Sustainable Geotechnical Engineering: Bridging Research and Industry

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EPFL Laboratory of Soil Mechanics

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Acknowledgment of Contributions from NGI Colleagues

My Geo-Journey & TEA

Outline

- **Norwegian Geotechnical Institute (NGI)**
  Brief Introduction
- **Computational GeoMechanics (CGM)**
  Competencies, R & D, Consultancy…
- **Environments Beyond Earth**
  Laboratory/Virtual Testing, Calibration Chambers
- **Bridging Research and Industry**
  Selected Ongoing Projects
- **Some Remarks**
  Key Points, Key Actions

NGI

NGI in brief


NGI
Norges Geotekniske Institutt
Sognsveien 72
P


NGI
XTH 225 LC
NGI | Geotechnical laboratory

NGI Employees

(NGI Total, 2024)

3
continents

Theory

Total

372
permanently employed

46
nationalities

Male / Female

68%

32%

Education

PhD
36%

Uni
89%

BSc
10%

MSc
54%

Market areas

1. GeoData & Technology
2. Geotechnics & Environment
3. Natural Hazards
4. Offshore Energy

Offshore Energy

1. Computational Geomechanics
2. Energy Geomechanics and Geophysics
3. Geohazards and Dynamics
4. Offshore Geotechnical Characterisation
5. Offshore Geotechnical Design

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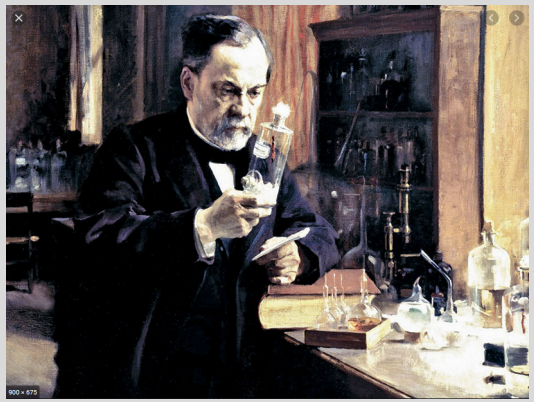
NGI Lab

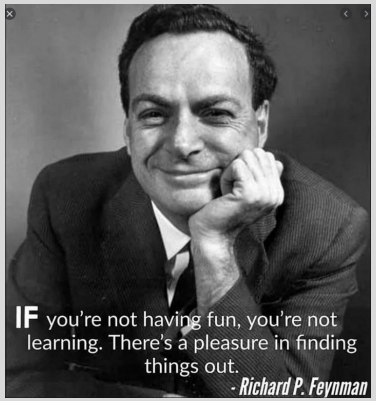
T.E

Theory Experiment



“Sans laboratoires les savants sont des soldats sans armes.”
— Louis Pasteur (1822-1895)

NGI lab, Blinderen 1955



“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.”
— Richard P. Feynman (1918-1988)

NGI lab, Oslo 2020

One of the largest geotechnical laboratories in the world

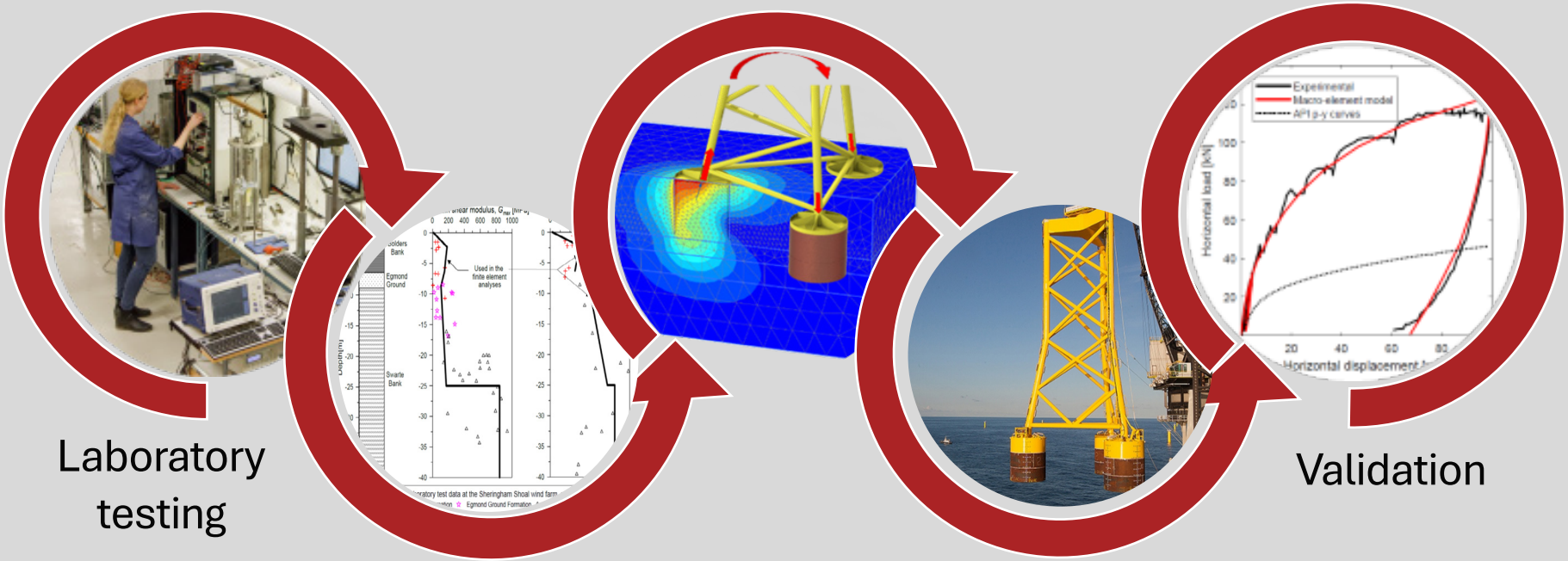
NGI

NGI - Fully Immersed in Geosciences

70 years of experience integrating geosciences

T.E.A

Theory Experiment Application



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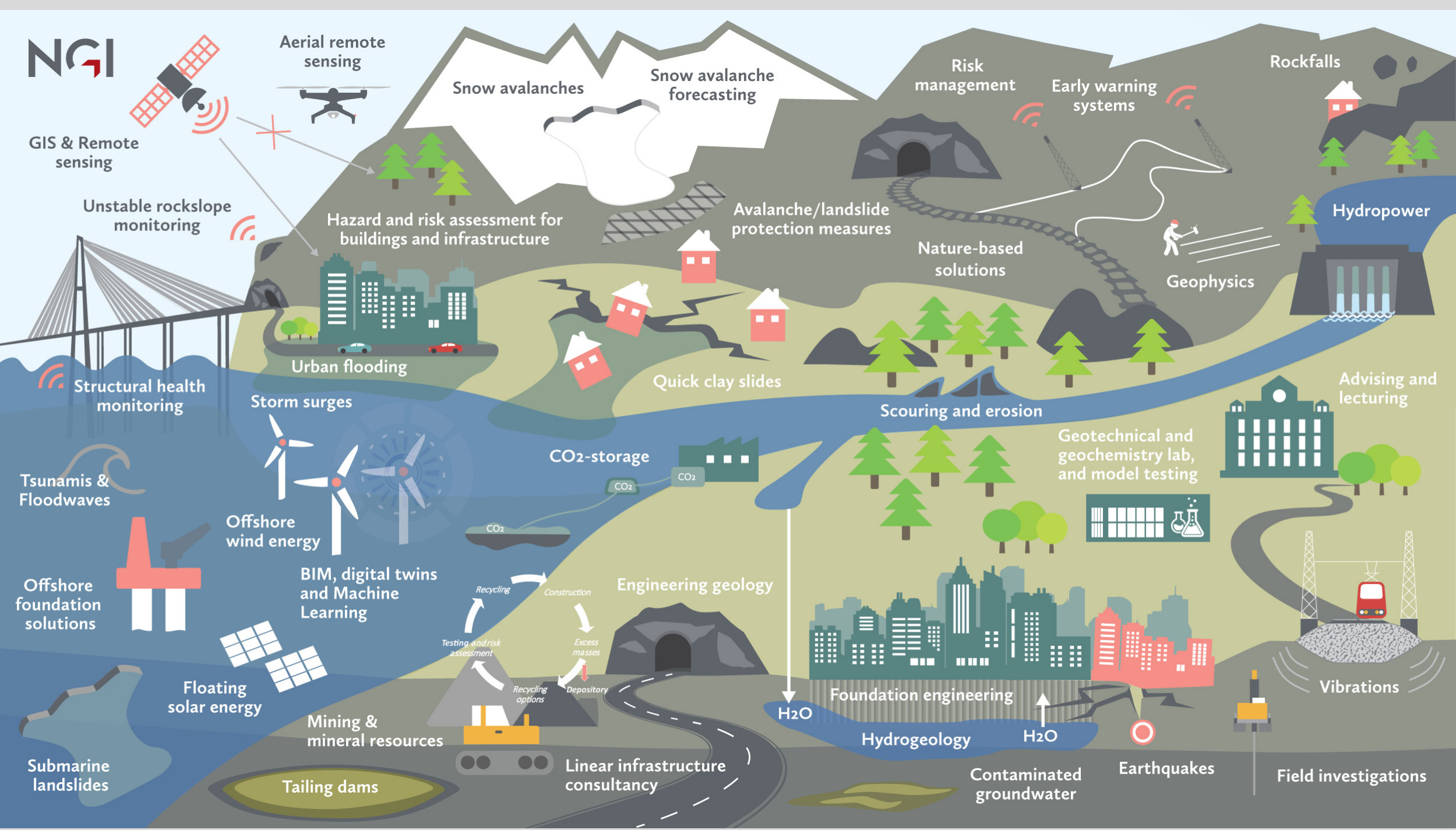
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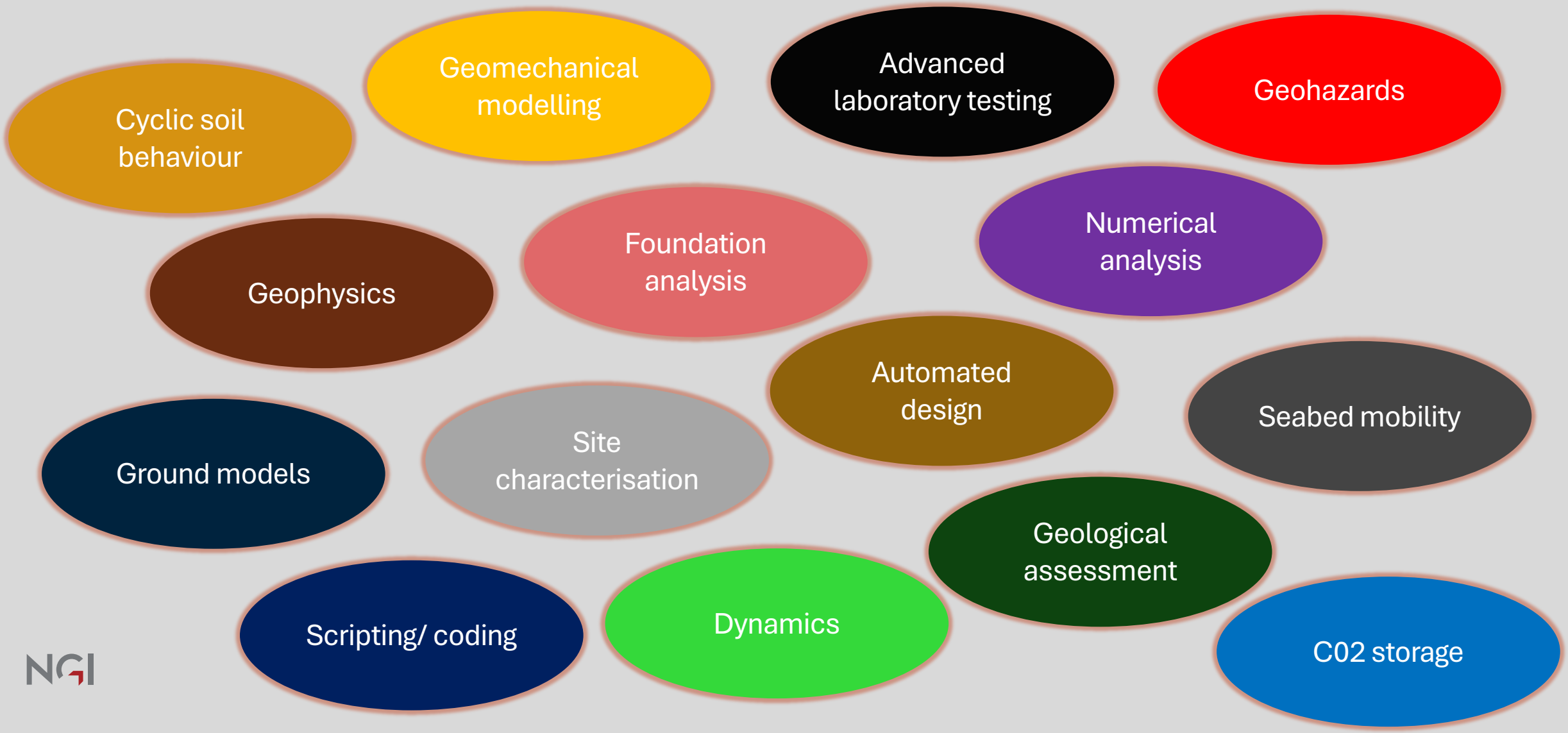
Aerial remote sensing
GIS & Remote sensing
Snow avalanches
Snow avalanche forecasting
Risk management
Early warning systems
Rockfalls
Unstable rockslope monitoring
Hazard and risk assessment for buildings and infrastructure
Avalanche/landslide protection measures
Nature-based solutions
Geophysics
Hydropower
Urban flooding
Quick clay slides
Structural health monitoring
Storm surges
Scouring and erosion
Advising and lecturing
Geotechnical and geochemistry lab, and model testing
CO2-storage
CO2
Tsunamis & Floodwaves
Offshore wind energy
BIM, digital twins and Machine Learning
Offshore foundation solutions
Recycling
Construction
Testing and risk assessment
Excess masses
Recycling options
Depository
Engineering geology
Floating solar energy
Mining & mineral resources
Foundation engineering
H2O
Hydrogeology
Vibrations
Submarine landslides
Tailing dams
Linear infrastructure consultancy
Contaminated groundwater
Earthquakes
Field investigations

Computational Geomechanics (CGM)

Overlapping/Complementary Skills and Resources



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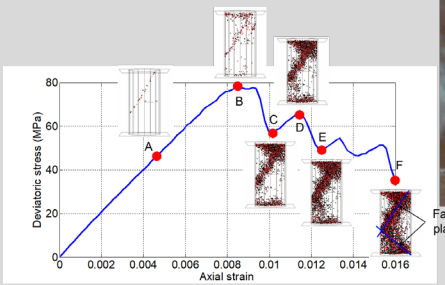
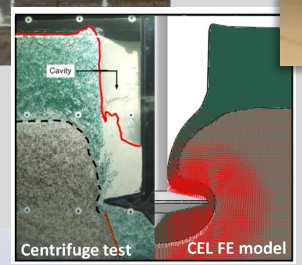
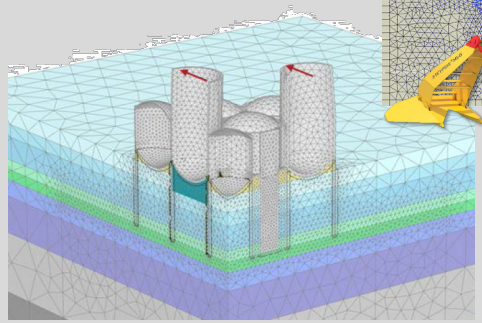
Project Snapshots

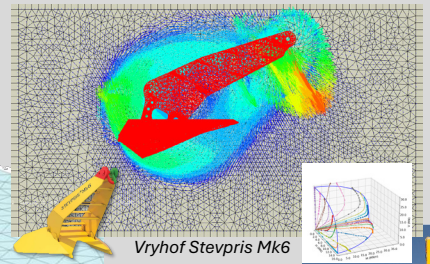


Red: shear failure, Black: tensile failure

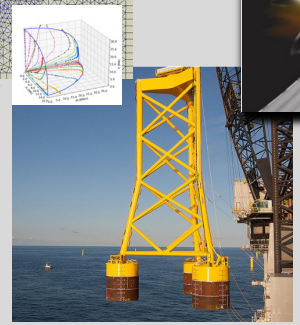
Failure planes

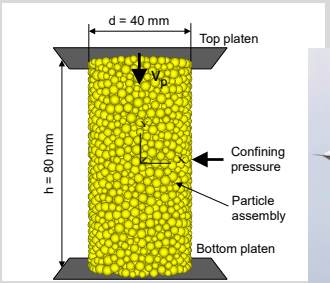


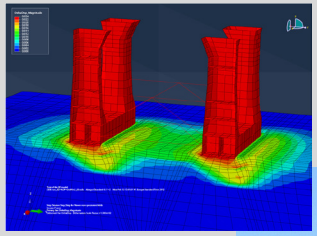


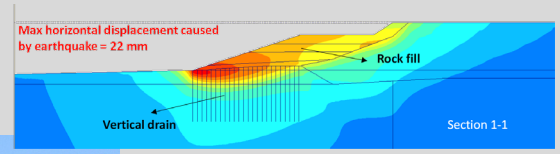


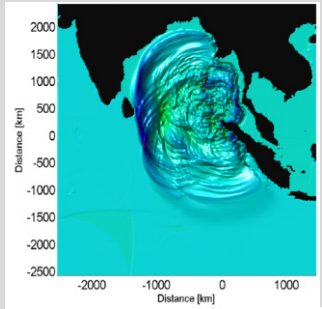
Vryhof Stevpris Mk6

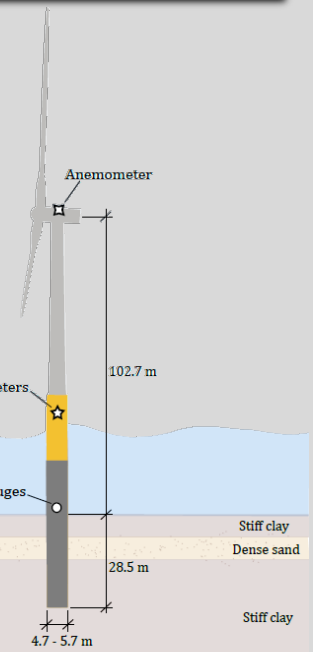


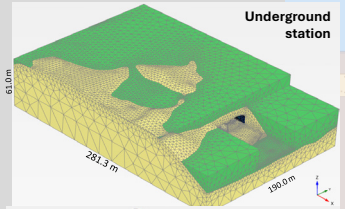


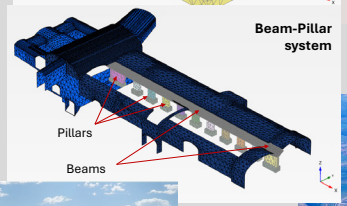


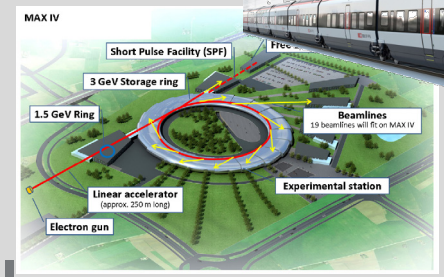


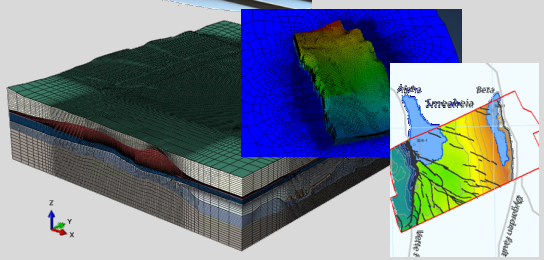


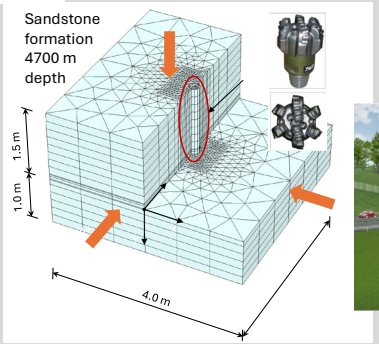












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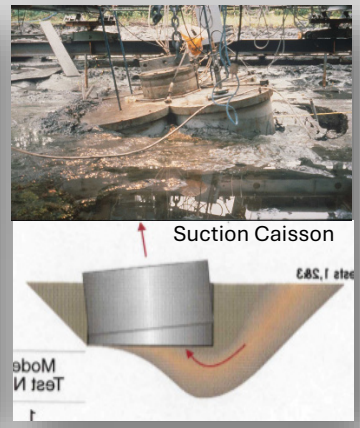
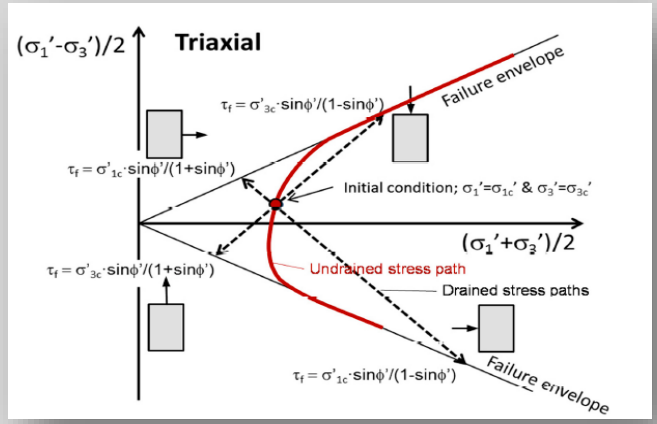
Core Services/Activities

