Earthquake Geotechnics in Offshore Engineering

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Amir M. Kaynia

Technical Expert, Vibration and Earthquake Engineering, NGI

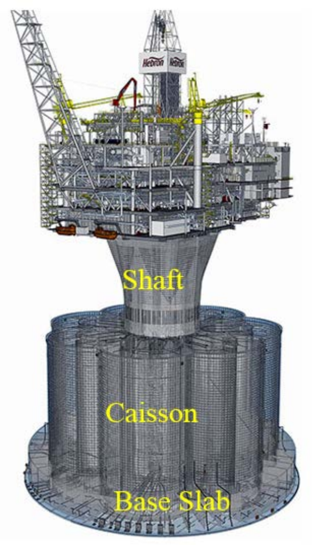
Adjunct Professor, Norwegian University of Science and Technology, NTNU

Outline

- Earthquake Design Philosophy
- Response of submarine slopes
  - Effect of strain softening
  - Multi-directional loading
  - 3D geometry
- Earthquake response of pipelines
- SSI in analysis of platforms
  - Flexible base
- Seabed facilities
- Offshore wind turbines

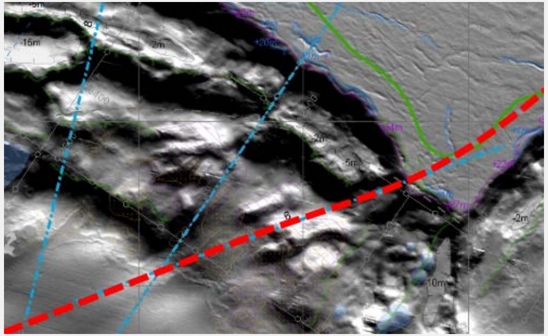
Earthquake Design Philosophy

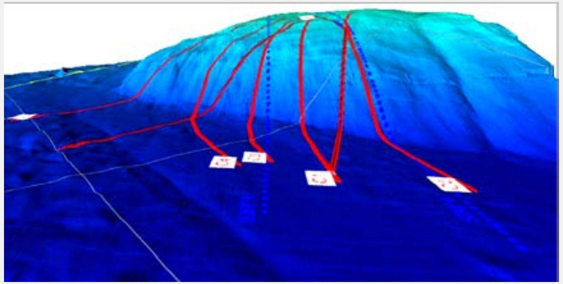
- Two-tier design approach according to ISO with two performance expectations
  - Little or no damage or interruptions to normal operations during frequent earthquakes referred to as Extreme Level Earthquake (ELE): typical return periods 300-700 years.
  - No serious HSE consequences in rare earthquakes referred to as Abnormal Level Earthquake (ALE) although the facility could be irreparable and result in economic loss: typical return periods 2500-3500 years.
- For ALE event, earthquake shaking is often large resulting in large soil nonlinearity and permanent displacements; therefore, one needs to use nonlinear models rather than equivalent linear methods.



Earthquake response of submarine slopes

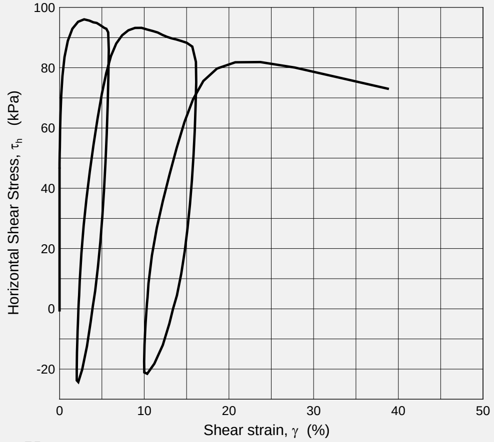
- Important for two reasons:
  - Impact on pipelines traversing slope
  - Debris flow from slope failure impacting subsea facilities/pipelines
- Tools:
  - Empirical equations
  - 1D, 2D, 3D FEM/FDM
- Some important issues seldom considered in design and often on un-conservative:
  - Strain softening
  - Multi-directional shaking
  - 3D geometry

