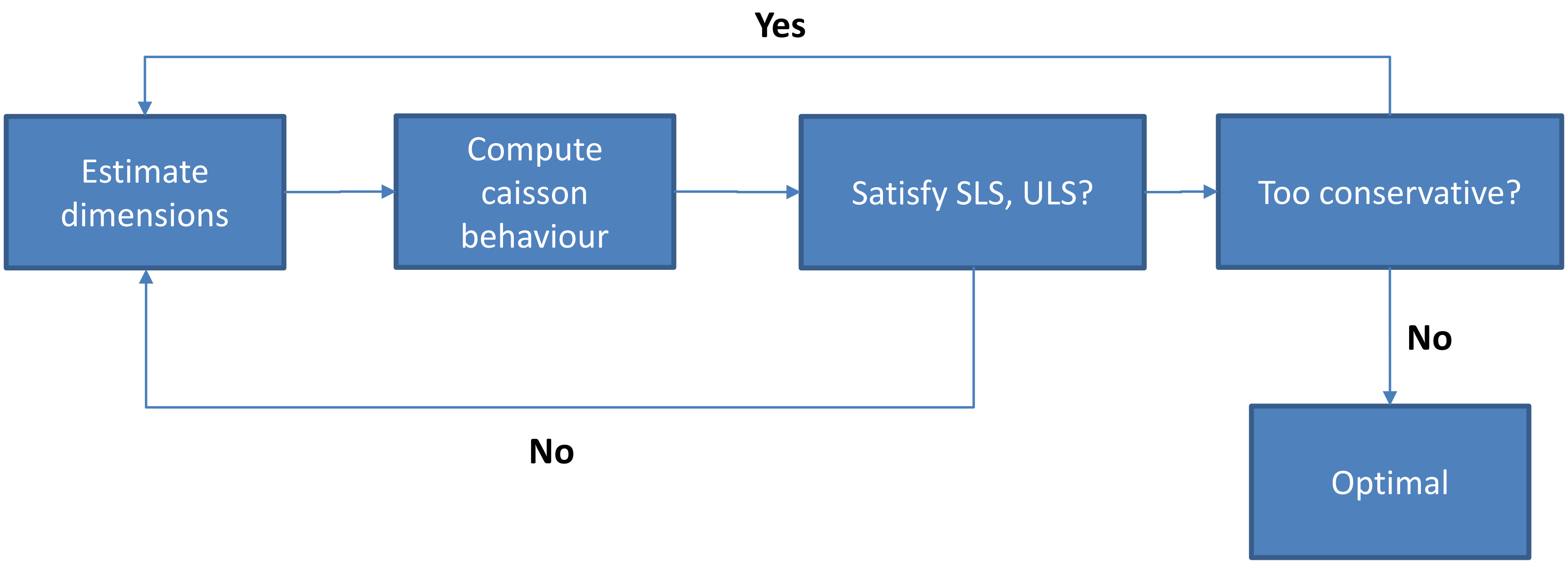
Case Study (Traditional Approach)

- Iterative
- Manual
- Labour Intensive



Case Study (Optimisation Problem)

- Manual iterative process unnecessary
- Design problem can be cast as an optimisation problem
- Decision variables: D and L/D

Caisson Steel Volume

$$\underset{D,\, L/D}{\text{minimize}} \quad \pi D^3 \left(0.004975 \frac{L}{D} + 0.0125\right)$$

$$\text{subject to} \quad \mathrm{d}_{\mathrm{ULS}} \leq 1 \quad (\mathrm{ULS}),$$

$$\theta_{\mathrm{M}} \leq 0.5^\circ \quad (\mathrm{SLS})$$

- Two ways to solve it:
  Graphical (manual) or use a solver (automated)

