UCLouvain

02/10/2025

ALERT Doctoral school
"The role of geomechanics in the energy transition"

Cyclic behavior of geomaterials for energy applications
Focus on monopile foundations for offshore wind

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&

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Lecture structure

Context and Definitions	Design of monopiles: Monotonic lateral loading	Design of monopiles: Cyclic lateral loading	Monopile installation with vibratory driving
Application domains	$p - y$ curves	Challenges	Principles
Significant examples	PISA approach	Old practice	Example of research
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		Interactive exercise	
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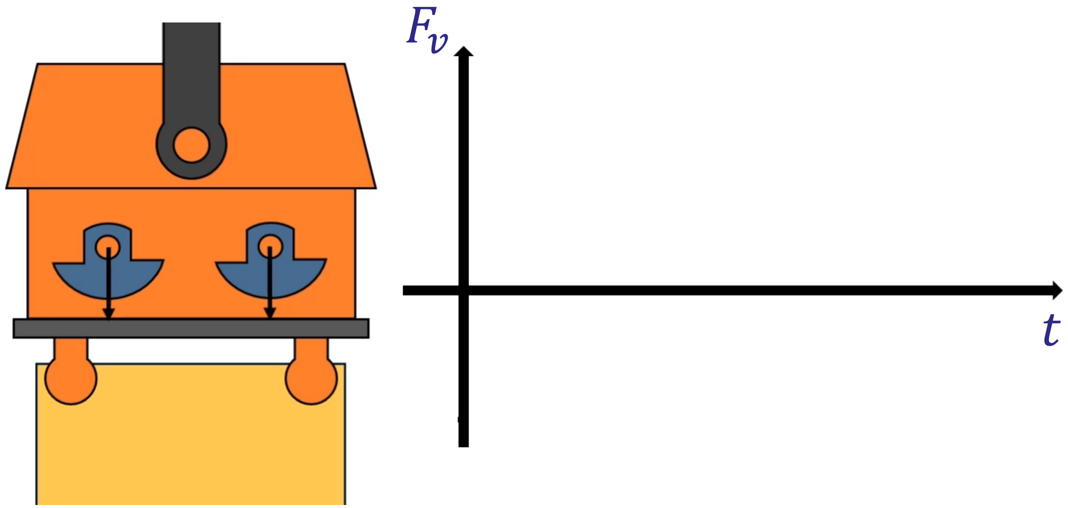
Vibratory driving: a harmonic cyclic driving force

SAGE-SAND project

Vertical harmonic force: $F_v = M_e \omega^2 \sin \omega t$

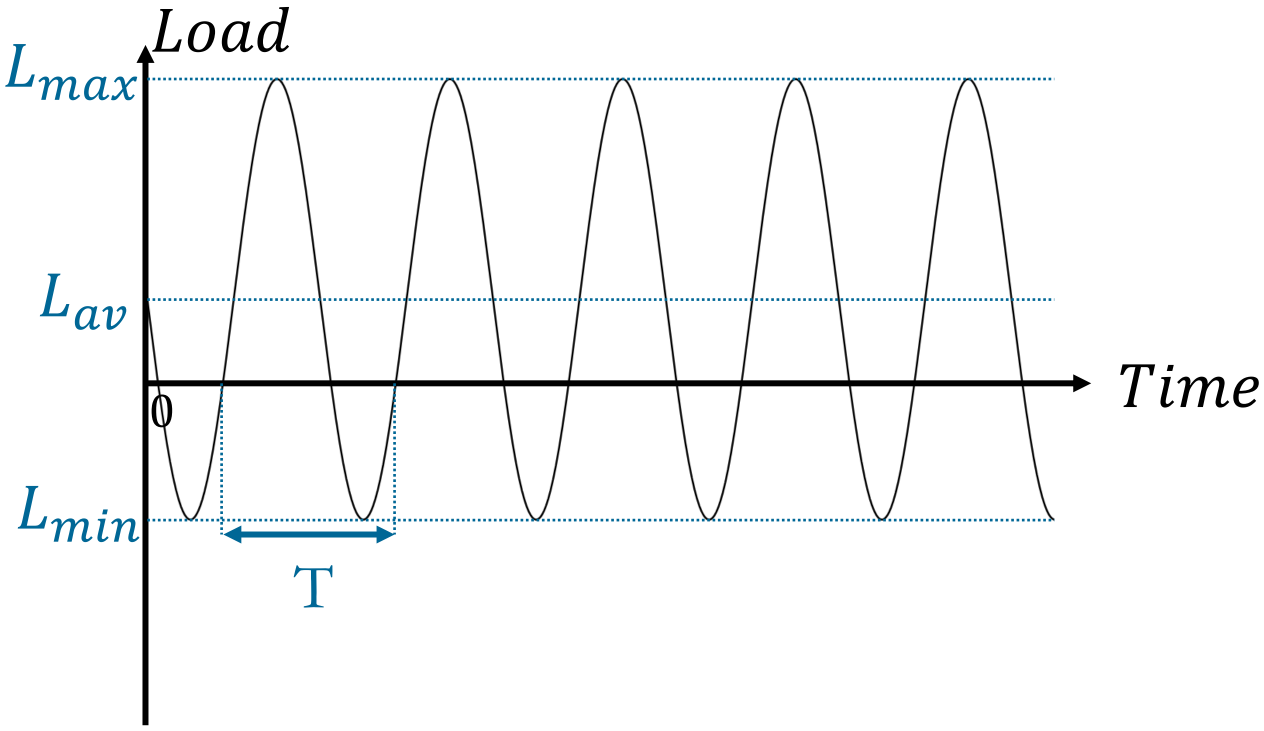
- M_e eccentric moment
- $\omega = 2\pi f$ angular velocity
- f vibration **frequency (10-50 Hz)**

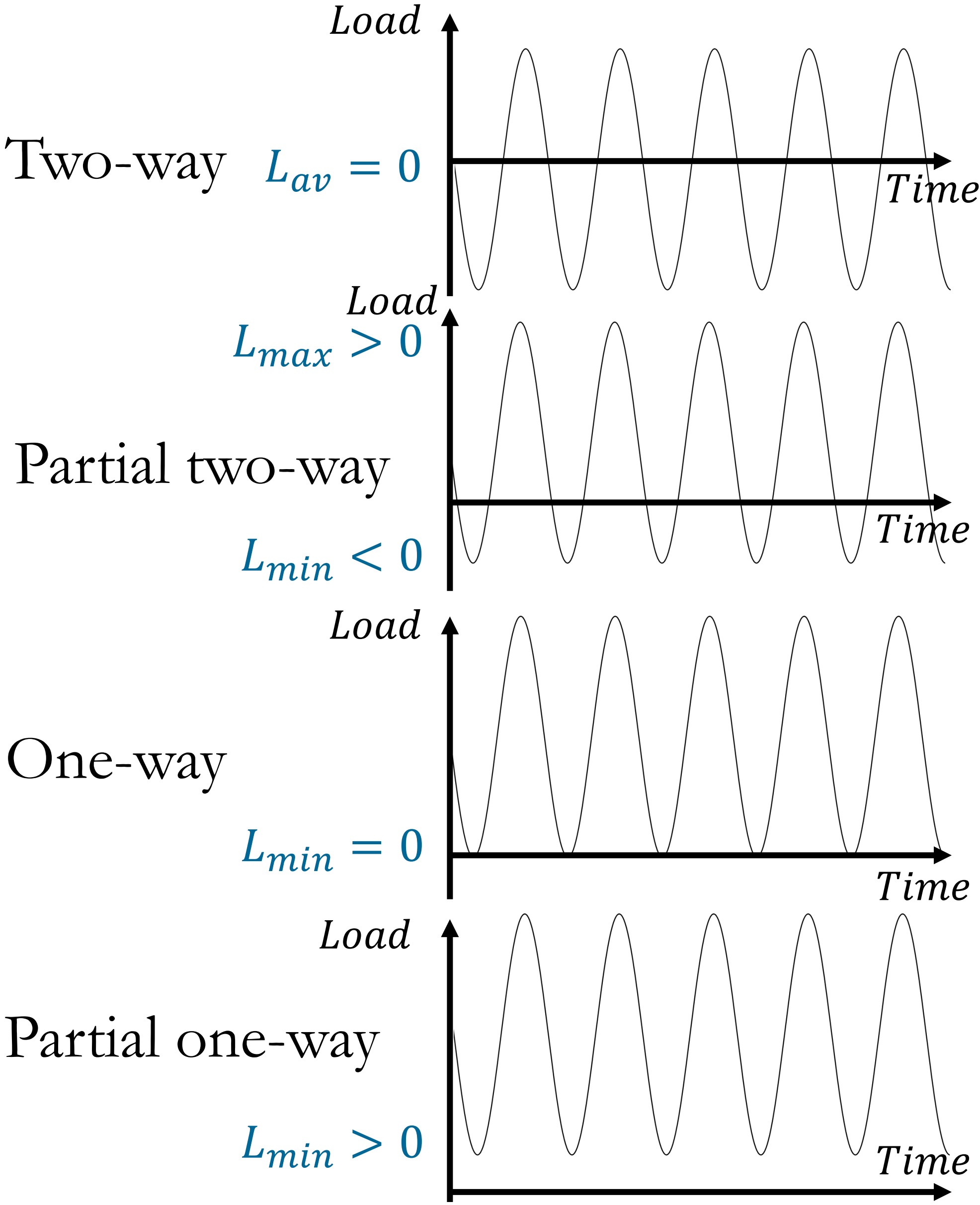
Total duration ~ 30min



Credit: Pauline André

Harmonic cyclic loading definitions





- **Frequency:** $f = \frac{1}{T}$
- **Amplitude:** $A = (L_{max} - L_{min})/2$
- **Mean load:** L_{av}

Load-deformation behaviour during a cycle

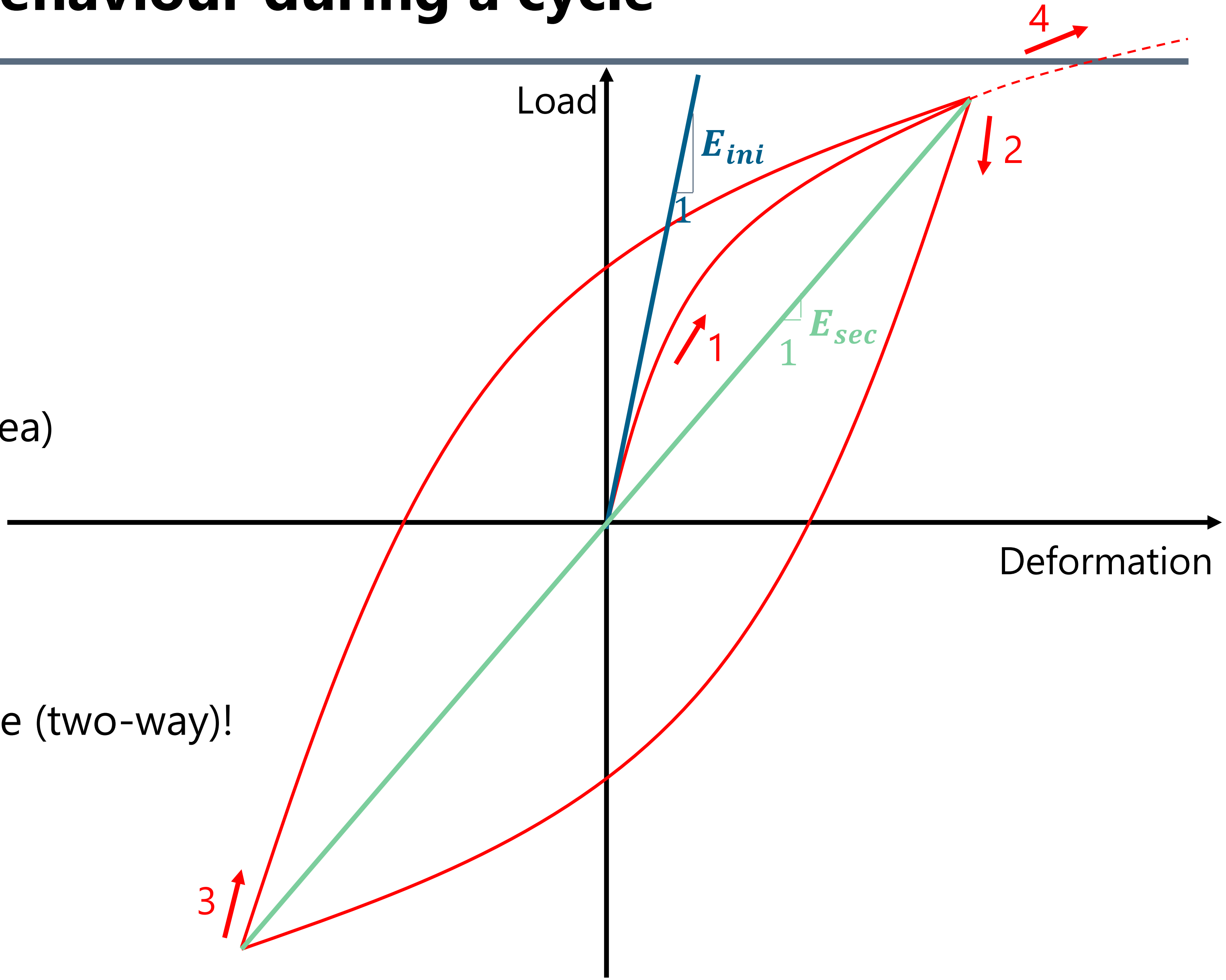
<u>Hysteresis</u> loop:

- Initial stiffness ($\boldsymbol{E_{ini}}$)
- Secant stiffness ($\boldsymbol{E_{sec}}$)
- Energy dissipation (loop area)

$1 + 4 \rightarrow$ backbone curve

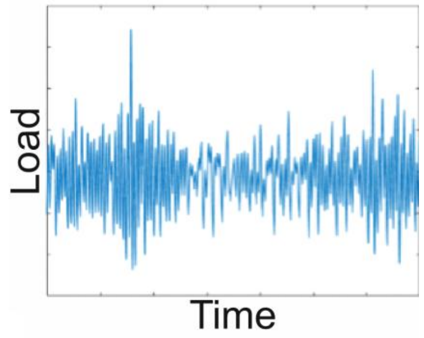
Note that this is a symmetric cycle (two-way)!

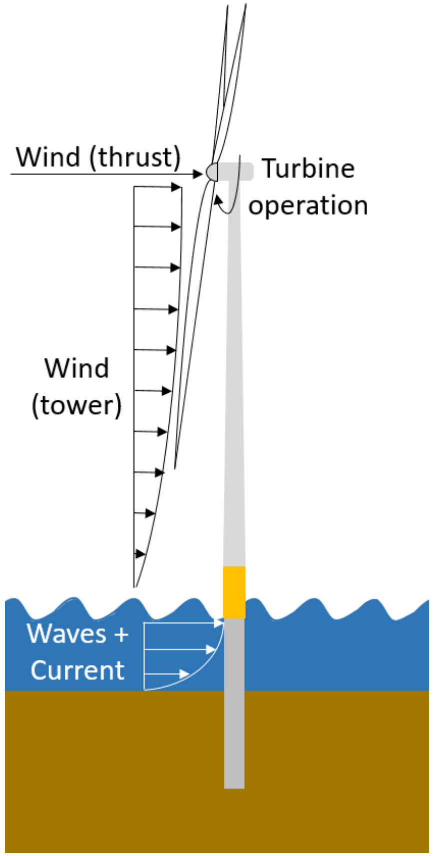
$$L_{max} = -L_{min}$$



Wave & Wind loading: a pseudo-random cyclic loading

Credit: Mark Qiu

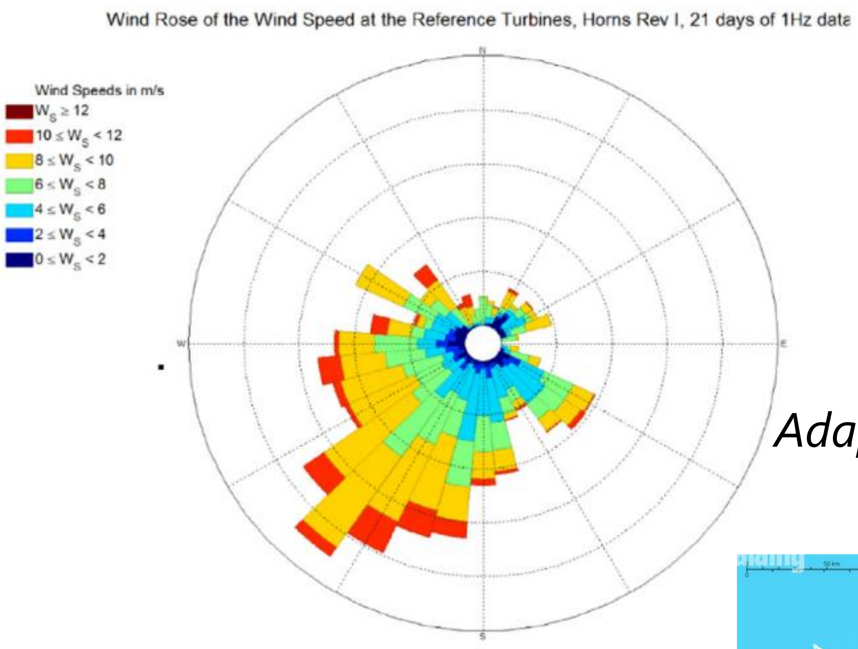


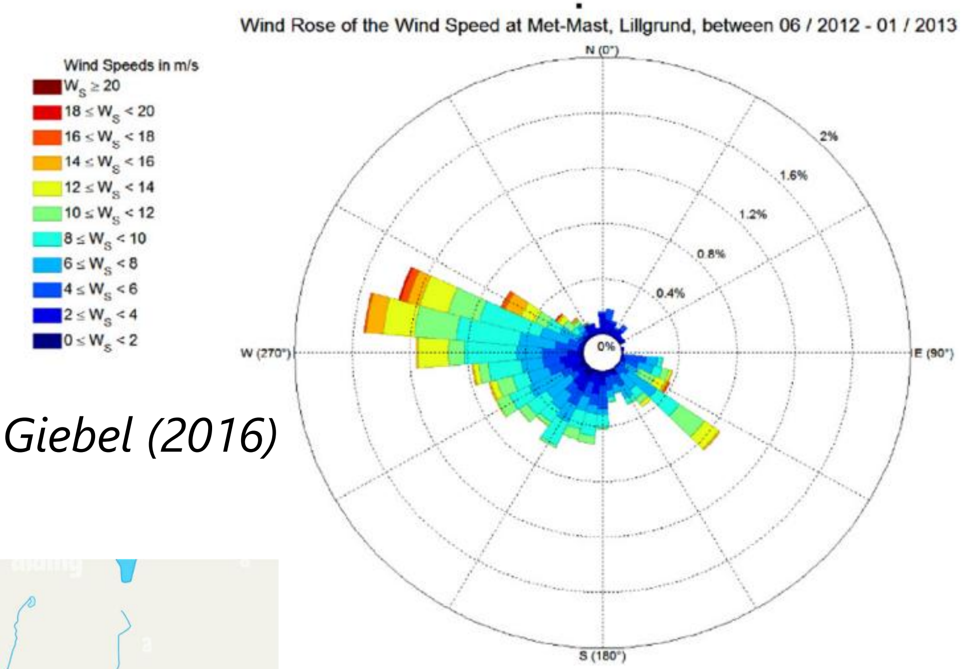


Wind & wave forces vary in:

- **Amplitude**
- **Frequency**
- **Directionality**
- **Repartition** between wave, wind & operational loads.

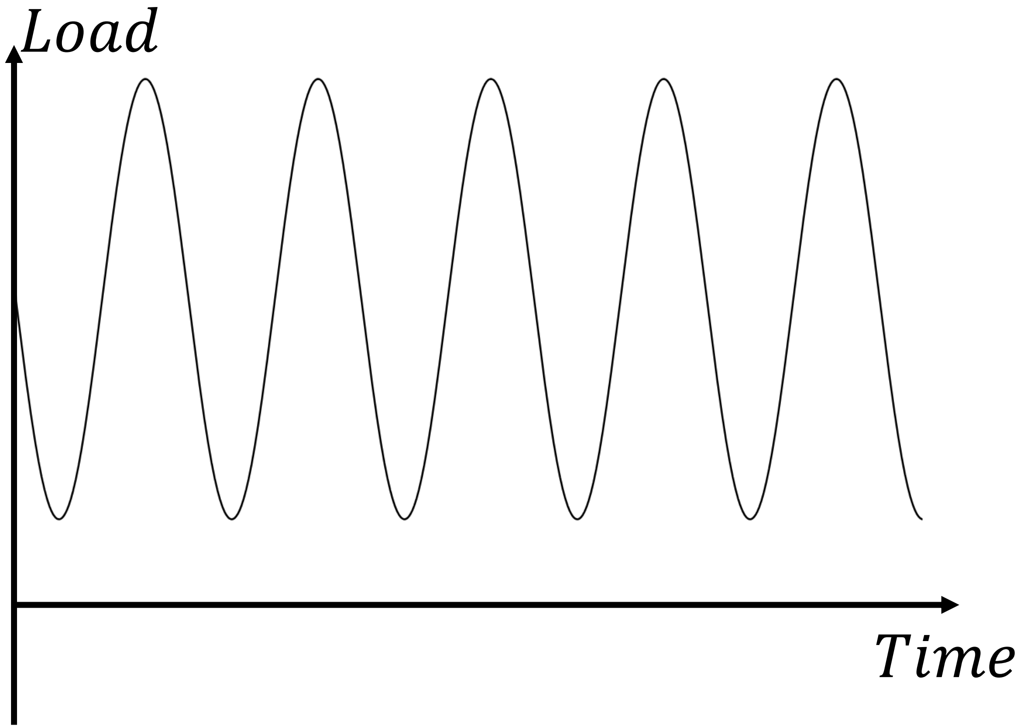
Wind & wave loading: Directionality of loading

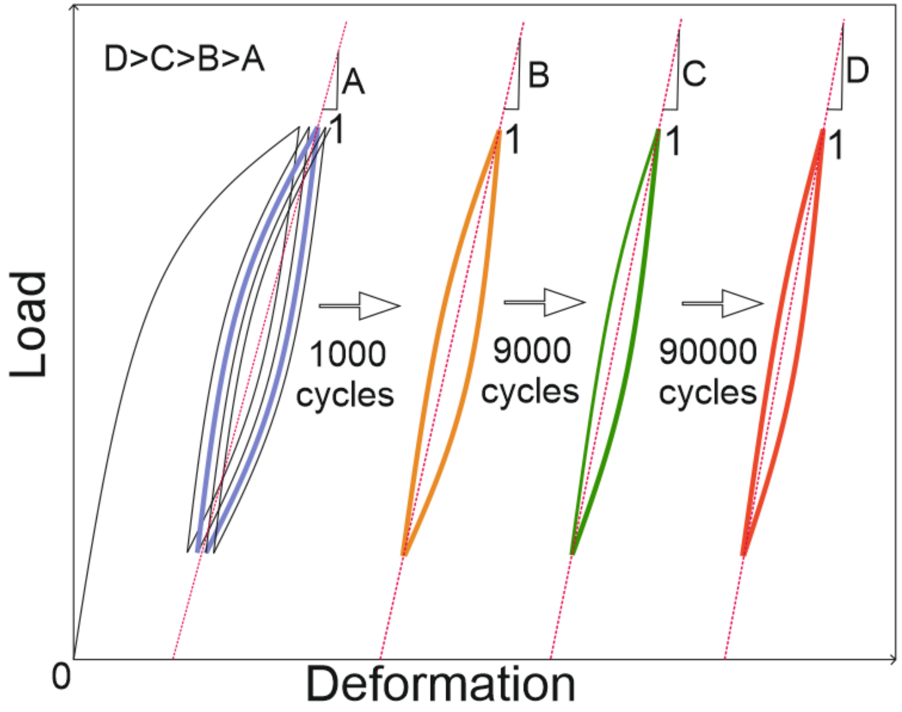




Adapted from Göçmen et Giebel (2016)

Wind & wave loading: <u>load bias</u> → <u>ratcheting</u>





Ratcheting: accumulation of strain/deformation/displacement.