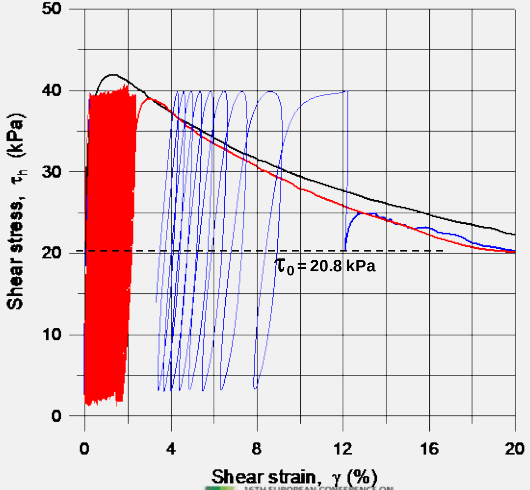




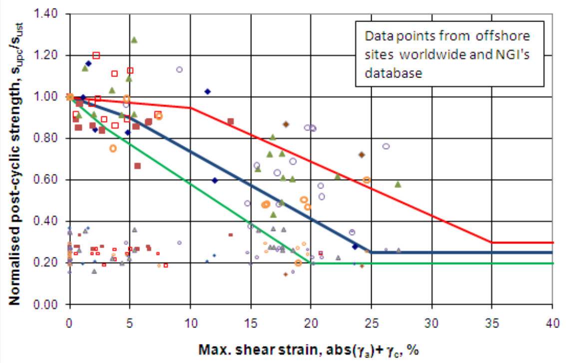
Strain softening

Example of shear stress-strain for a marine clay sample in DSS test under unsymmetrical loading representing slope angle. (A number of recent centrifuge tests at UC Davis and CCORE will hopefully help us better understand the mechanism of earthquake response of sensitive clay)





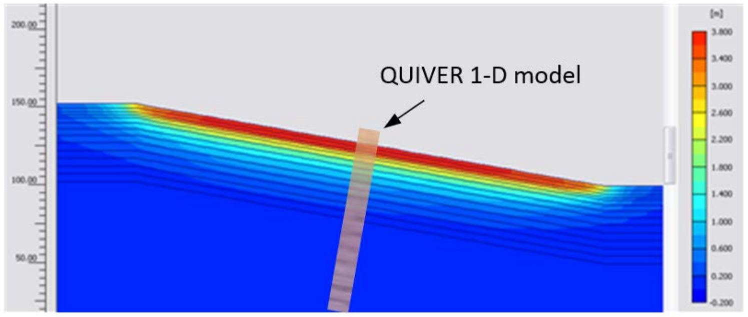
The reduction of shear strength with strain (de-structuration) appears to follow the strain softening curve of static (monotonic) tests.

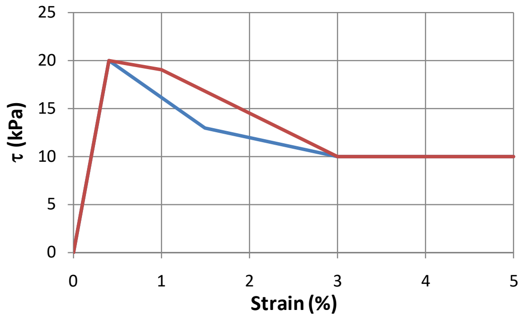


Data points from offshore sites worldwide and NGI's database

Effect of strain softening on slope response

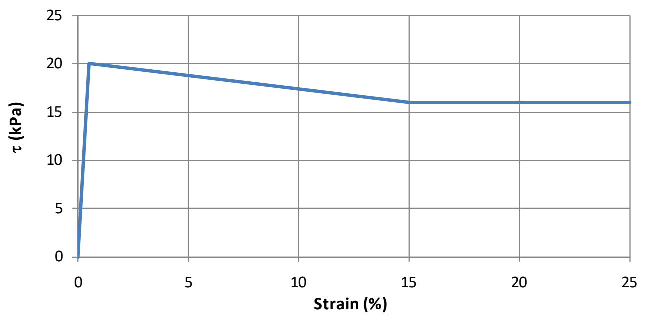
1-D slope response model QUIVER (Kaynia, 2012) was developed to account for strain softening in the shear stress-strain response of soil layers