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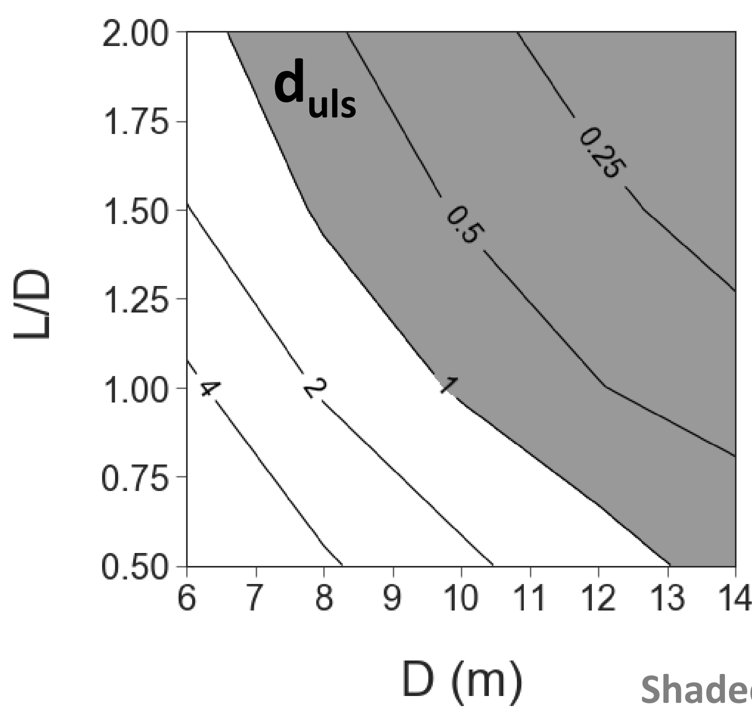
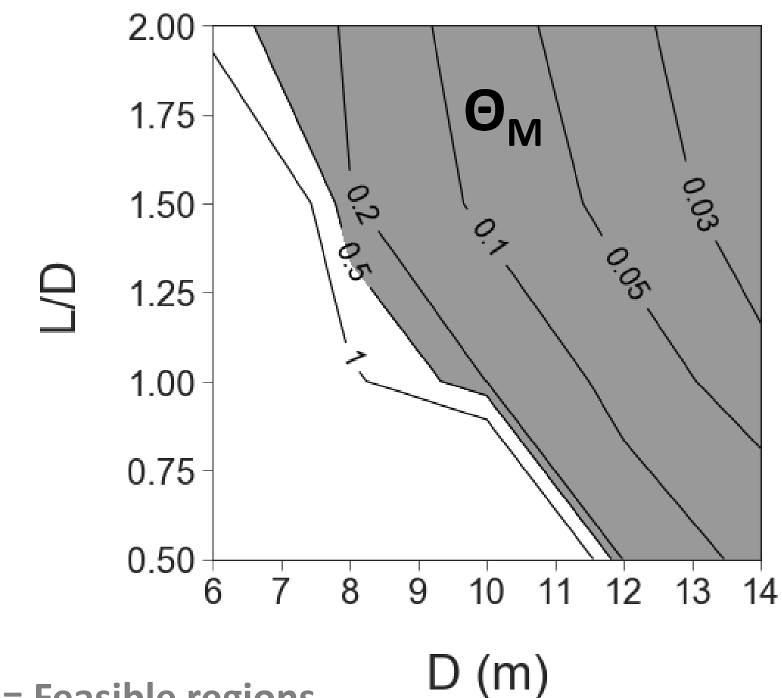
Case Study (Graphical)

- Compute d_{uls} (oxCaisson-LEPP) and Θ_M (oxCaisson-NLE) at a few points: D = 6, 8, 10, 12, 14 and L/D = 0.5, 1, 1.5, 2
- Generate contour plots using interpolation (Matlab 'contour')