Takes place during asymmetric cycling (one-way, partial one/two-way, non-symmetric pseudo random) ↔ if there is a load bias.

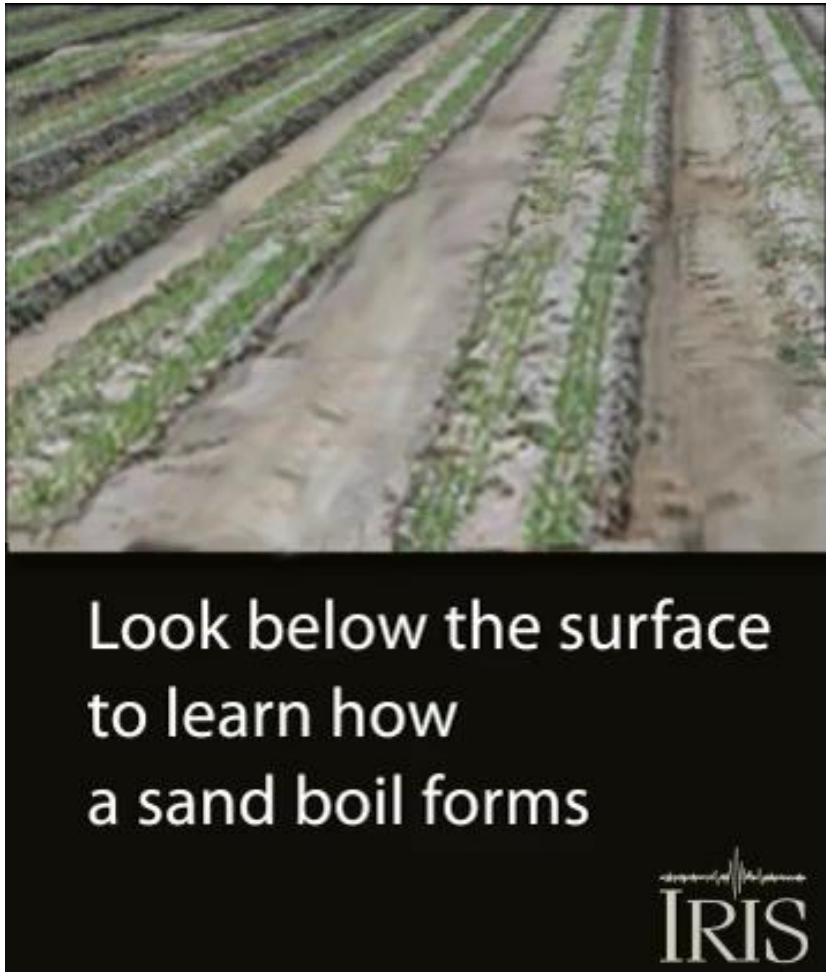
Duration of loading: seismic vs offshore loading

	Seismic loading	Offshore loading
Duration	**10-30s** strong shaking, total<90s	**20-30 years** with ~10M cycles
Frequency content	Broadband, pseudo-random, 0.1-10Hz	Narrow-band, quasi-harmonic with superimposed irregular spectra (storms)
Spatial distribution	Large soil mass, deep	Localised around foundation
Failure mechanisms	Pore pressure build-up, leading sometimes to liquefaction, cyclic softening in clay	Ratcheting, change of dynamic properties, storm loading

Seismic loading: rapid & large amplitude → <u>liquefaction</u>

Niigata Earthquake (1964). Source: *Wikipedia*

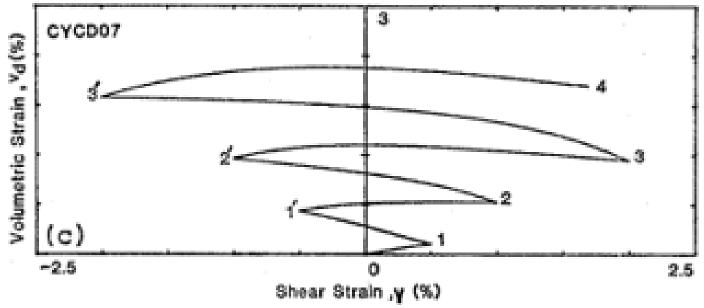
Buildings sunk in the ground.

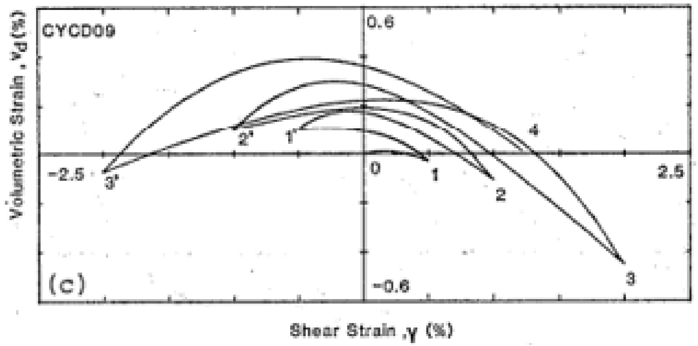


Source: *Youtube @IRISEarthquakeScience*

Context and Definitions

Liquefaction

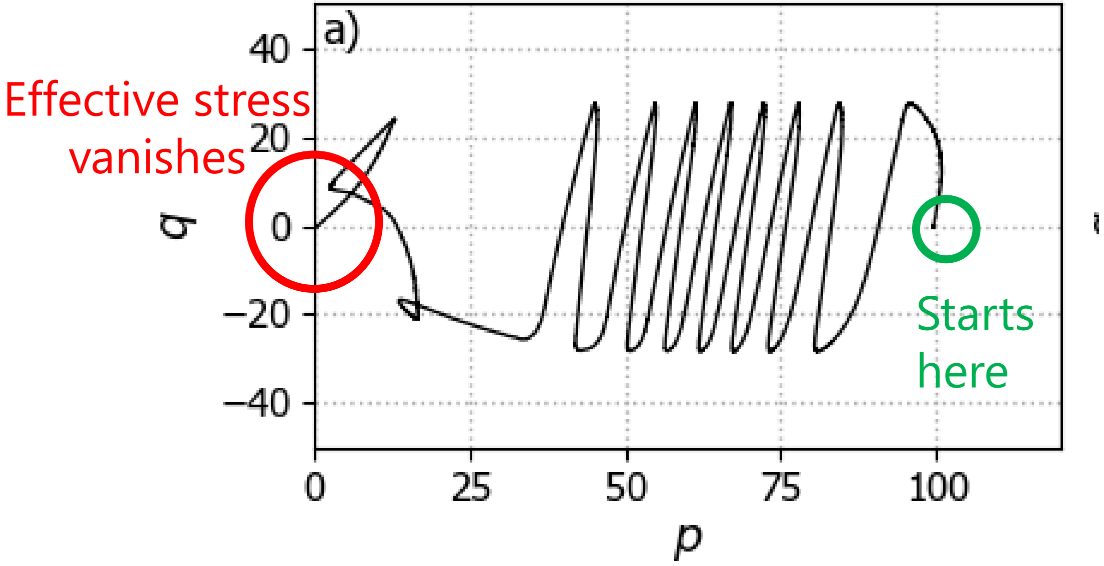




Drained (volume change)

Source: *Pradhan (1989)*

In drained conditions, one observes an accumulation of contraction.



Undrained (no volume change)

Source: *Adamidis and Anastasopoulos (2022)*

In undrained conditions, the pore pressure increases, which can lead to liquefaction: The pore pressure equals the mean effective stresses.
→ the grains "float" and the force chains in the grain skeleton vanish → the media behaves like a fluid.

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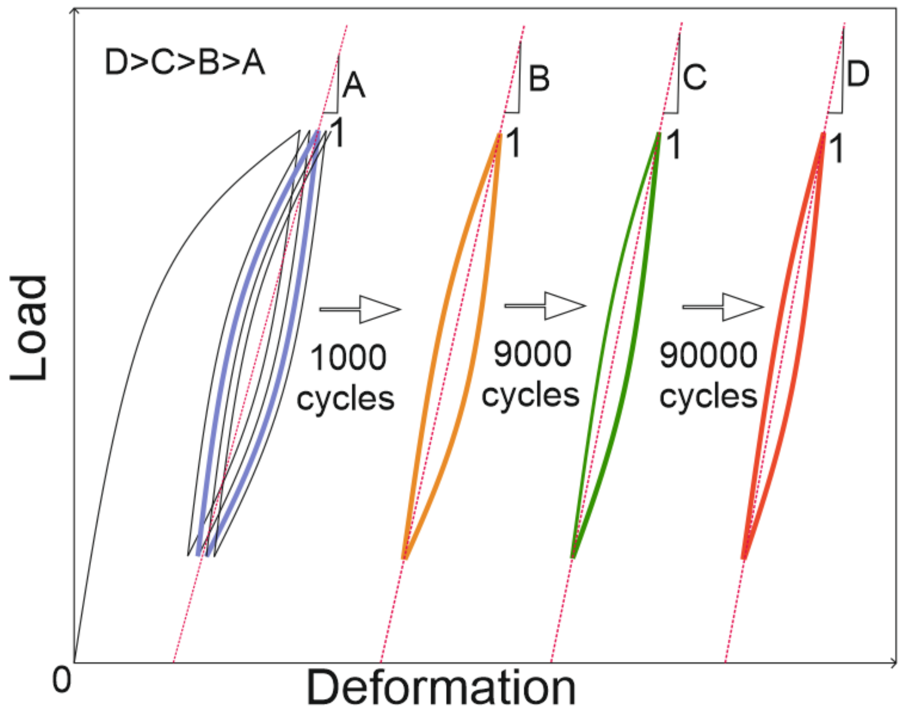
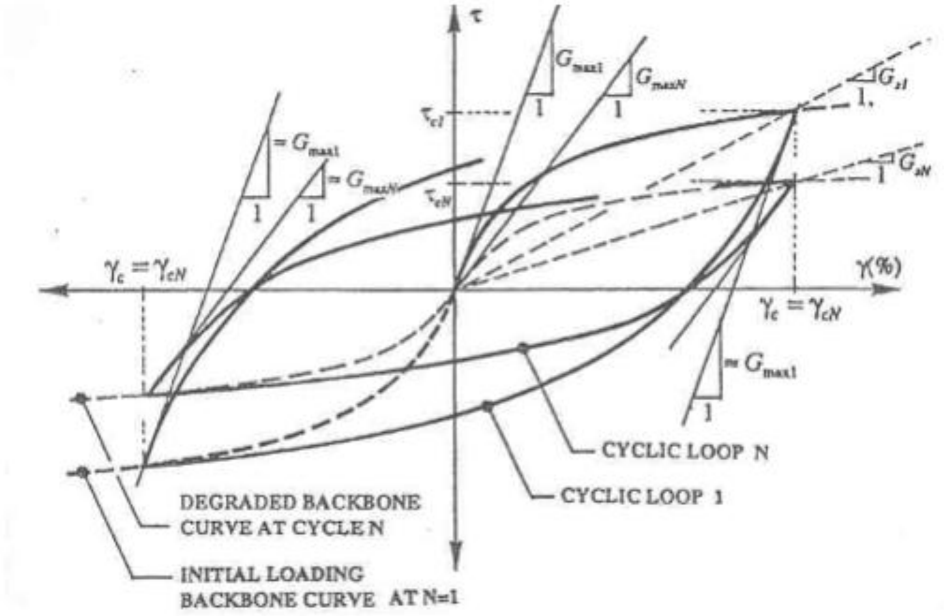
Changes in dynamic properties (and in strength?)



Stiffness degradation and loss of strength

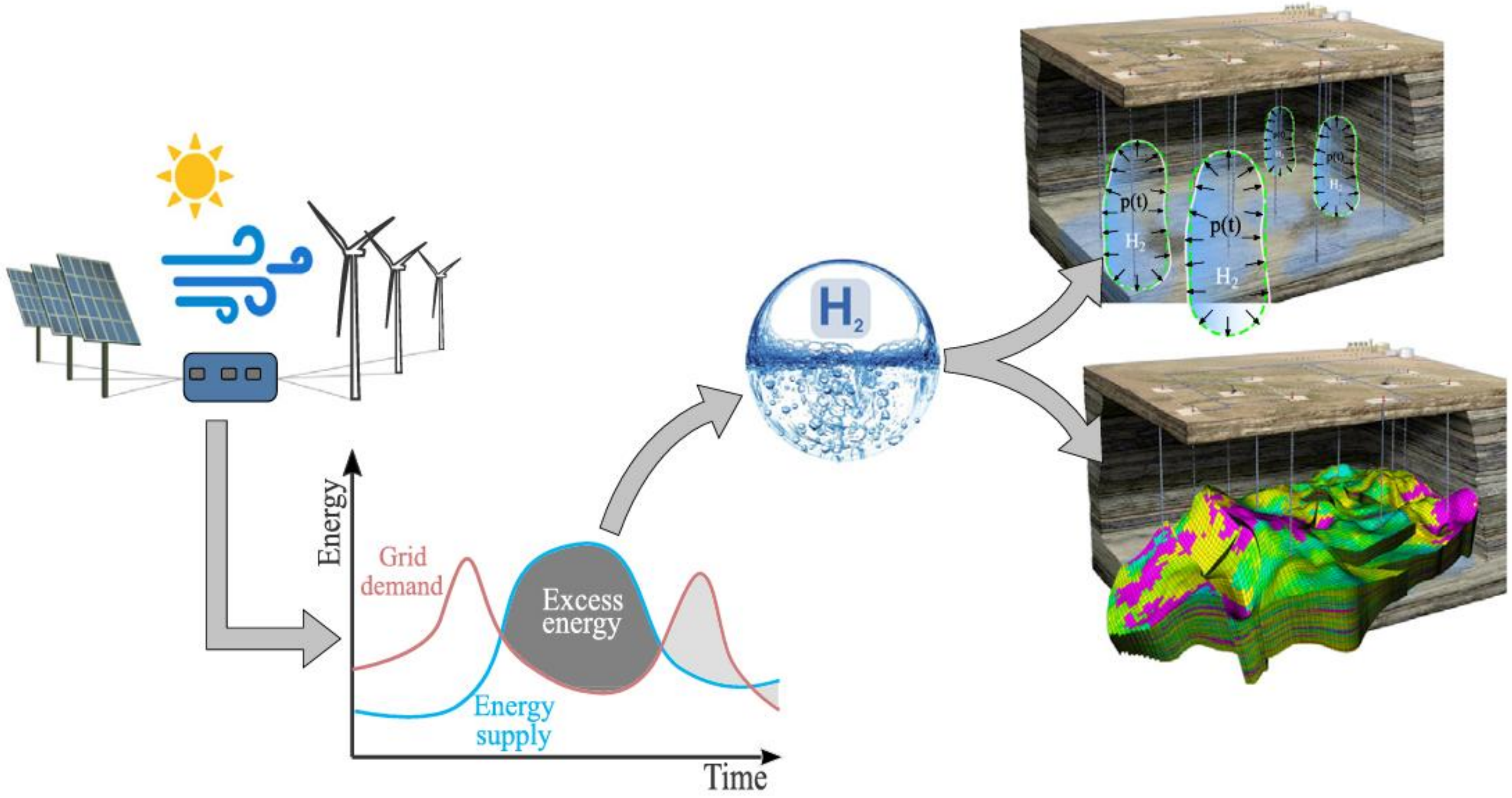
Changes of:

- Stiffness
- Damping (hysteresis loop)



Source: *Pecker (2005)*

Hydrogen storage



Source: *Ramesh Kumar et al. (2023)*

Duration: long
Number of cycles: low

Cyclic thermal loading

Both geothermal and thawing

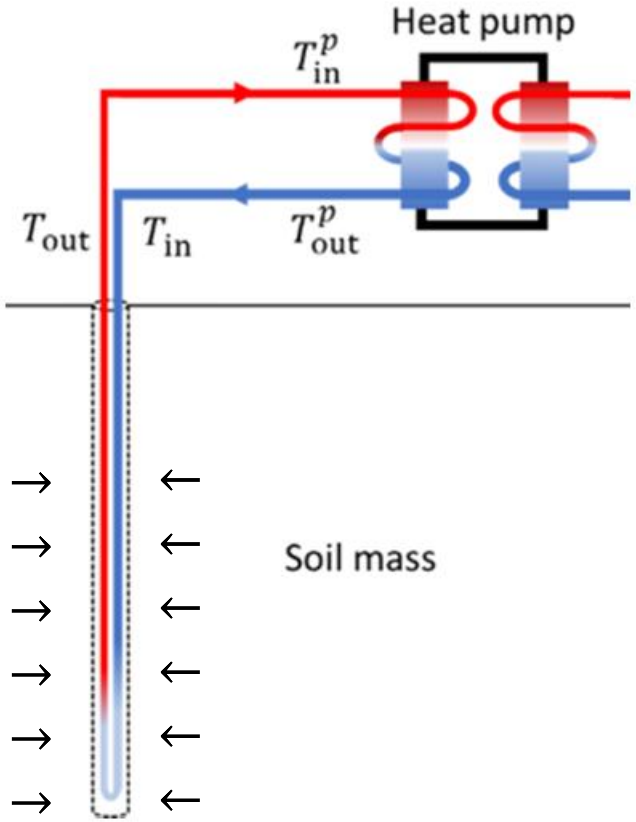


Fig. 12. Heat pump – heat exchanger set-up.

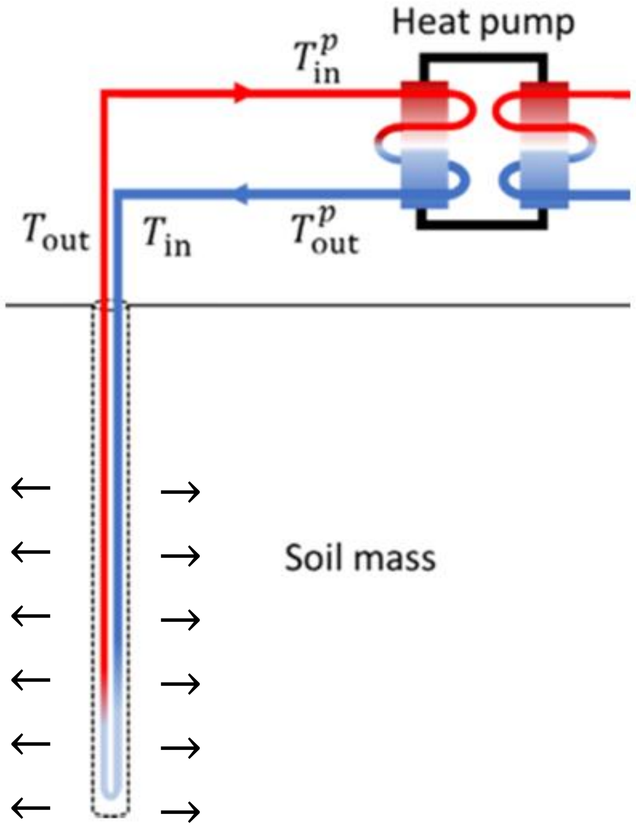
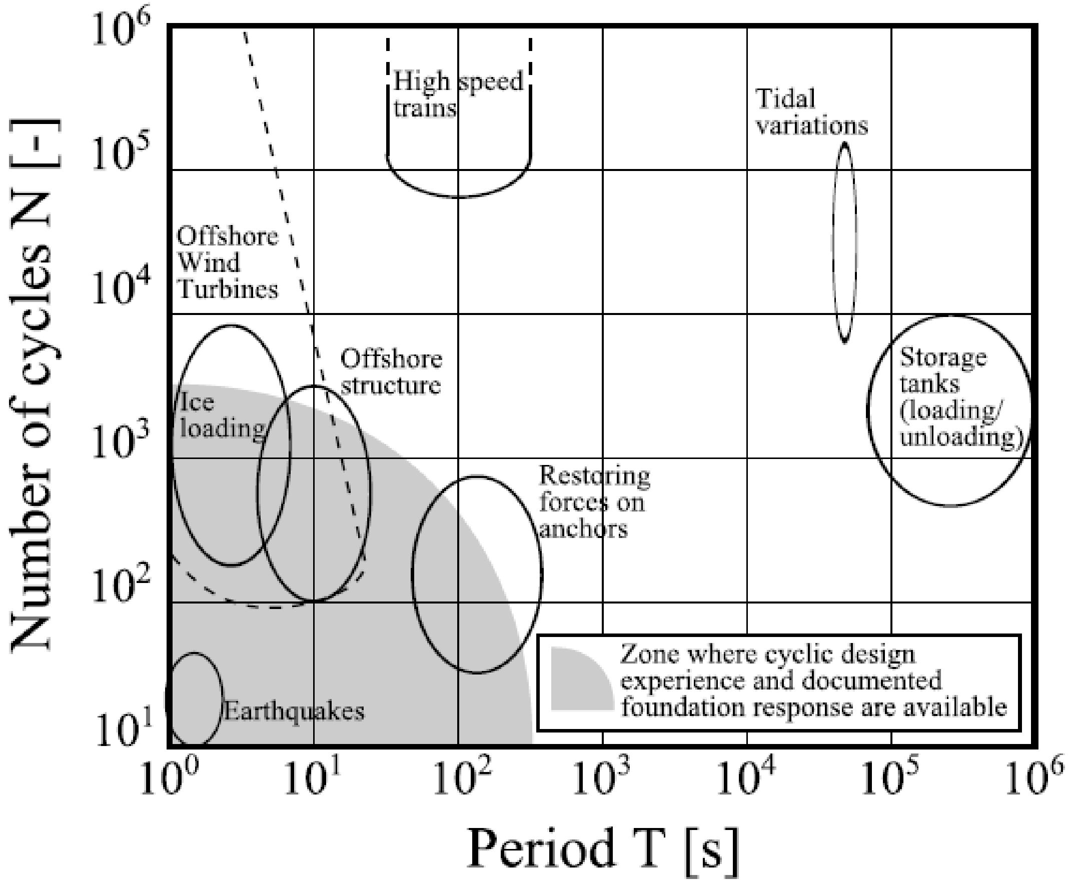


Fig. 12. Heat pump – heat exchanger set-up.