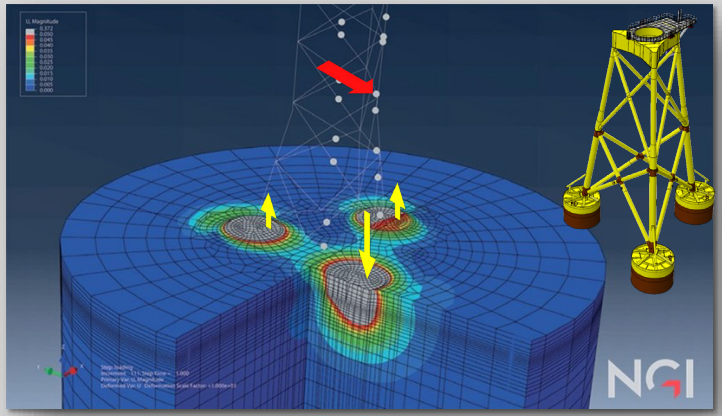
Interpretation of lab and model tests



Development of constitutive models



Advanced numerical modelling



Development of calculation tools

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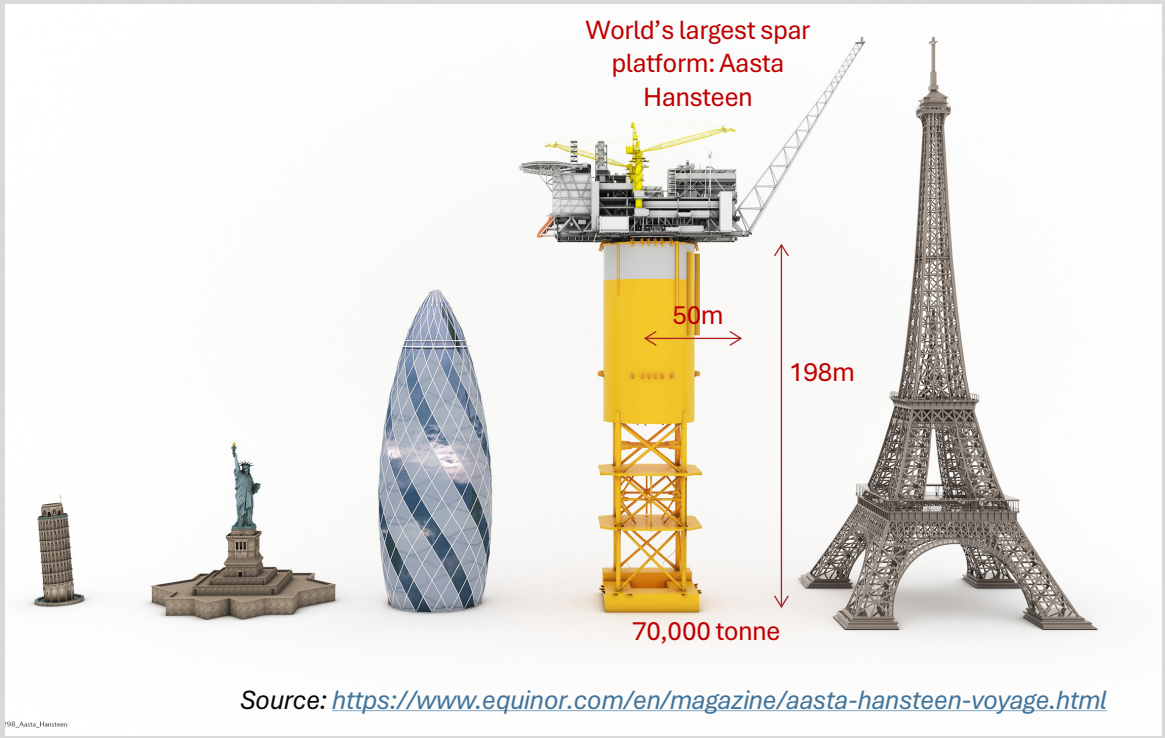
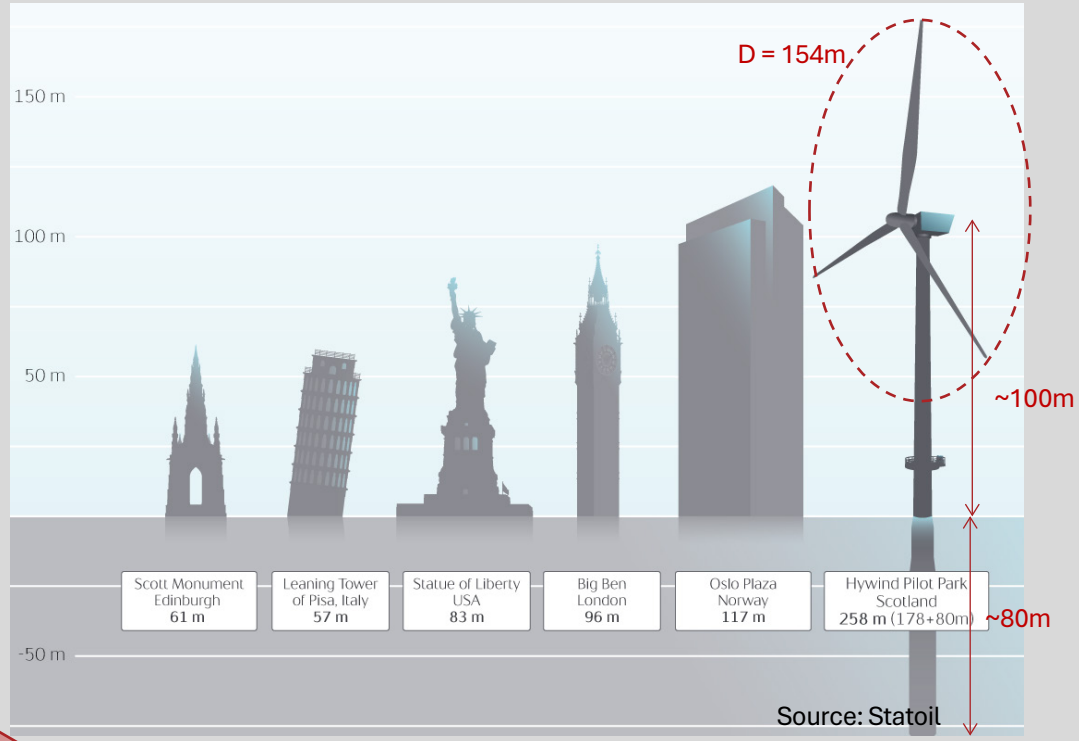
Offshore Energy: from Oil & Gas to Wind



Source: https://www.equinor.com/en/magazine/aasta-hansteen-voyage.html



TAILOR MADE

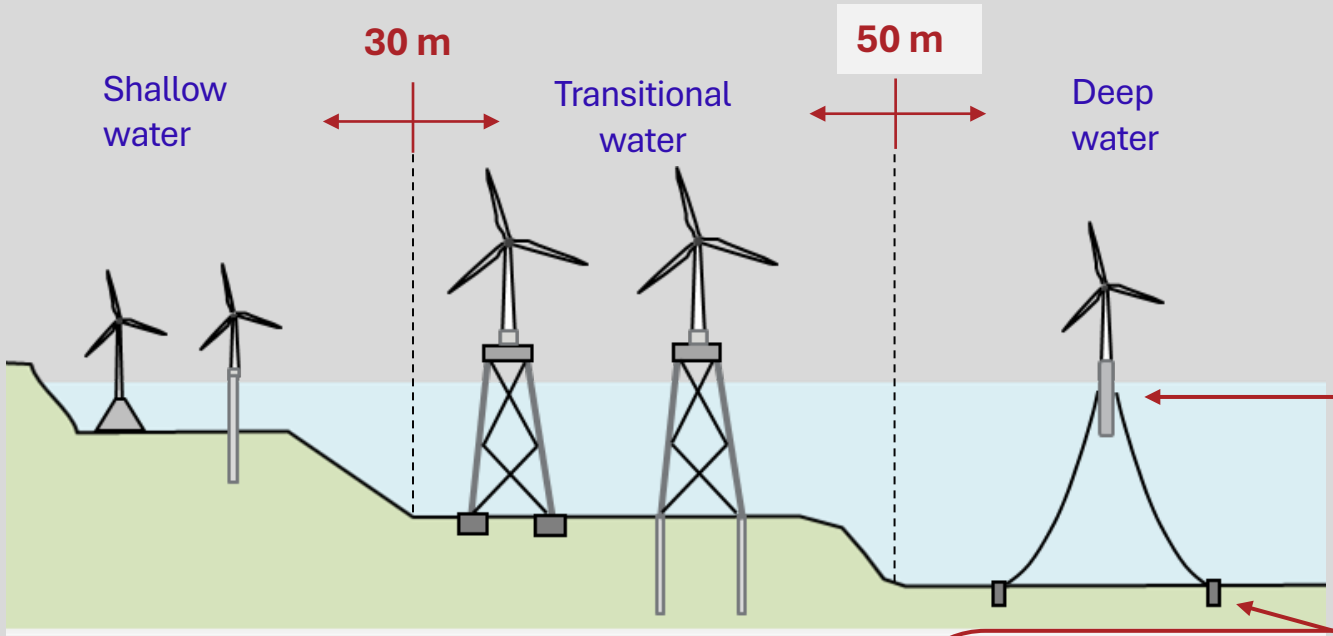
- Single structure (platform or buoy)
- Typically a large and robust structure
- Cyclic loads from waves dominates
- Designed to high HSE standard
- Large return of investment

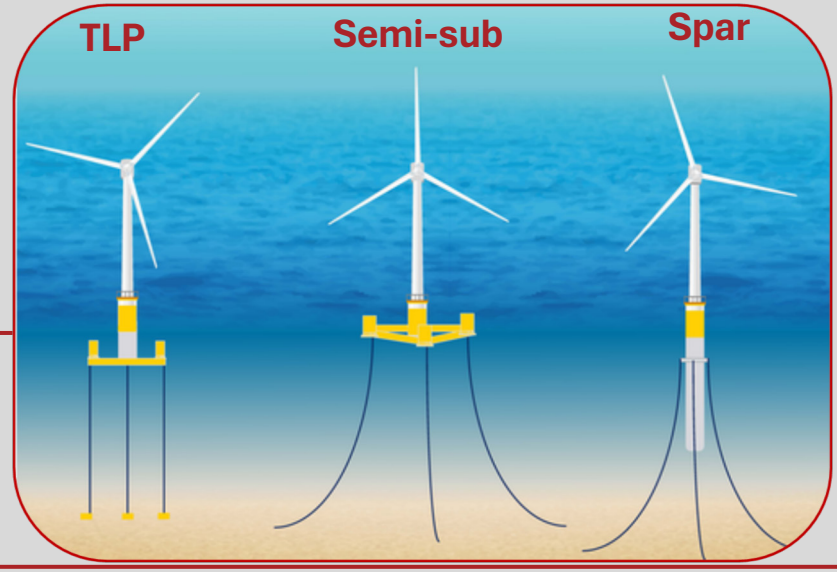
New philosophy and optimised workflows for field characterisation, design, fabrication & installation

MASS PRODUCTION

- Array of structures (OWTs)
- Typically slender structures
- Different dynamic characteristics
- Unmanned, so allow lower reliability
- Limited return of investment

Offshore Wind Turbine Foundations





Fixed

Source: Reuters/C. Charisius

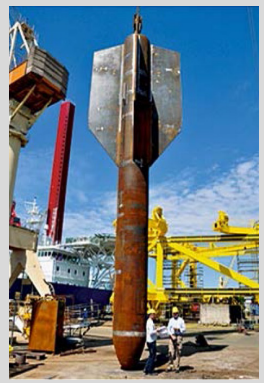
Source: SPT-07-2021-EN-Trackrecord

Floating

Suction anchors

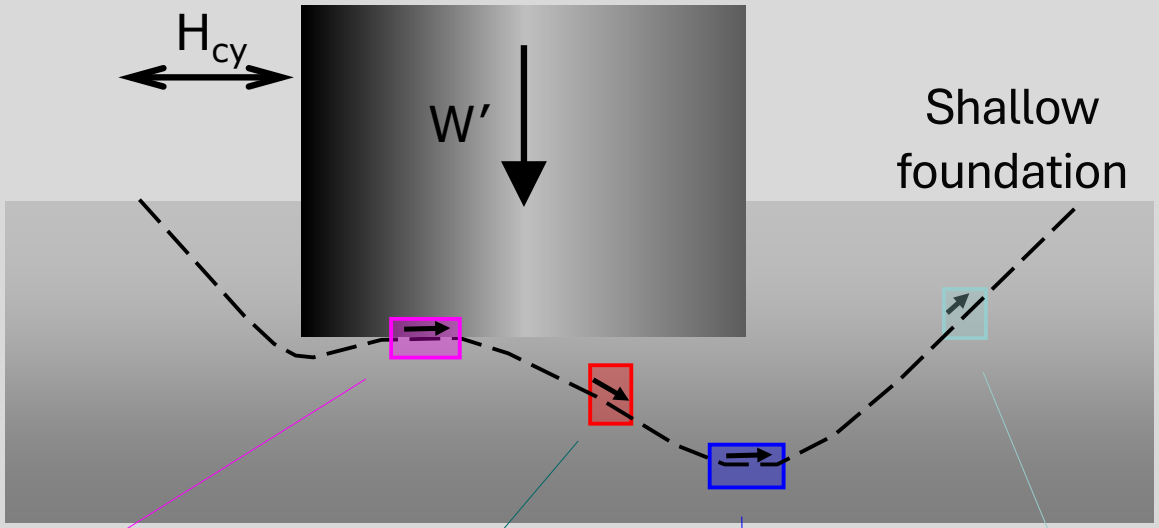
Pile anchors

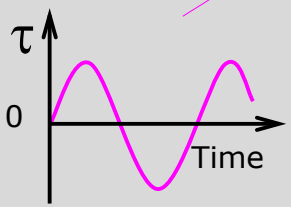
Drag anchors



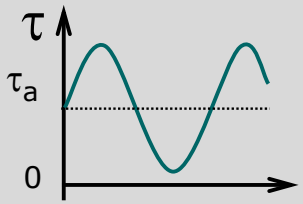
Torpedo anchors

Offshore Foundation Design

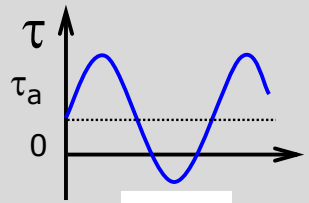




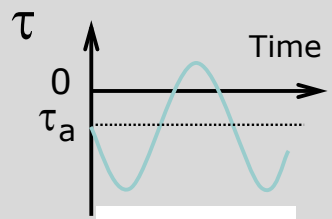
DSS



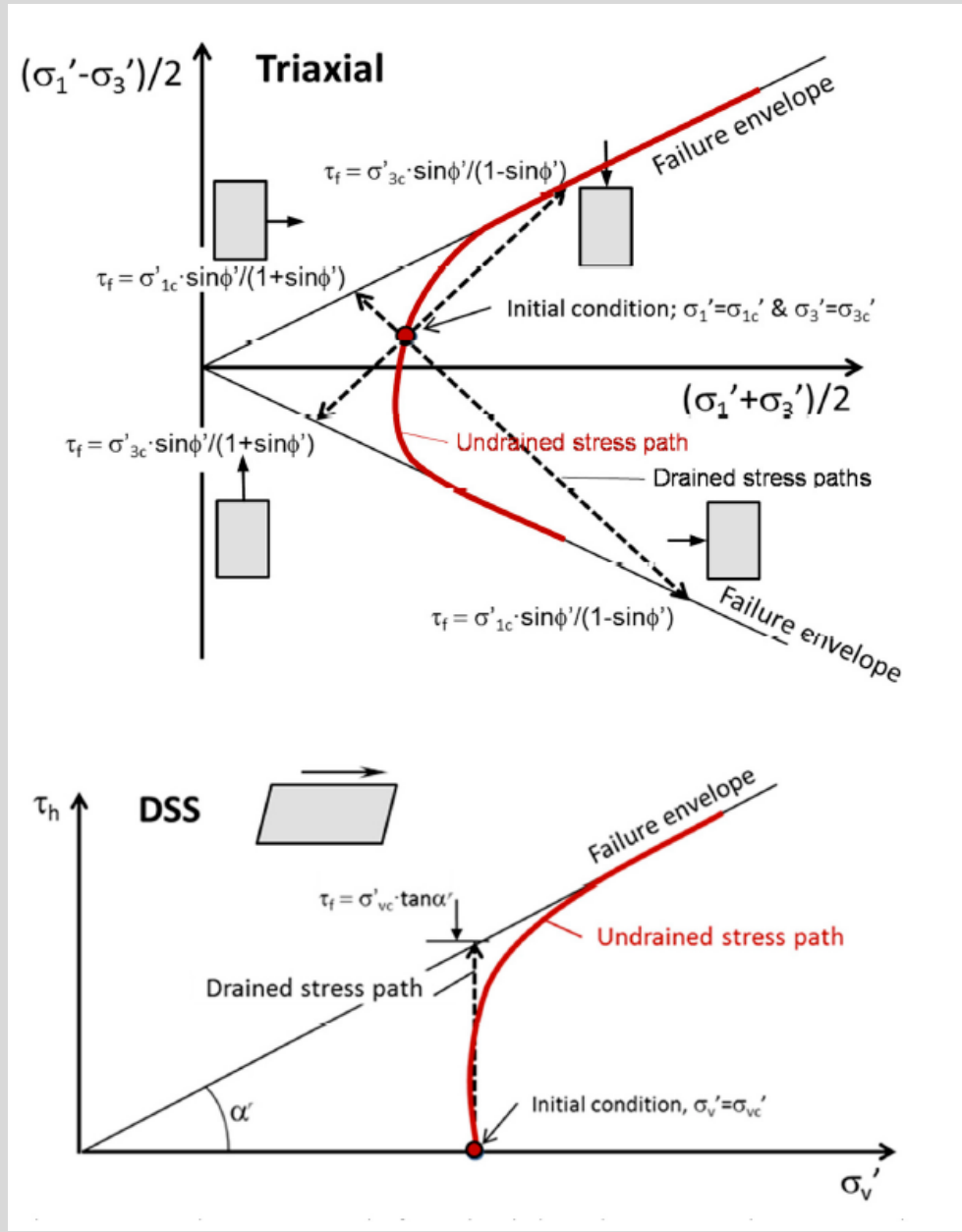
Triax comp.



DSS



Triax ext.



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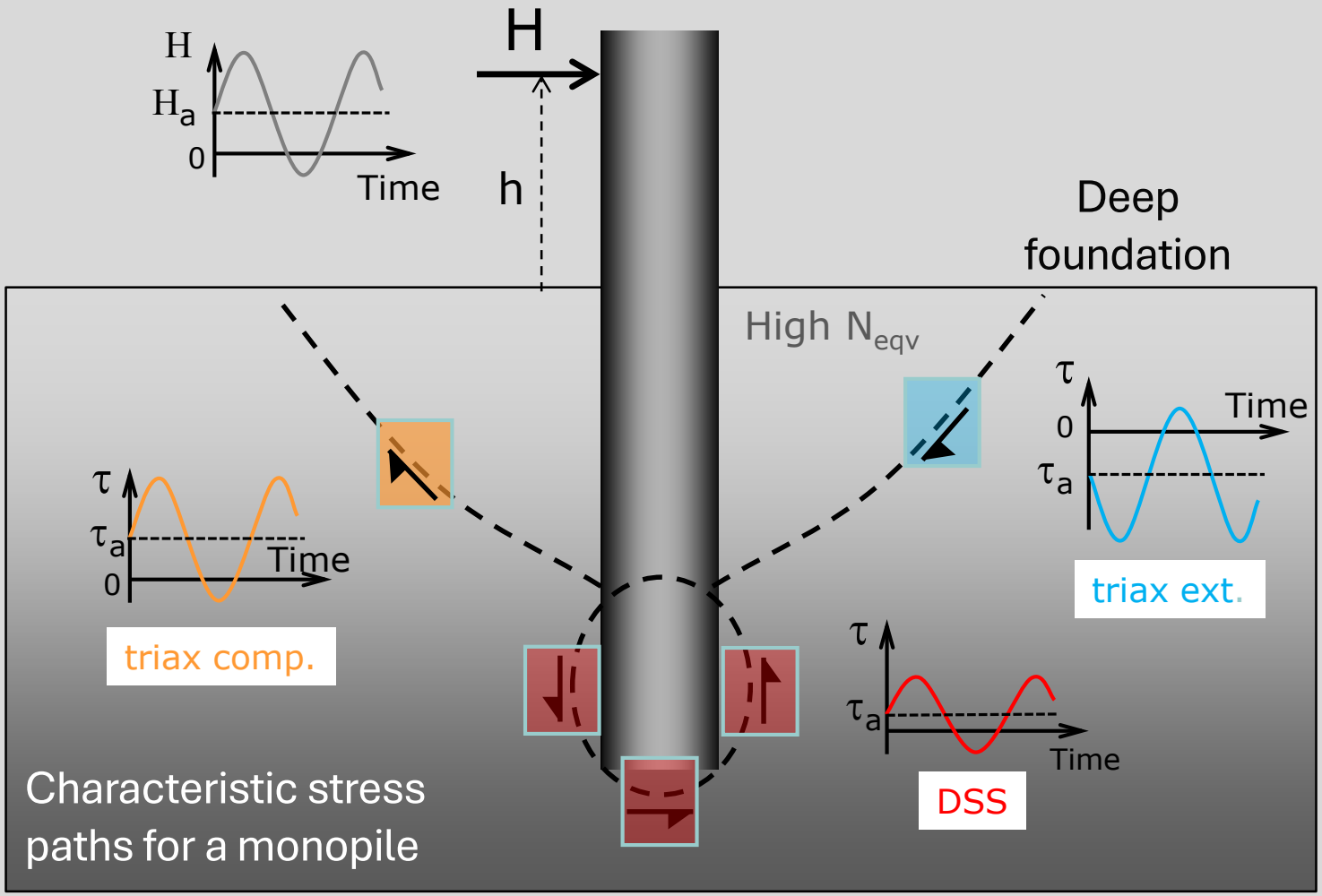
Offshore Foundation Design



Response based on laboratory results (stress path dependent)!