Shaded = Feasible regions

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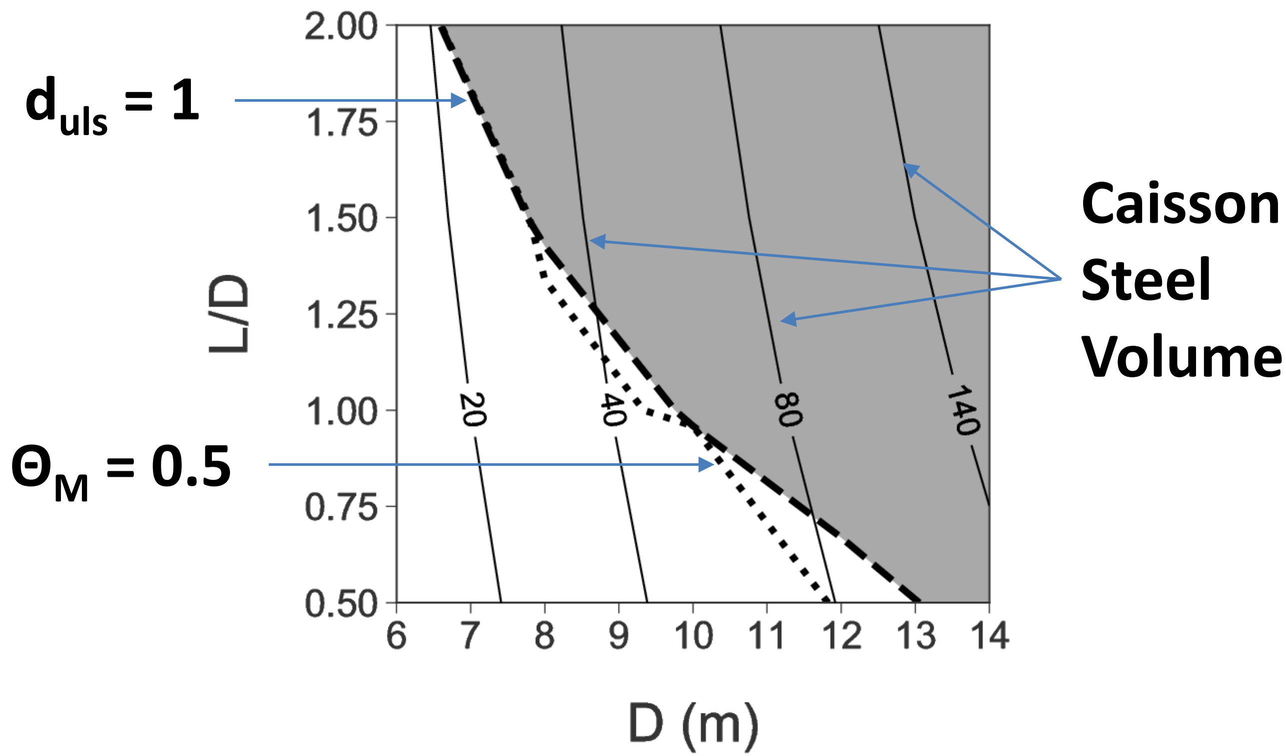
Case Study (Graphical)