Source: *Arzanfudi et al. (2020)*

Cyclic loading: what matters?

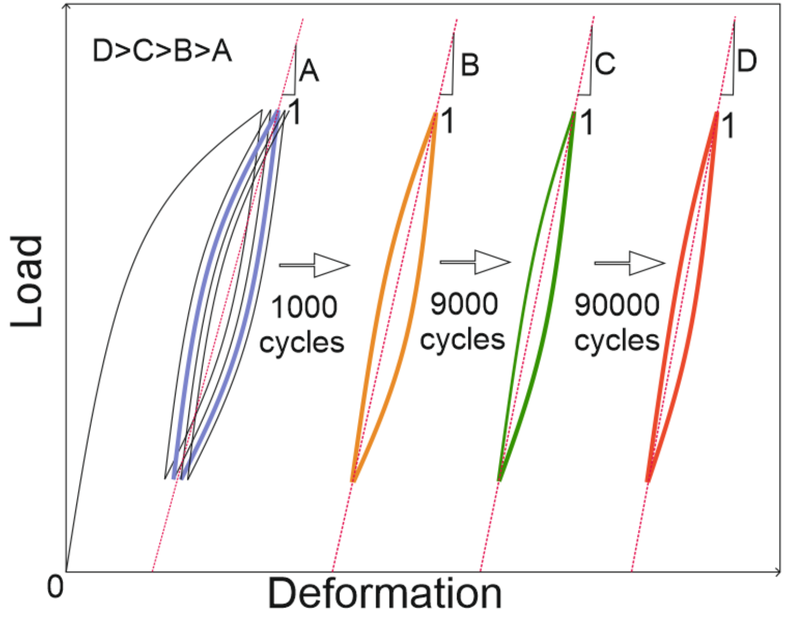


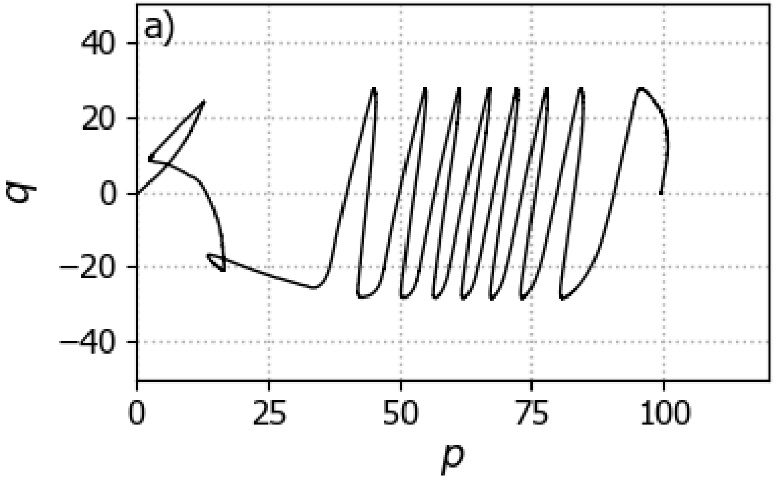
Source: *Cerfontaine (2014)* adapted from *Andersen (2013)*

Significant factors:

- Duration/number of cycles
- Frequency
- Amplitude
- Impacted zone
- Soil nature

Cyclic loading: what phenomena can be encountered?





Phenomena:

- Ratcheting
- Changes of strength, stiffness, damping
- Pore-pressure accumulation (up to liquefaction)

Micromechanical sources in materials:

- Soils: re-organisation of the fabric (anisotropy, void ratio)
- Rock: micro-fractures and their orientation.

An overarching idea: **the memory of geomaterials**

Source: *Adamidis and Anastasopoulos (2022)*

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Optimisation loop for the design

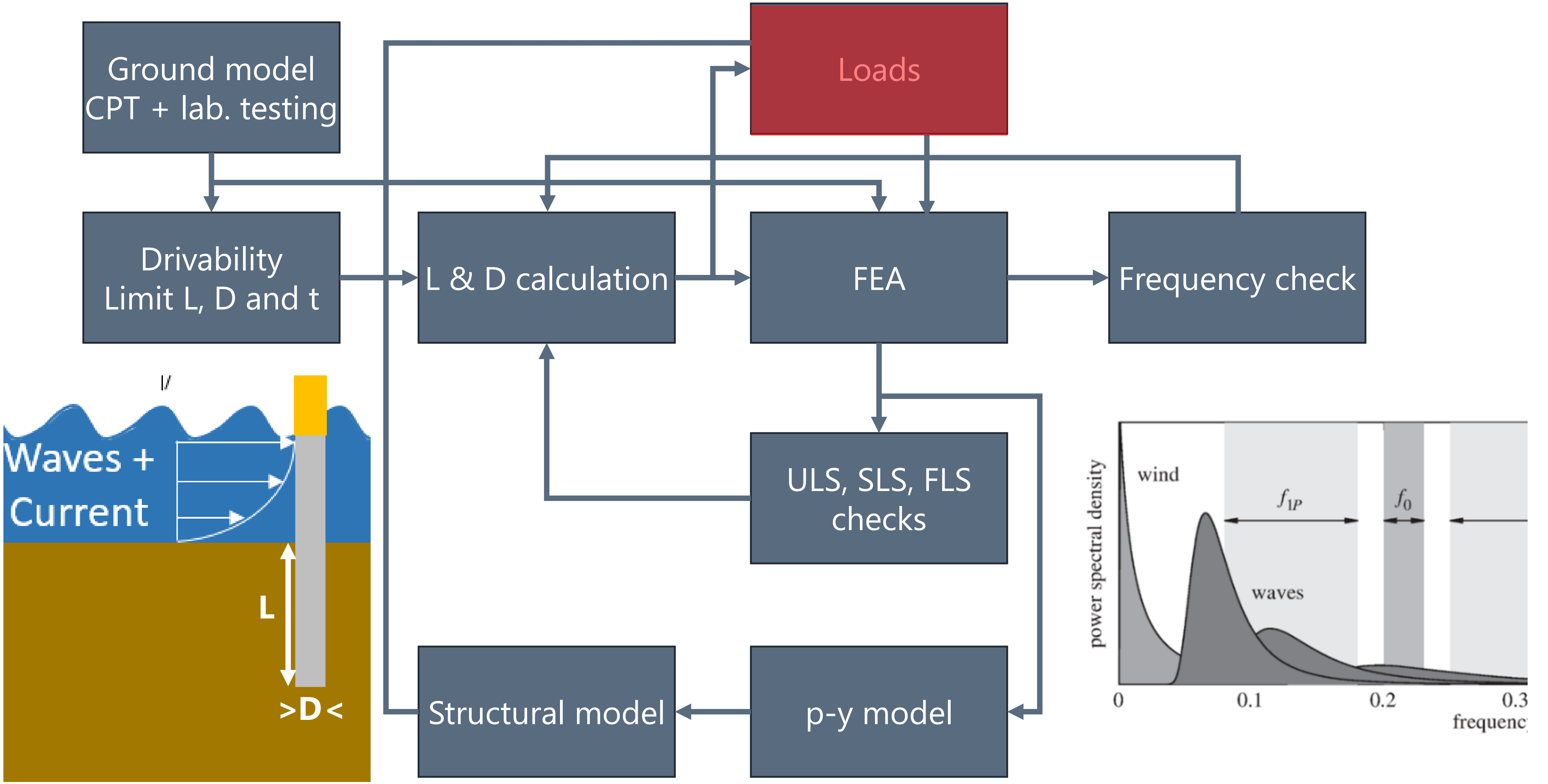
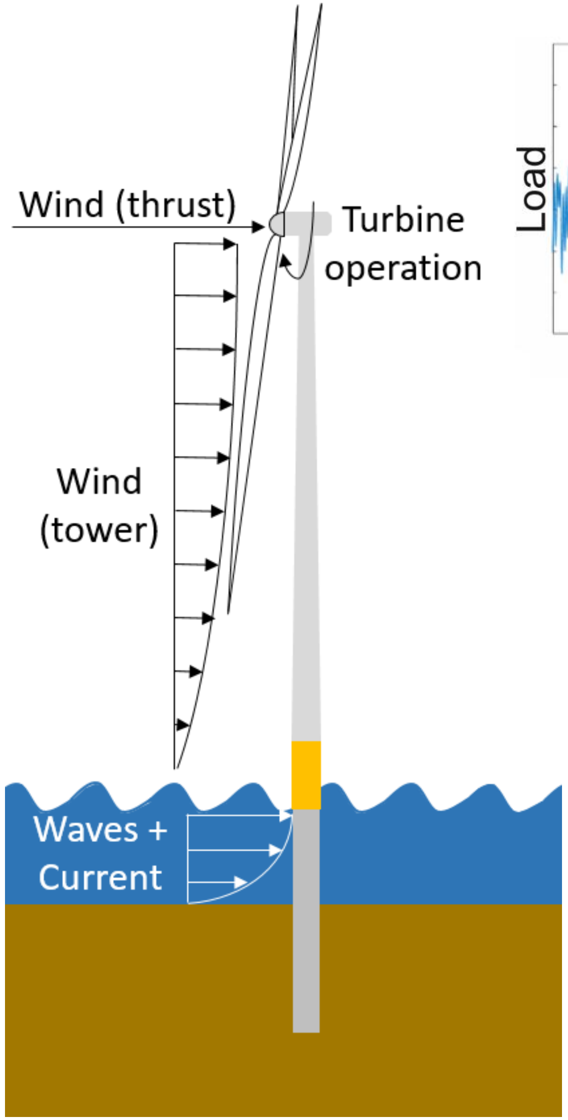
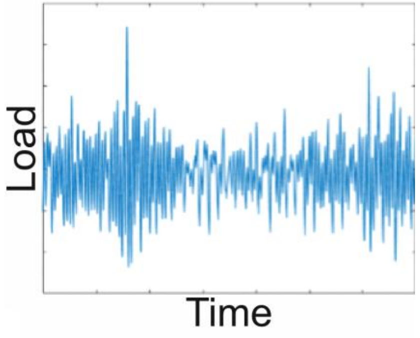


Illustration of loadings



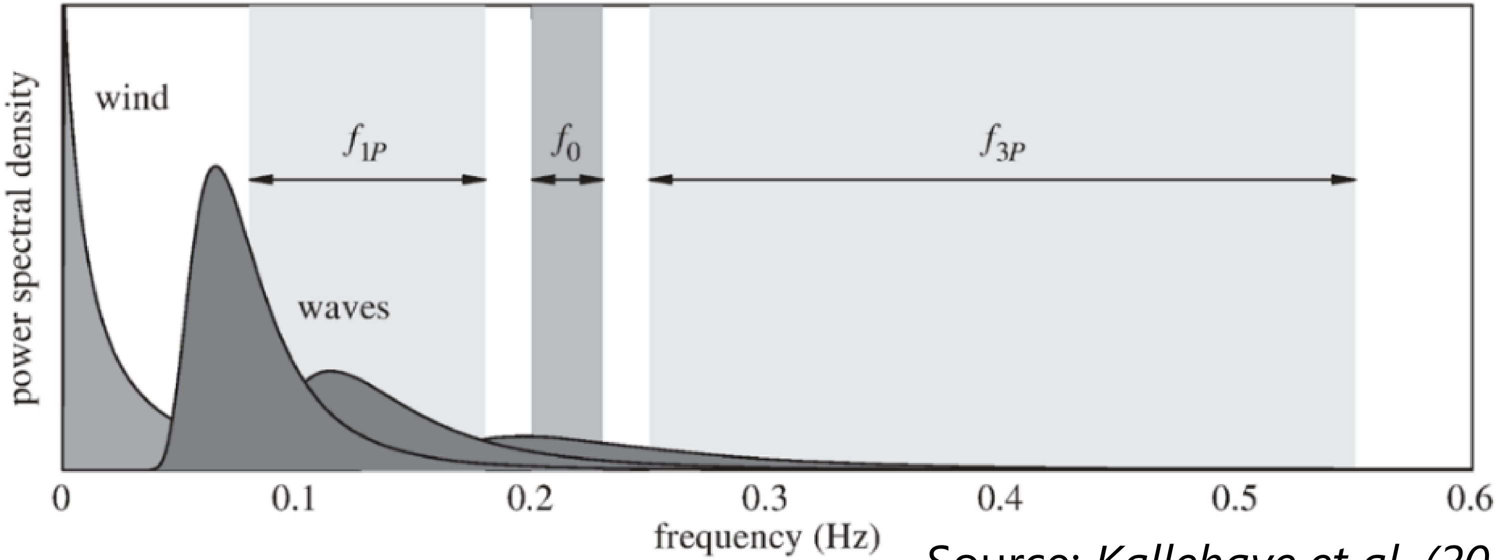


Environmental loading:

- Wind
- Waves
- Currents
- Ice?

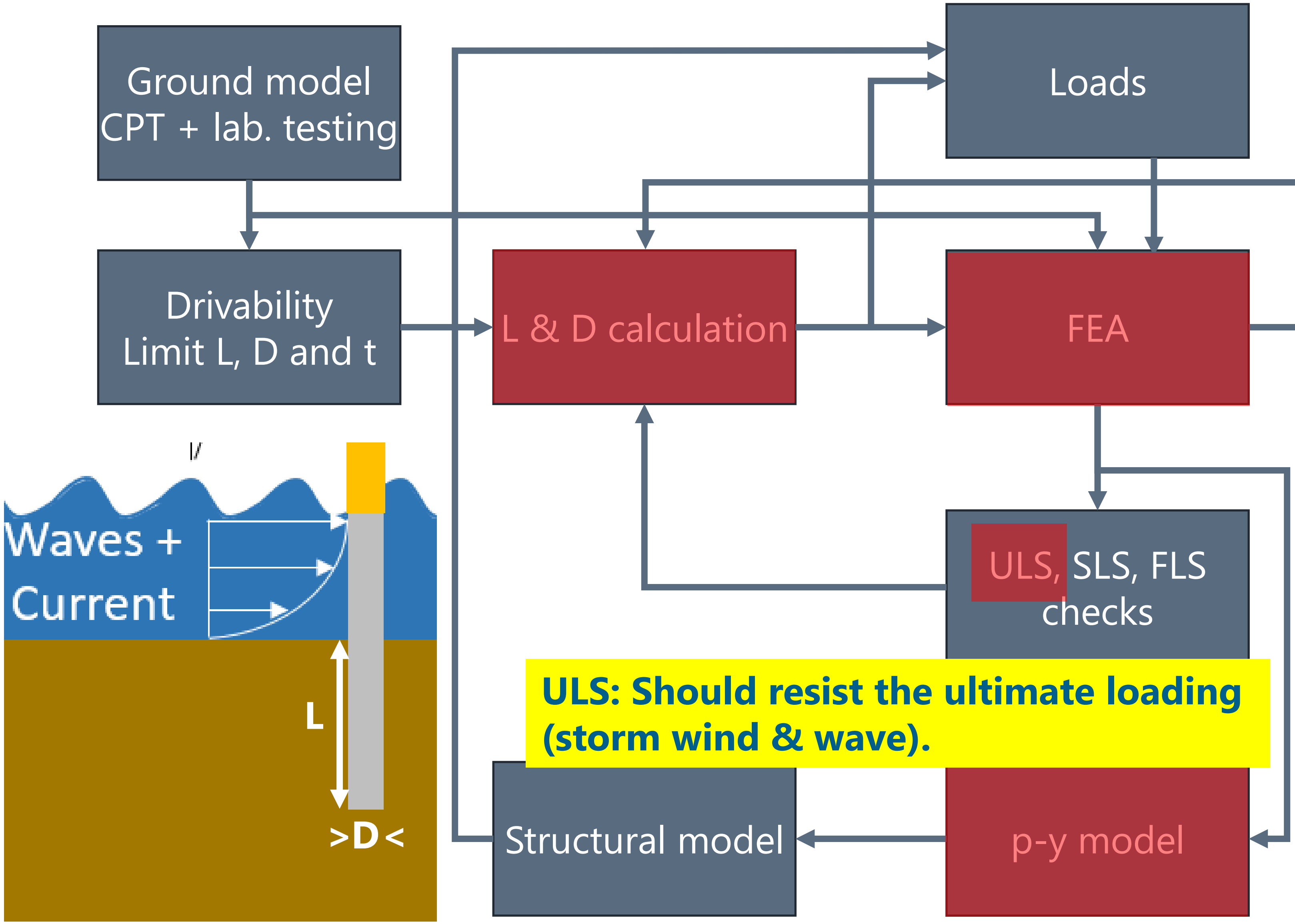
Operational loadings

Accidental/extreme loadings

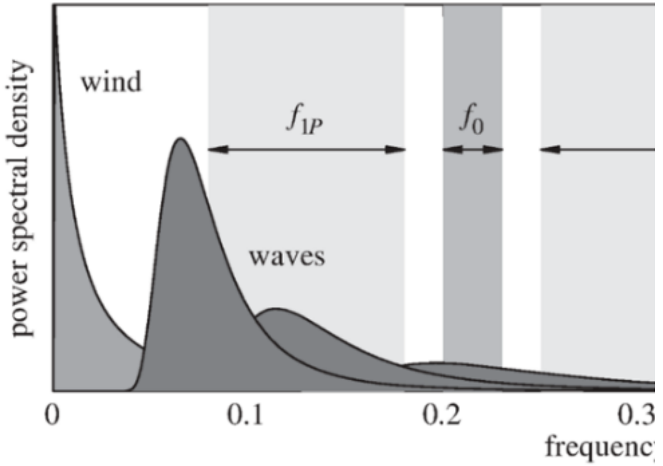


Source: *Kallehave et al. (2015)*

Optimisation loop for the design: explanations

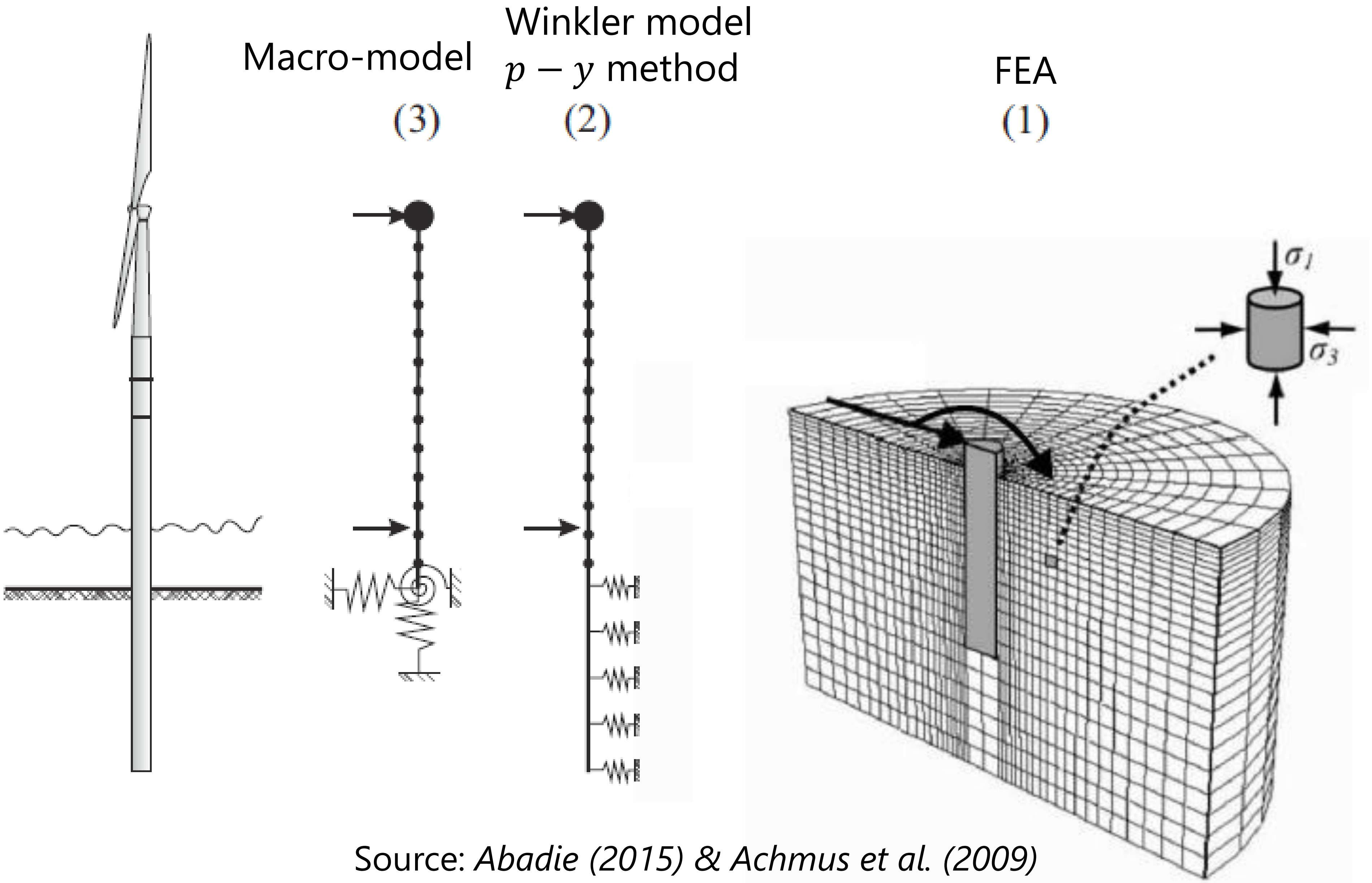


ULS: Should resist the ultimate loading (storm wind & wave).