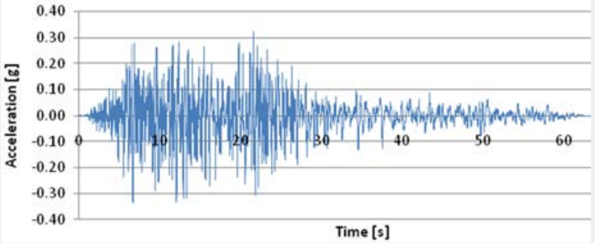


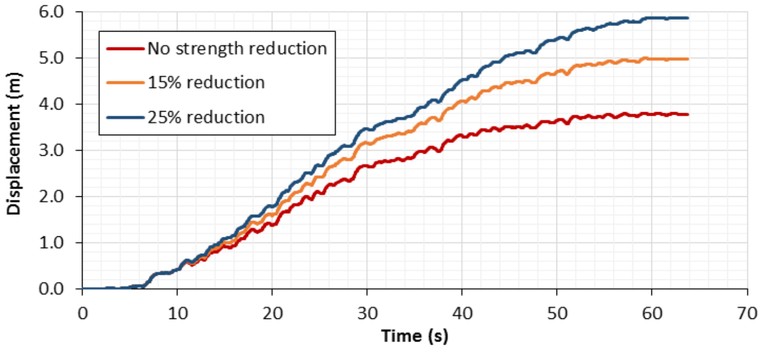


Effect of strain softening on slope response

Comparison of seabed displacements of a deep NC clay slope for cases of perfect-plastic behavior and shear strength reductions of 15% and 25% at 15% shear strain

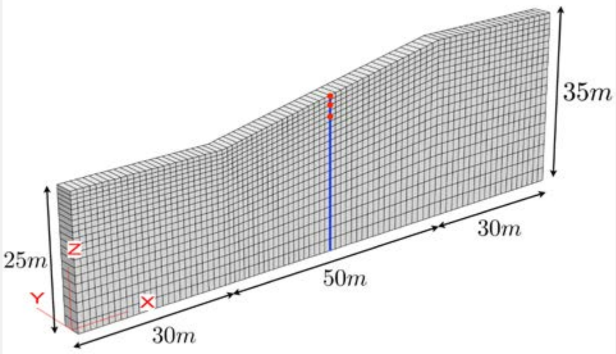


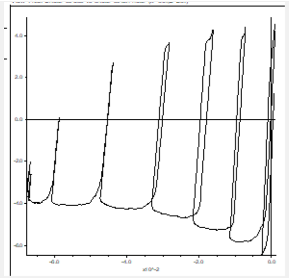




Effect of strain softening on slope response

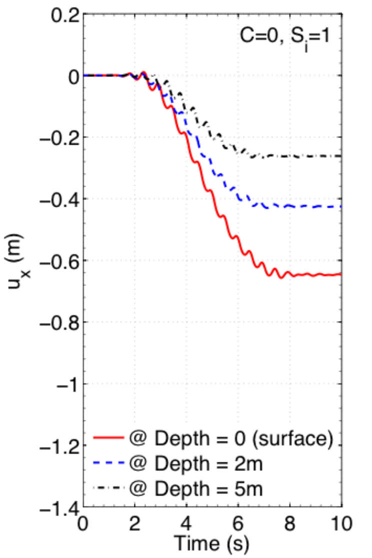
Similar behavior has been observed using rigorous plasticity model SANICLAY implemented in FLAC3D (Taiebat, Kaynia & Dafalias 2011)