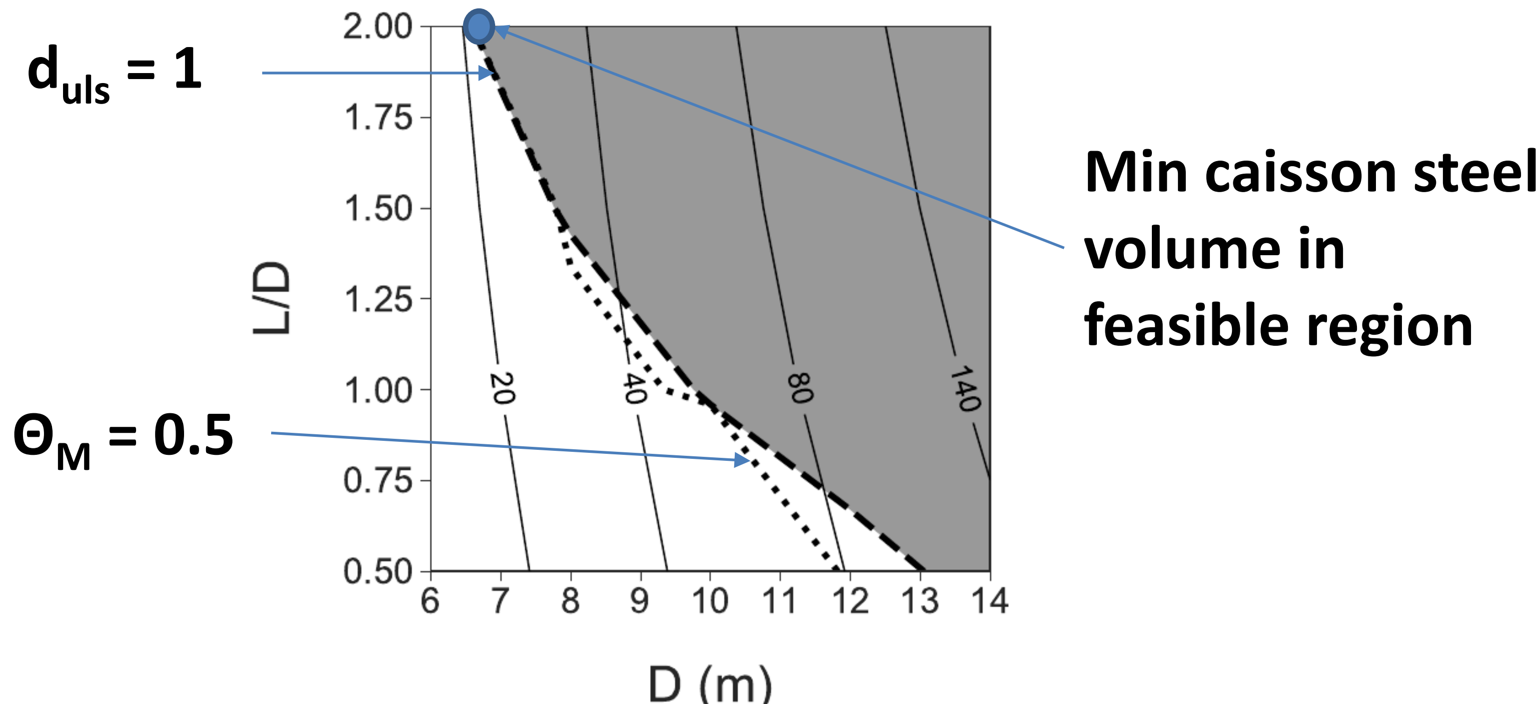
- Generate contour plots of caisson volume (use Matlab ‘fcontour’)
- Overlay the constraints contours for SLS and ULS
- ULS governs

Shaded region = Feasible region under both SLS and ULS conditions



Case Study (Graphical)

- Optimal dimensions: **D = 6.7m, L/D = 2 (Volume = 21.2m^3)**
- This is just an estimate, as contours are interpolated
- More computed points required for more accurate answers



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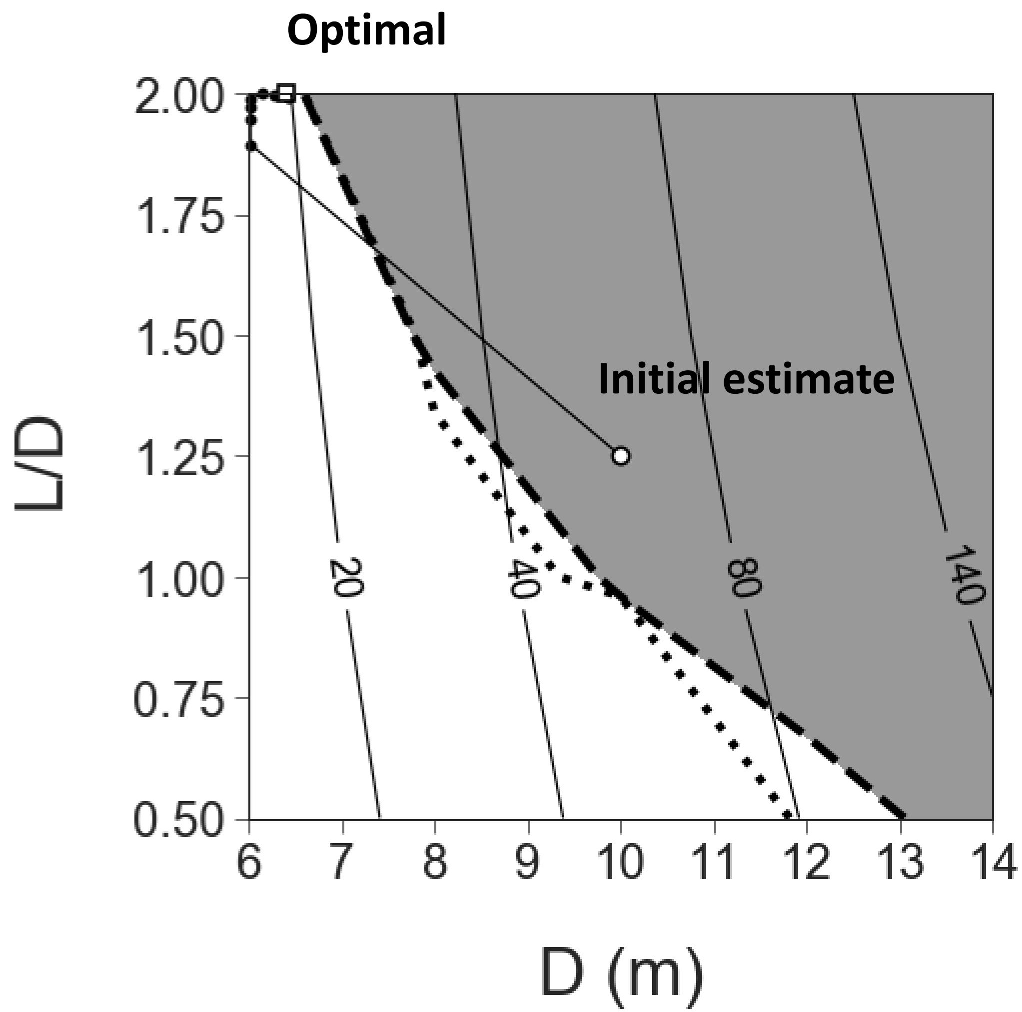
Case Study (Solver)