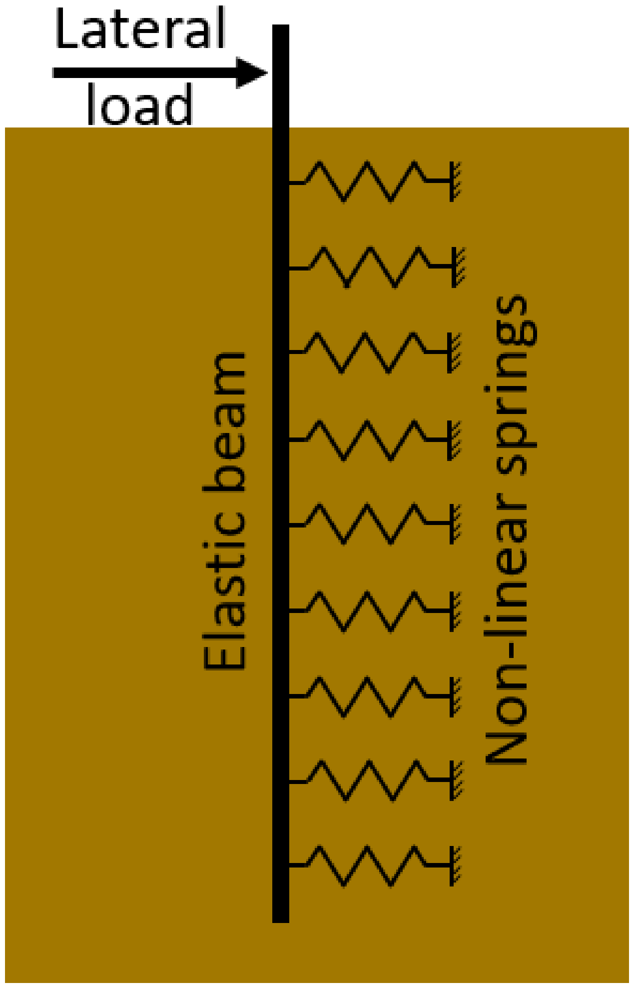
Source: *Kallehave et al. (2015)*

Modelling options



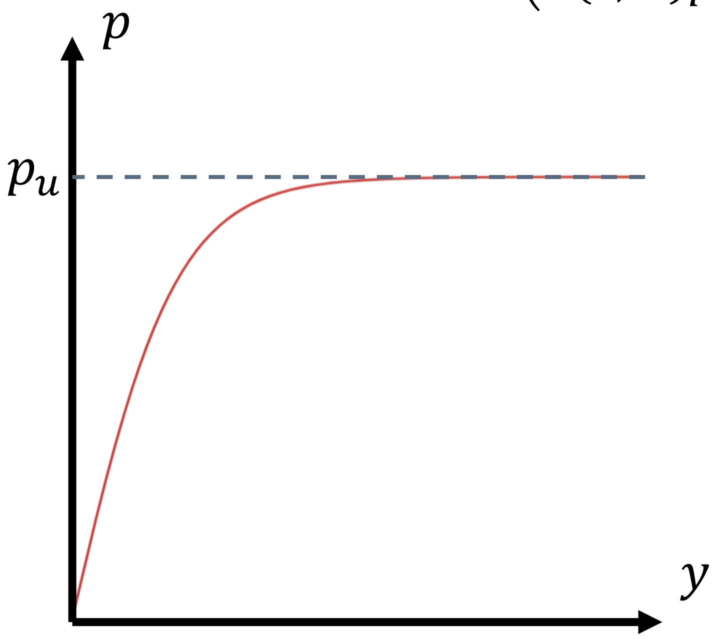
Source: *Abadie (2015) & Achmus et al. (2009)*

p-y modelling



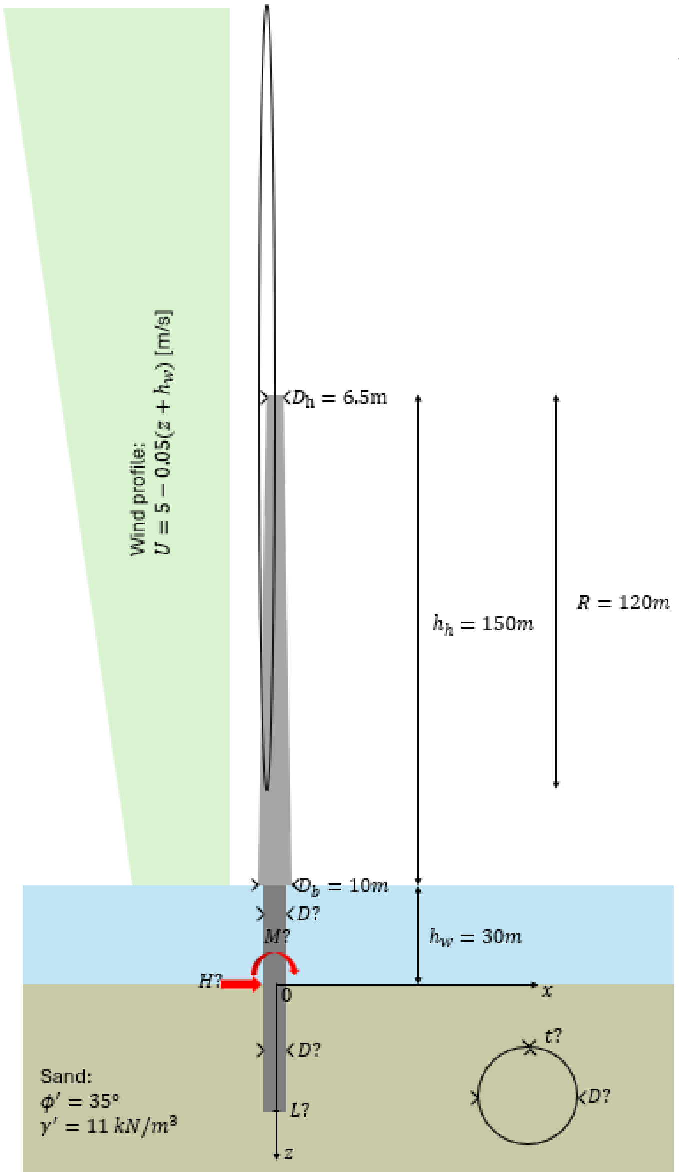
API equation for sand:

$$p(\mathrm{y,z,D}) = A(z,D)\, p_u(z,D) \tanh\left(\frac{k\,z}{A(z,D)p_u(z,D)}\, y\right)$$



Iterate on L and D
→ max. displacement at the mudline <0.1D for ultimate load.
→ no failure of the pile wall.

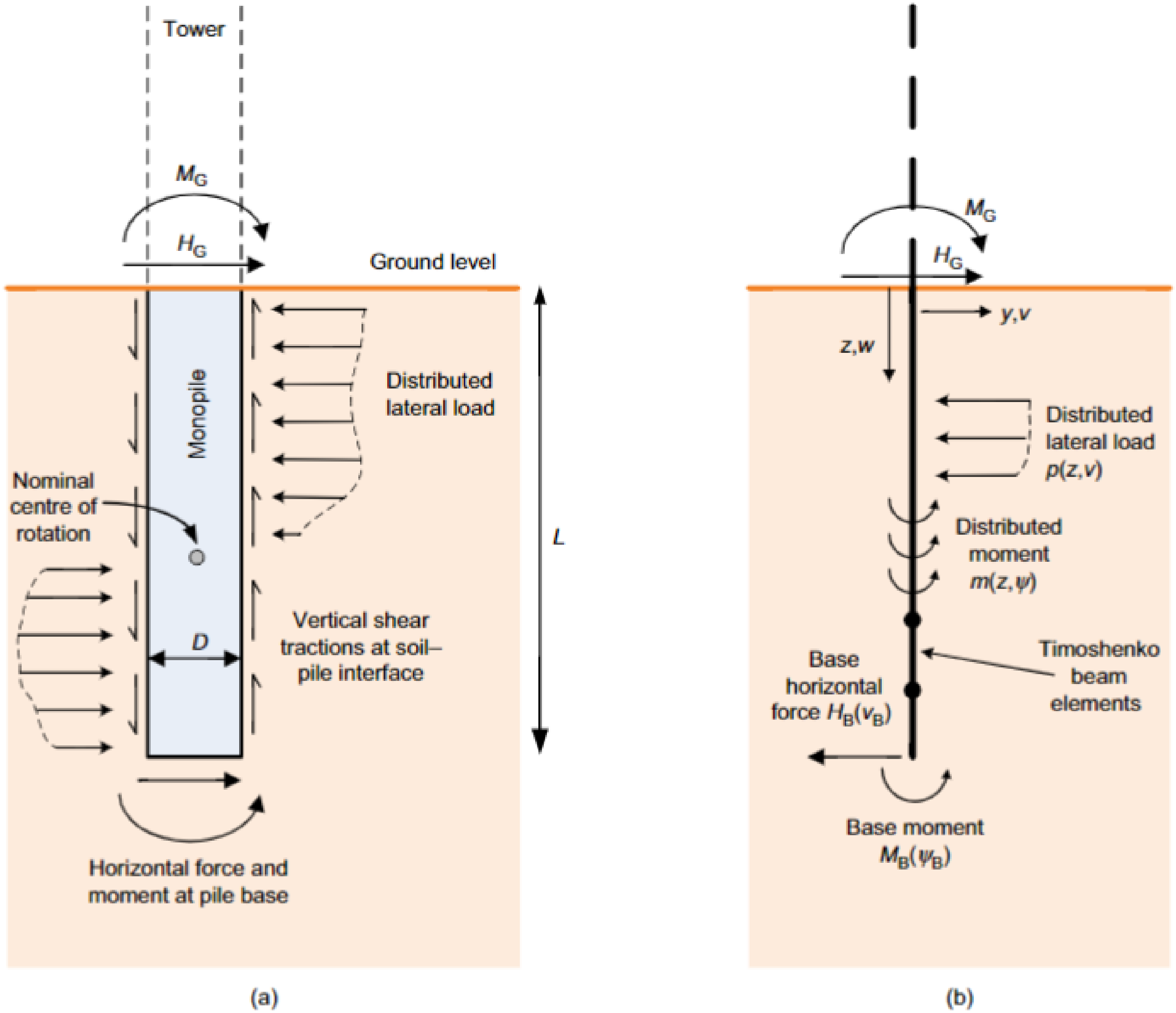
Exercise: determine L and D of monopile for ULS



Your goal is to optimise the diameter (D) and embedded length of the monopile foundation (L) to minimise the quantity of material (steel) used while guaranteeing no soil or pile wall failure.

alert2025.streamlit.app

Design under monotonic loading: PISA approach



Source: *Burd et al. (2020)*

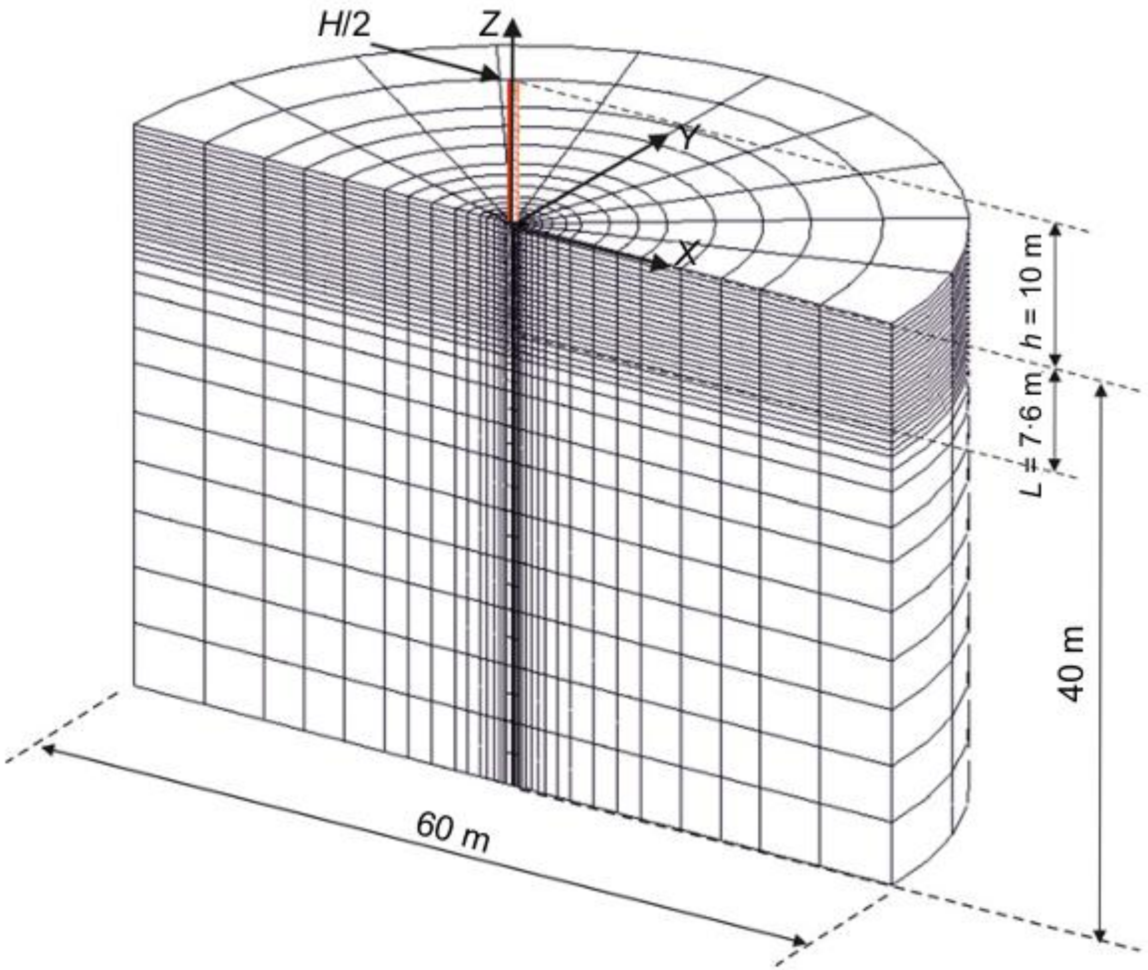
Additional soil reactions:

- Shear on the shaft.
- Shear at the toe.
- Moment at the toe.

Essential for OWT piles because of the low slenderness.

Design under monotonic loading: PISA approach

Source:
Zdravković et al. (2022)



PISA design process:

- FE simulations covering the parametric space (soil, L, D, loading).
- Infer from the FE simulations dedicated reaction curves function of these parameters.
- Conduct optimisation of the whole wind farm (c.f. Cerfontaine) via 1D beam model with reaction curves.

! Important prerequisite **!**

Adequate constitutive models

Progressive optimisation of the design

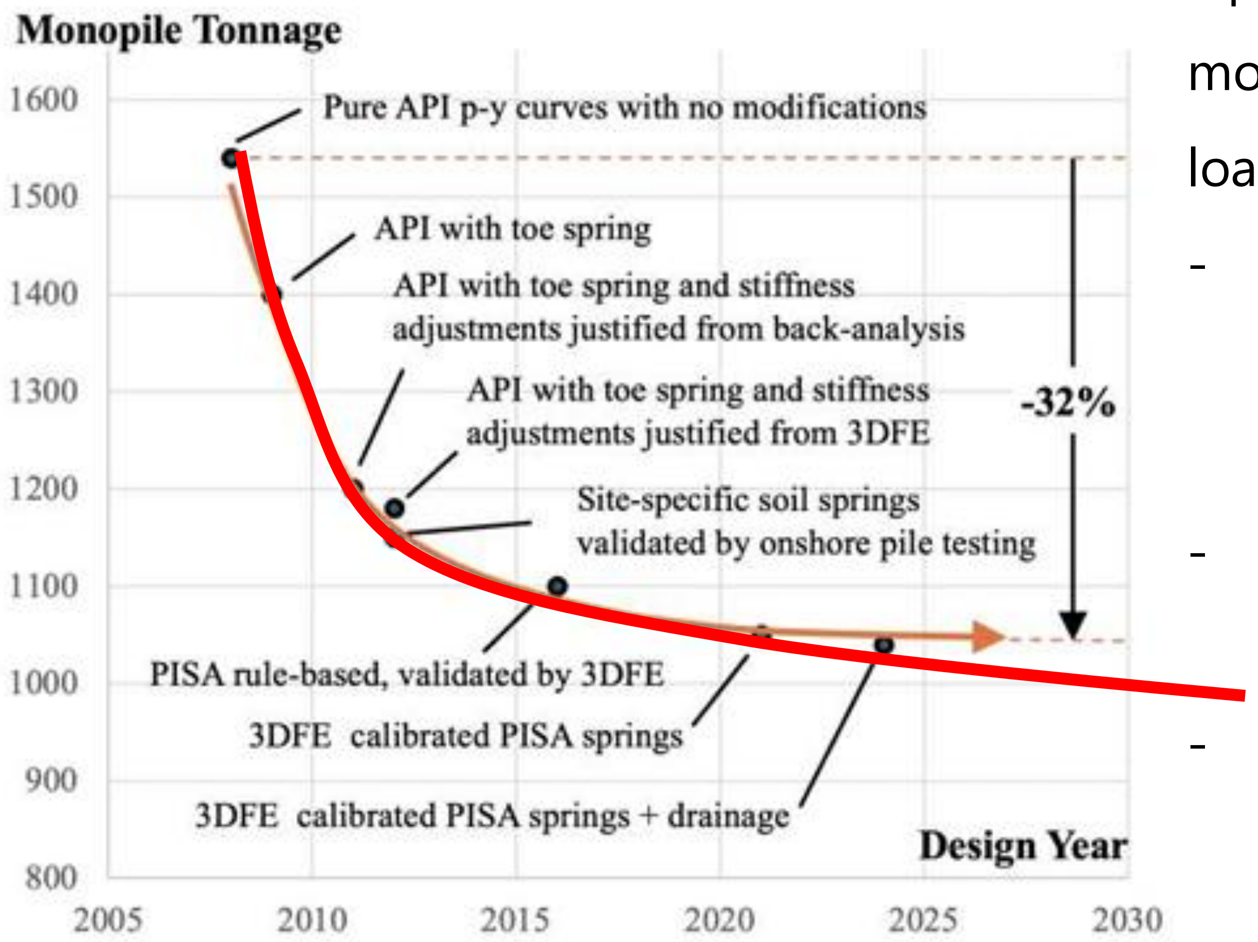


Figure 12. Achieved material efficiency gains due to geotechnical design evolution.

Source: *Wood and Thilsted (2025)*

Optimisation of design methods of monopile foundations under monotonic loading have been driven by:

- Experimental campaigns giving insight into the behaviour of this new format of piles.
- Taking into account a wider array of soil reactions.
- Numerical methods backed by experimental comparison leading to a new design method.

Leading to a large ↓ of the use of steel and thus ↓ cost of OW energy.

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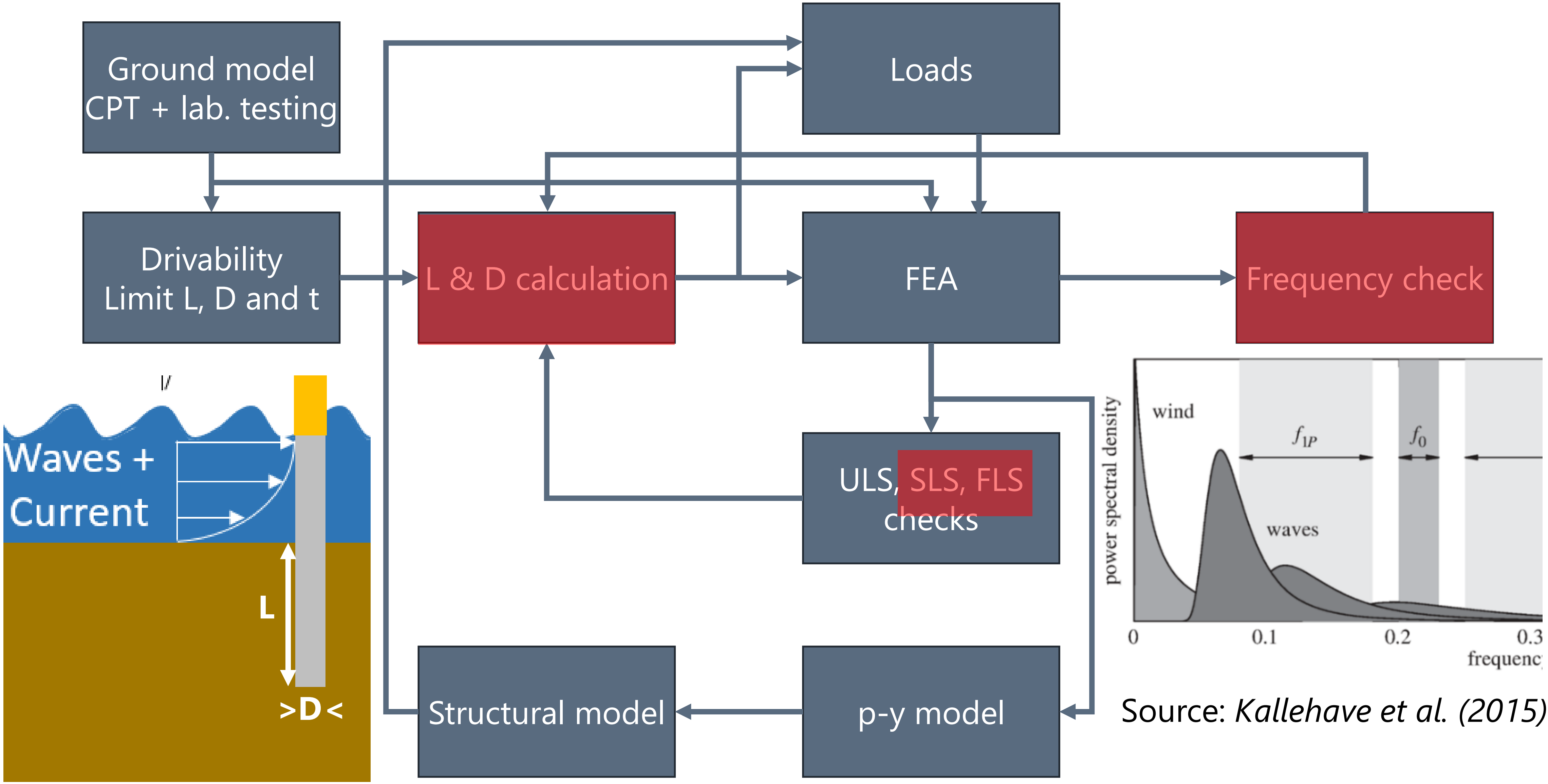
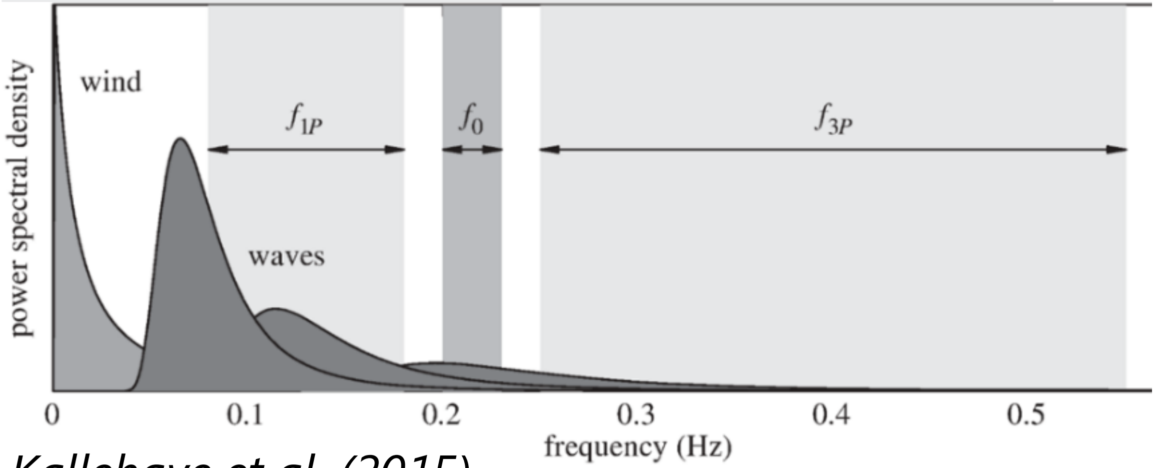