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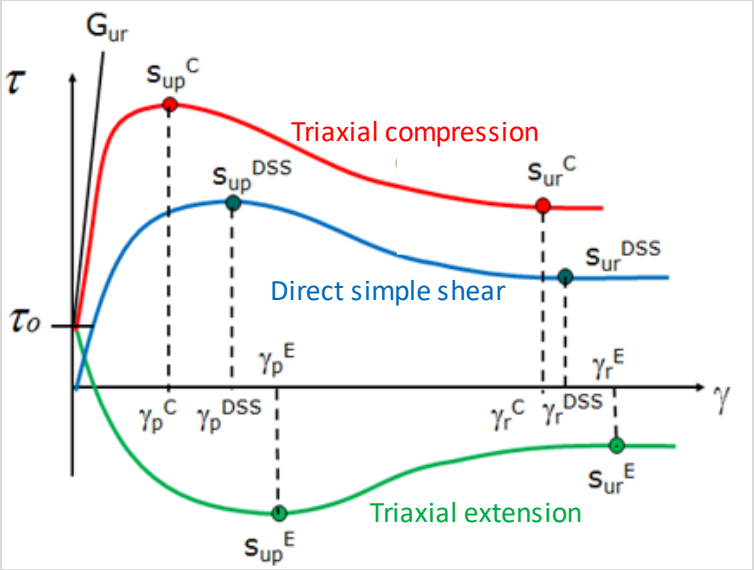
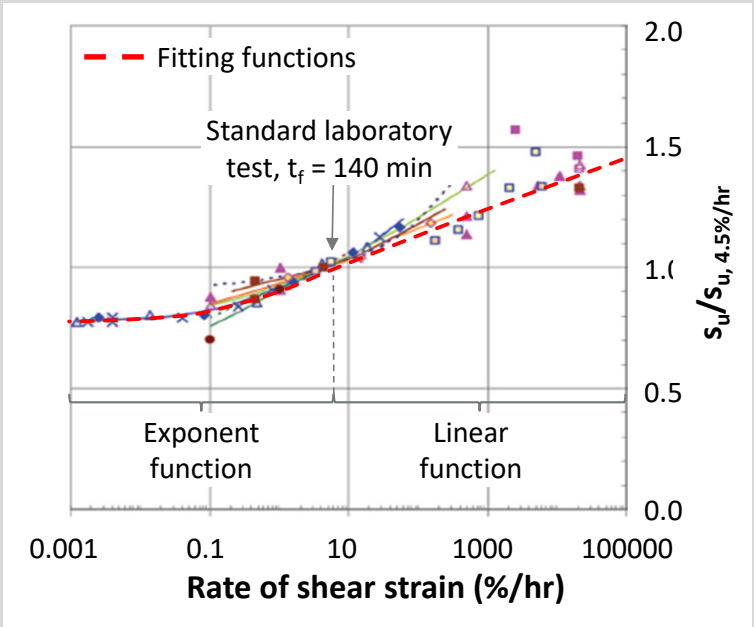
Monotonic Loading

- **NGI-ADP** material model:
  - Input parameters for (undrained) shear strength for three different stress paths/ states (Active, Direct Simple Shear, Passive)
  - A yield criterion based on a translated approximated Tresca criterion.
  - Elliptical interpolation functions for plastic failure strains and for shear strengths in arbitrary stress paths.
  - Isotropic elasticity, given by the unloading/reloading shear modulus, Gur.
- Additional features: Strain softening, Strain rate, Non-local strain, SHANSEP NGI-ADP
- Available in different programs: Plaxis, Bifurc, Abaqus, Anura MPM, etc.

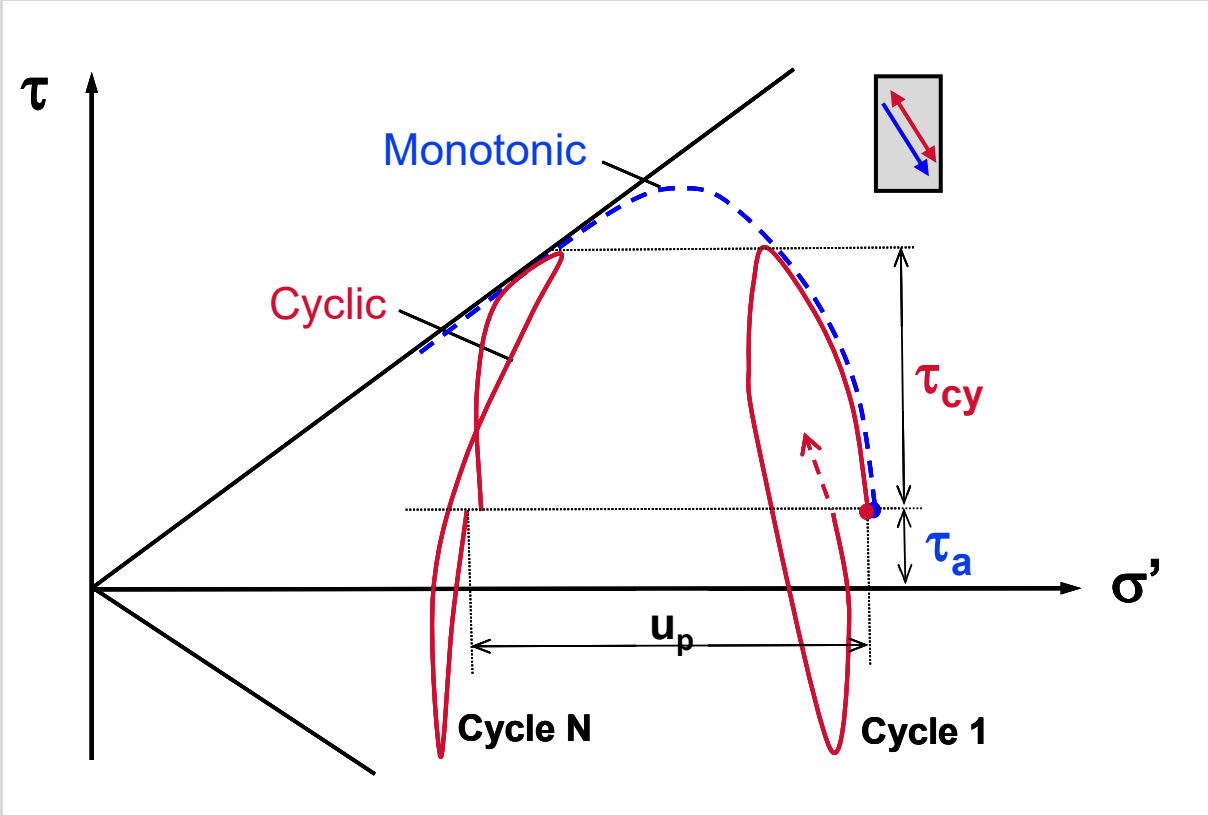




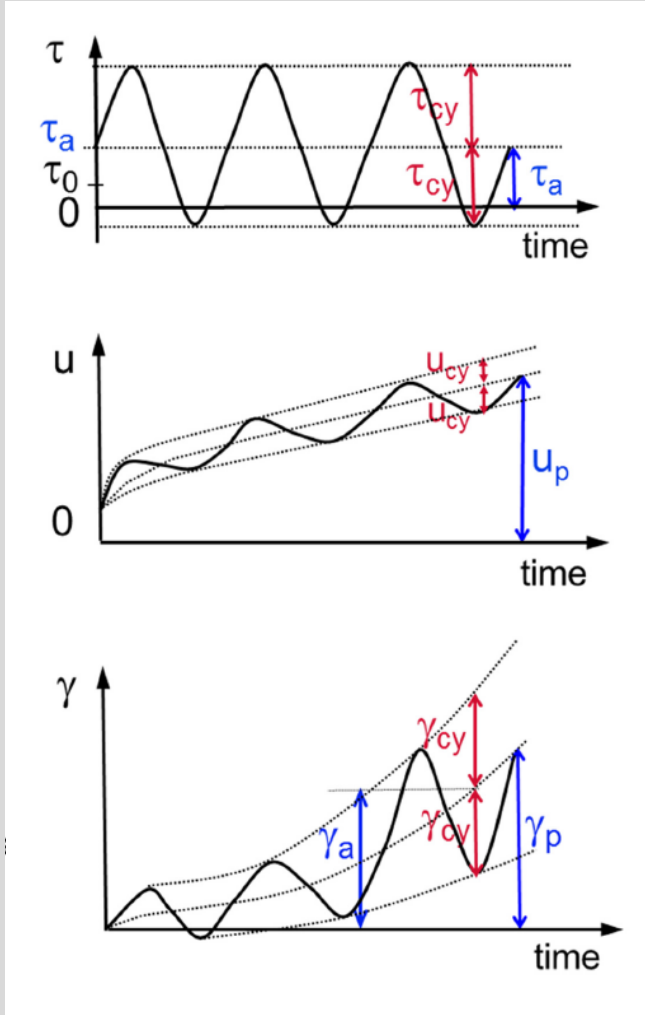
Grimstad et al. 2010, Grimstad et al. 2012, Khoa et al. 2019

Cyclic Loading: How Does Soil Behave?

Cyclic loading generates pore pressure



Pore pressure & shear strain increase with no. of cycles



Cyclic and average shear stresses

Cyclic and average and permanent pore pressure generation

Cyclic and average and permanent shear strains

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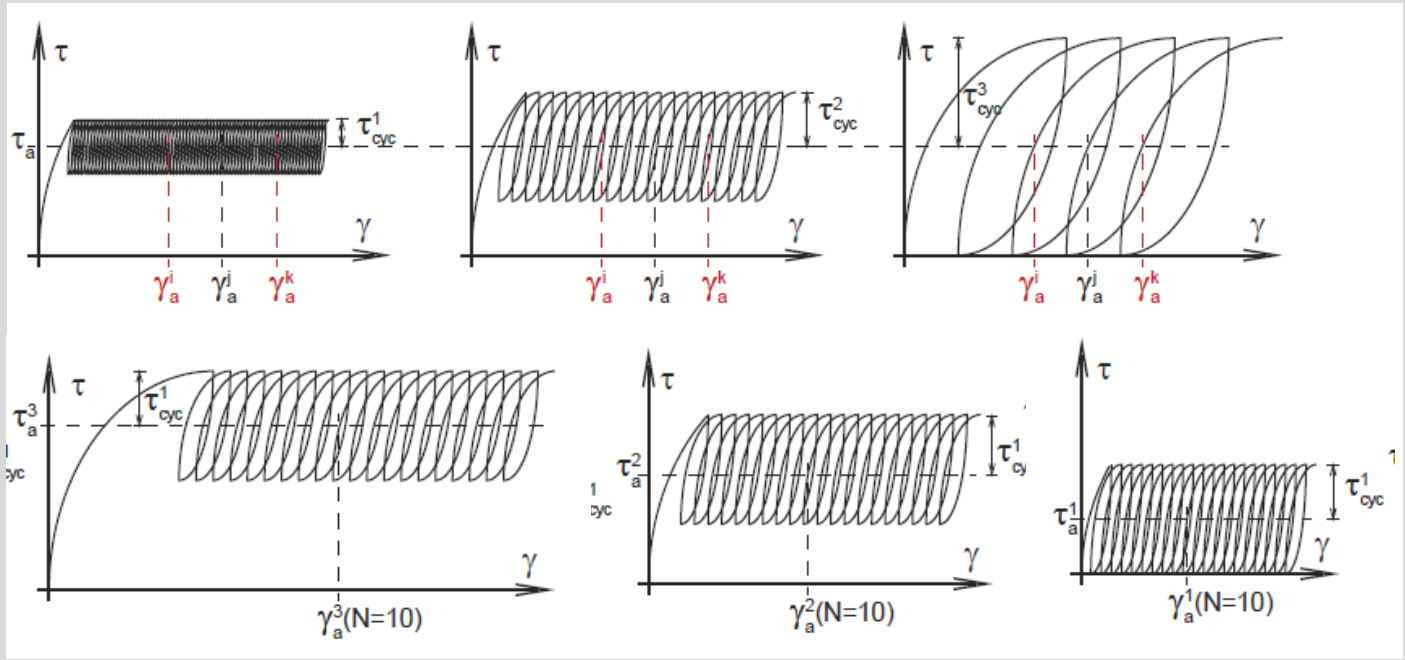
Andersen 2015

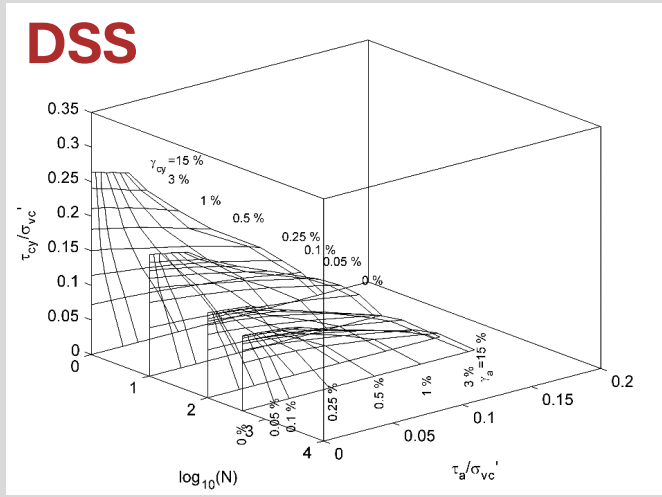
Cyclic Loading: NGI Cyclic Contour Diagrams

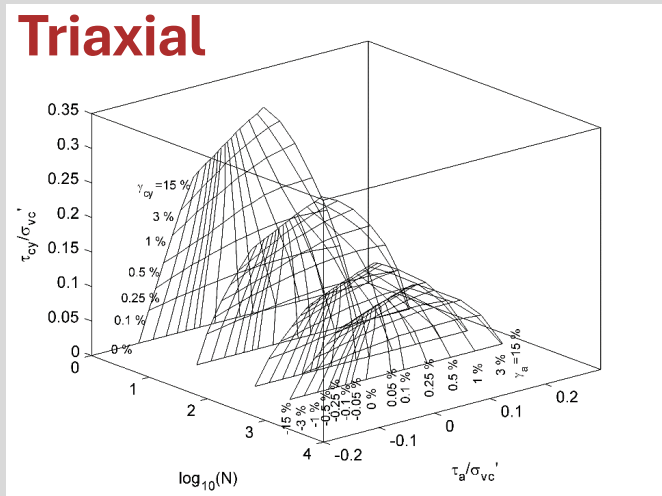
- Monotonic tests (DSS, Triaxial Comp./Ext.)
- Cyclic tests
- Constant rate of strain (oedometer)

τ_a cst.

τ_{cy} cst.







NGI

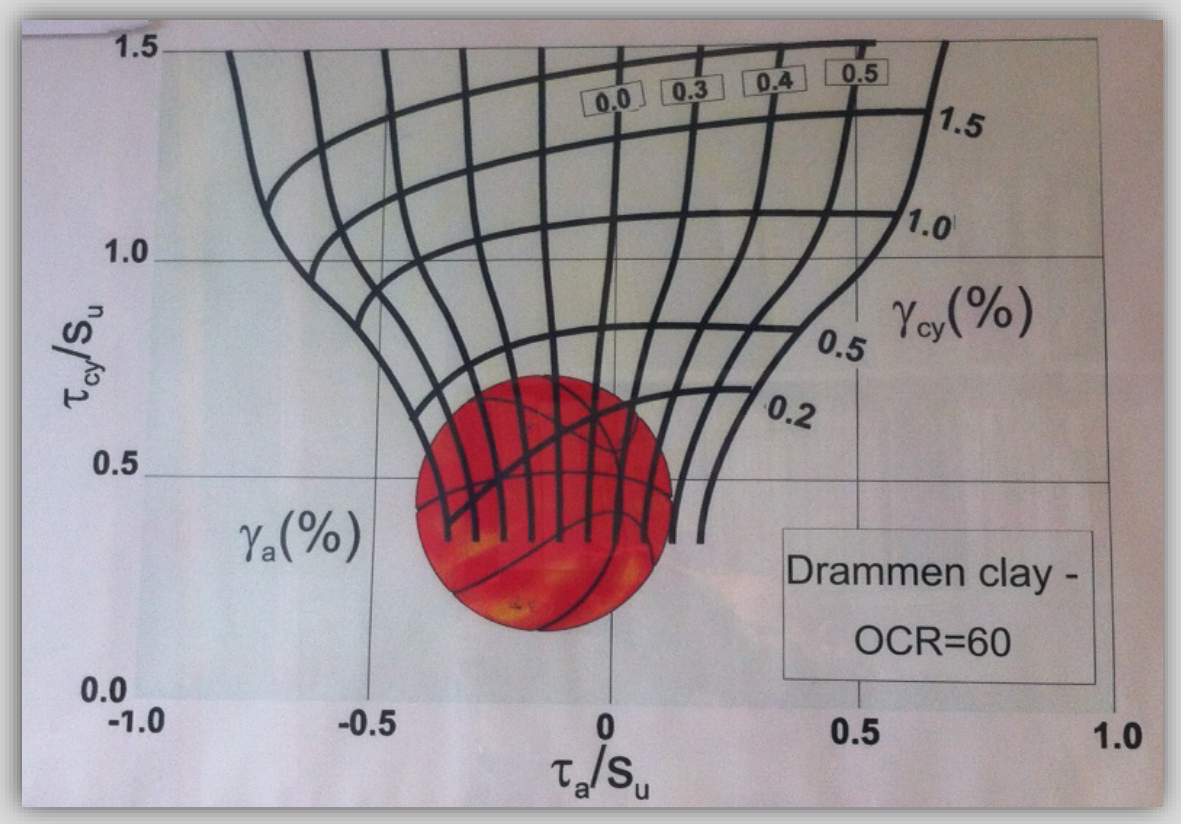
Andersen 2015

Cyclic Loading: NGI Cyclic Contour Diagrams

Cake contours

Prepared by Ana Page

Basket ball contours



Linda Hårvik

NGI

Cyclic Loading: NGI Procedure for Cyclic Soil Degradation

- Cyclic contour diagrams
- Cyclic loading parcels

NGI procedure

- Cyclic degradation of soil stiffness and shear strength

Soil model: UDCAM, PDCAM

(available in FE programs: Bifurc, Plaxis, Abaqus, etc.)