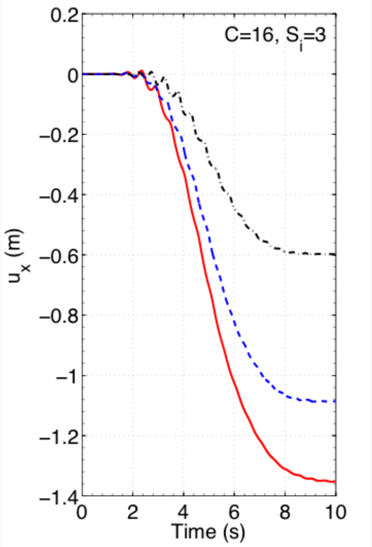


Seabed displacements at 3 depths

Case 1: isotropic, no strain softening



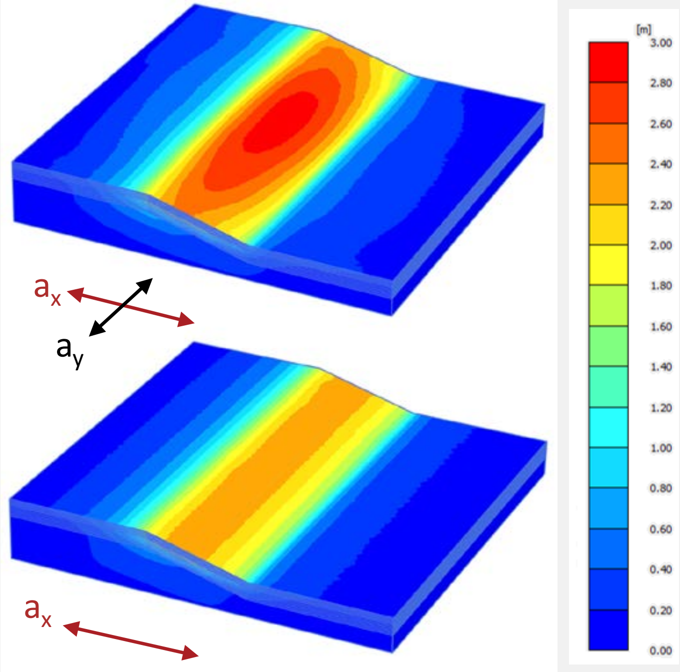
Case 2: anisotropic, strain softening



Effect of multi-directional shaking

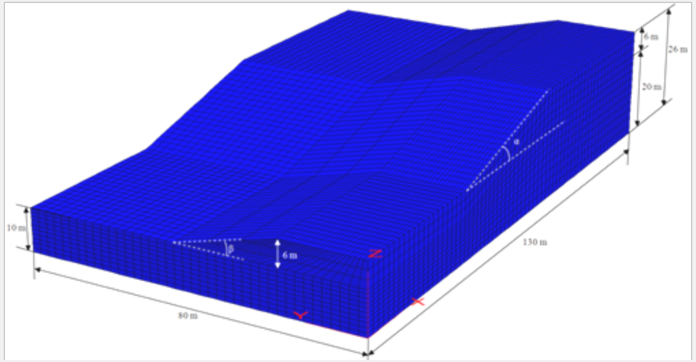
Typical results of numerical simulations in which 3-D slopes of NC clay with simple Mohr-Coulomb failure criterion were subjected to one-component and 3-component earthquake excitations (Carlton & Kaynia, 2016).

- Soil profile: shear strength increasing linearly with depth with from 5 kPa on surface to 300 kPa at depth 300 m.
- Earthquake input: magnitude 6.5 California earthquake of 1954 at Ferndale City Hall scaled to 0.6 g