Source: *Kallehave et al. (2015)*

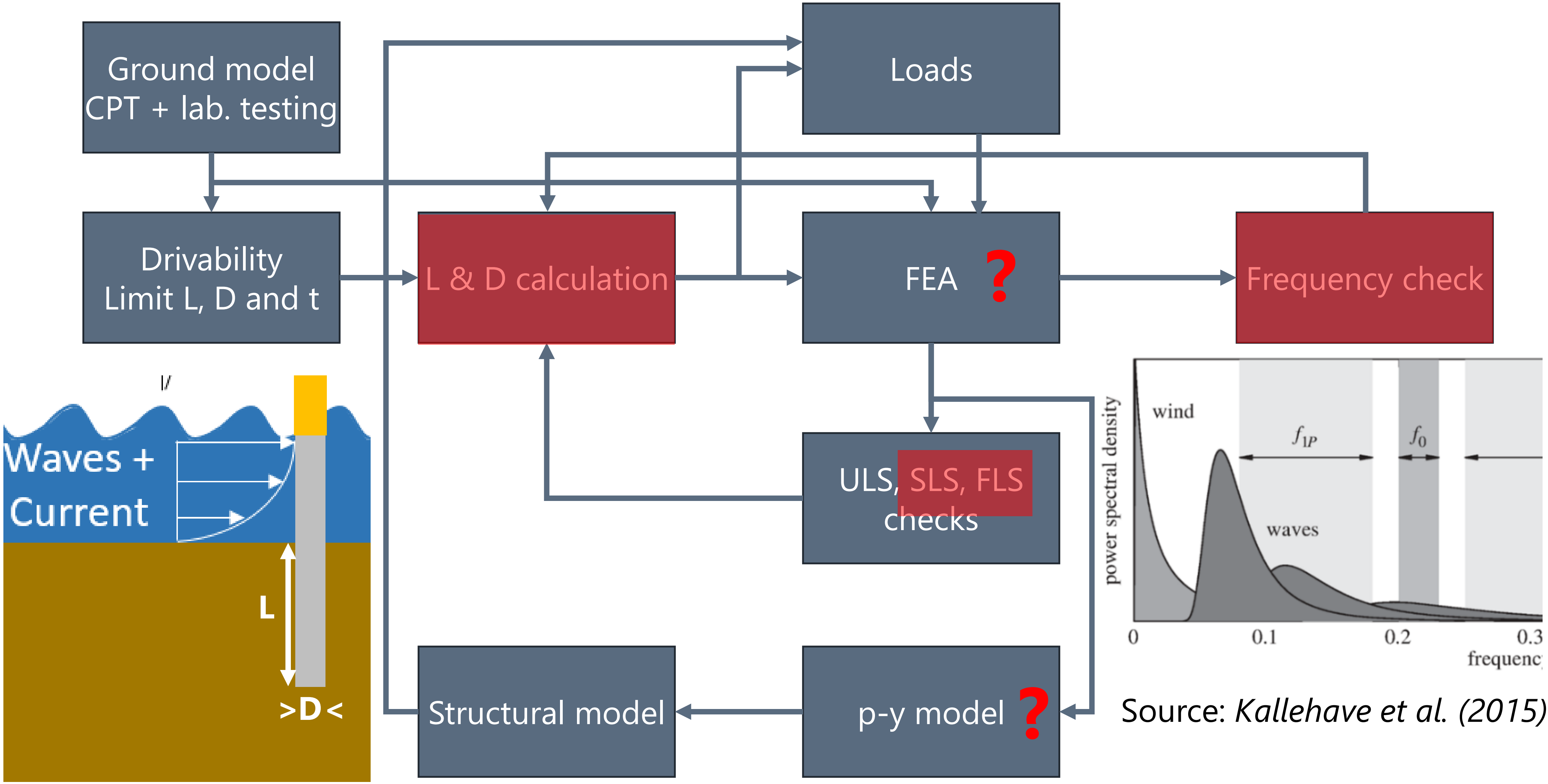
SLS and FLS checks

SLS	FLS
Accumulated rotation/displacement at mudline (typically target < ~0.5°).	Concerned with **progressive accumulation of damage** under millions of load cycles.
Dynamic response: natural frequency must remain outside excitation bands (1P, 3P, wave loading) → avoid resonance.	Requires assessment of **soil–structure interaction evolution over lifetime**, not just extreme events.
Cyclic degradation of stiffness/strength: ensure foundation resists extreme events (e.g. storm after 20 years).	



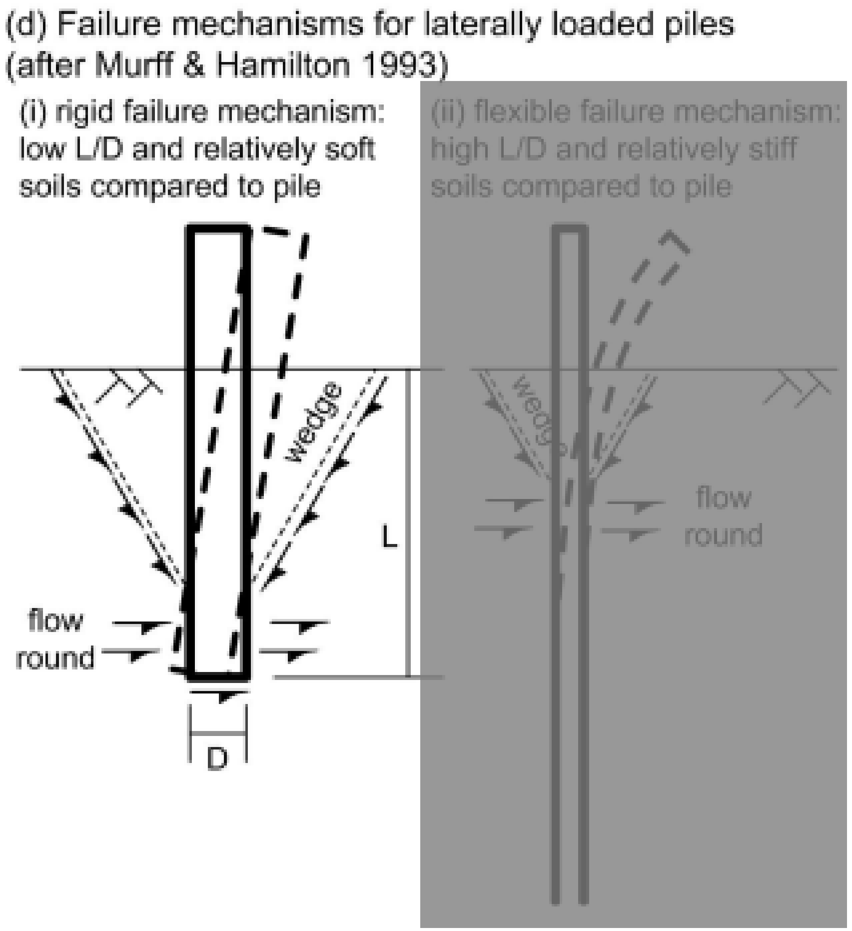
Source: *Kallehave et al. (2015)*

Optimisation loop for the design: explanations



Source: *Kallehave et al. (2015)*

Different scales of cyclic loading



Source: *Schneider and Senders (2010)*

<u>At the scale of the structure</u>

A <u>soil structure interaction problem</u>.

<u>At the scale of the soil</u>

Local cyclic loading of the soil:

- Different confinements.
- Different load paths.

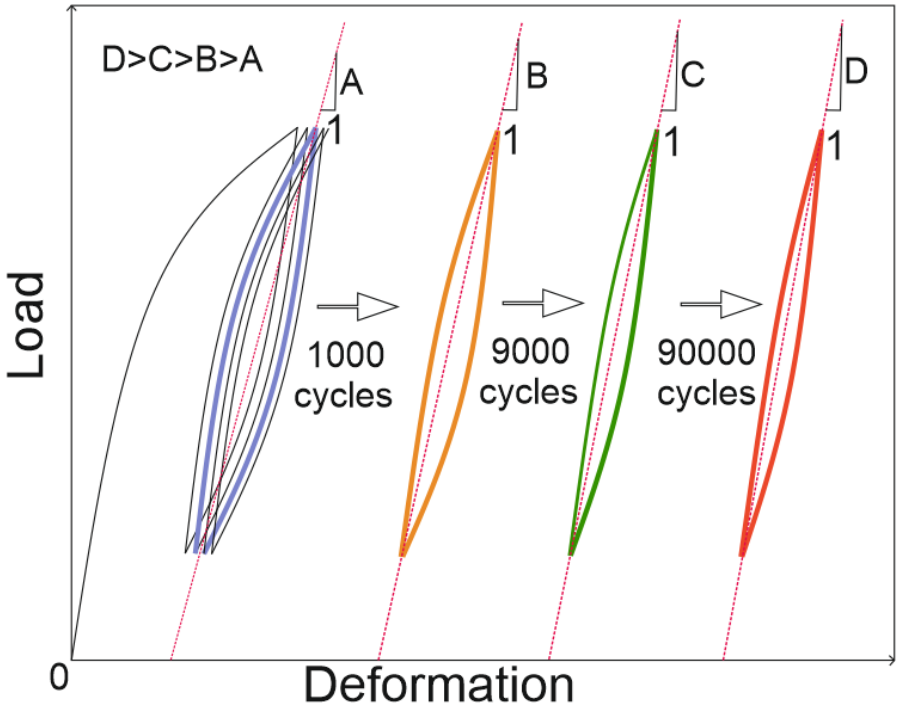
As you move away from the pile:

- diminution of the amplitude of the loading.

Phenomena at the macroscale and guidelines

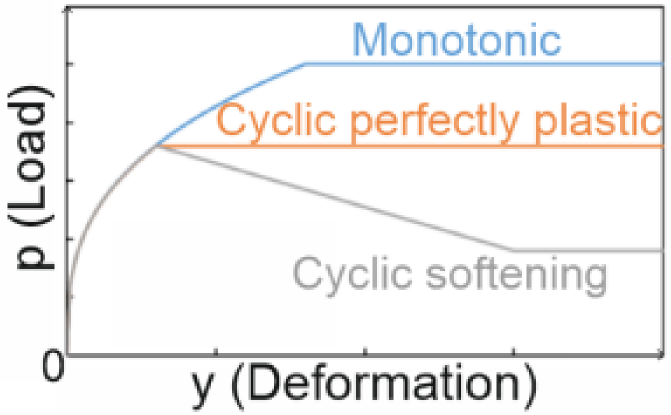
What we are interested in:

- ratcheting
- Stiffness change
- Damping change
- Strength change

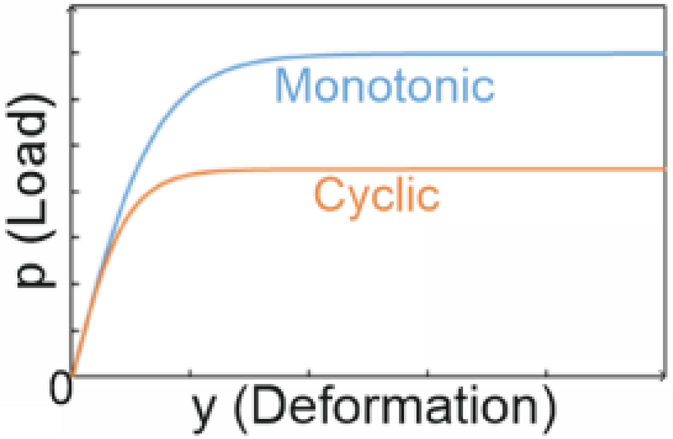


Vs

Old DNV guidelines
concerned with strength degradation



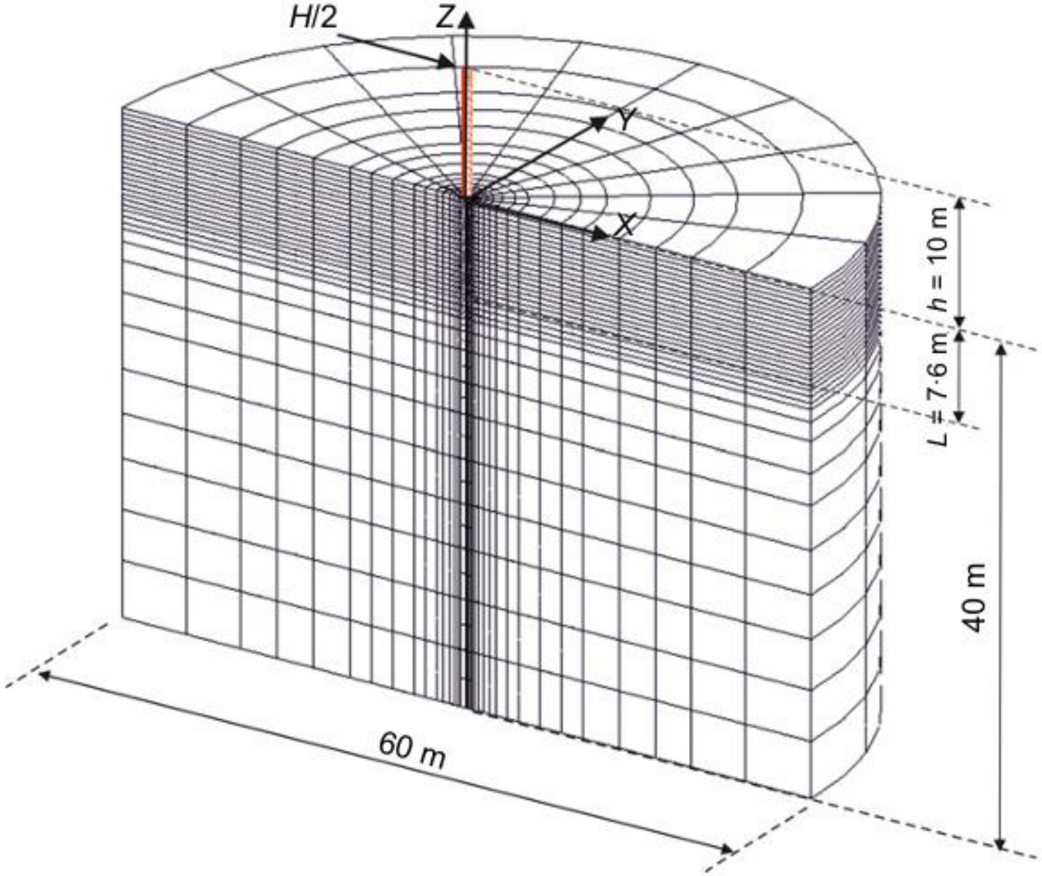
Clay



Sand

Finite element simulation to derive PISA style model?

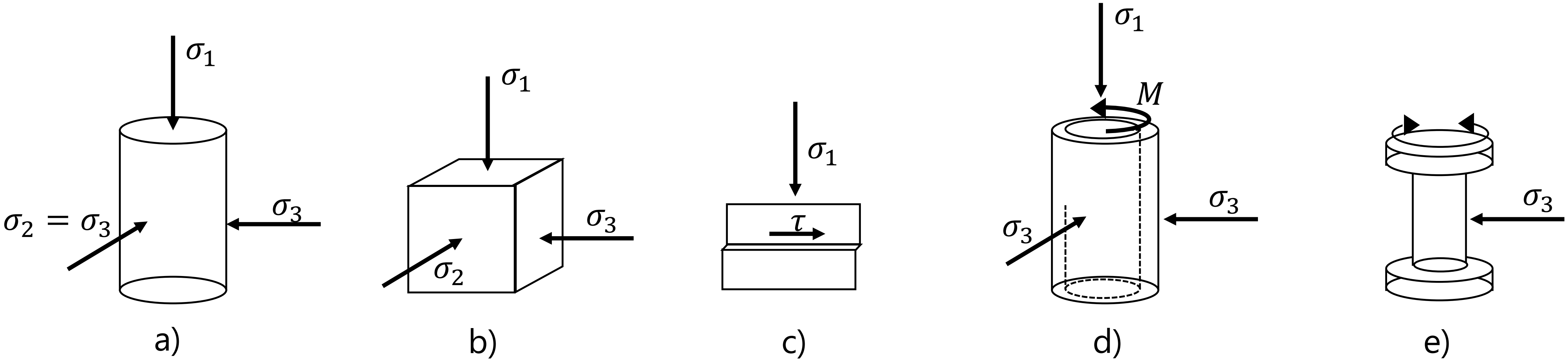
Source:
Zdravković et al. (2022)



To model the macro-scale phenomena, one needs <u>advanced constitutive models capable of capturing cyclic behaviour</u> of the soil at the meso-scale for the different stress paths and amplitudes that will be sustained by the OWT surrounding soil.

Soil element testing

One needs <u>data</u> to inform advanced constitutive models at the meso-scale! This data can be obtained from <u>element testing</u>. Testing should encompass the stress conditions and the stress-strain paths of the geotechnical problem.



Triaxial	True triaxial	Direct shear	Hollow cylinder Torsional test	Resonant column
Axisymmetric Stress state	Control three principal stresses	Much use in the industry. Little control on the stress state	Control three principal stresses + stress rotation.	Small-strain Behaviour.

Soil element testing

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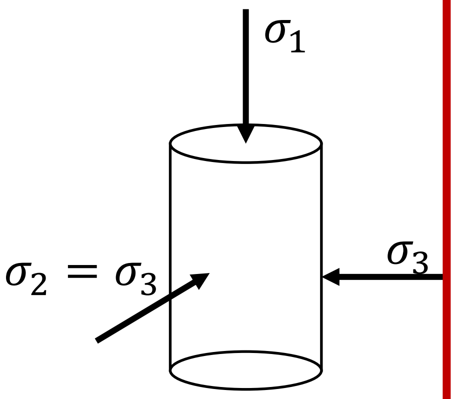


a)

Triaxial

Axisymmetric Stress state

Great tools to explore soil behaviour in controlled and repeatable conditions.

but…

<u>Watch out!</u>

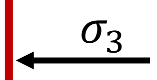
Stress initial conditions and path.

Sample representativity of in-situ conditions.

Heterogeneity of in-situ conditions.

No soil structure interaction!

Little control on the stress state



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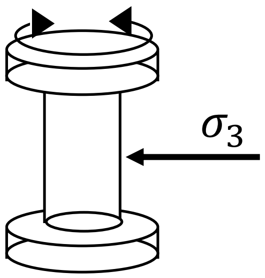
ree esses + stress rotation.

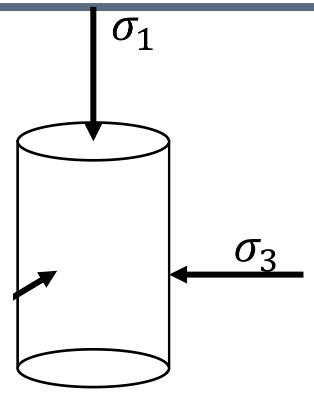


e)

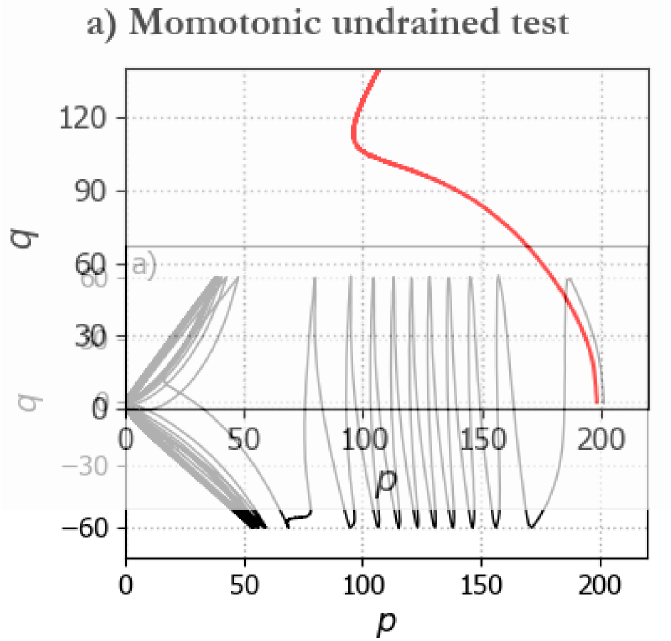
Resonant column

Small-strain Behaviour.