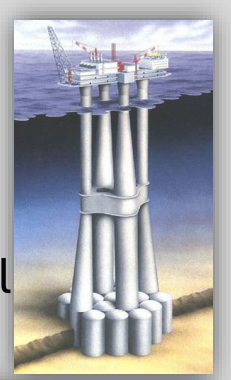
UDCAM: UnDrained Cyclic Accumulation Model

PDCAM: Partially Drained Cyclic Accumulation Model

NGI

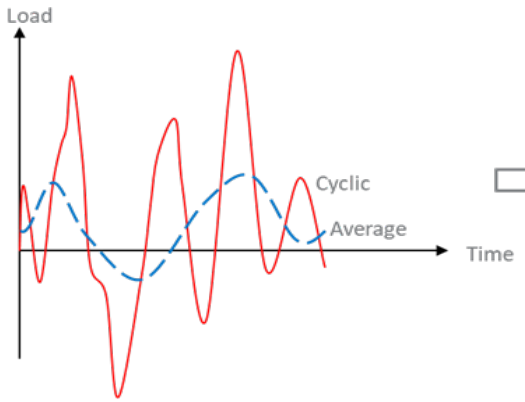
Andersen 1976, Khoa & Jostad 2018, Jostad & Andresen 2009, Jostad et al. 2014, Jostad et al., 2015

Cyclic Loading: Accumulation Procedure of UDCAM-S

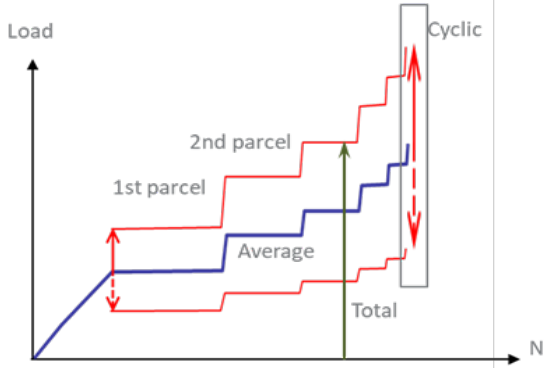


1G model test of Troll Platform

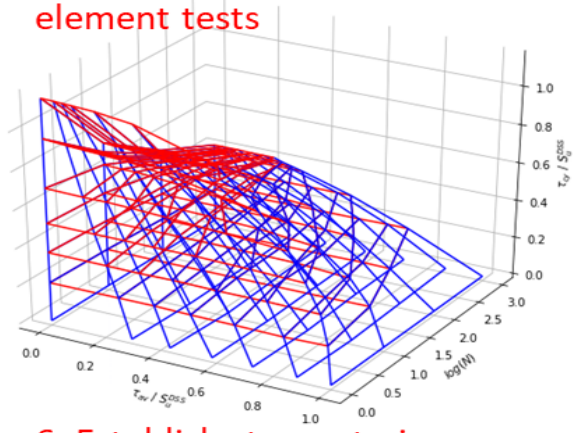
1. Loads from time domain analysis



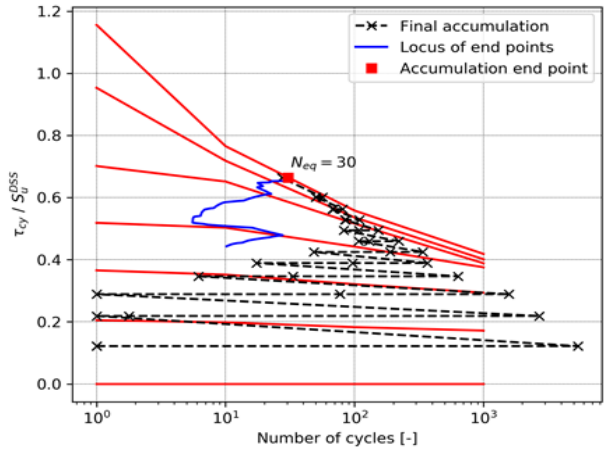
2. Geotechnical load history



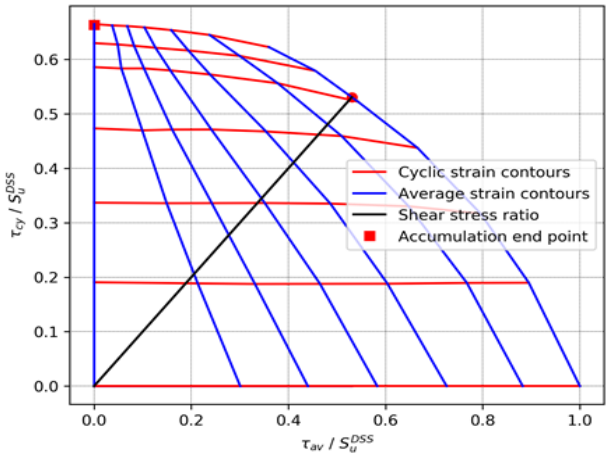
3. Contour diagram from cyclic element tests



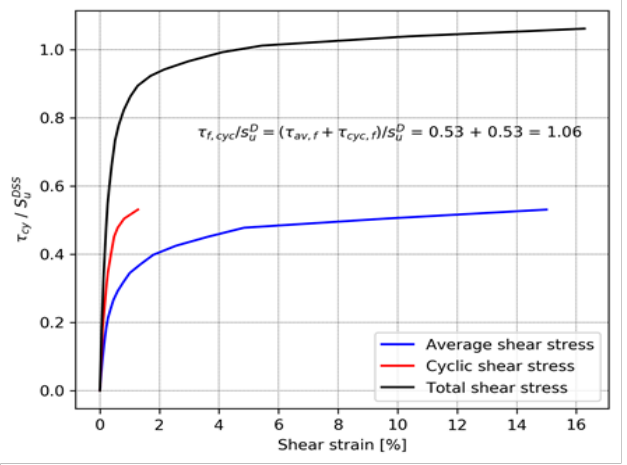
4. Cyclic accumulation, find N_{eq}

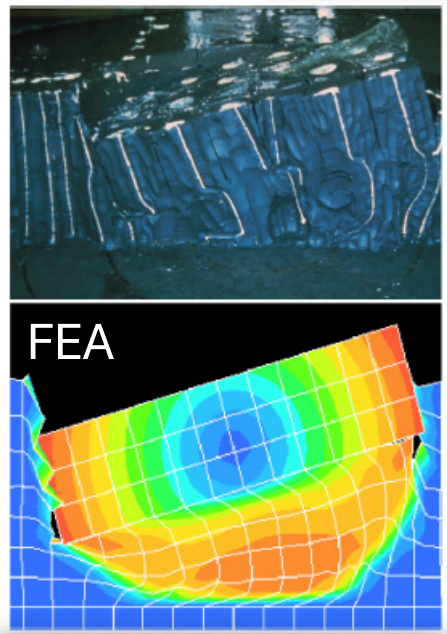


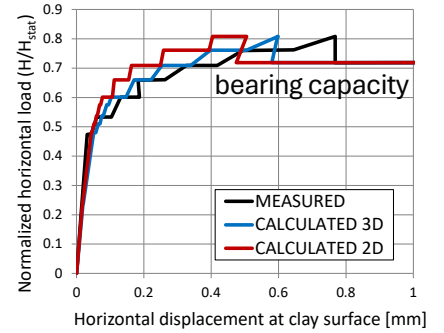
5. Use load ratio in Neq section



6. Establish stress-strain curves







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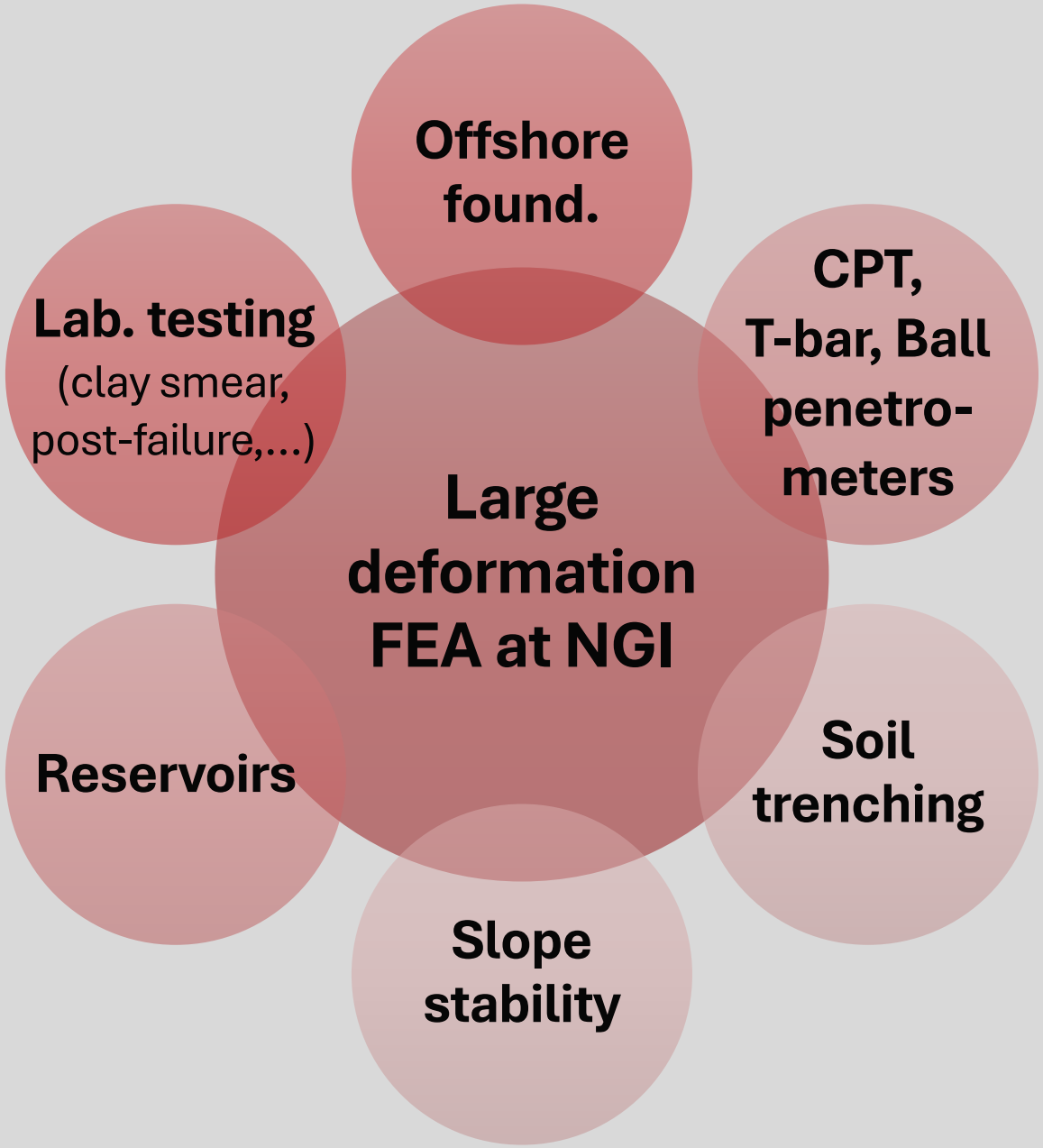
Khoa & Jostad 2018, Klinkvort et al. 2020, Norén-Cosgriff et al. 2015

Large Deformation Analyses

- Stability, run-out
- Installation effects
- Set-up effects
- Soil-structure interactions
- Capacity, stiffness

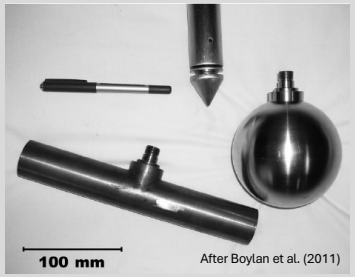
- In-built material models
- UDSM: NGI's in-house models, HP, Sanisand, etc.

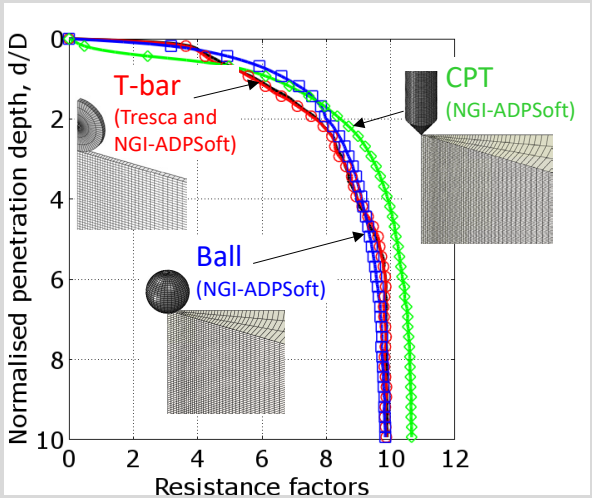


Large Deformation Analyses

- Examples of Penetration analyses

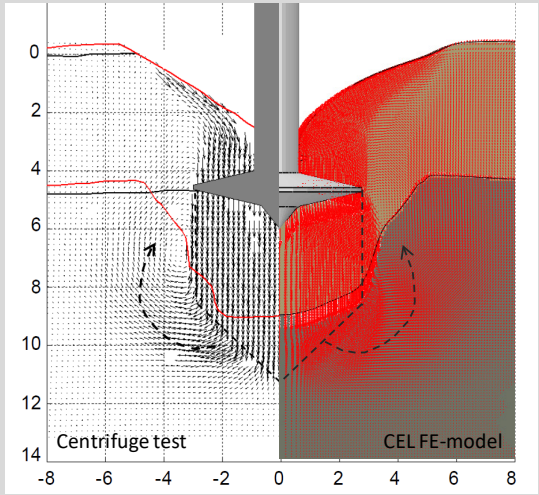
Penetrometer tests (CPT, T-bar, Ball)



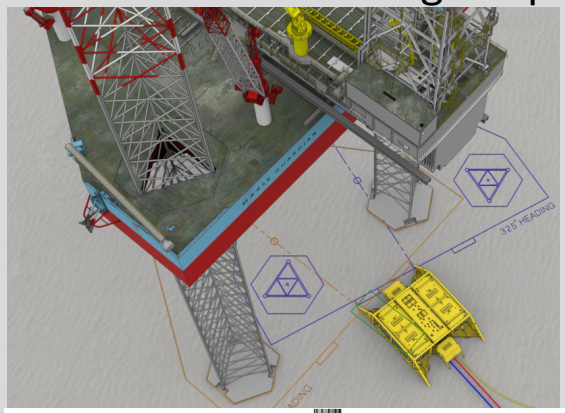


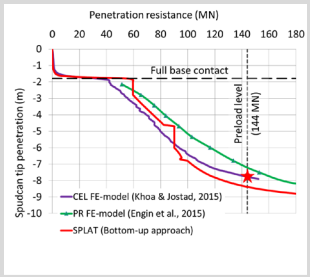
Validation against centrifuge tests

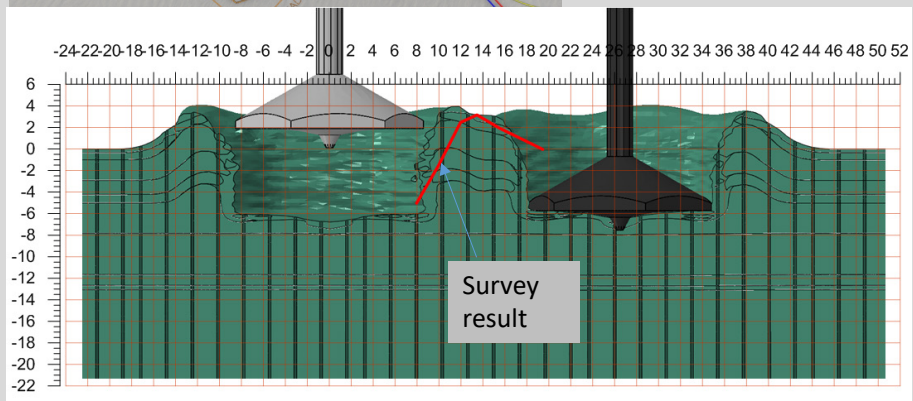

Jack-up drilling leg (after ConocoPhilips)



Spudcan penetration on existing footprint





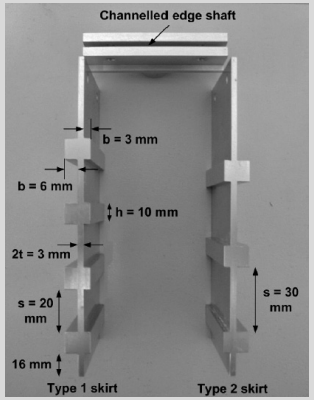


Khoa & Jostad 2016, Khoa et al. 2019

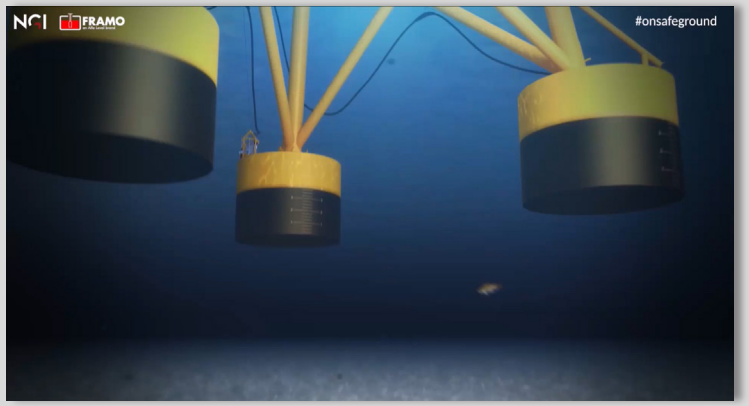
Large Deformation Analyses

- Examples of Drivability assessment

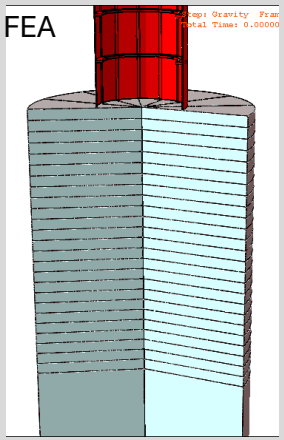
Centrifuge

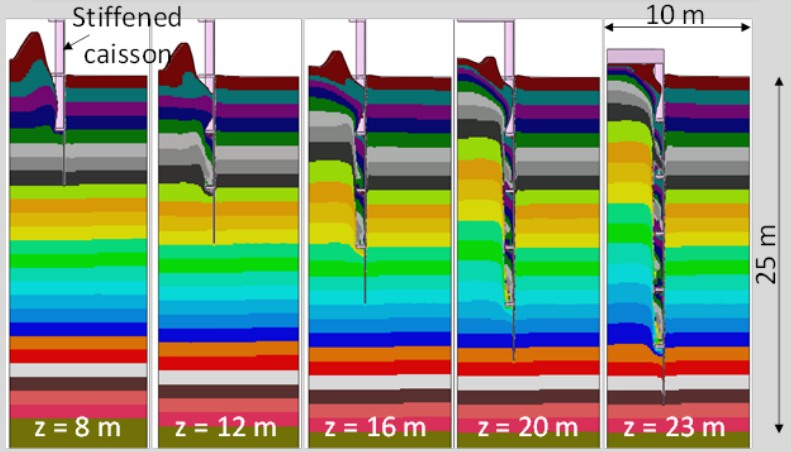


Suction caissons



FEA





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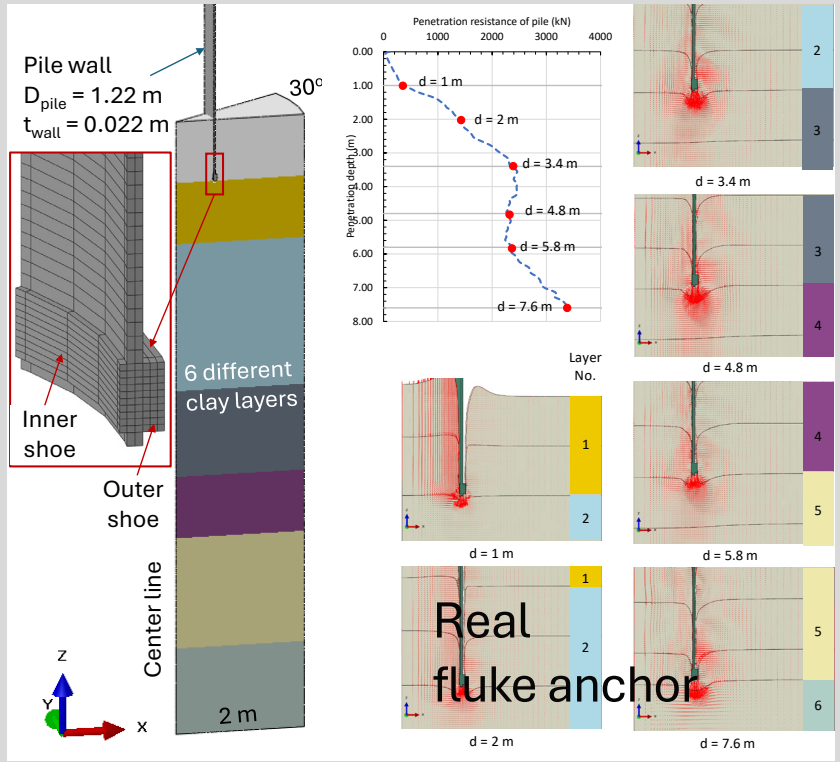
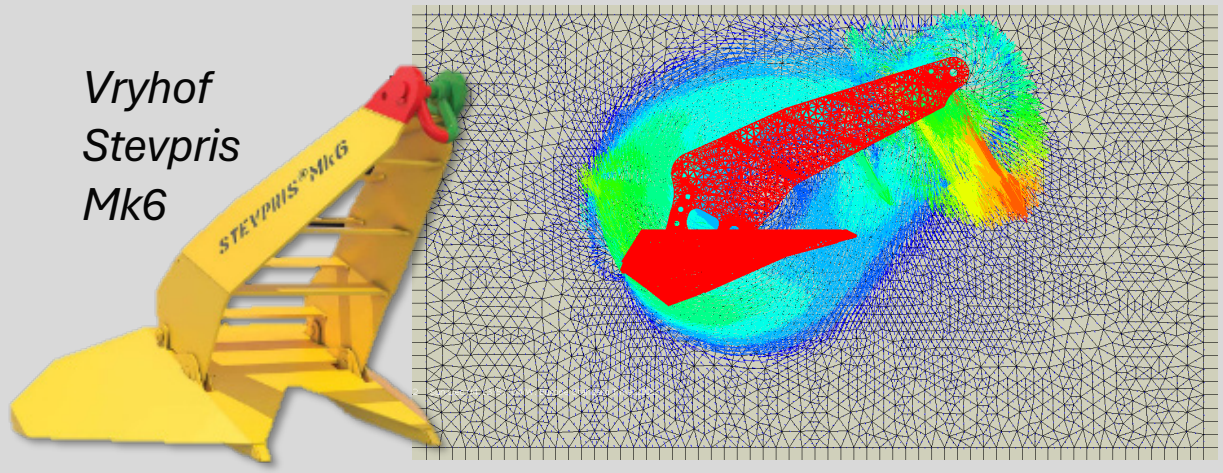
Jostad et al. 2015

Monopiles w/wo driving shoes



Fluke anchor capacity for anchoring floating structures

Vryhof Stevpris Mk6



Calculation Tools

- In-house programs

Programs	Brief description
ACCUMUL	Shear strain and pore pressure accumulation during cyclic loading
GroundModel	Integrated ground model
SPLAT	Calculate spudcan penetration using ISO/SNAME methods
SWIFT	Foundation capacity assessment for jack-up vessels

SPudcan Leg Analysis Tool (SPLAT)

S P L A T

INPUTS

1. SPUDCAN GEOMETRY

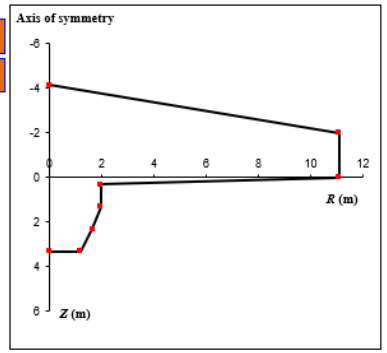
Foundation Type	Spudcan
Footing Library	
Geometry point	8