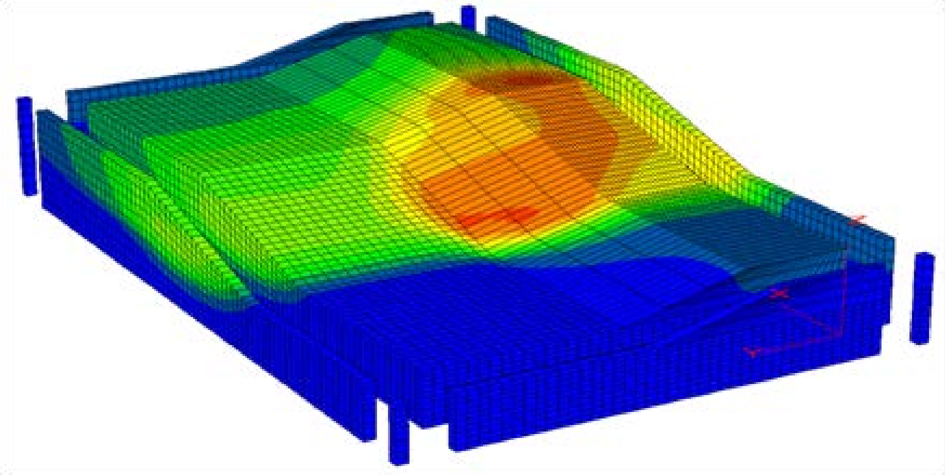


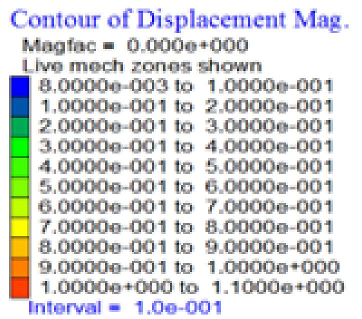
Inclusion of earthquake component perpendicular to slope direction has increased permanent displacements and shear strains in slope by 25%-50% and by 10%-50%.

Effect of 3-D Geometry



Earthquake response of 3D slope due to shaking in one direction - Example results: displacement contours for 10 cycles of sine wave, frequency = 2 Hz, peak acceleration = 0.15g, and α = β = 1:4