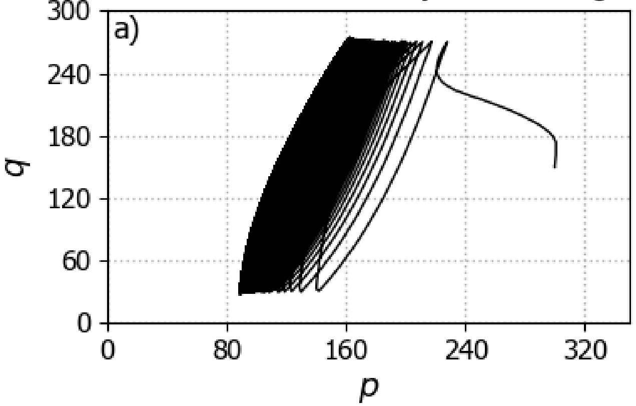
Triaxial testing: pore-pressure generation and ratcheting



Mean effective stress:	$p = \dfrac{\sigma_1 + 2\sigma_3}{3}$	Deviatoric stress:	$q = \sigma_1 - \sigma_3$
Volumetric strain:	$\epsilon_p = \epsilon_1 + 2\epsilon_3$	Shear strain:	$\epsilon_q = \dfrac{2}{3}(\epsilon_1 - \epsilon_3)$



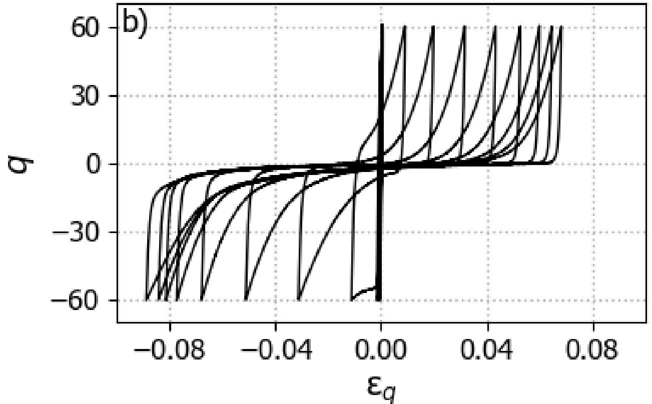
Anisotropic initial stress state
Partial one-way loading



Pore pressure generation

Liquefaction
Large initial rate
Slow down
Pick-up again

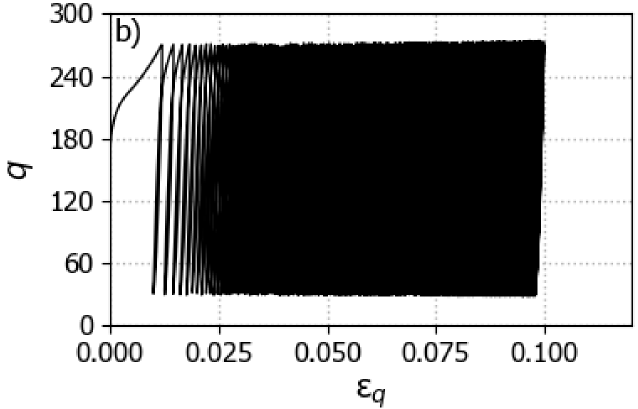
No liquefaction if partial one-way.
Large initial rate
→ slows down



Ratcheting

No ratcheting
Large deformation during liquefaction

Ratcheting



Source: Wichtmann (2016) & website

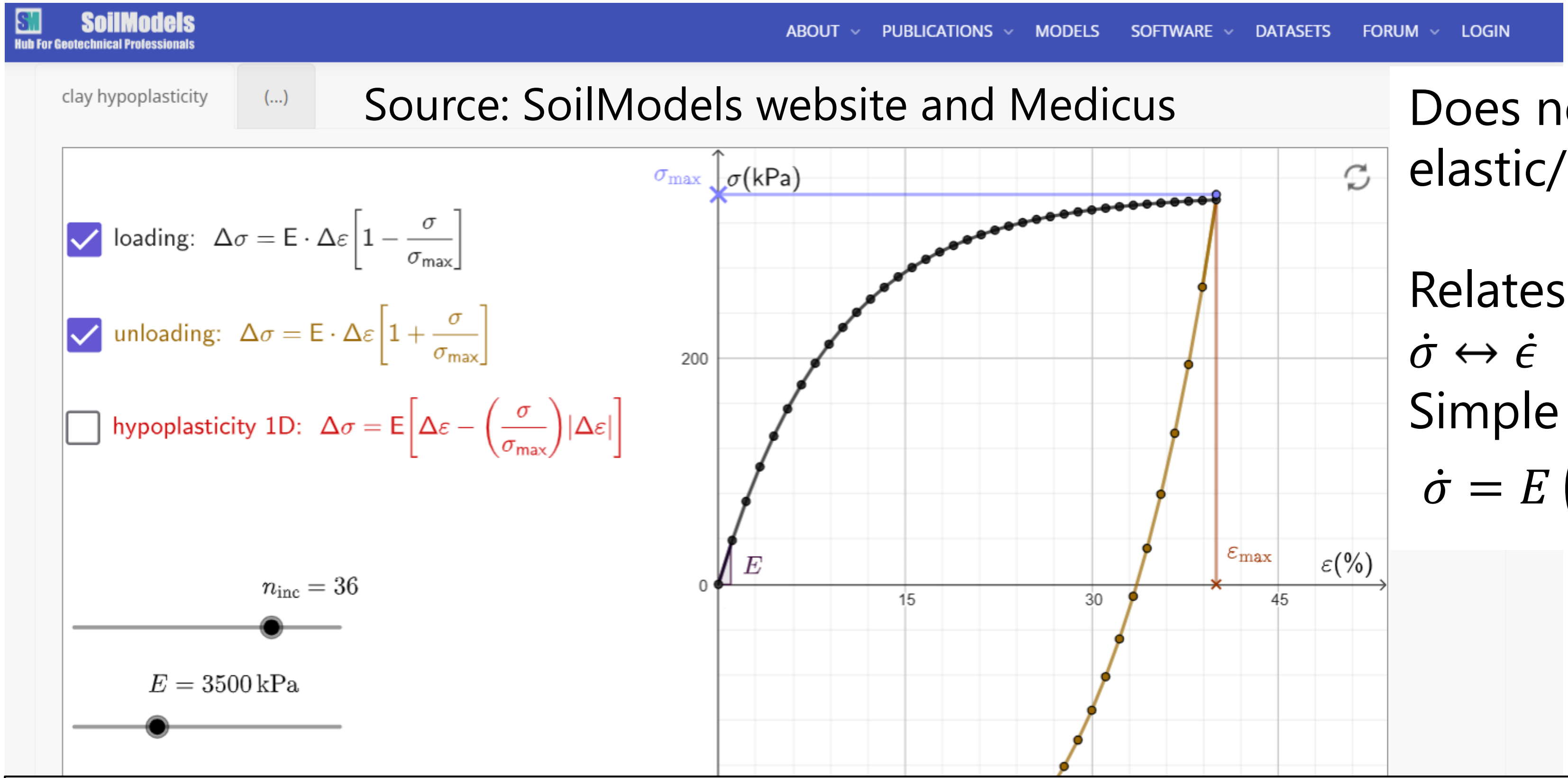
Constitutive modelling approaches

Introducing three families of models:

- Hypoplasticity (1980s →)
- Bounding surface plasticity (1970s →)
- Multi-surface plasticity (1960s →)

The development of these theories initially aimed to capture the non-linear response of materials and their cyclic response.

Constitutive modelling approaches: Hypoplasticity



Source: SoilModels website and Medicus

Does not distinguish elastic/plastic.

Relates stress and strain <u>rates:</u>

$\dot{\sigma} \leftrightarrow \dot{\epsilon}$

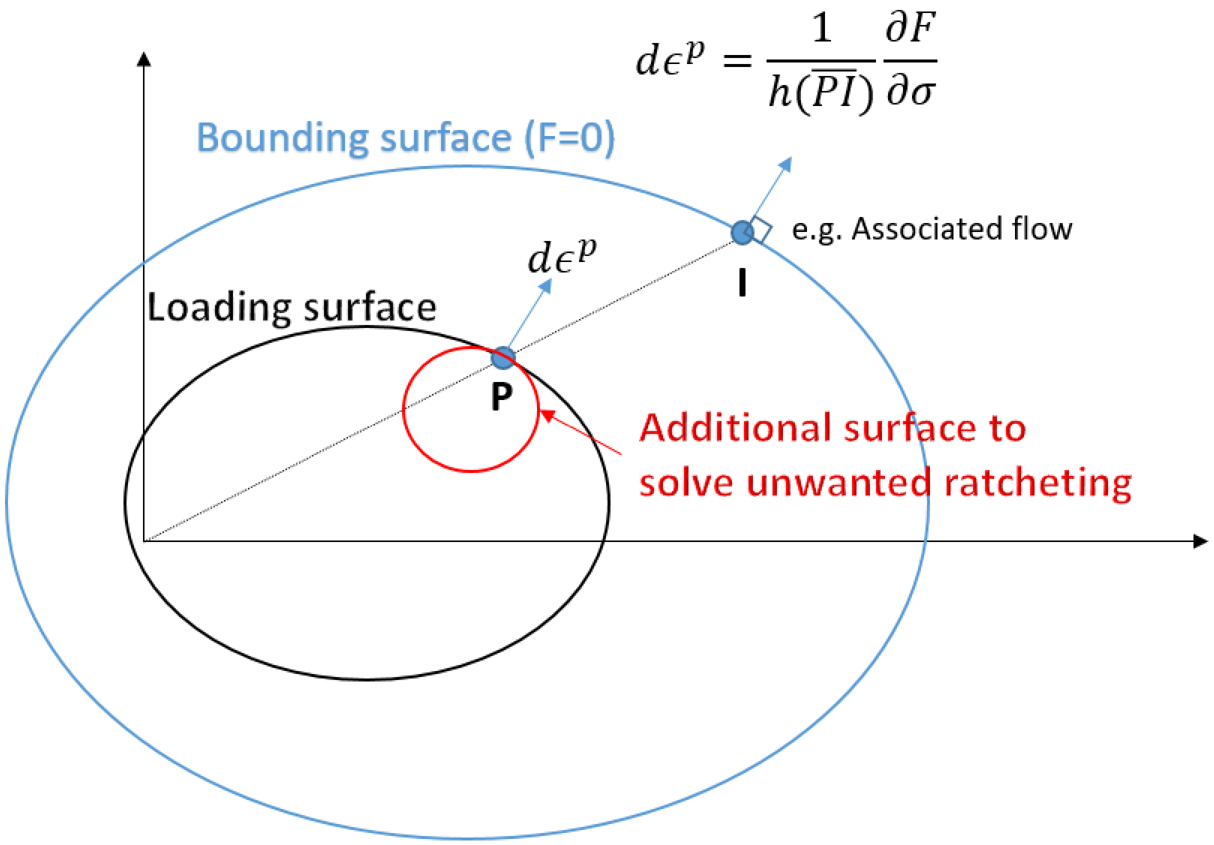
Simple example:

$$\dot{\sigma} = E\left(1 - \frac{\sigma}{\sigma_{max}} S(\dot{\epsilon})\right)\dot{\epsilon}$$

Work on the integration of memory/historiotropy in the models:

- Integrates an intergranular concept for cyclic loading (to avoid unwanted ratcheting),
- new models integrate anisotropy (AVISA by Tafili *et al.* for clay, current work by Mugele *et al.* for sand).

Constitutive modelling approaches: Bounding surface

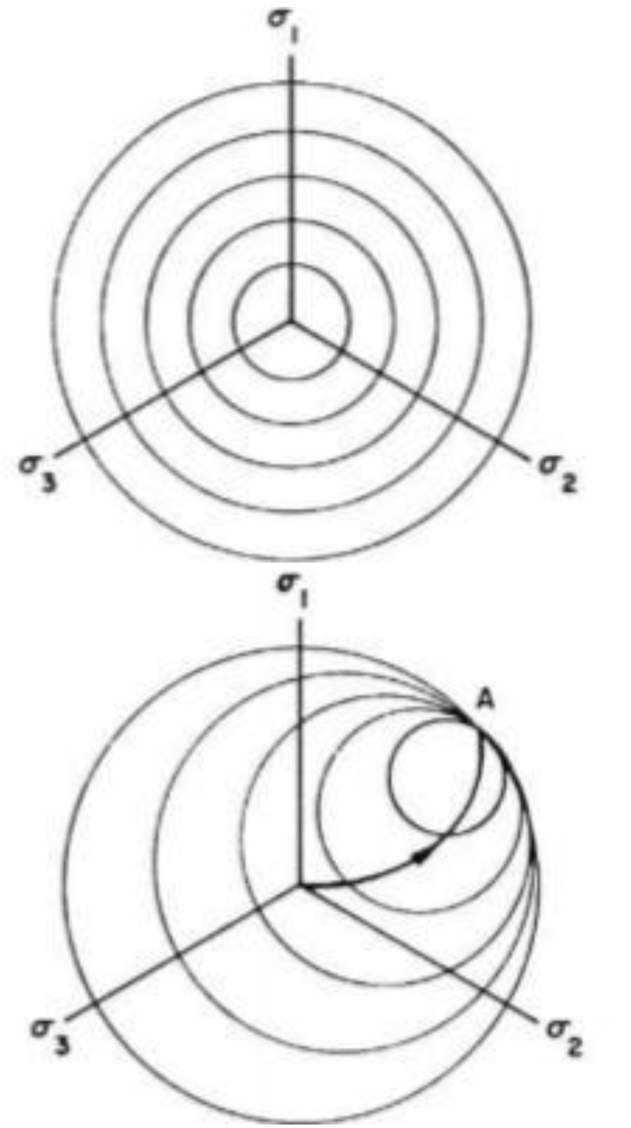


- A single bounding surface defines the outer limit of possible stress states.
- Stress points inside the surface may still generate plastic strains (unlike classical plasticity).
- The plastic modulus (h) depends on the distance between the stress point and the bounding surface → smooth transition to plastic behaviour.

Addition of a <u>memory surface</u>: introduces an internal surface that records past stress excursions → improves cyclic prediction (ratcheting).

Examples of models: SANISAND family (Z, MS, MSf), PM4SAND.

Constitutive modelling approaches: Multi-surface plasticity

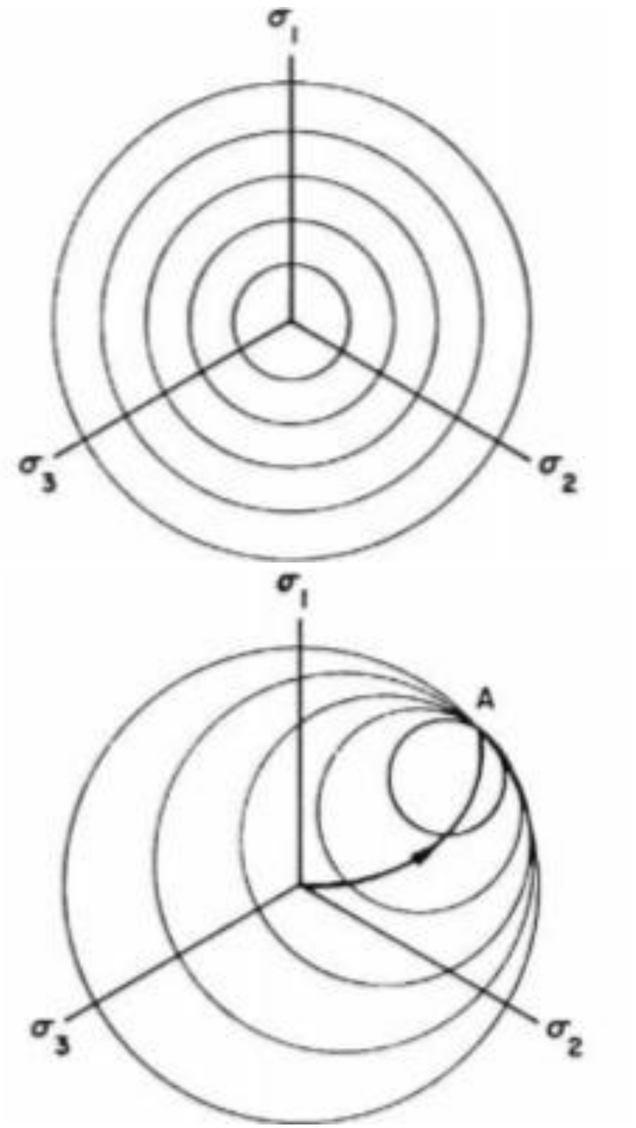


Source: Krabbenhoft (2019)

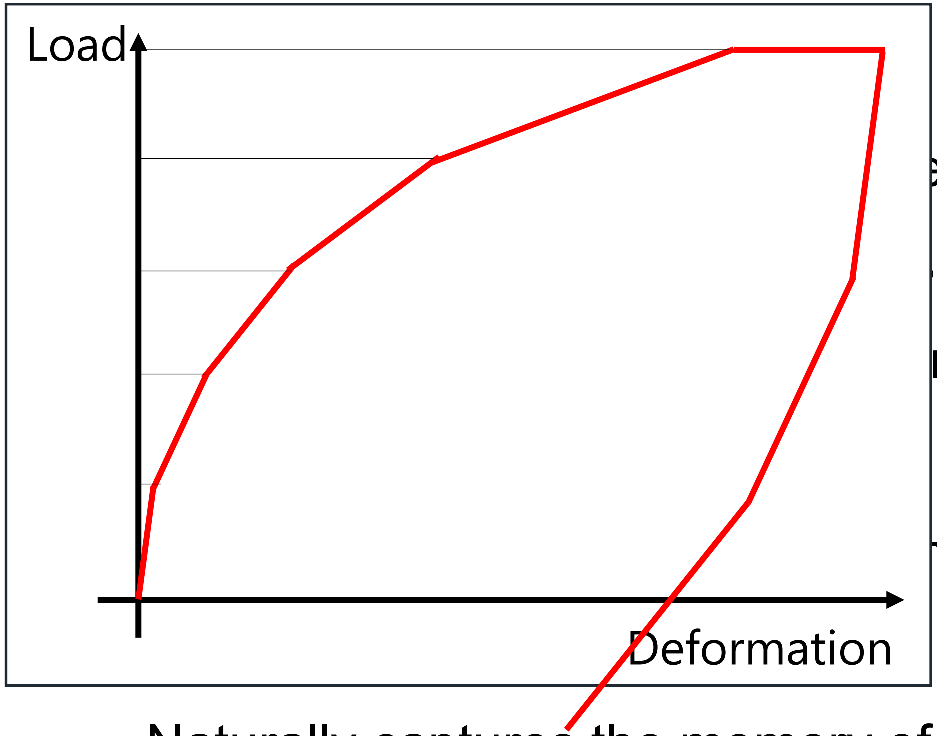
- Replaces the single yield surface of classical plasticity with a series of nested (<u>or not</u>) yield surfaces.
- As loading progresses, the stress point activates successive surfaces, approximating a smooth nonlinear stress–strain curve.
- Enables reversible plasticity when load reverses (Bauschinger effect).
- Naturally captures the memory of the ground by its natural propension to remap the stress space.

Example of a recent model: HySand (Simonin, 2025)

Constitutive modelling approaches: Multi-surface plasticity



Source: Krabbenhoft (2019)



of classical plasticity

eld surfaces.

point activates

ng a smooth nonlinear

n load reverses

- Naturally captures the memory of the ground by its natural propension to remap the stress space.

Example of a recent model: HySand (Simonin, 2025)

Monopile: Cyclic design

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The Role of Geomechanics in the Energy Transition

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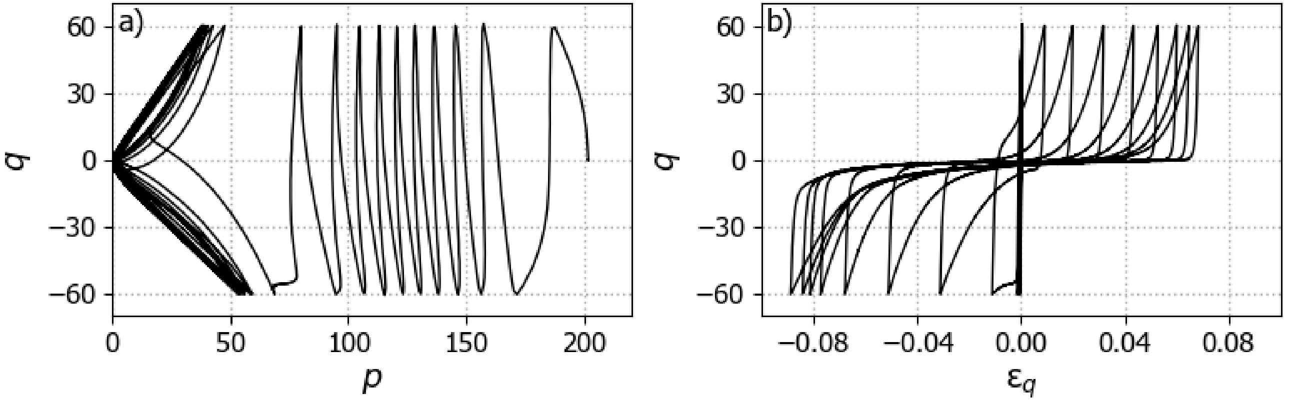
Multi-surface plasticity: calibration exercise

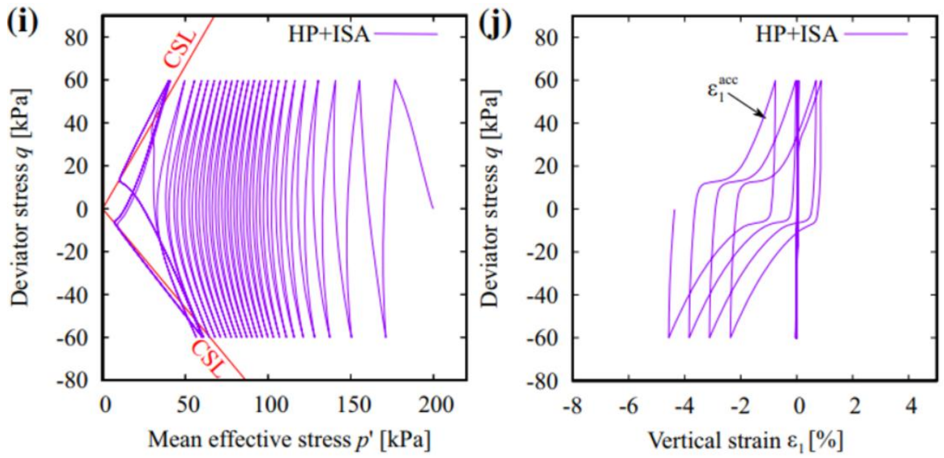
To match a monotonic loading curve, the students can play around with:
Ultimate strength
Hardening moduli
Number of surfaces

https://alert20252.streamlit.app/

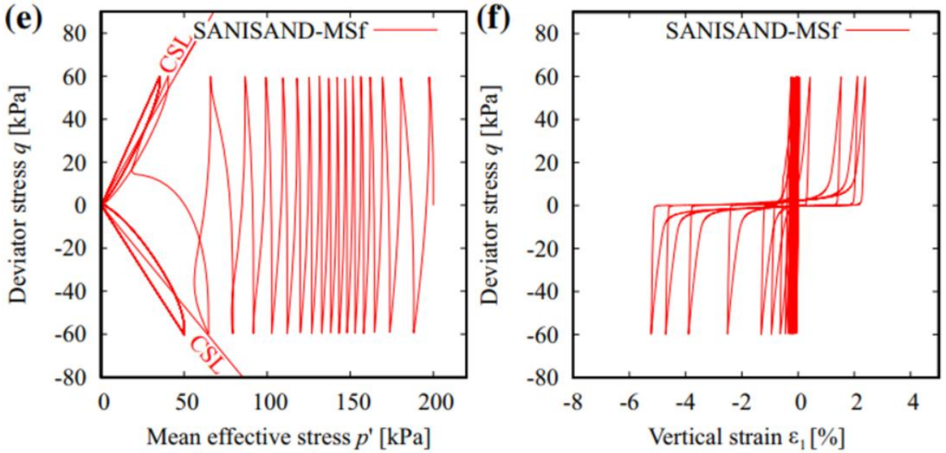
Performance of advanced models for sand cyclic loading