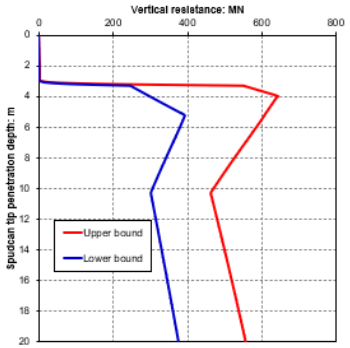
AUTO FILL

MANUAL

	Z (m)	R (m)
1	3.3	0
2	3.3	1.2
3	2.3	1.64
4	1.3	1.97
5	0.3	1.97
6	0	11.08
7	-2	11.08
8	-4.15	0

Diameter of the footing (m)	22.16
Area of the footing (m²)	385.7
Total volume (m³)	1123.3
Footing roughness (0 - 1)	0.5





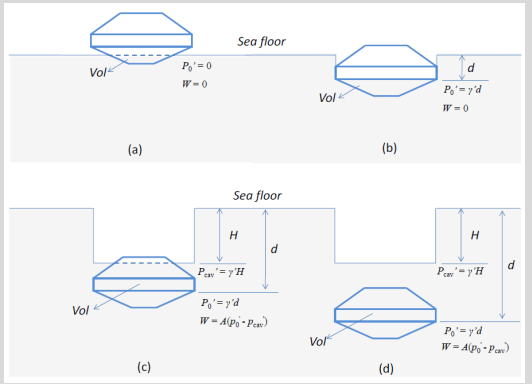
2. SOILS

SOIL LAYERS	Layer information				LOWER BOUND							UPPER BOUND							Pre/First Run Method
	Soil type	Z_top (m)	Z_bottom (m)	γ' (kN/m³)	Clay parameters				Sand parameters			Clay parameters				Sand parameters			
					$s_{u...}$ (kPa)	(kPa/m)	S_t	ξ_{ss}	ϕ (°)	D_r (%)	$F_{...}$	$s_{u...}$ (kPa)	(kPa/m)	S_t	ξ_{ss}	ϕ (°)	Dr (%)	$F_{...}$	
2	sand	0	7	9.5					27.5							32.5			Brinch Hansen (1970)
	clay	7	39.9	10.3	105	1.35						165	1.35						Brinch Hansen (1970)

Image courtesy IMI

Jack-up drilling leg (after ConocoPhilips)

Different stages of penetration



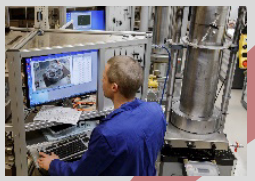
3. OTHER ANALYSIS PARAMETERS

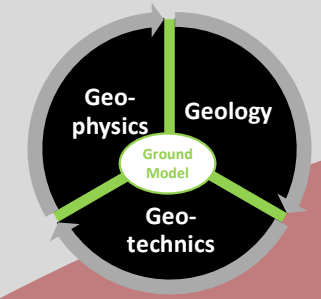
Load spread factor	3
Squeezing factor	3
Backflow mode	calculate
Incremental size (fraction of R)	0.01
Final tip penetration (m)	20
Leg buoyancy (kN/m)	0
Preload per leg (MN)	210.8
Calcualtion method	Second Run

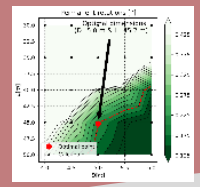
CALCULATION METHOD	GUIDELINES	NOTE
SINGLE CLAY LAYER		
Skempton (1951)	ISO	Average s_u in 0.5D below footing base is used, dc= 1 + 0.2*d/B ≤ 1.5
Brinch Hansen (1970)	SNAME	Average s_u in 0.25D below the footing base is used, dc = 1 + 0.4arctan(d/D)
Martin Houlsby (2003)	SNAME Comm./ISO/INSAFE	s_u taken as the strength at footing base, soil heiterogeinity, conical shape, roughness, embedment considered
Hossain and Randolph (2009a, b)		s_u taken as the stength at footing base, relevant mechanisms at various stages of penetration explicitly considered
SINGLE SAND LAYER		
Brinch Hansen (1970)	SNAME Comm.	ϕ reduced by 5° from lab traxial results for input
Vesic (1975)	SNAME	ϕreduced by 5° from lab traxial results for input
Martin ABC	ISO	N_γ, N_q factors based on results from Martin's ABC program, consideration should be given to choose the appropriate ϕ
INSAFE (2011)	INSAFE	Use Cassidy and Houlsby (2002) N_γ factors, peak ϕ as input, a reduction factor F_{mob} = 0.25-0.5 and a roughness = 0.5 recommended
MULTI LAYERS (no. of layers ≥ 2)		
Pre Run		Apply general shear to all layers, no treatment of conical shape at layer interface
First Run		Apply general shear to all layers, with treatment of conical shape at layer interface
Second Run	SNAME/ISO	Apply general shear/punch through/squeezing mechanims judged on the Pre Run capacity, with treatment of conical shape at layer interface. For stiff clay overlying soft clay, the Brown and Meyerhof (1969) method is used; for sand overlying clay, the load spread method is used; for clay overlying stiff soil, the squeezing equation by Meyerhof and Chaplin (1953) is used.
ADDITIONAL METHOD ONLY FOR TWO LAYERS		
Hossain and Randolph (2009c)	Recommended in INSAFE	For stiff clay over soft clay, punch-through type site
Hanna and Meyerhof (1980)	SNAME/ISO	Punching shear method for sand over clay profile, K_s value read from graph based on ϕ and Q_{clay}/Q_{sand}
Hu et al. (2013)	Allowed in ISO, INSAFE	Stress dependent model for sand over clay profile, constant volume friction angle ϕ_{cv} and relative density I_d are required for sand

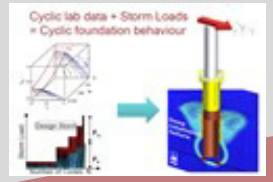
Zhang et al. 2015

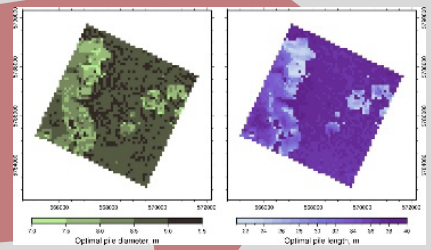
Data-Driven Geotechnics - Ground Model to Design











Data collection

- High quality geophysics
- In-situ testing (including S wave)
- Laboratory testing
- Imported into unified database

Integrated geomodel (G^4)

- Data integration and cross-correlation, supported by physical models, statistics and machine learning
- Provides fundamental geotechnical design basis for entire 3D seabed cube
- Includes both parameters and associated uncertainty

Foundation design

- Input drawn from ground model
- Rapid sizing across wind farm
- Screening of entire lease area for optimal dimensions (“zonation heat maps”)
- Streamline approach allows iterations and updates through project phases
- Works for standard foundations like monopiles, GBSs, suction bucket jackets etc (Different load input needed)

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Integrated Ground Model – Overview

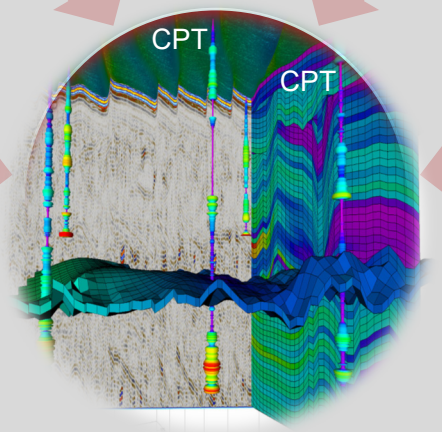
- Quantitative ground model combining geology, geophysical and geotechnical data

Geophysics

Geostatistics

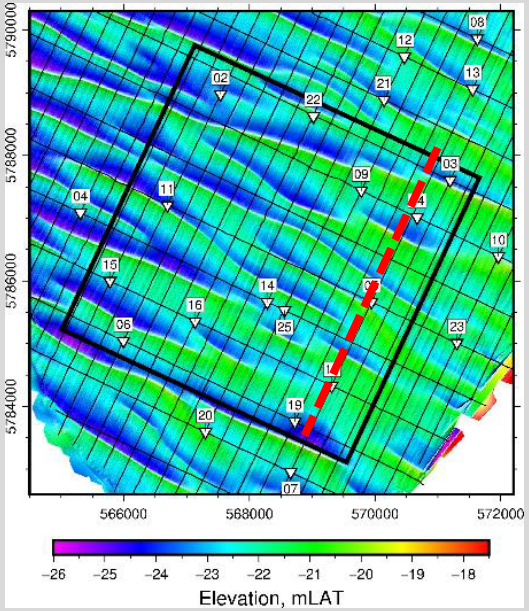
Geology

Geotechnics

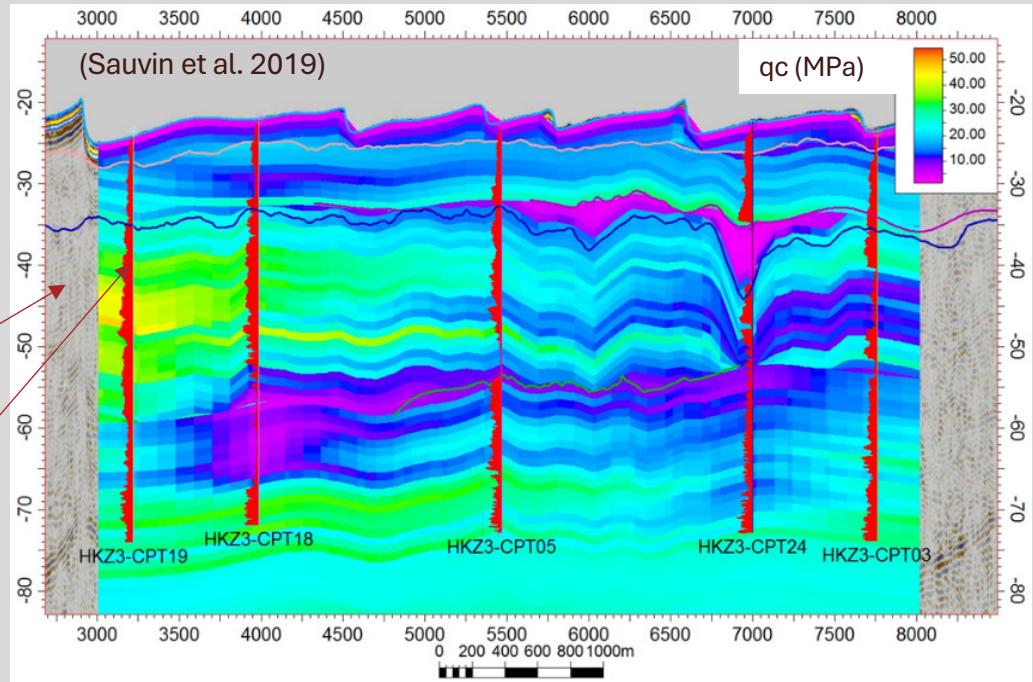


Integrated ground model

- **Geostatistical**/machine learning techniques to create a 3D volume of geotechnical data for design



- **Geophysical**: 2D seismic profile
- **Geotechnical**: CPT tests (q_c)



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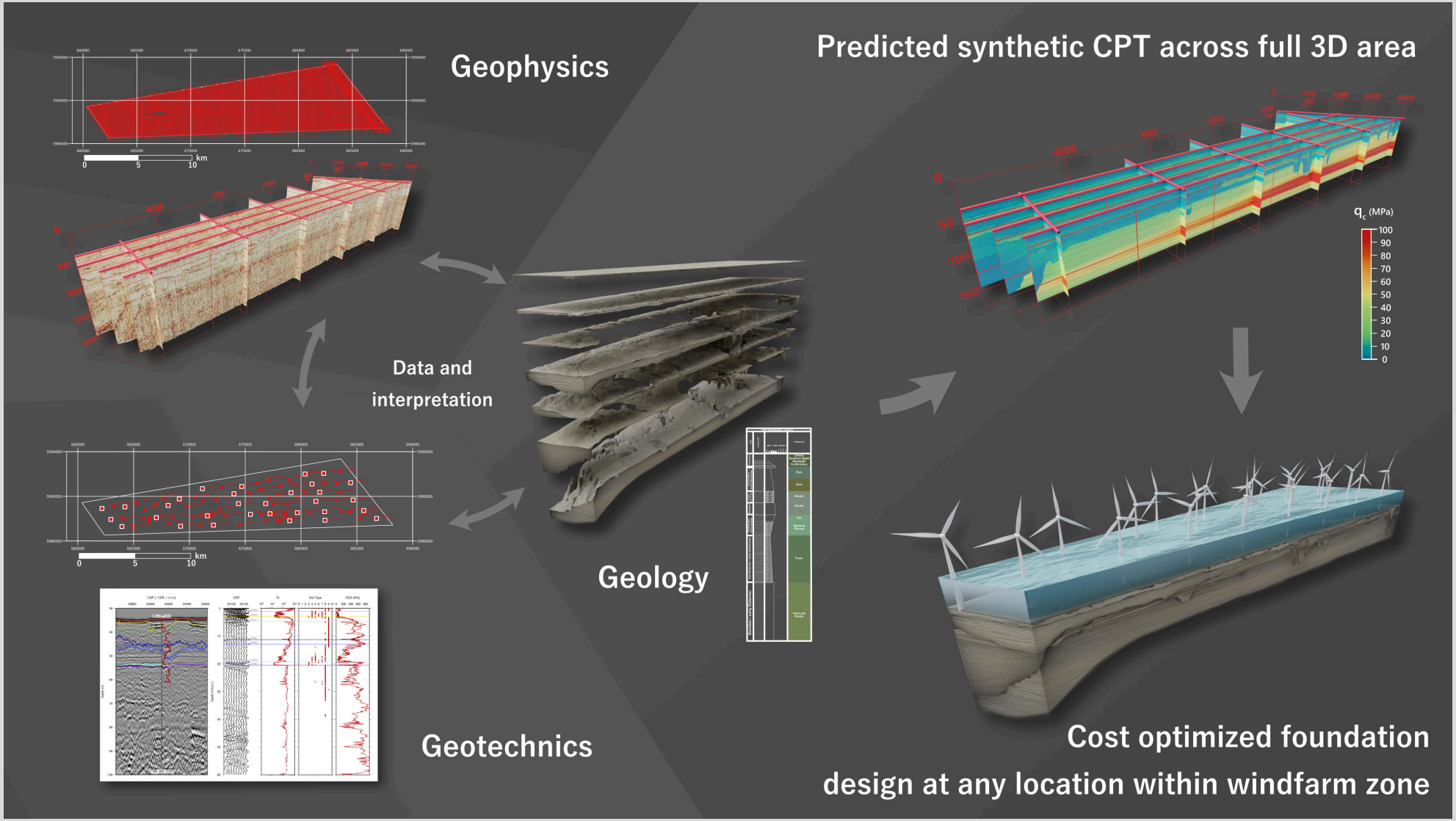
Vanneste et al. 2022, Sauvin et al. 2019

Data-Driven Geotechnics - Ground Model

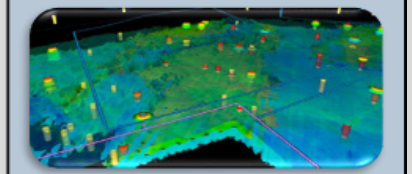


Sauvin et al. 2022

Ground Model to Foundation Design

In-situ site conditions

Integrate geodata
- Geophysical data,
- Geology,
- In-situ testing



Laboratory testing
- Monotonic profiles,
- Cyclic contours

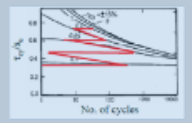
Quantified geo-model
- Soil parameters

Load data from wind turbine

Realistic soil behaviour

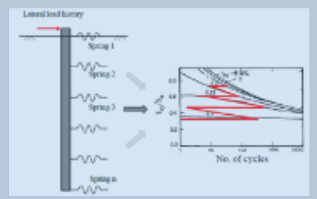
Cyclic soil conditions

Undrained accumulation
- Per soil unit



or

Undrained / Partially drained accumulation
- Per pile location

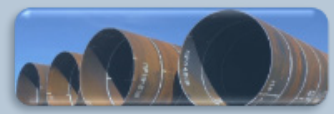


SUMO –SUper fast MOnopile design

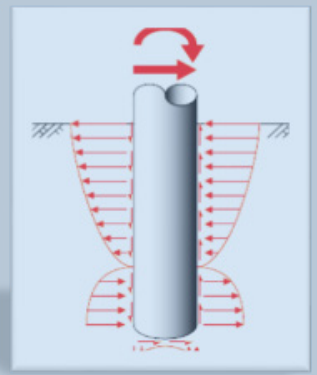
Geotechnical design

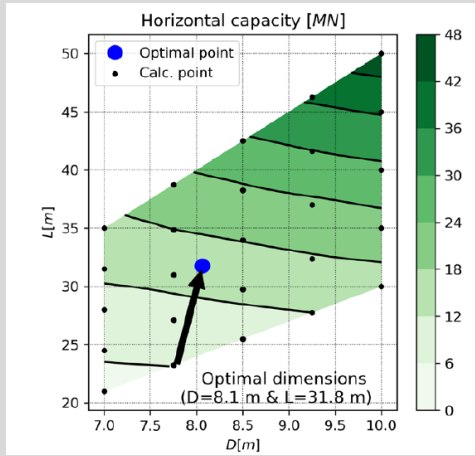
Foundation Sizing

Location specific design
- Diameter, length and thickness



Super fast finite element solver





Structural design

Foundation stiffness

Global (REDWIN) or local (PISA) Springs for load and fatigue analysis

Efficiency & optimisation with reliable technical models

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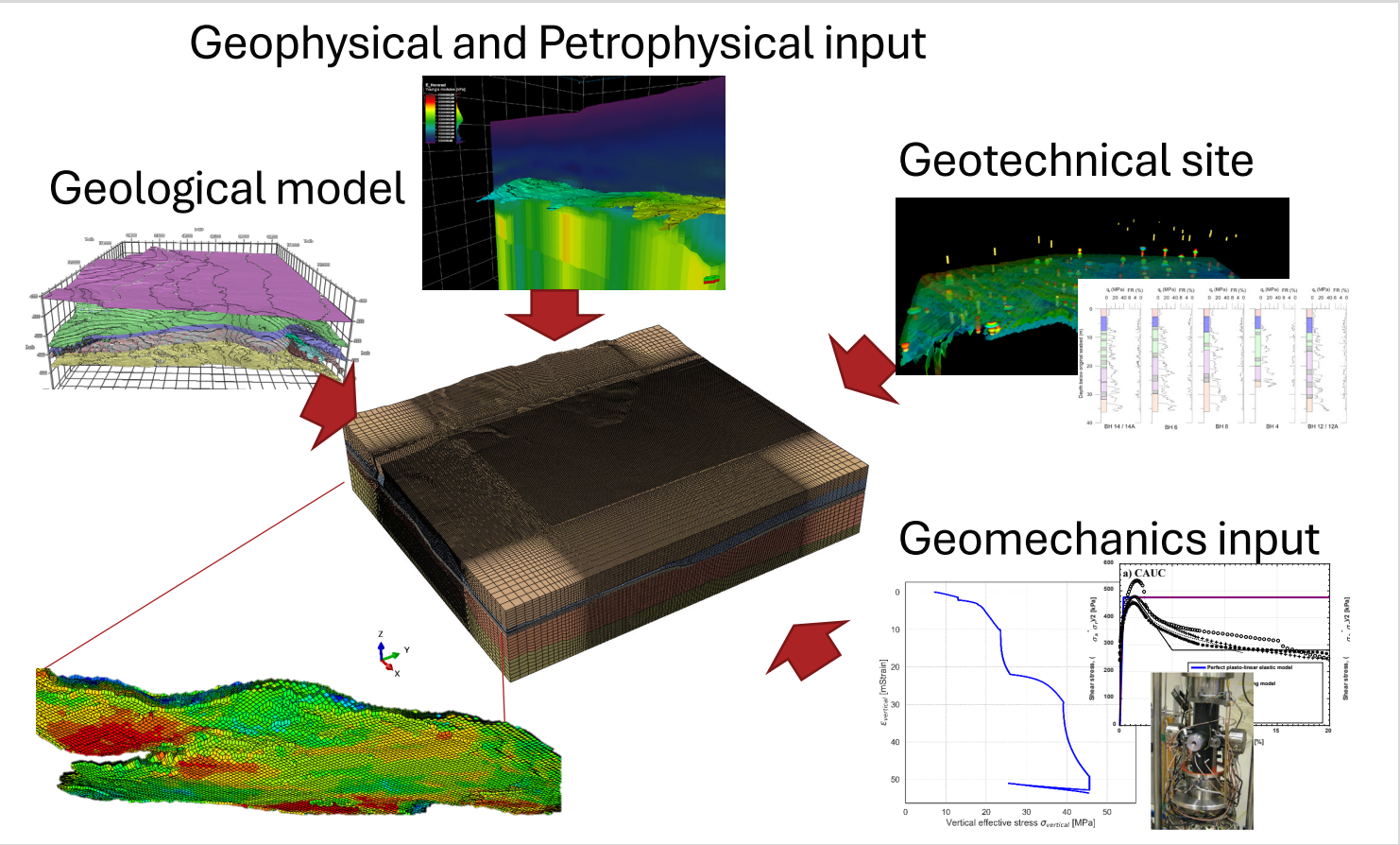
Klinkvort & Sivasithamparam 2021

Ground Model to Petroleum Geomechanical Modeling



- 2D and 3D geomechanical modeling in FE Tools (i.e. Plaxis, Abaqus, Comsol…)
- Coupling of field scale model towards 4D seismic interpretation and detailed models for wellbore and fault stability.