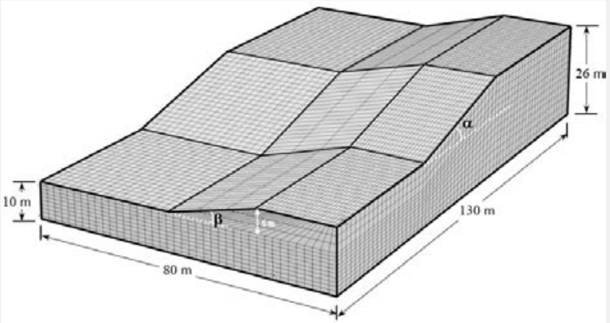


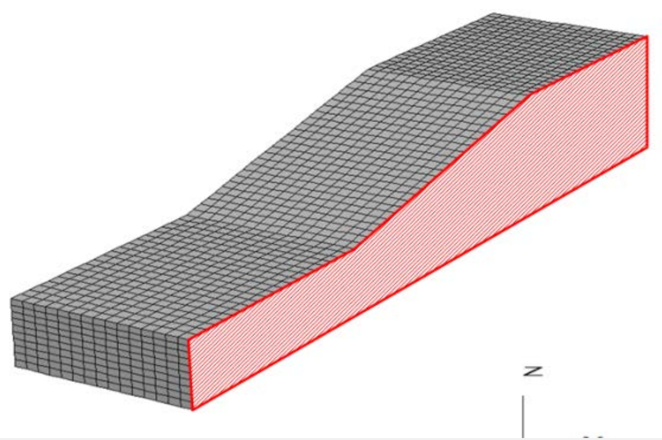


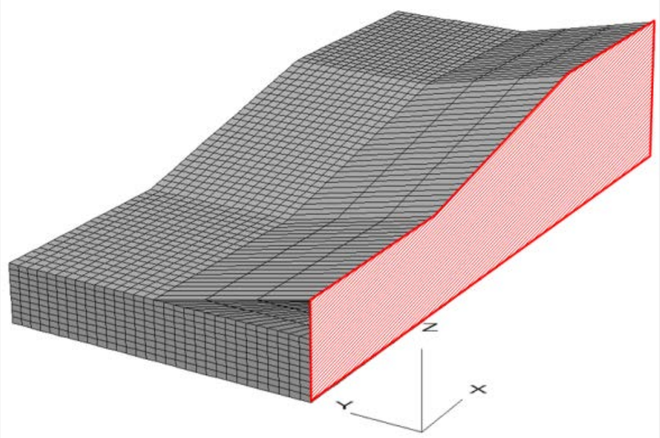
Contour of Displacement Mag.
Magfac = 0.000e+000
Live mech zones shown
🟦 8.0000e-003 to 1.0000e-001
🟦 1.0000e-001 to 2.0000e-001
🟩 2.0000e-001 to 3.0000e-001
🟩 3.0000e-001 to 4.0000e-001
🟩 4.0000e-001 to 5.0000e-001
🟩 5.0000e-001 to 6.0000e-001
🟨 6.0000e-001 to 7.0000e-001
🟨 7.0000e-001 to 8.0000e-001
🟧 8.0000e-001 to 9.0000e-001
🟧 9.0000e-001 to 1.0000e+000
🟥 1.0000e+000 to 1.1000e+000
Interval = 1.0e-001

Effect of 3-D Geometry

Effect of 3rd Dimension – Stresses and strains on 2-D sections across slope

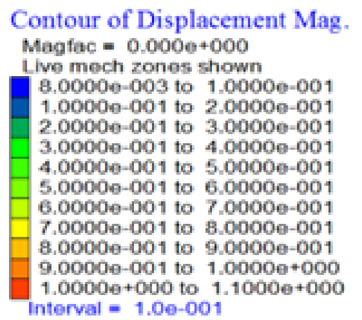




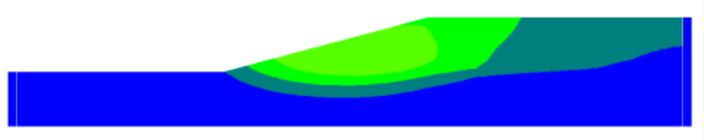


Effect of 3-D Geometry

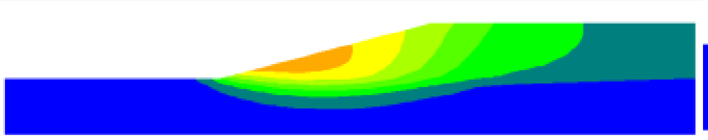
Effect of 3rd Dimension: Response of 2-D sections across slope



Shallow sections

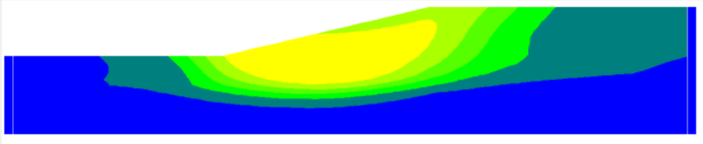


2-D model

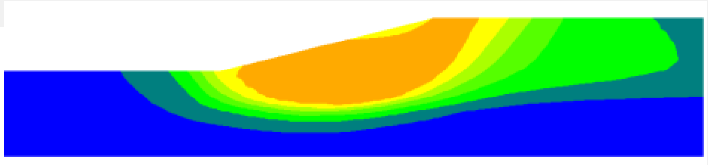


3-D

Deep sections



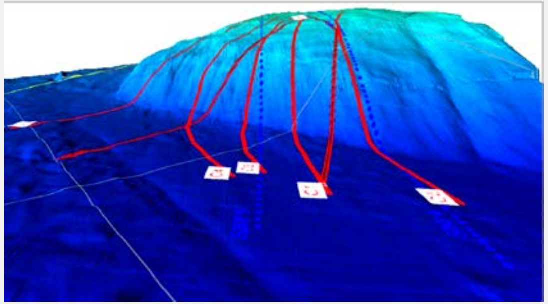
2-D model

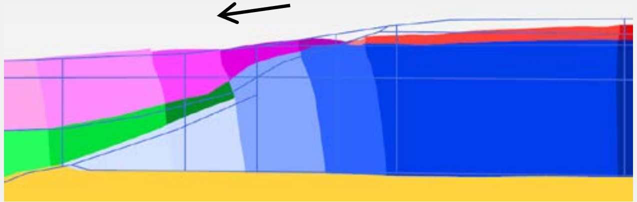


3-D

Pipelines on slopes

- Considering soft soil conditions of most offshore pipelines, earthquake forces due to soil strains are often small compared to onshore buried pipelines.
- However, offshore pipelines are vulnerable to permanent ground motions caused by earthquakes.
- Common cases are pipelines traversing submarine slopes which tend to experience large downslope displacements due to earthquakes.