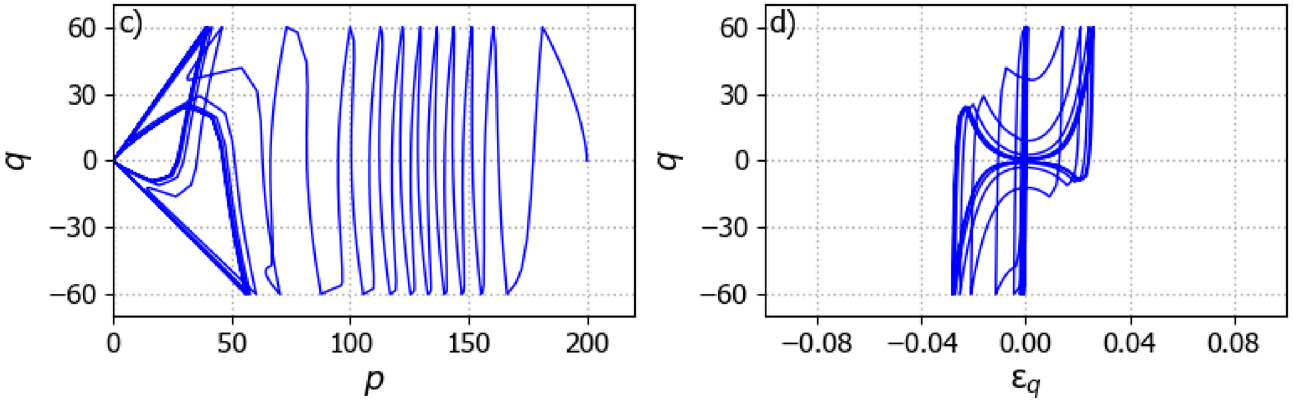
Data (Source: *Wichtmann's website*)



HP+ISA (Source: *Duque et al. (2022)*)



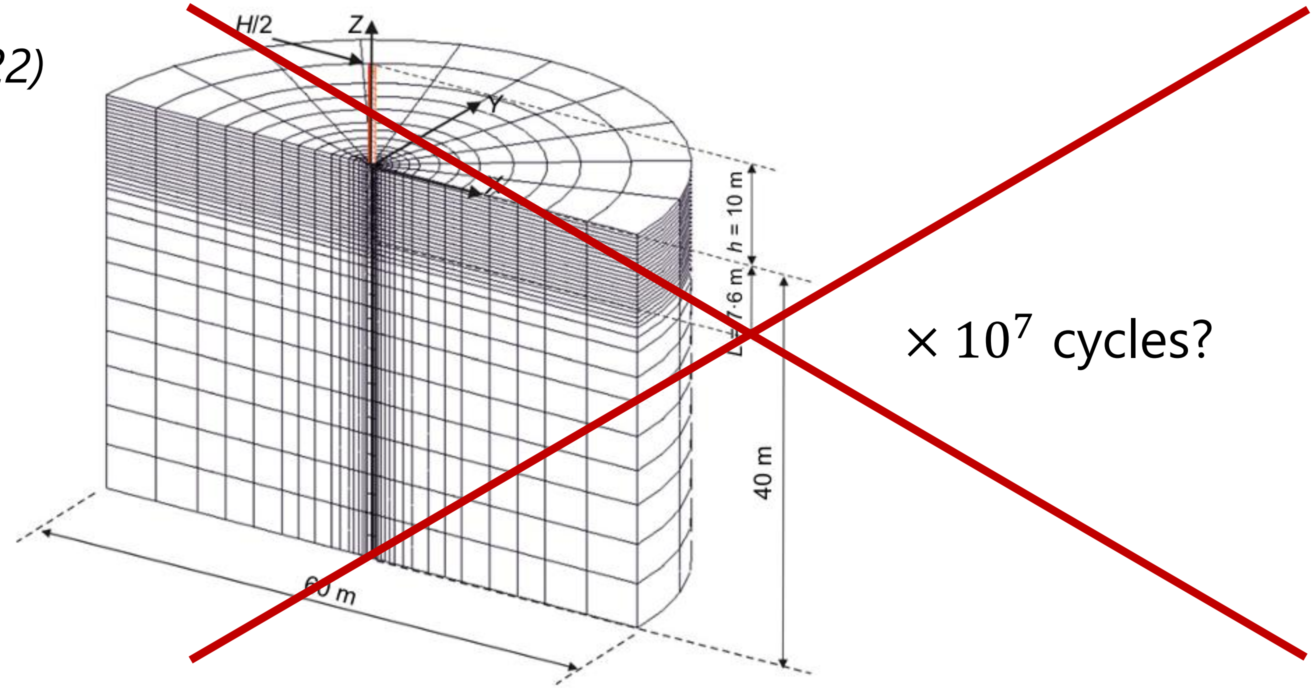
SANISAND-MSf (Source: *Duque et al. (2022)*)



HySand

3D FE of cyclic loading?

Source:
Zdravković et al. (2022)



$\times\ 10^7$ cycles?

You cannot model millions of cycles…

- Calculation cost
- Accumulation of numerical errors
- Accumulation of constitutive behaviour errors?

So… how do we infer the cyclic behaviour of an OWT foundation?

Monopile: Cyclic design

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The Role of Geomechanics in the Energy Transition

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Learn through the monitoring of the structures?

Developers (owners of wind parks) are very protective of data… but we know for example that observed the 1st natural frequency to be 5% to 20% higher than designed (*Kallehave et al. 2015*).

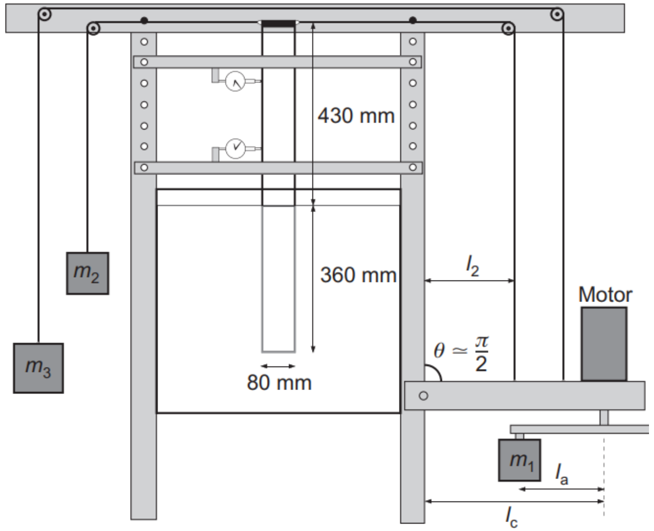
Experimental approach: scaled modelling (1g, small scale)

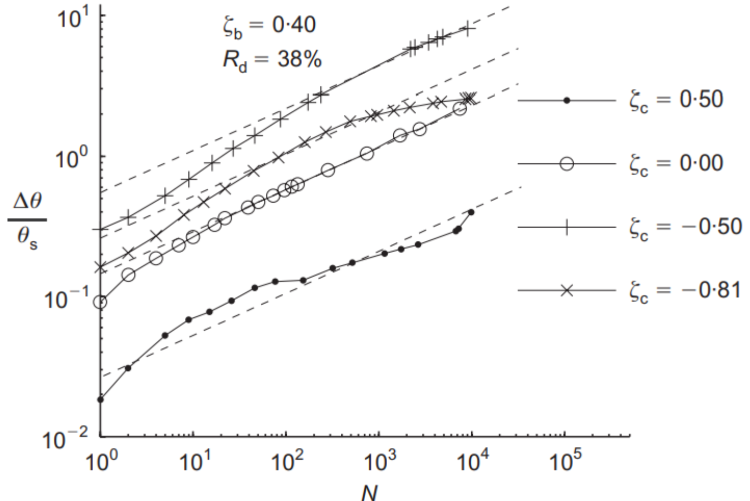
Advantages: you can tackle complex problems at a low cost, explore a large range of conditions, and determine global trends, soil structure interaction.

Disadvantages: scaling problems, boundary problems, good for macro-observation but harder for meso- or micro-phenomena, hard to generalize(e.g. how to deal with a pseudo-random loading different from the one tested).

Examples: see Bakri (2021) for a large list of 1g scaled modelling on OWT lateral loading.

Leblanc, 2010 (ratcheting)





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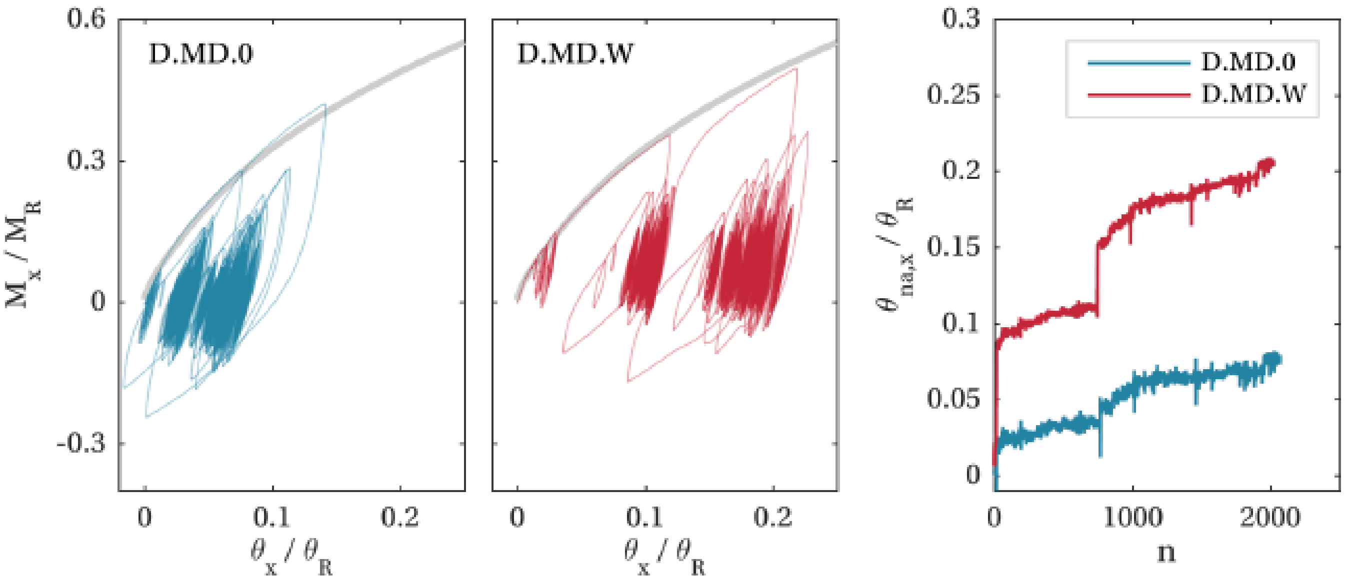

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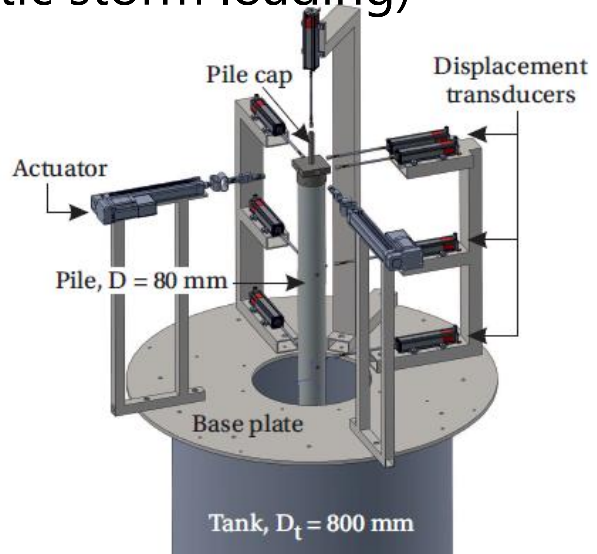
Richards, 2019 (multi-directionality, realistic storm loading)



Experimental approach: scaled modelling (medium scale)

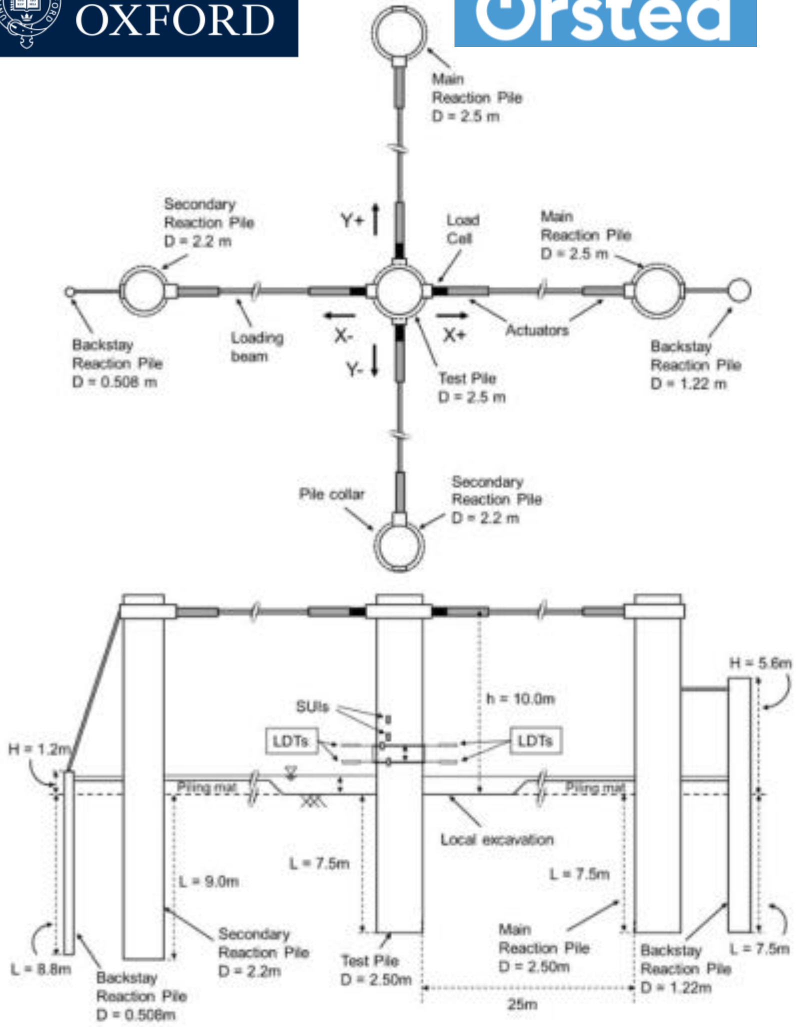


Figure 4. Schematic for large diameter multi-directional cyclic test (P09).

PICASO: cyclic testing of medium diameter piles (up to $\emptyset 2.5m$). Mono- and multi-directionality, harmonic and pseudo-random, partial one-way to two-way.

Here illustrated for the sand site, also done in clay.

Source: *Byrne et al. (2025)*

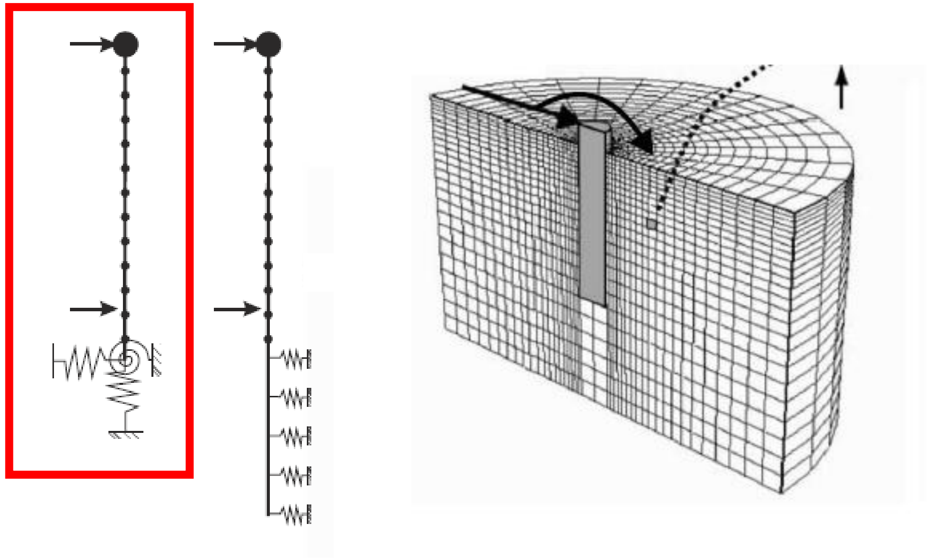
Modelling strategies

Simple ratcheting laws obtained from scaled models: can you trust them? What about dynamic properties? What about complex storm loading?

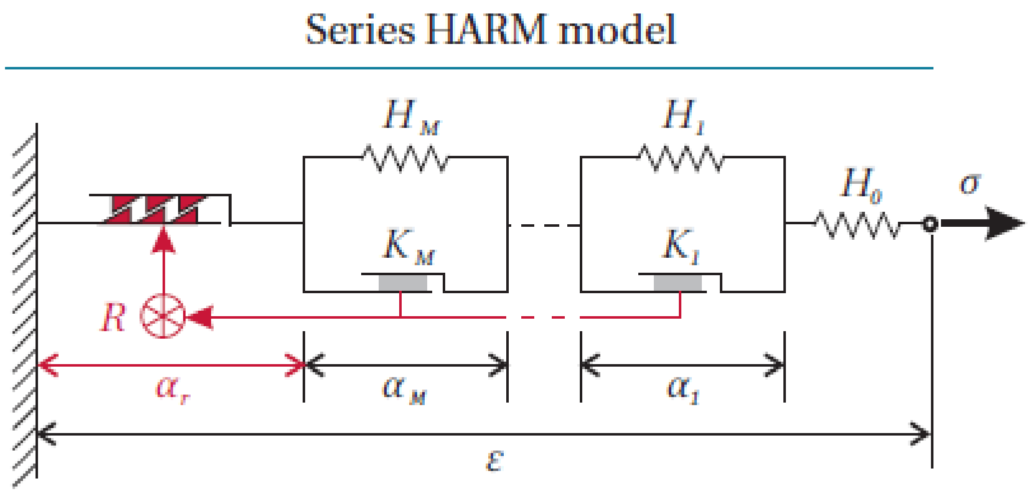
Macro-models: Interpret the load-displacement, or moment-rotation, with a constitutive law.

Advanced modelling strategies.
Intermittent FE with HCA, contour models, or laws for ratcheting, anisotropy, consolidation
Informed by micro-mechanics (anisotropy? Ratcheting?)

Modelling strategies: macro-models



Source: *Abadie (2015)*



Source: *Houlsby et al. (2017)*

Macro-models (HARM, REDWIN, CLAP) are efficient, but:

- Treat response as one constitutive relation.
- Hard to calibrate and generalise (geometry, soil variability, multidirectional loading).

Note: this kind of constitutive law could also be done at a Winkler-type level (p-y).

Modelling strategies: contour diagrams

Concept:

- DSS undrained tests → Represent cyclic soil response via a **diagram of displacement /rotation contours** as a function of load amplitude and number of cycles. (also dynamic properties evolution).
- Each contour = threshold of accumulated deformation.
- Use these to inject accumulated strains (and change of dynamic properties) in FE model.

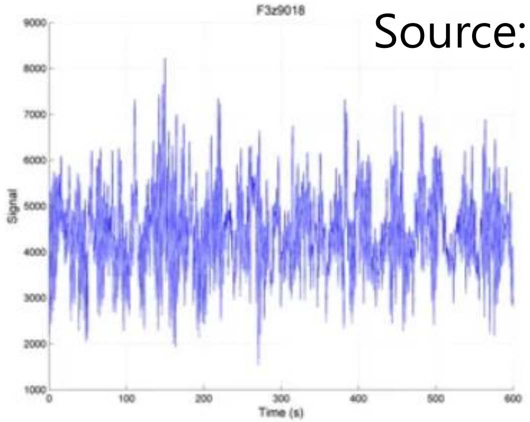
Advantages:

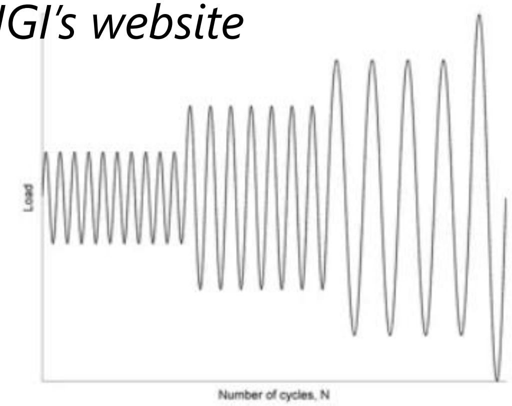
- “Simple” visualisation of soil response.
- Relies on experimental data.

Disadvantages:

- Strongly empirical, limited extrapolation to new geometries/soils.
- Hard to extend to **multidirectional, irregular loading**.
- Not mechanistic: does not provide full insight into soil behaviour, nor soil structure interaction

Source: *NGI’s website*





Converting pseudo-random loading into equivalent harmonic load packets.