Routines for data import

- Detailed geometry and property distribution from seismic horizons and geological model (i.e. RMS or Petrel)
- Detailed pore pressures distribution (from reservoir simulator i.e. ECLIPSE simulations).

Petrophysical properties dependent mechanical properties

- Reservoir: Petrophysical data (e.g. porosity, NTG)
- Overburden/cap rock: Geophysical data (e.g. Vp)
- Seabed: CPT data
- Stress: 3D density cube and K0 ratio

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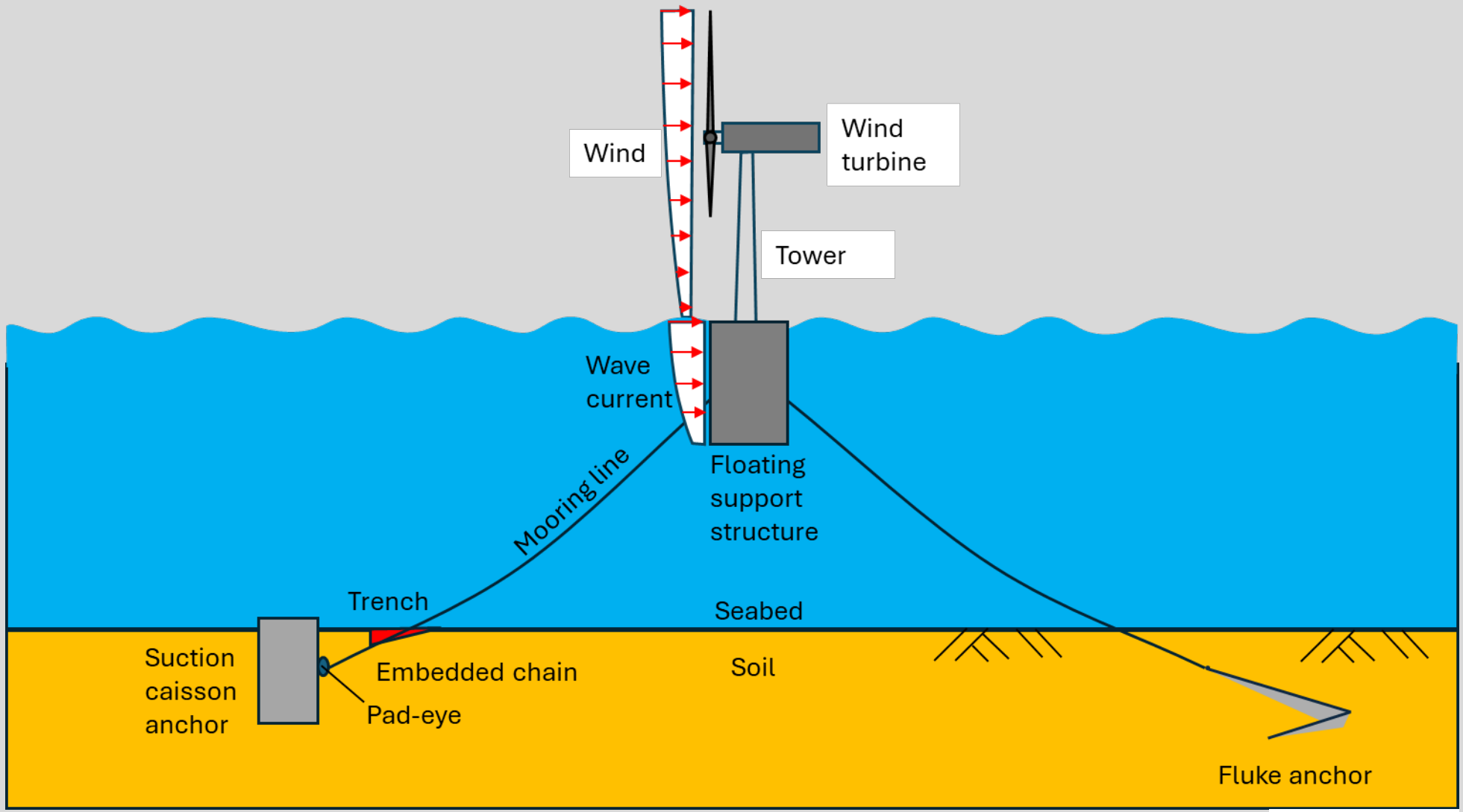
Fully Integrated Analyses Including Seabed Soil



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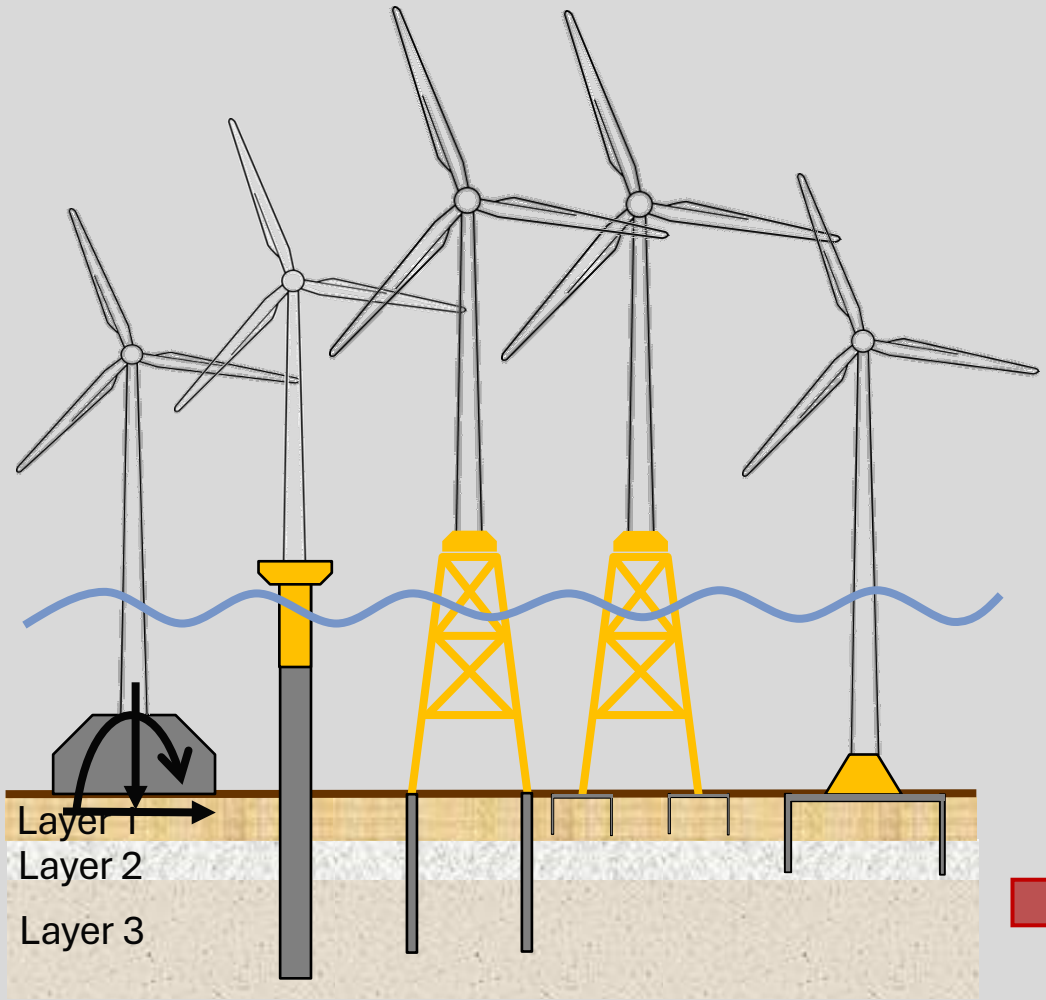
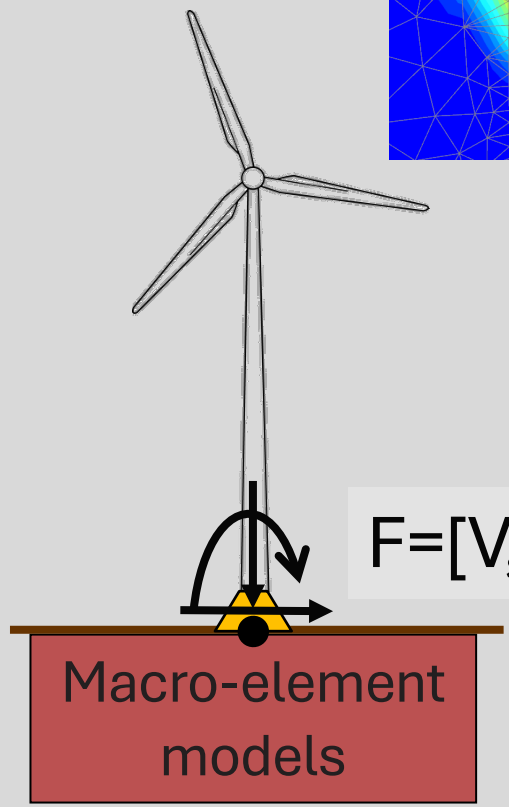
BLUES
Floating structures for the next generation ocean industries

Fully Integrated Analyses Including Seabed Soil





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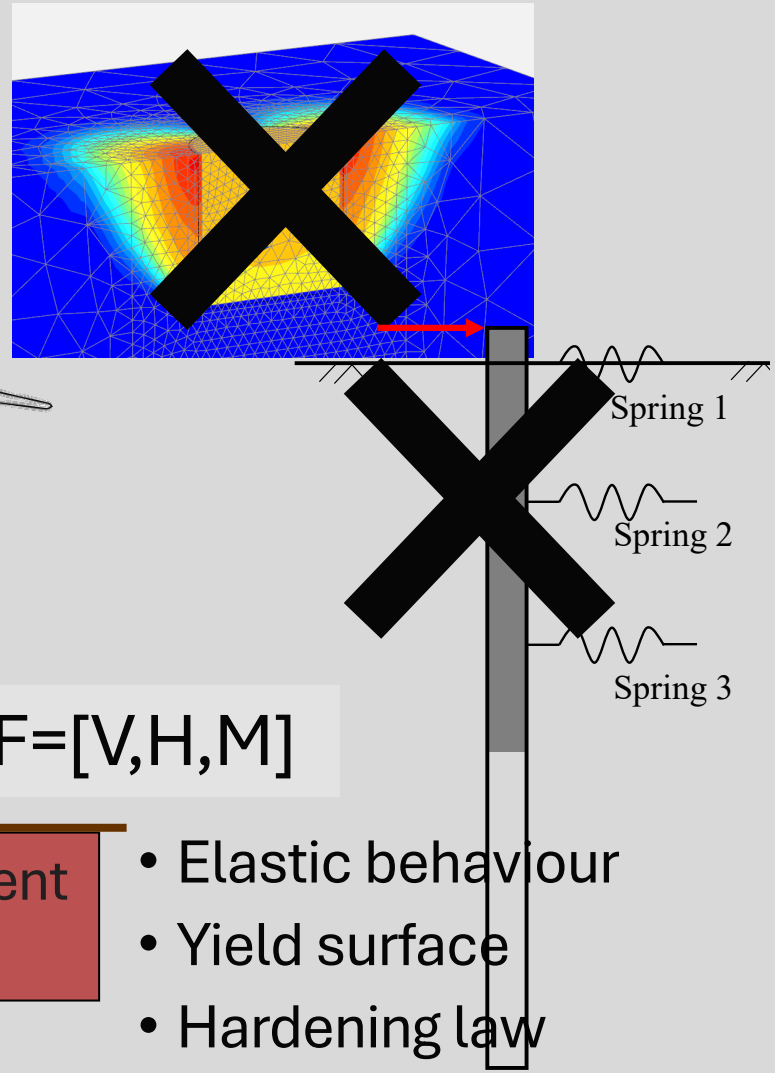

- Elastic behaviour
- Yield surface
- Hardening law
- Flow rule

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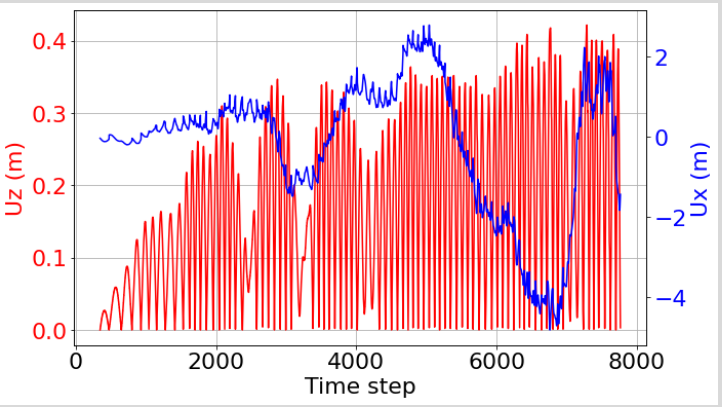
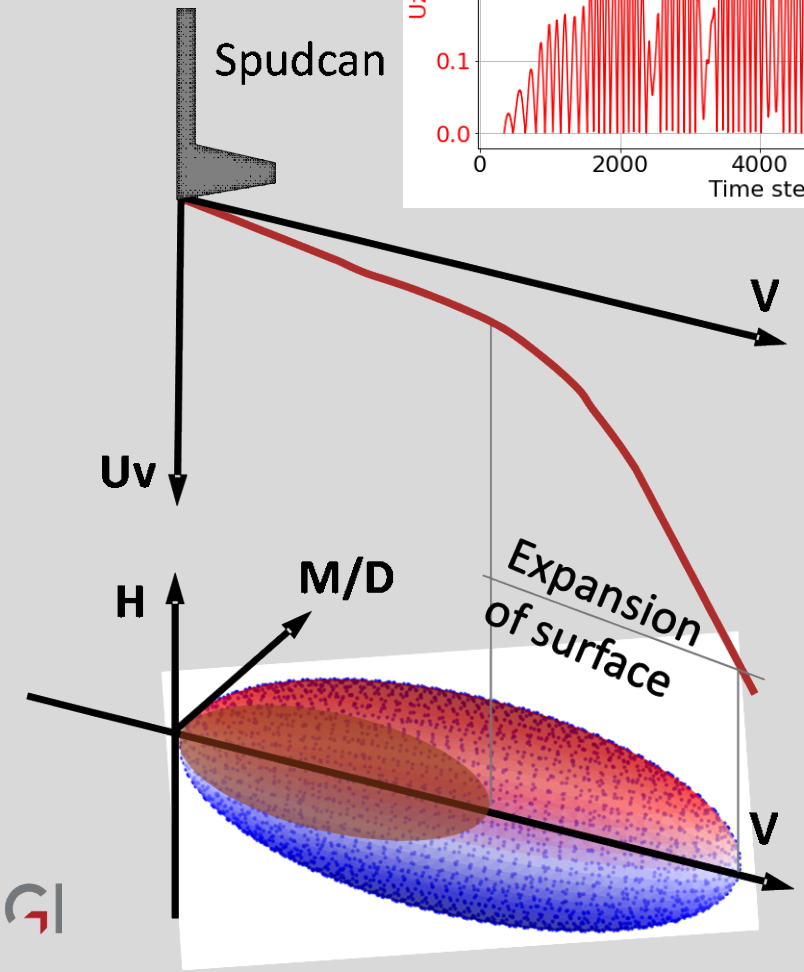
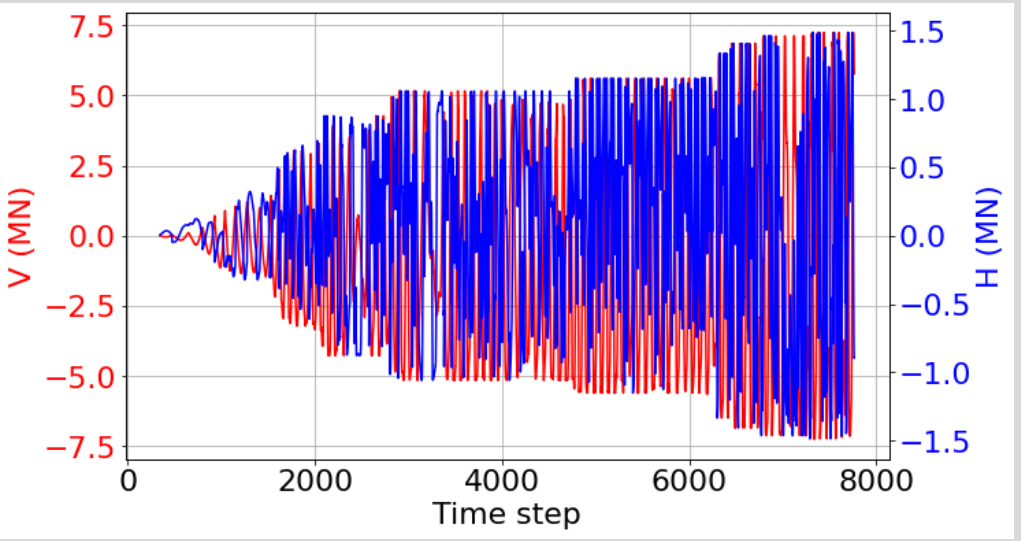
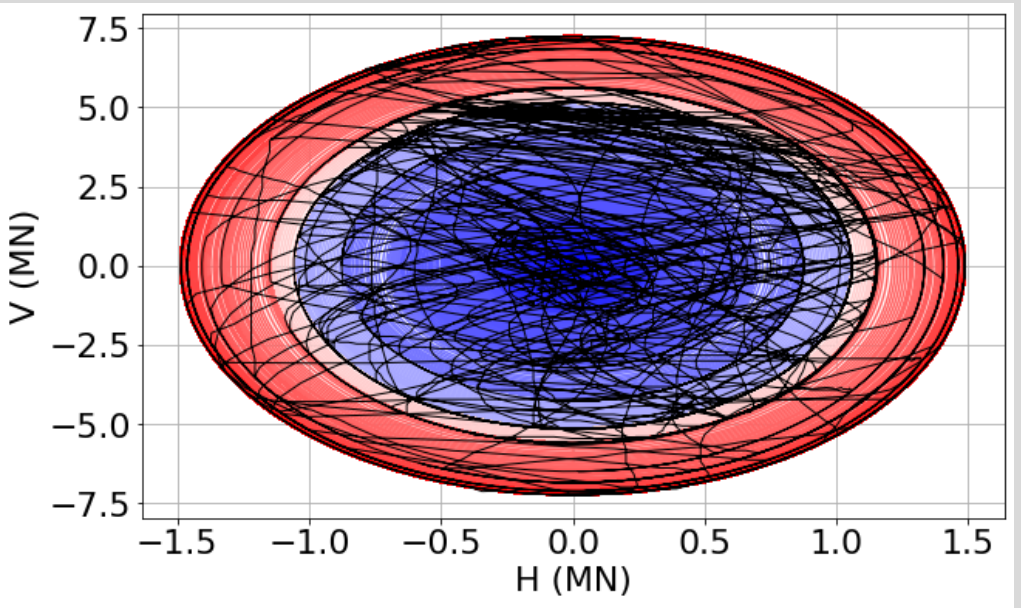
Macro-Model for Spudcan Foundations









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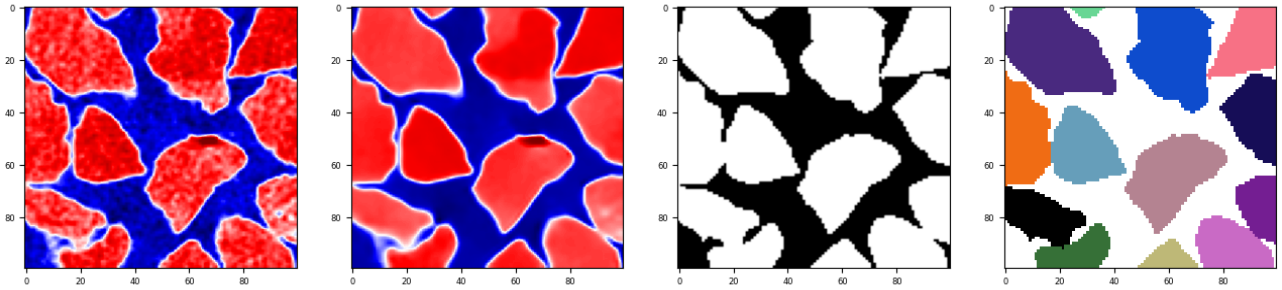
Virtual Lab for Granular Materials

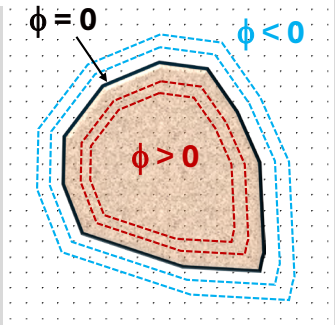
- Database of sand grains

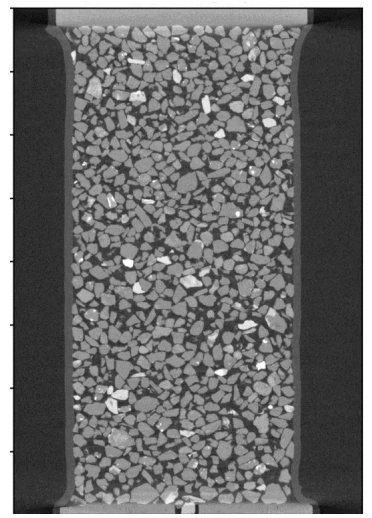
From X-ray Computed Tomography (XRCT) to «digital grains»