- Graphical approach is an improvement over the iterative approach, but is still manual
- Solve the optimisation problem automatically using a solver (Matlab ‘fmincon’)
- Just give the parameter search space:
  D = 6 to 14 m, L/D = 0.5 to 2
- Just give an initial estimate (not sensitive):
  D = 10m
  L/D = 1.25

Case Study (Solver)

- Optimal dimensions **(D = 6.4 m, L/D = 2)** obtained after 11 trials

Step	Volume	D	LD
1	58.81	10.00	1.25
2	15.03	6.02	1.89
3	15.19	6.02	1.95
4	15.30	6.02	1.97
5	15.39	6.03	1.99
6	16.30	6.14	2.00
7	17.39	6.27	2.00
8	18.63	6.42	1.99
9	18.66	6.42	1.99
10	18.46	6.40	2.00
11	18.45	6.40	2.00



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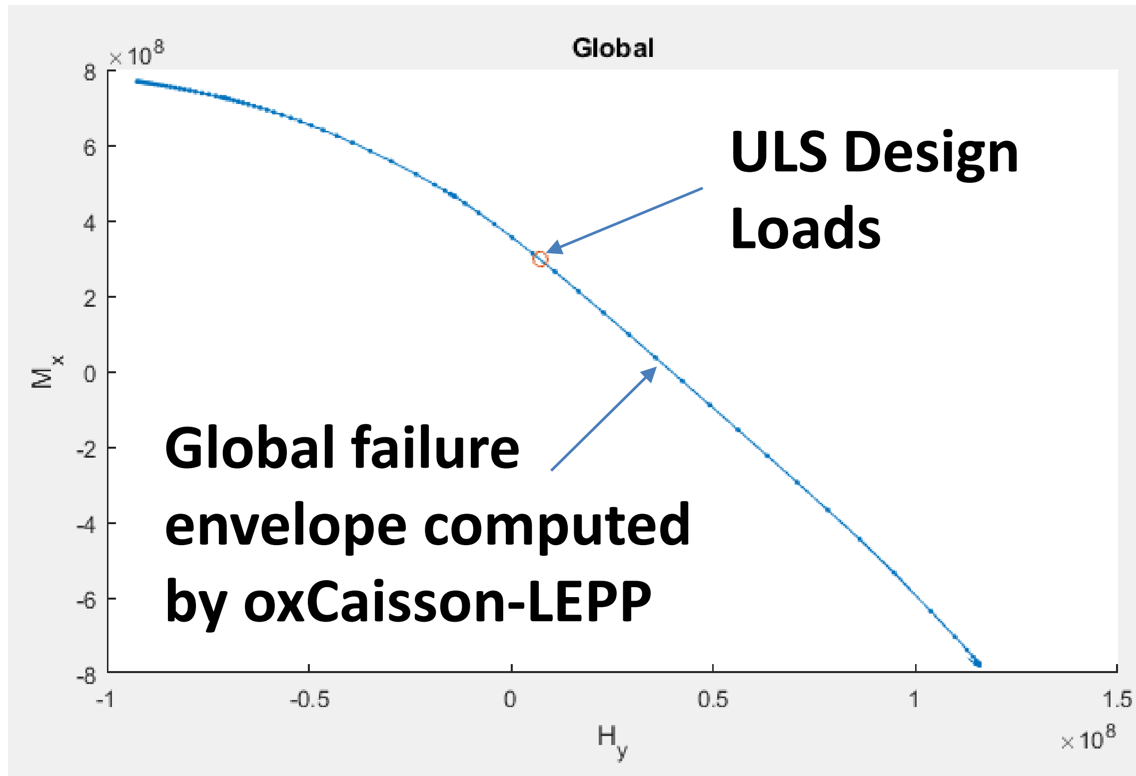
Case Study (Solver)