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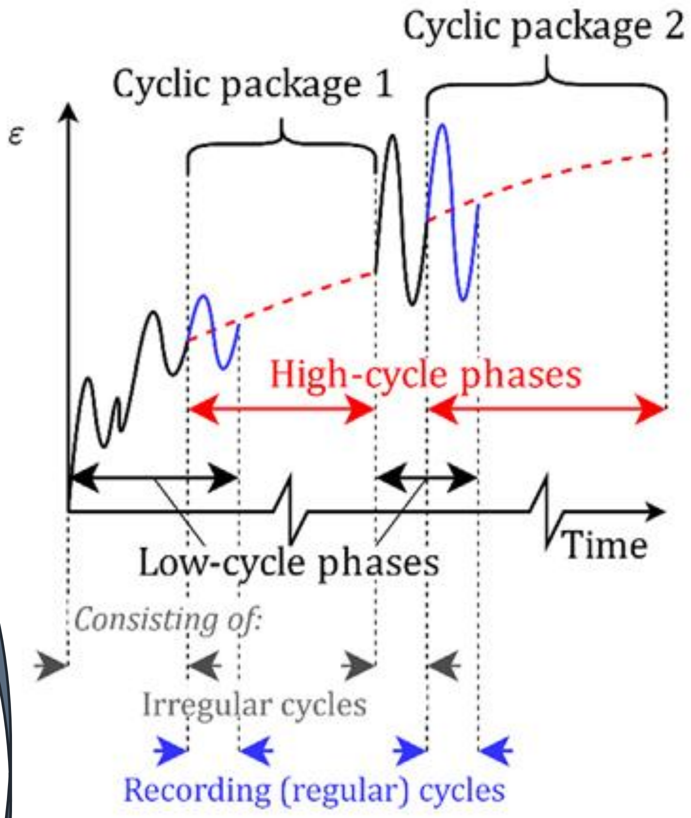
Modelling strategies: explicit/implicit FE

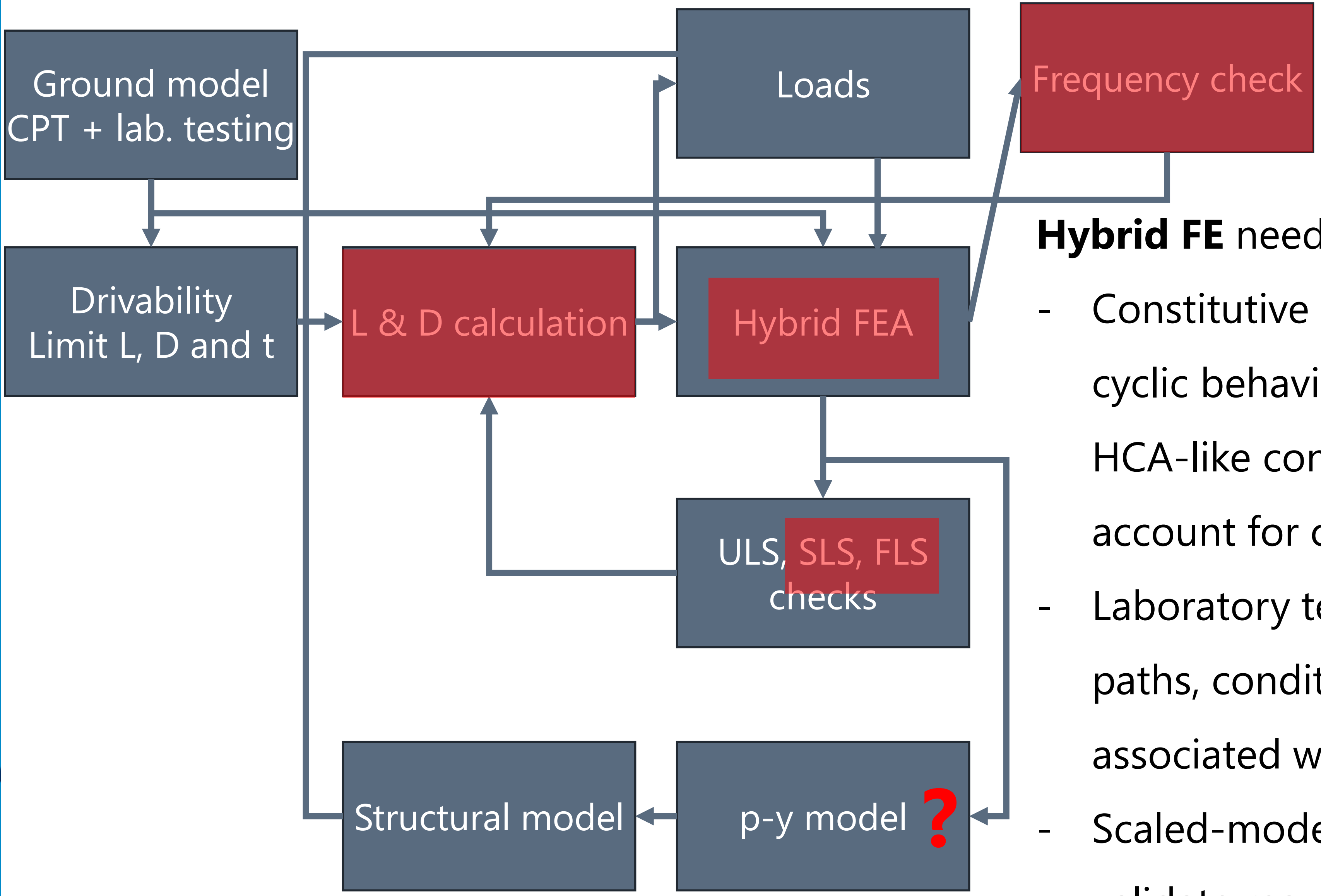
Using an FE model, but does not simulate millions of cycles cycle-by-cycle:

- set-up the boundary value model with an adequate constitutive model.
- Simulate few cycles (low-cycle phase).
- Identify the cyclic characteristics of the loading in each element and extrapolate (laws based on stress state, density, amplitude of cyclic strain, and a measure of the cyclic history the accumulation of strain in each element through several cycles (high-cycle phase).
- Update the constitutive model internal variables (~~or parameters~~) such that it “experienced” the cycles.
- Repeat!



Schematic of HCA framework (Niemunis *et al.*, 2005), source: *Tantivangphaisal et al. (2025)*

Still an active research area!



Hybrid FE needs:

- Constitutive models able to capture cyclic behaviour and compatible with HCA-like concepts (update model to account for cyclic history).
- Laboratory testing exploring stress paths, conditions, and soils associated with the loading.
- Scaled-modelling (or real data) to validate results.

Lecture structure

Context and Definitions	Design of monopiles: Monotonic lateral loading	Design of monopiles: Cyclic lateral loading	Monopile installation with vibratory driving
Application domains	$p-y$ curves	Challenges	Principles
Significant examples	PISA approach	Old practice	Example of research
Vocabulary	Interactive exercise	Modelling strategies	New research?
		Interactive exercise	
		Current research	

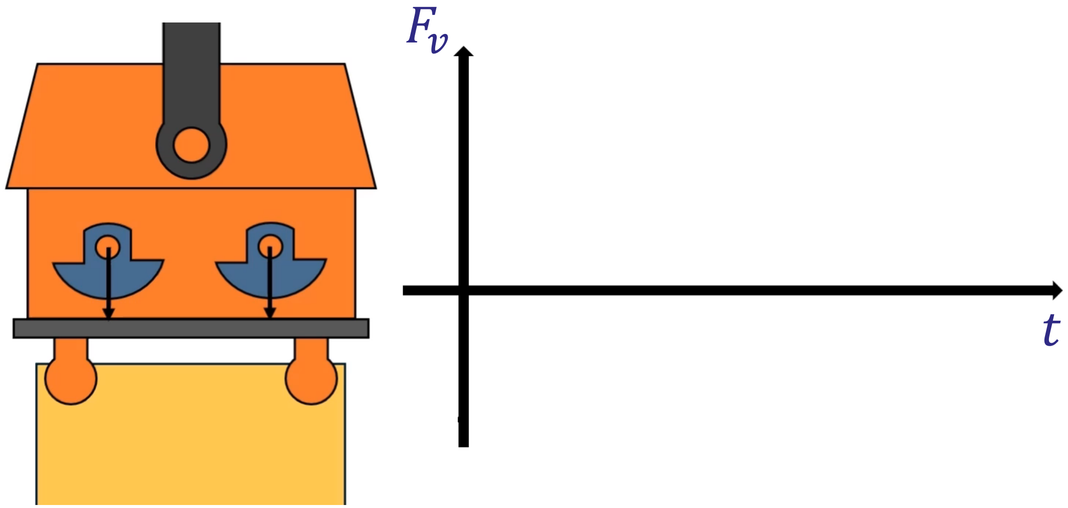
Vibratory-driving

Credit: *CAPE Holland*

Vertical harmonic force: $F_v = \mathrm{M_e}\omega^2 \sin \omega t$

- M_e eccentric moment
- $\omega = 2\pi f$ angular velocity
- f vibration **frequency (10-50 Hz)**

Total duration ~ 30min

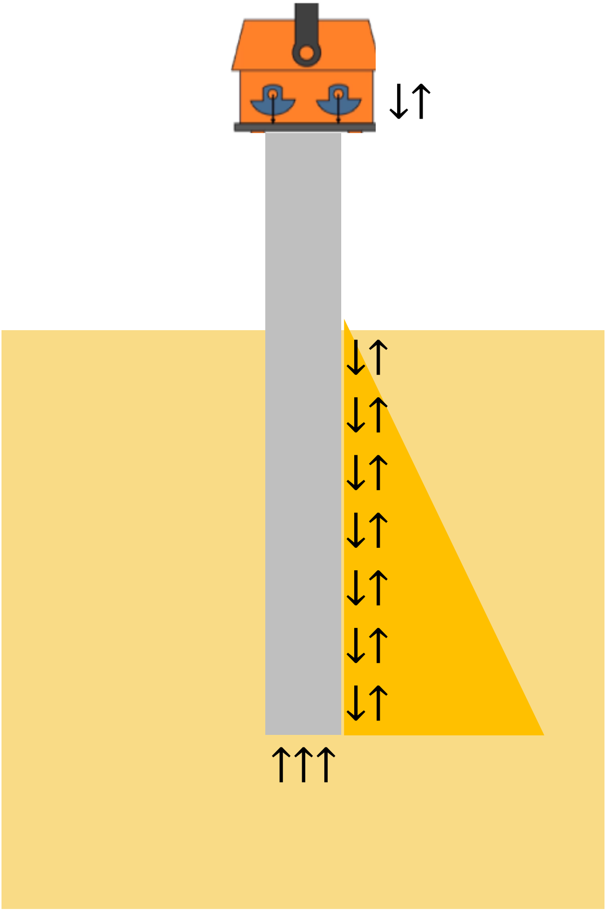


Credit: *Pauline André*

Vibratory-driving alters the resistance of the ground

Vibratory-driving alters the resistance of the ground:

- Friction reduction
- Densification
- Stress redistribution



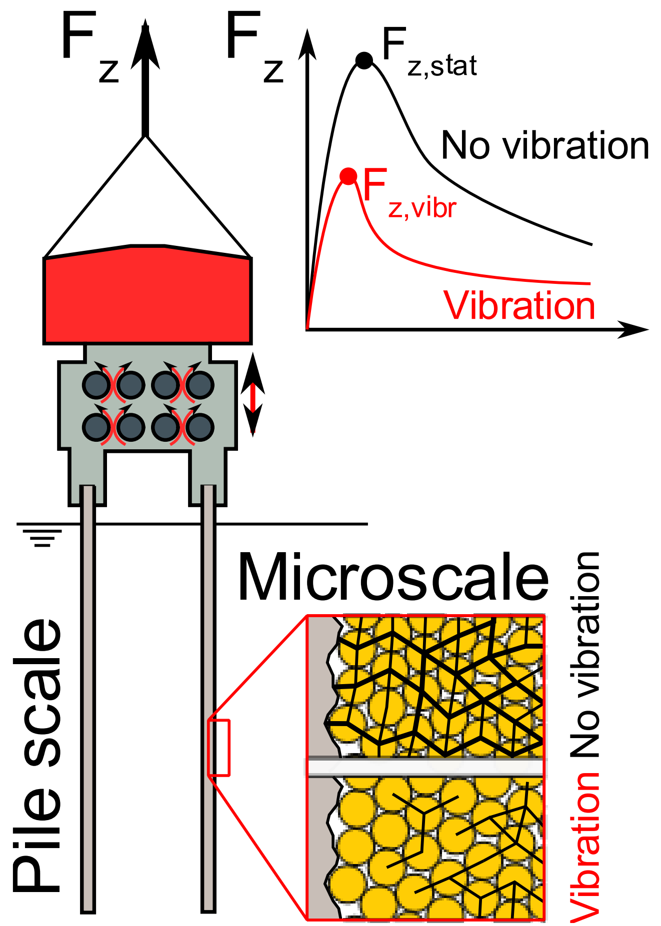
Driveability models:

HyperVib: looking at force equilibrium between vibration force, self weight, and degraded soil resistance based on the ratio between vibration force and resisting forces (iterative).

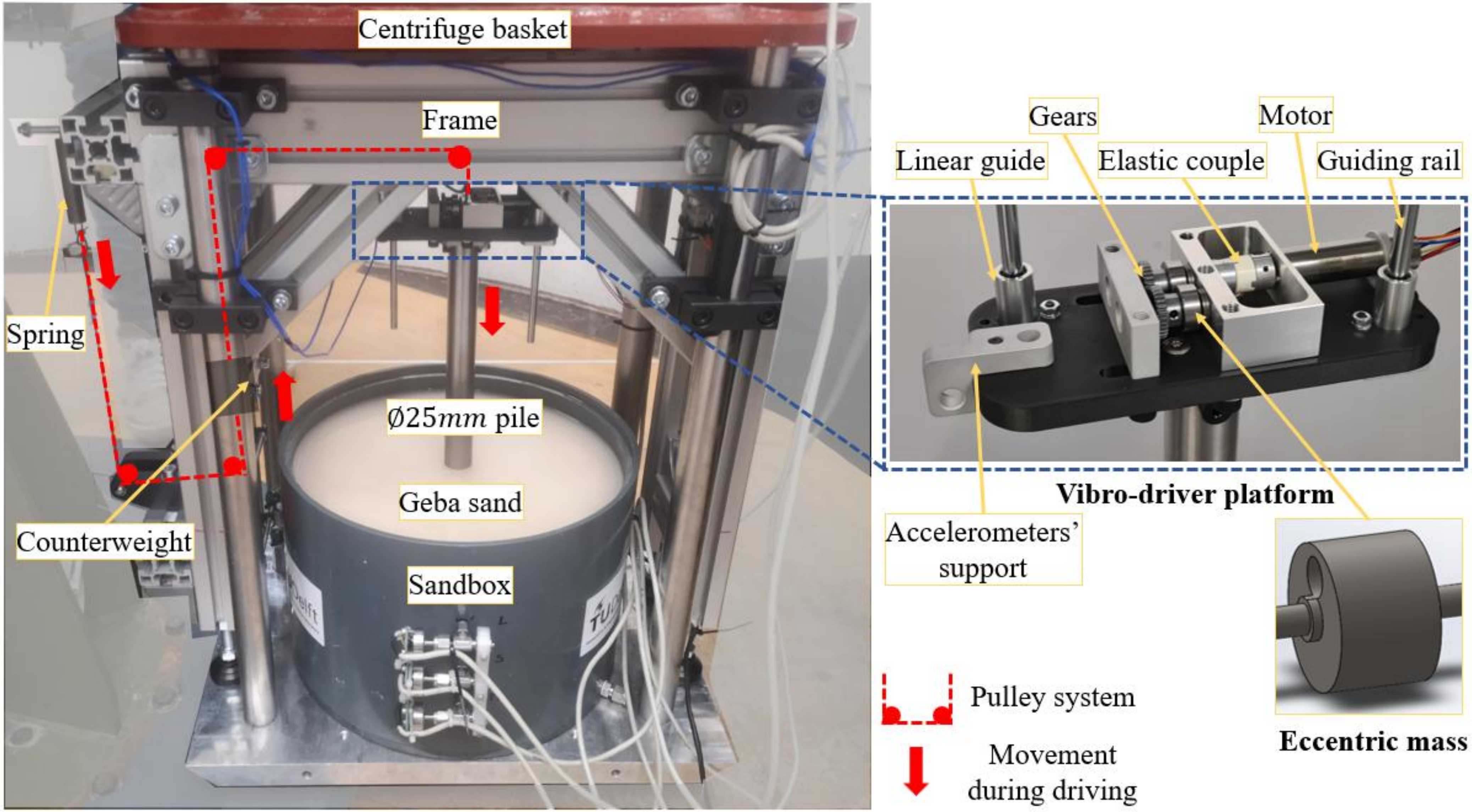
Liquefaction vs Fluidisation

Pore pressure generation diminishes the effective stress, thus the strength.

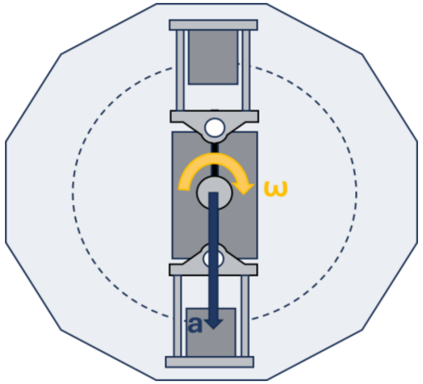
But, in dry sand, we have a similar diminution of soil resistance -> fluidisation.

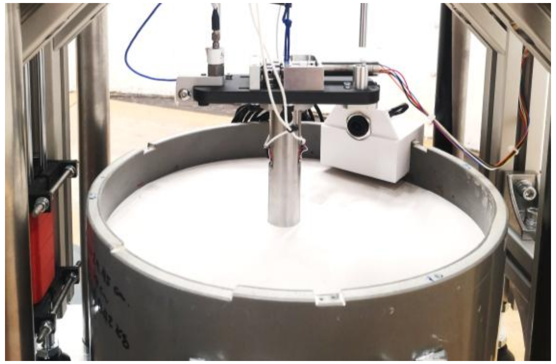


FoundEx project: centrifuge set-up

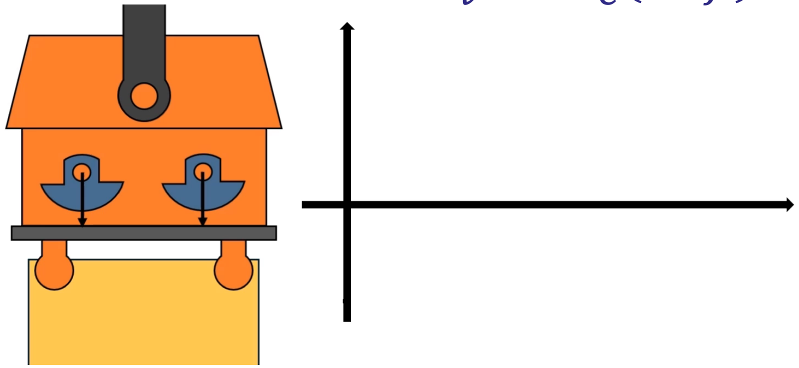


Influence of vibratory parameters: FoundEx project



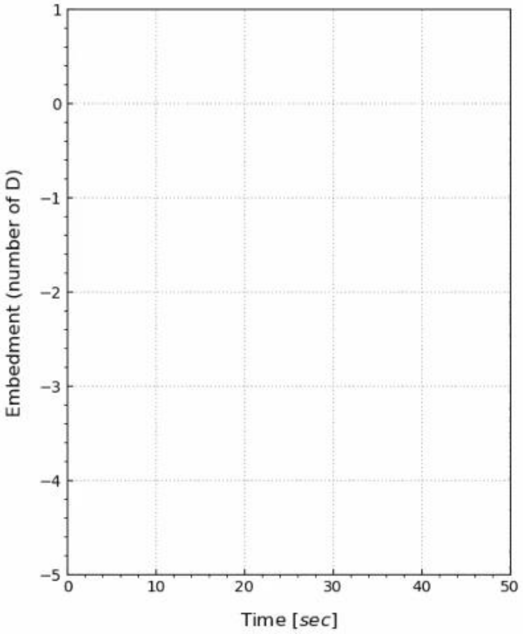


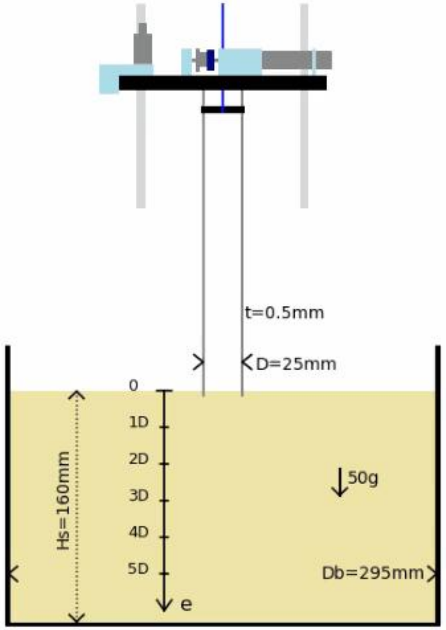
$F_v = \mathrm{M_e}(2\pi f)^2$



Scale	Acceleration	Sample dimensions	Pile dimensions	Vibratory driver properties	
Prototype	g	$\varnothing 14.75m$ $h = 8\mathrm{m}$	$\varnothing 1.25m$ $\mathrm{t} = 25\mathrm{mm}$	$M_e = 25kg.m$	$f = 20Hz$
Model	$50g$	$\varnothing 2950mm$ $h = 160\mathrm{mm}$	$\varnothing 25mm$ $t = 0.5\mathrm{mm}$	$M_e = 4g.mm$	$f = 1000Hz$

Influence of vibratory parameters: FoundEx project





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	ULS design	Interactive exercise:	
		Multi-surface plasticity	
		Current research	

Key messages

Cyclic loading can take many forms, with different: durations, frequencies, amplitudes, orientation, zone affected, soil types…

Most often, it involves multi-physics coupling: Hydro-Mechanical.

Cyclic loading requires multiple approaches to grasp its complexities and to be modelled: macro-approaches with small-scale modelling, constitutive and numerical modelling to grasp the meso-scale repartition, and micro-mechanics are at the heart of some cyclic phenomena.

Research challenges

Challenges emerge from the complex soil behaviour under cyclic loading and hydro-mechanical coupling (shear-volume dependence), and the varying nature of loadings.

Understanding and modelling cyclic lateral loading of OWTs is key to optimise their design and extend their lifetime.

Vibratory-driving and extraction are key to enable more sustainable practices and improve the life cycle of OW.

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02/10/2025

Thank you

Contact: luc.simonin@uclouvain.be