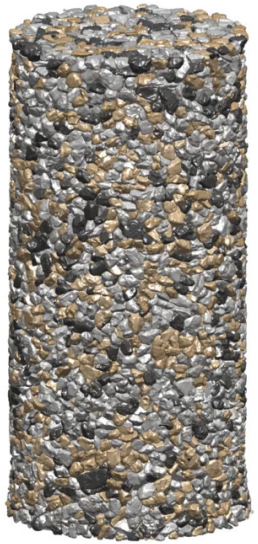


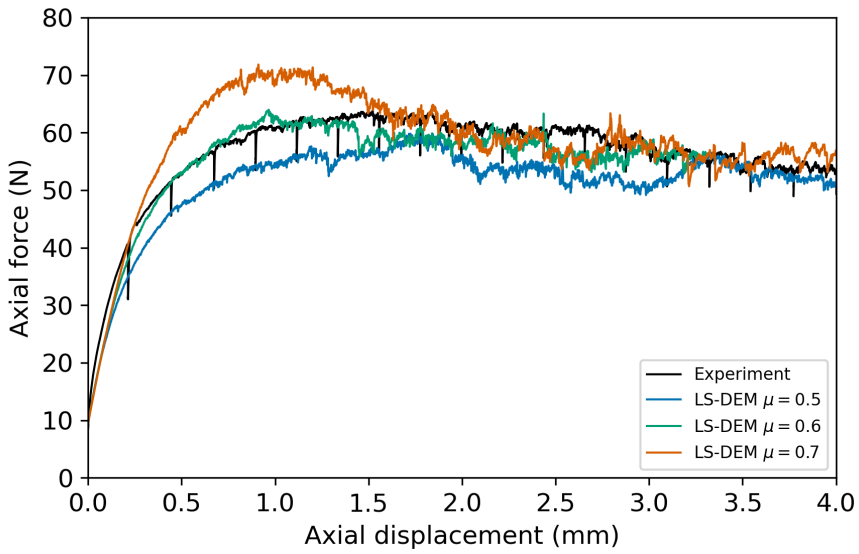
XRCT image | Filtered image (de-noising) | Binarized image (voids and solids) | Segmented image (individual grains)

Level set function





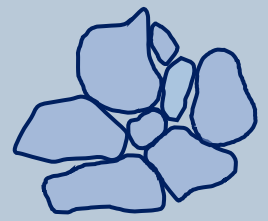




Torgersrud et al. 2024

Virtual Reality R & D

Micro Mechanics



Numerical

WP1
VR laboratory test simulator

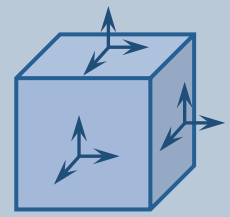
Comparison

WP2
Laboratory testing for digital twin

Experimental

VR tests

Continuum Mechanics



WP3
Deformation characteristics of sand

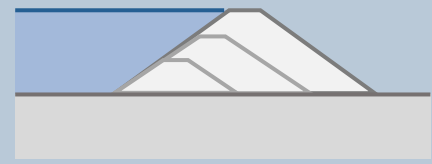
WP3.1
A comprehensive constitutive model

input properties and improved formulations

WP3.2
Deformation characteristics by DNN

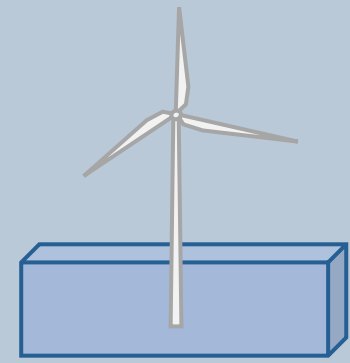
Applications

Engineering Design



Tailings dams

WP4
Workflow for enhanced geotechnical analyses



Offshore Wind Turbines

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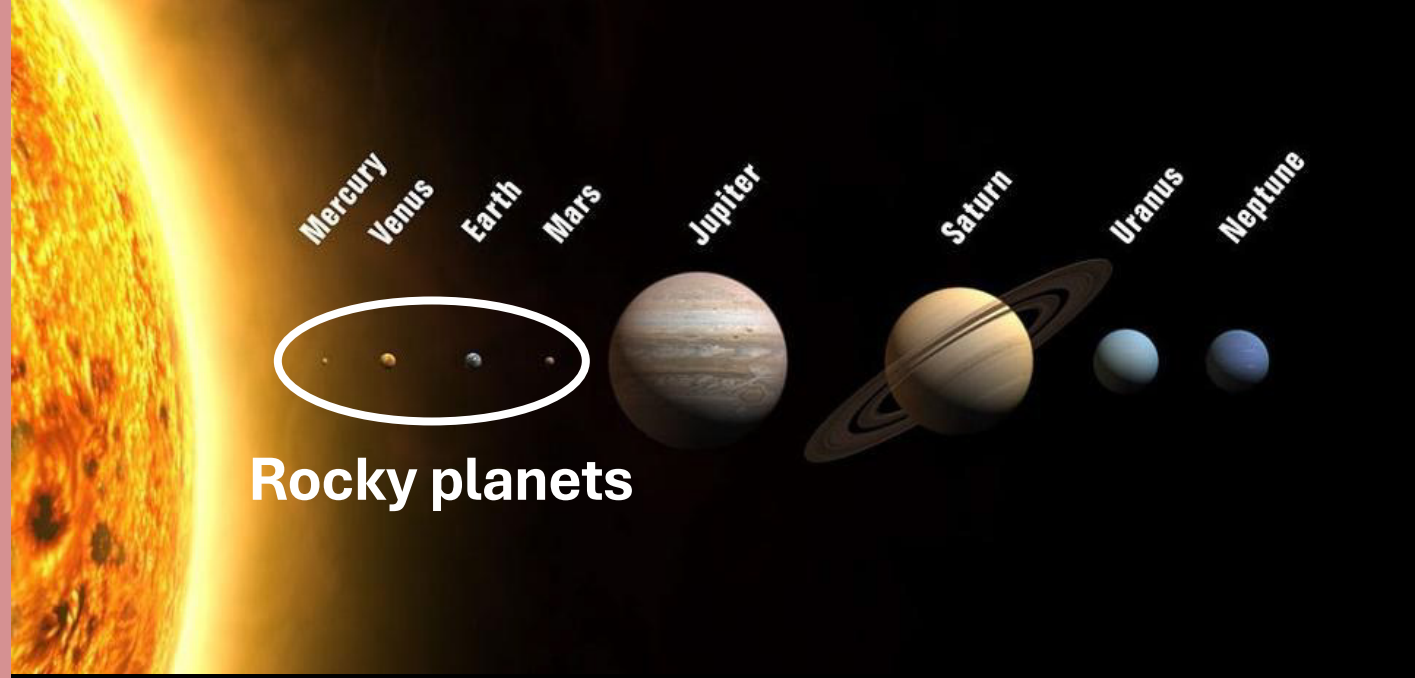
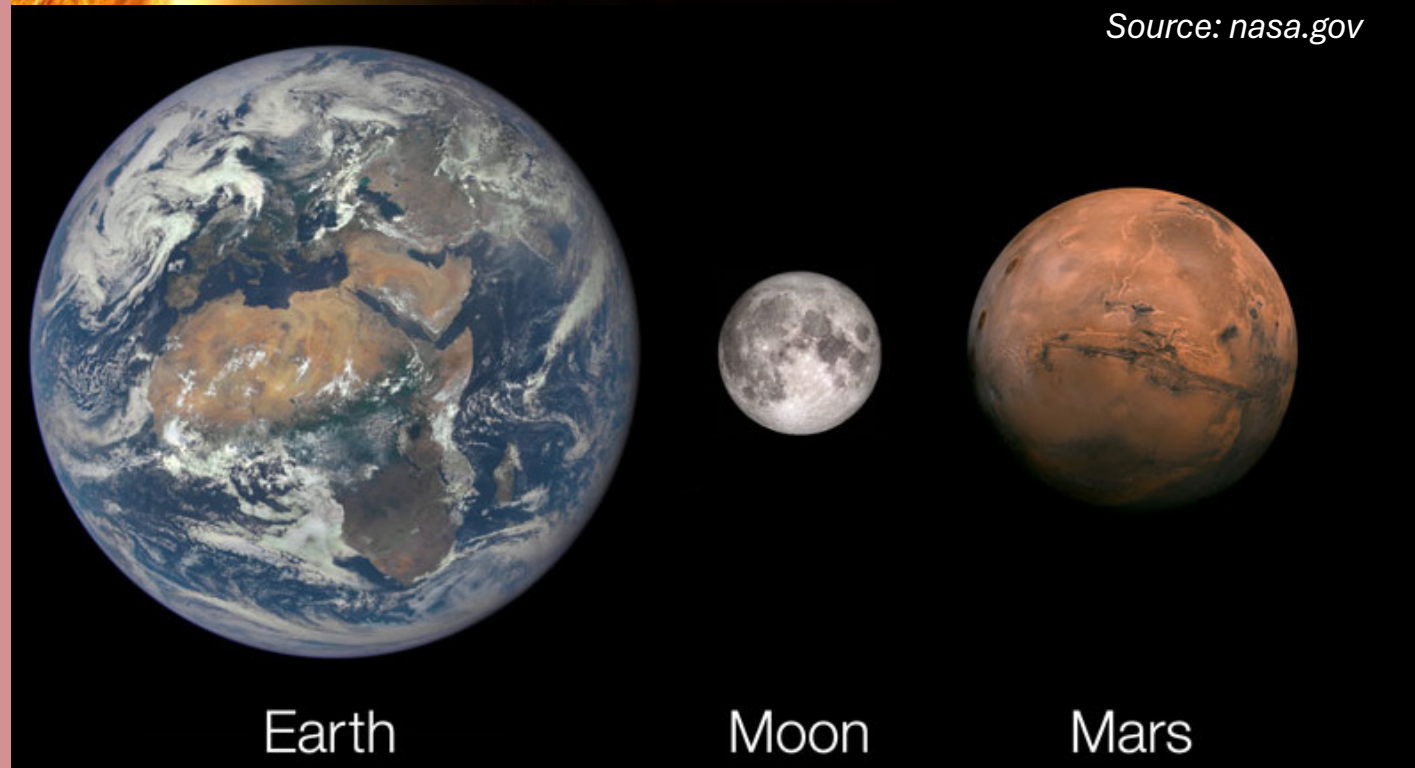
Environments Beyond Earth

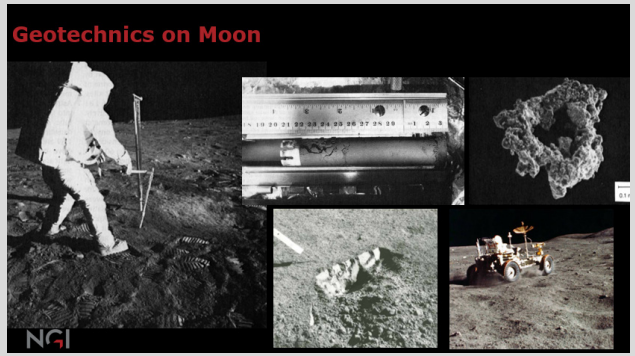


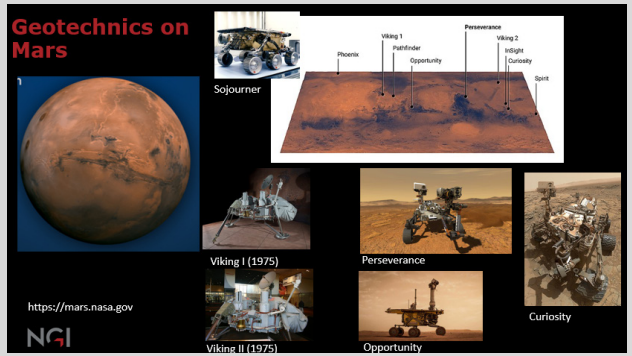
Source: nasa.gov



Earth, Moon and Mars: Key Differences & Characteristics

Feature	Earth	Moon	Mars
Distance from Earth	-	384,000 km	~79 million km
Visitors	Over 8 billion (human)	24 human visitors, 12 walkers	None (8 robotic missions)
Atmosphere	Nitrogen, Oxygen	None	Carbon dioxide
Radius	6,371 km	1,740 km	3,389.5 km
Temperature range	-88°C to +58°C	-248°C to +120°C	-140°C to +30°C
Gravity	9.8 m/s^2	1/6 of Earth	1/3 of Earth
Atmospheric pressure	101.3 kPa	0.3 nPa	~0.6 kPa
Humidity	Varies	Very low (0.01-0.04%)	Very low (Arid)
Special features	Life, water, biosphere	Bombardment by solar wind, meteorites	Largest volcano & deepest canyon





Current Projects at NGI

Research projects:

- Lunar Regolith laboratory testing (Including Apollo 14 samples)
- Icy regolith characterization (frozen lunar regolith ice content)
- Martian simulants strength characterization
- Shear wave velocity and particle shape effects (collaboration with France)
- LUNOR – Norwegian Lunar Regolith Simulant
- Calibration Chamber

Commercial projects:

- Lunar soil simulants testing (2023-2024, ESA, URS)
- Martian Simulants characterization (2023-2026, ESA)

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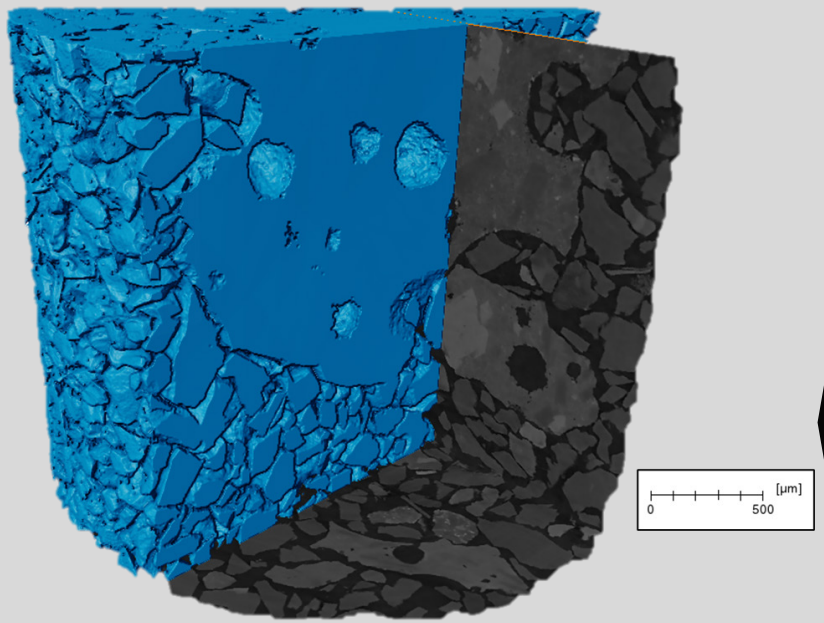
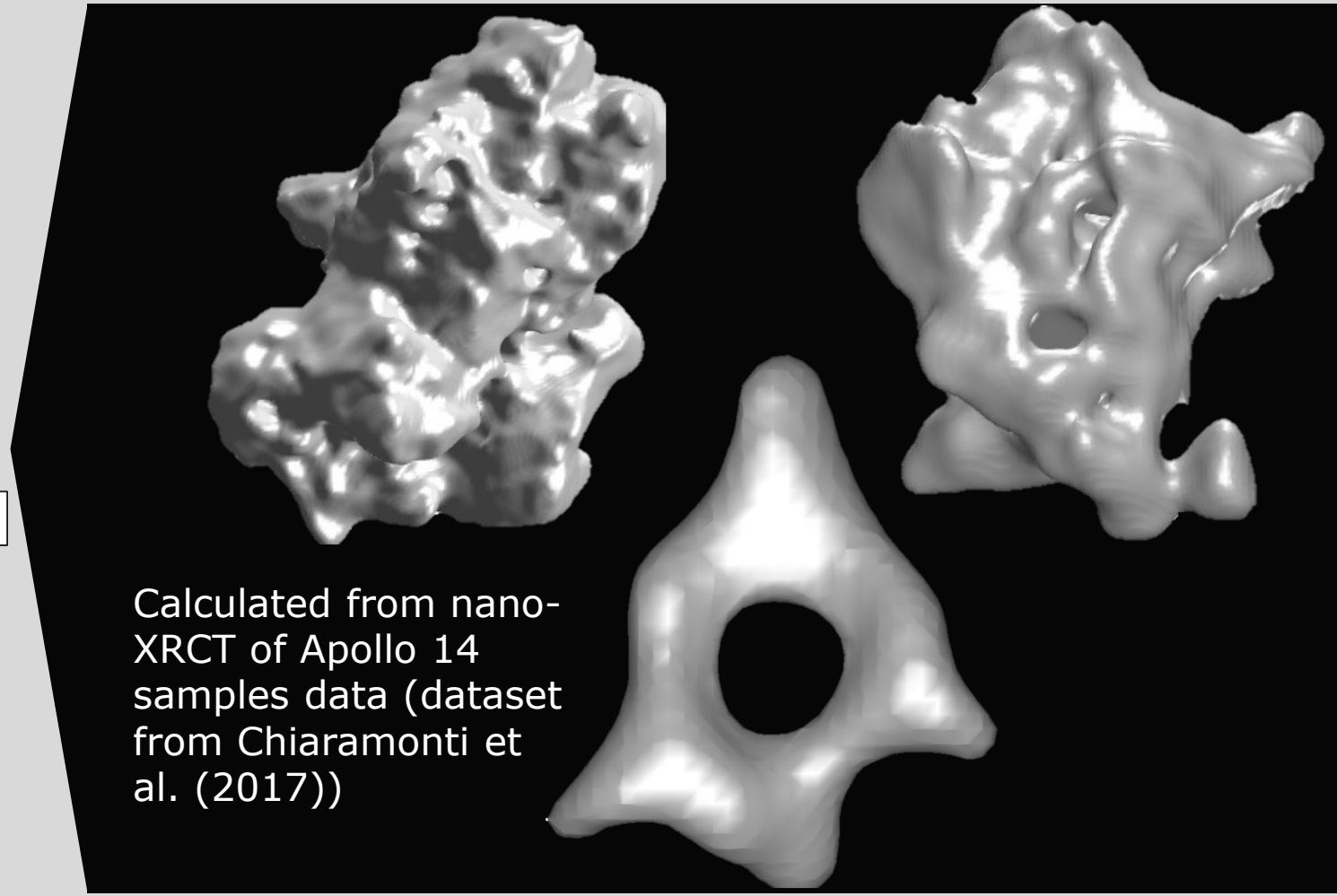
Lunar Simulants vs. Lunar Regolith

- Lunar simulants can't currently account for all aspects of the lunar regolith
- We processed and analysed X-ray nano CT images of regolith grains returned from the Apollo 11 and 14 missions and found some interesting shapes...