- Optimal dimensions
  (D = 6.4 m, L/D = 2)
- d_{uls} = 1 **(ULS OK)**
- Θ_M = 0.45 degrees (< 0.5 degrees) **(SLS OK)**



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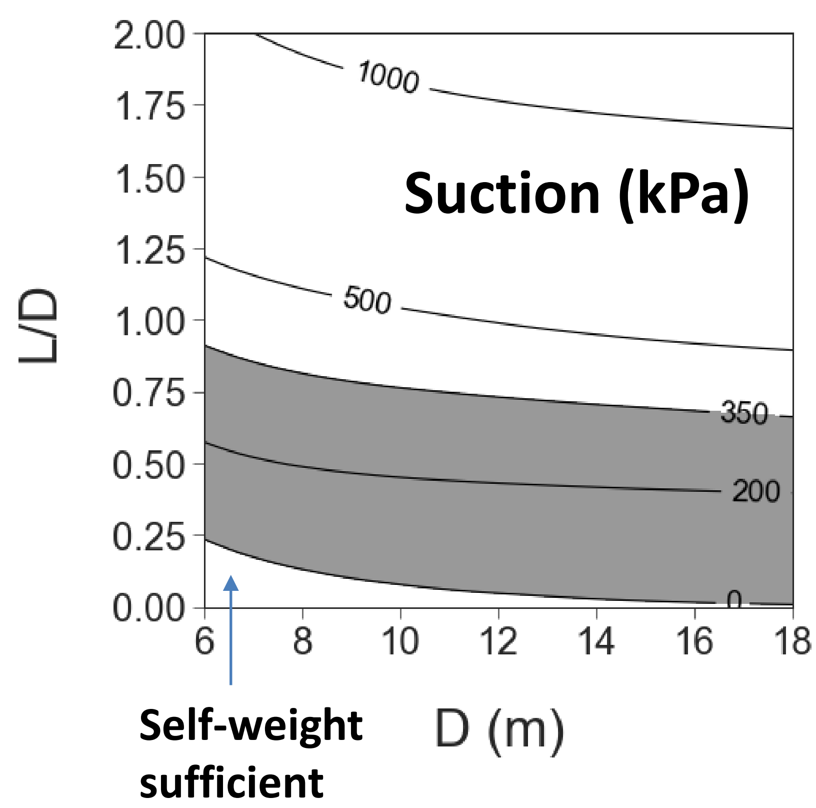
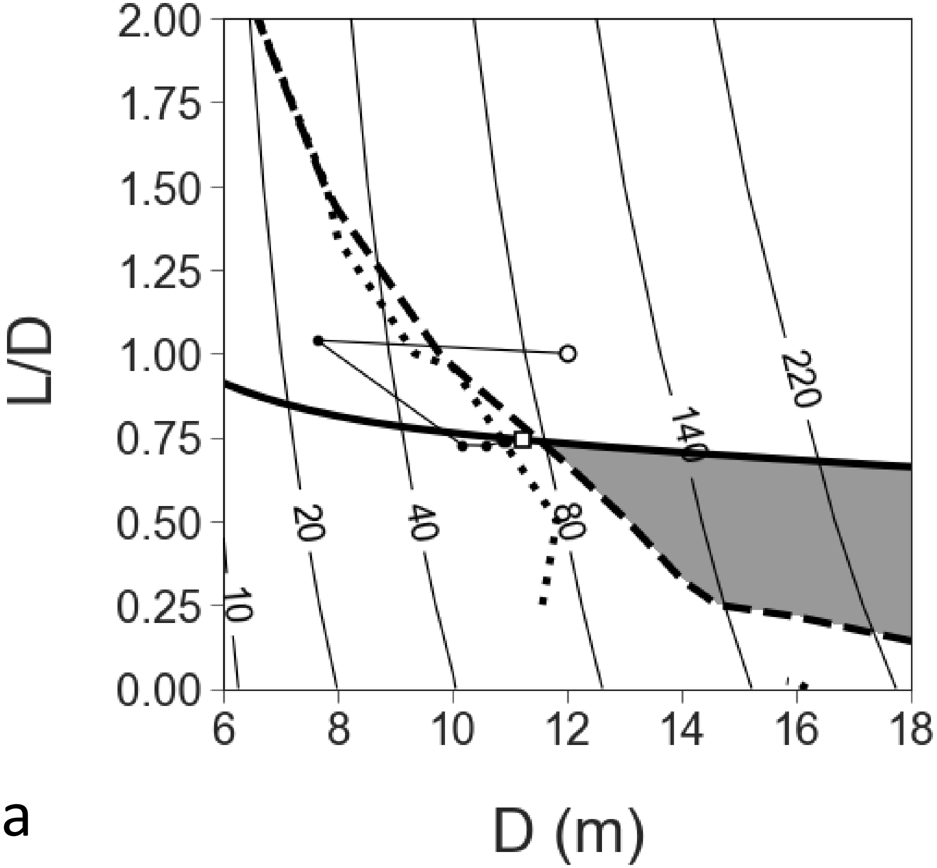
Case Study (Installation Constraints)