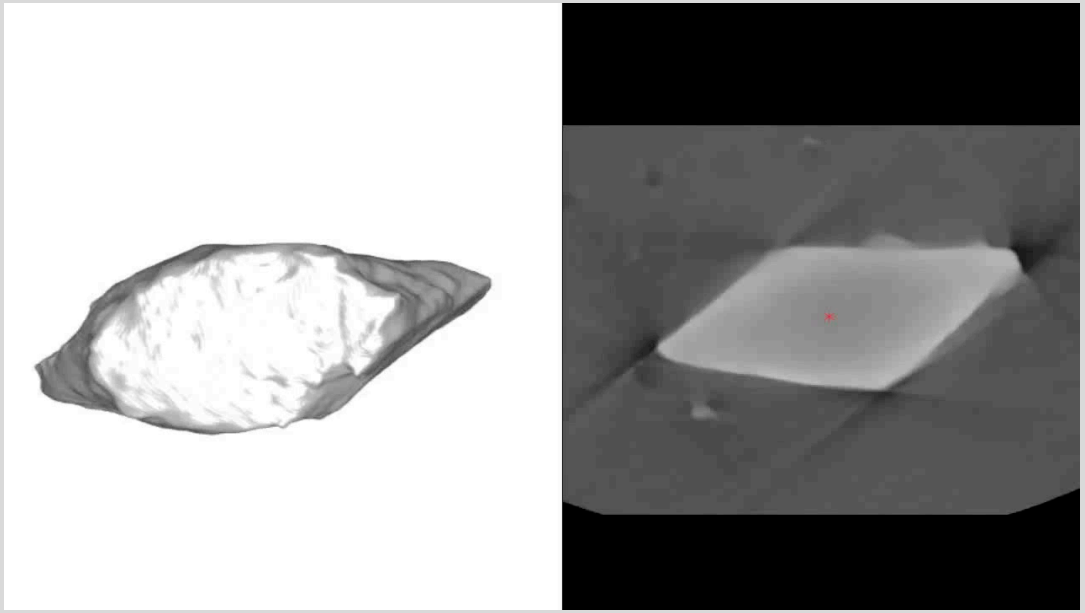


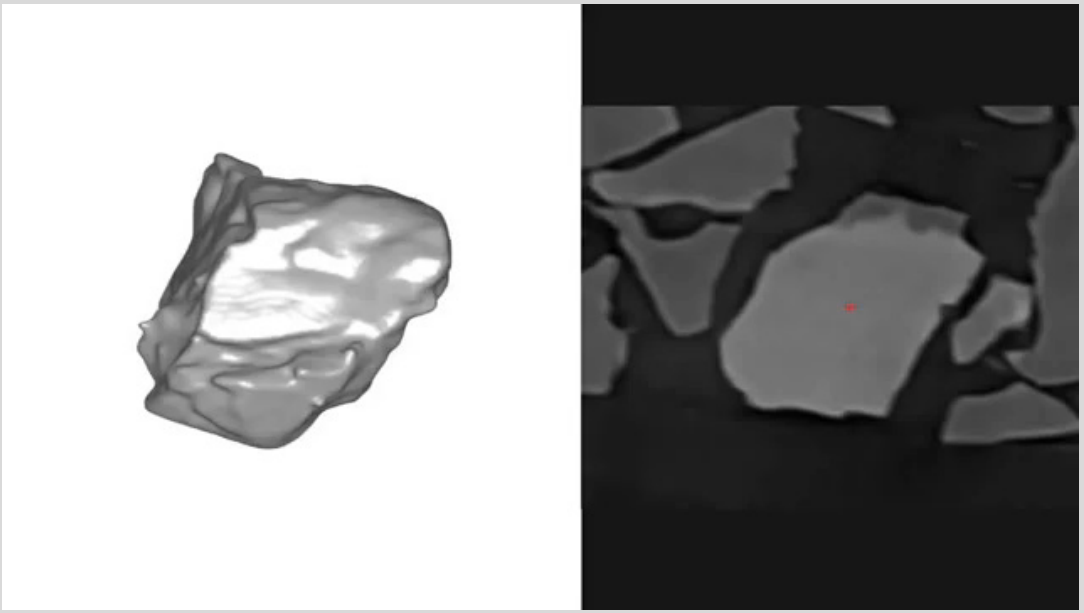
X-Ray Nano-CT scan of LHS-1

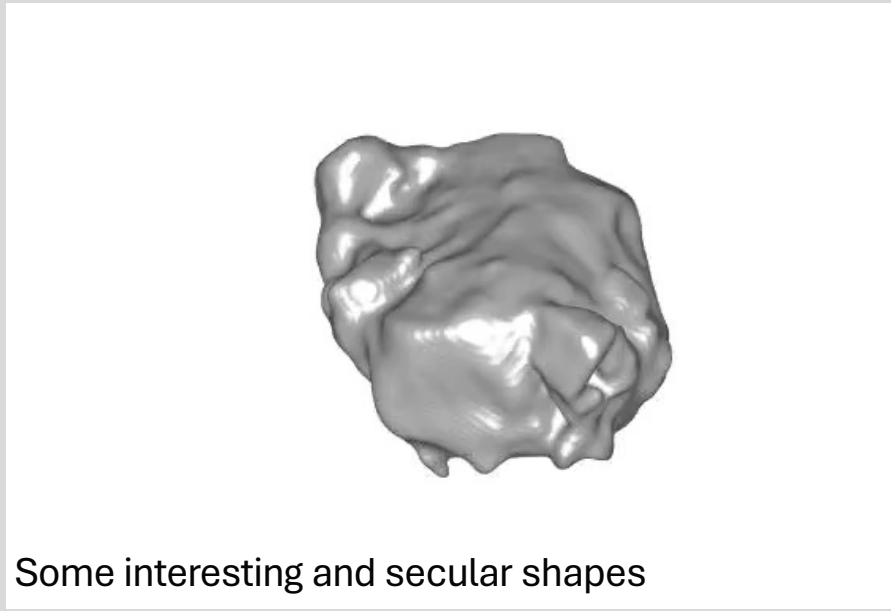


Calculated from nano-XRCT of Apollo 14 samples data (dataset from Chiaramonti et al. (2017))

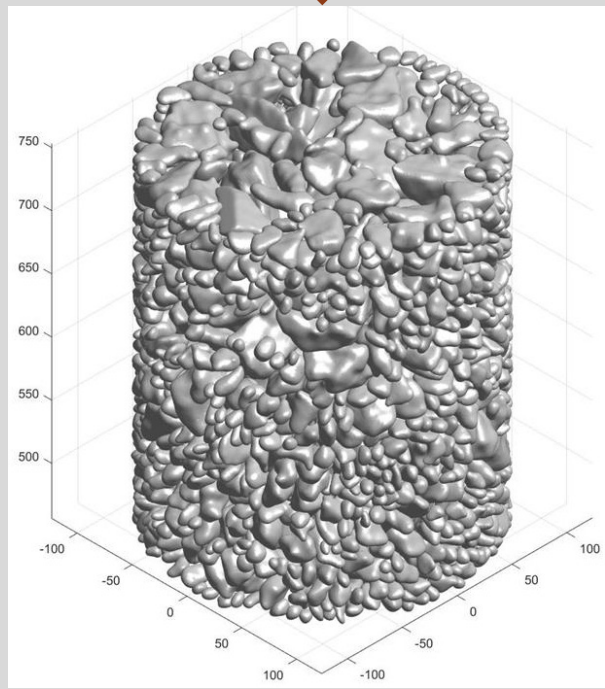
LS-DEM: Particle Morphology







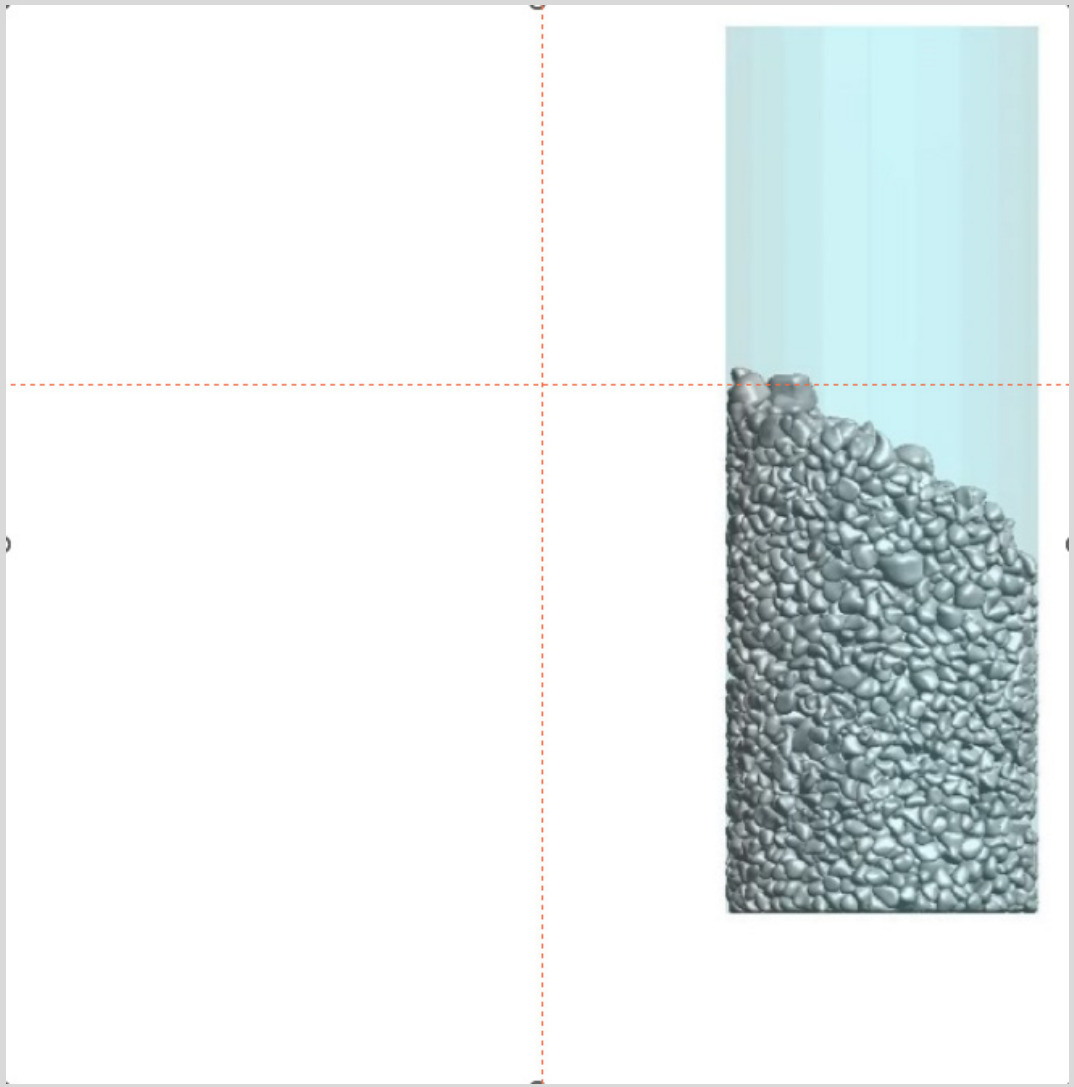
Some interesting and secular shapes

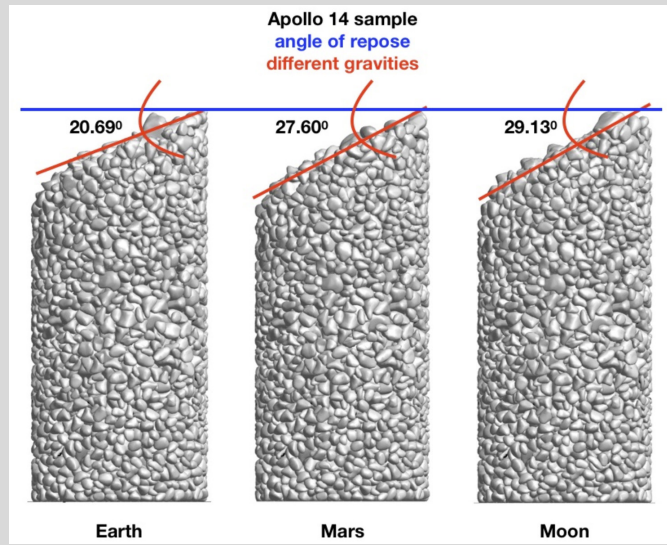


LS-DEM: A Digital Twin of Lunar Soil

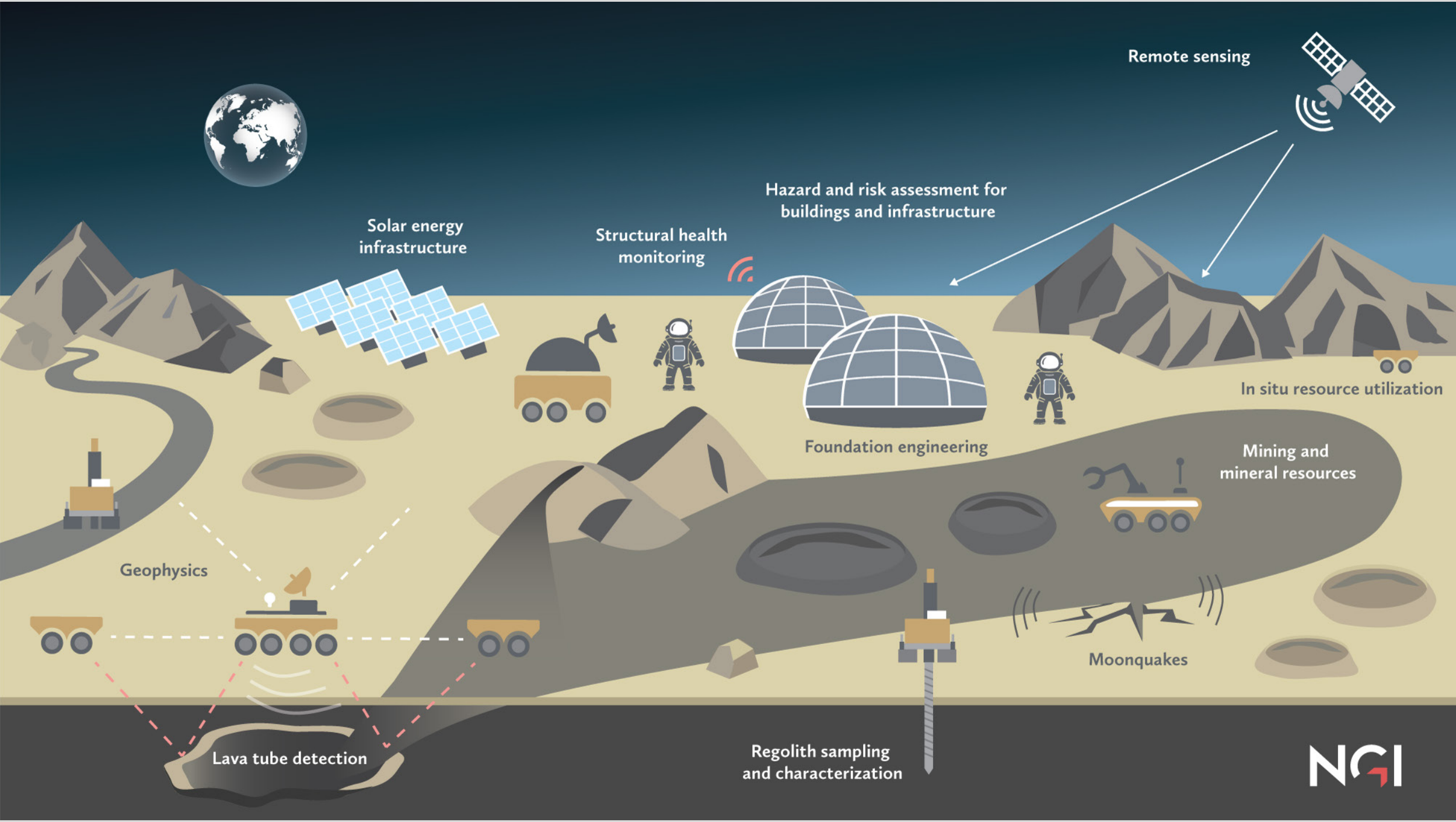
- Simulations with varying gravity

Near vertical walls on the Moon due to high cohesion, frictional shear strength. *NASA, from Carrier et al., Lunar Sourcebook (1991)*





Through numerical simulation, we see that lower gravity leads to higher angle of repose.


Remote sensing
Hazard and risk assessment for buildings and infrastructure
Solar energy infrastructure
Structural health monitoring
In situ resource utilization
Foundation engineering
Mining and mineral resources
Geophysics
Moonquakes
Lava tube detection
Regolith sampling and characterization
NGI


MARS SAMPLE RETURN
https://www.youtube.com/@NASAJPL

Bridging Research and Industry

BLUES

Floating structures for the next generation ocean industries

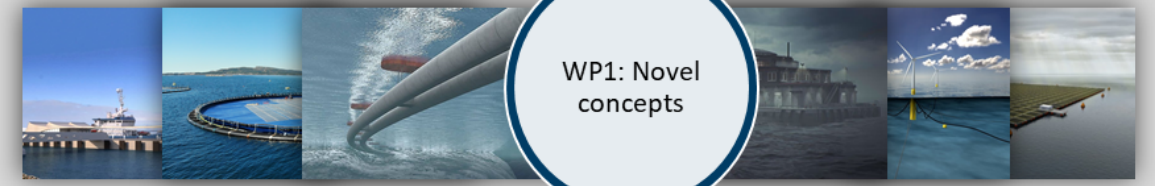
sfi = Centre for Research-based Innovation

Input

- *New needs for marine support structures*
- *New ideas for concepts*
- *New technology*
- *External influence, such as:*

SUSTAINABLE DEVELOPMENT GOALS

Concepts



WP1: Novel concepts

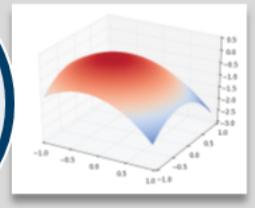
New concepts define needs for design tools

Improved design tools enable new concepts

Tools

WP2: Digital Fjordlab

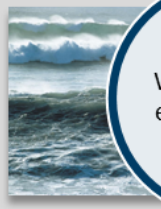
WP3: Design optimization



New requirements define needs for new knowledge

Novel physical models improve design tools

Physics

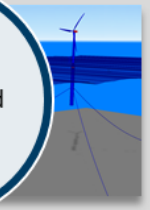


WP4: Marine environment

WP5: Wave-structure interaction

WP6: Advanced material technology

WP7: Mooring and anchors



Results and innovations

- *New products*
- *New services*
- *Spin-off projects*
- *New design tools*
- *New design methods*
- *Newly educated MSc's and Phd's*
- *New knowledge*

FME NorthWind

A strategic research and innovation action to reduce the cost of wind energy, facilitate its sustainable development, create jobs and grow exports

Partners: SINTEF (host), NTNU, NINA, NGI, UiO and 50 industry partners

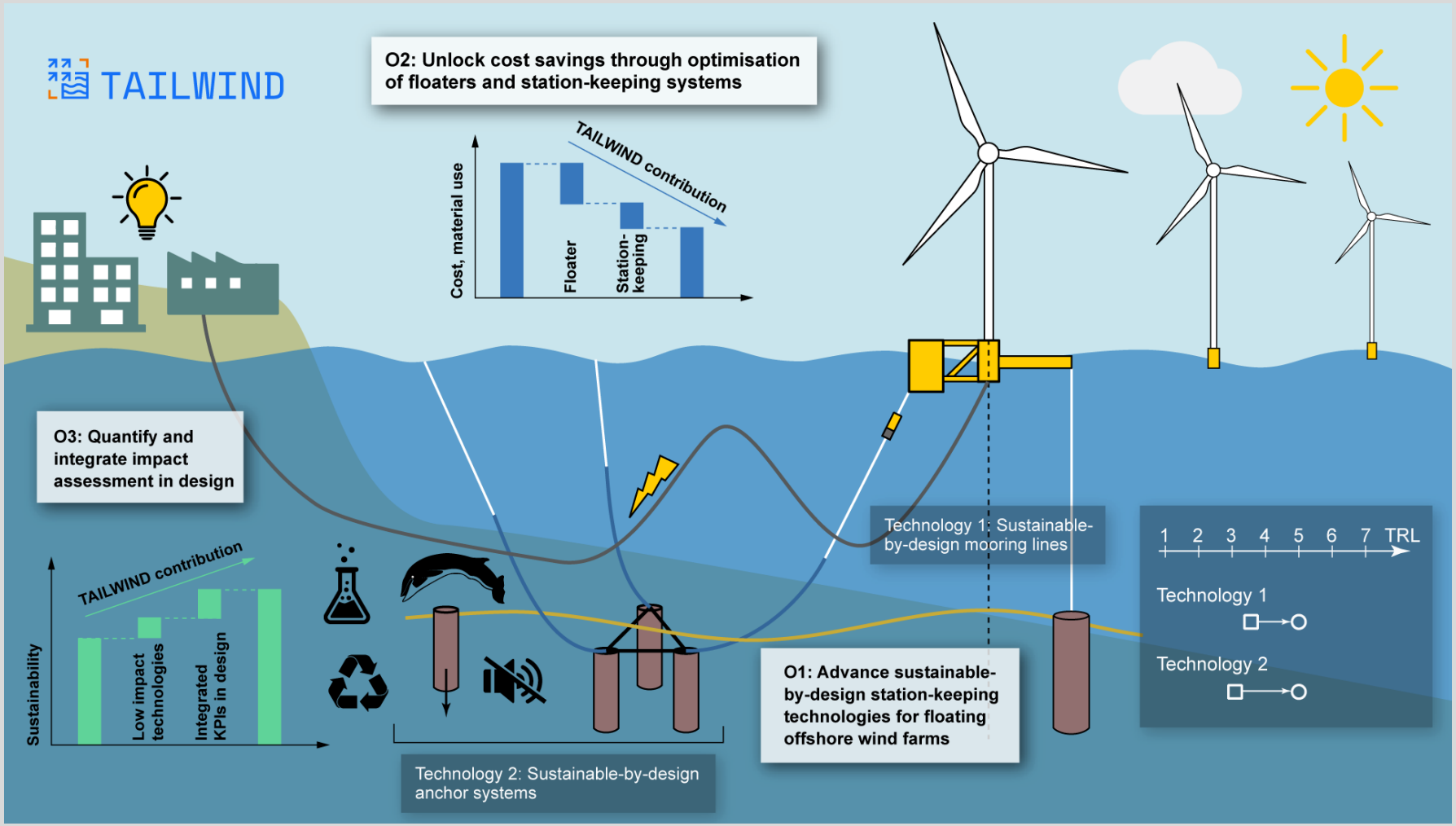
Total budget 2021-2029: 350 MNOK financed by Research Council of Norway, industry and research partners

FME NORTH WIND

Norwegian Research Centre on Wind Energy

TAILWIND susTainable stAtion-keepIng systems for fLoating WIND

PROJECT OVERVIEW



European Commission

NGI Clarke Modet +

SINTEF

DTU TU Delft

NKT

subsea 7

Bekaert

University of Southampton

Nautilus

ICONS

tecnalia

Remarks

Key Points

- Interdisciplinary innovation
- Industry-Academia collaboration
- Data-driven decision making
- Sustainable practices
- Skill development and knowledge transfer
- Real-time application of advanced models

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Key Actions

- Establish joint research projects
- Develop specialized training programs
- Foster knowledge-sharing platforms
- Implement pilot projects for new technologies
- Incentivize sustainability-driven research
- Regularly review and update industry standards
- Create internship and exchange programs

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Acknowledgment of Contributions from NGI Colleagues

Aligi Foglia

Ana Page

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Hans Petter Jostad

Jung Chan Choi

Nallathamby Sivasithamparam

Øyvind Torgersrud

Santiago Quinteros

and many others ....

"Tea is a cup of life."

Anonymous

Just like a good cup of T.E.A,
three elements blend together,
supporting one another and
strengthening our work

Thank you!

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