- D = 6.4 m, L/D = 2 is actually not feasible for installation
- Water depth = 25 m
  Max allow. suction limited by cavitation = 350 kPa
- Assuming total vertical load of 3 MN:
  required suction = 962 kPa
  (> 350 kPa)



Case Study (Installation Constraints)

- Optimal dimensions
  (D = 11.2 m, L/D = 0.74)
  Caisson Steel Volume:
  71.5 m³



- d_{uls} = 0.9996 **(< 1: ULS OK)**

- Θ_M = 0.22 degrees
  (< 0.5 degrees: SLS OK)

- Suction Pressure: 349.93 kPa
  (< 350 kPa: Installation OK)

Case Study

- Pros of Graphical approach
  - Good for visualising the feasible regions
- Cons of Graphical approach
  - Manual approach

12 mins

- Pros of Solver approach
  - More accurate (Graphical is based on interpolation)
  - Automated approach
- Cons of Graphical approach
  - Cannot visualise the feasible regions

13 mins

Case Study

- Example case study demonstrates the use of the oxCaisson design methods to quickly optimise one foundation design.
- It can be easily applied to hundreds of foundations for large scale designs
- Imagine doing this with 3DFE analysis!

Conclusion

- Design of offshore wind farm is a large scale design exercise
- Proper optimisation of offshore wind farm designs require fast design methods
- oxCaisson is a family of fast and accurate design methods for suction caisson foundations
- oxCaisson-LE ~ 3DFE analyses in linear elastic soil (FLS)
- oxCaisson-NLE ~ 3DFE analyses in small-strain, non-linear elastic soil (SLS)
- oxCaisson-LEPP ~ 3DFE analyses in linear elastic, perfectly plastic soil with von Mises yield criterion (Undrained clay)
- oxCaisson-LEPP for sand is currently in the works.

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