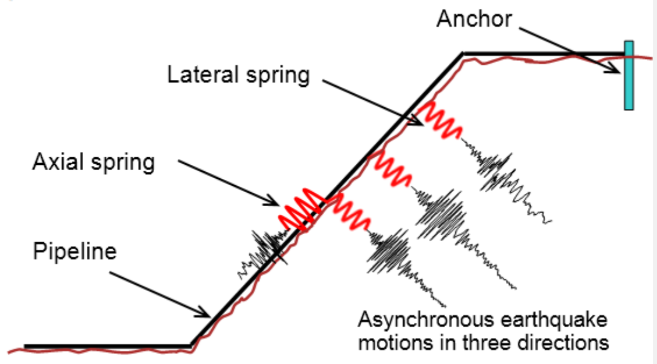


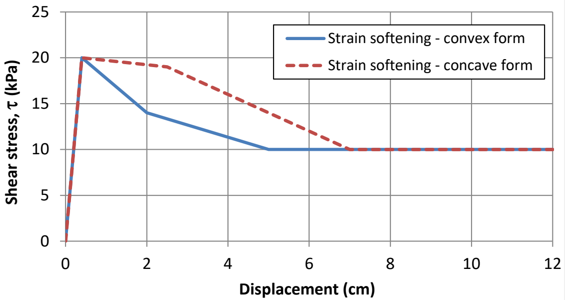
Downslope displacements due to earthquake

Pipelines on slopes

Numerical model for 3-D earthquake response of pipeline on slopes. Relevant issues are:

- Inertial loads in pipeline due to pipe mass (as opposed to static conditions, dynamic loads are large).
- Asynchronous ground accelerations due to long extension of pipeline and topographic features.
- Strain-softening behavior at soil-pipeline interface.



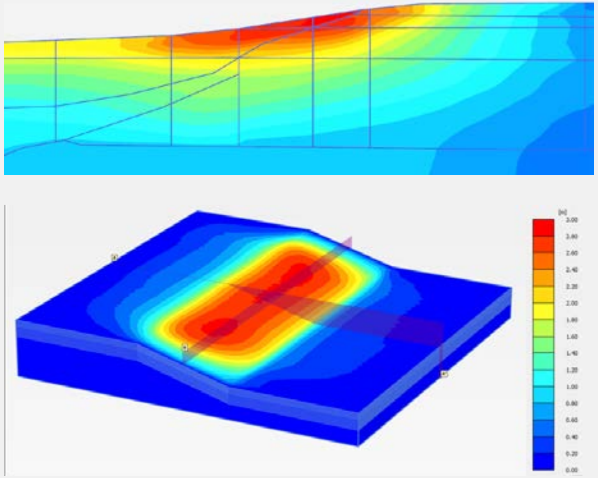


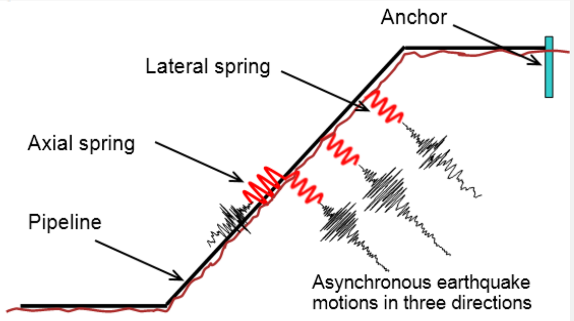
Pipelines on slopes

Pipe-soil interaction analysis is divided into two steps (Kaynia et al. OTC 2014):

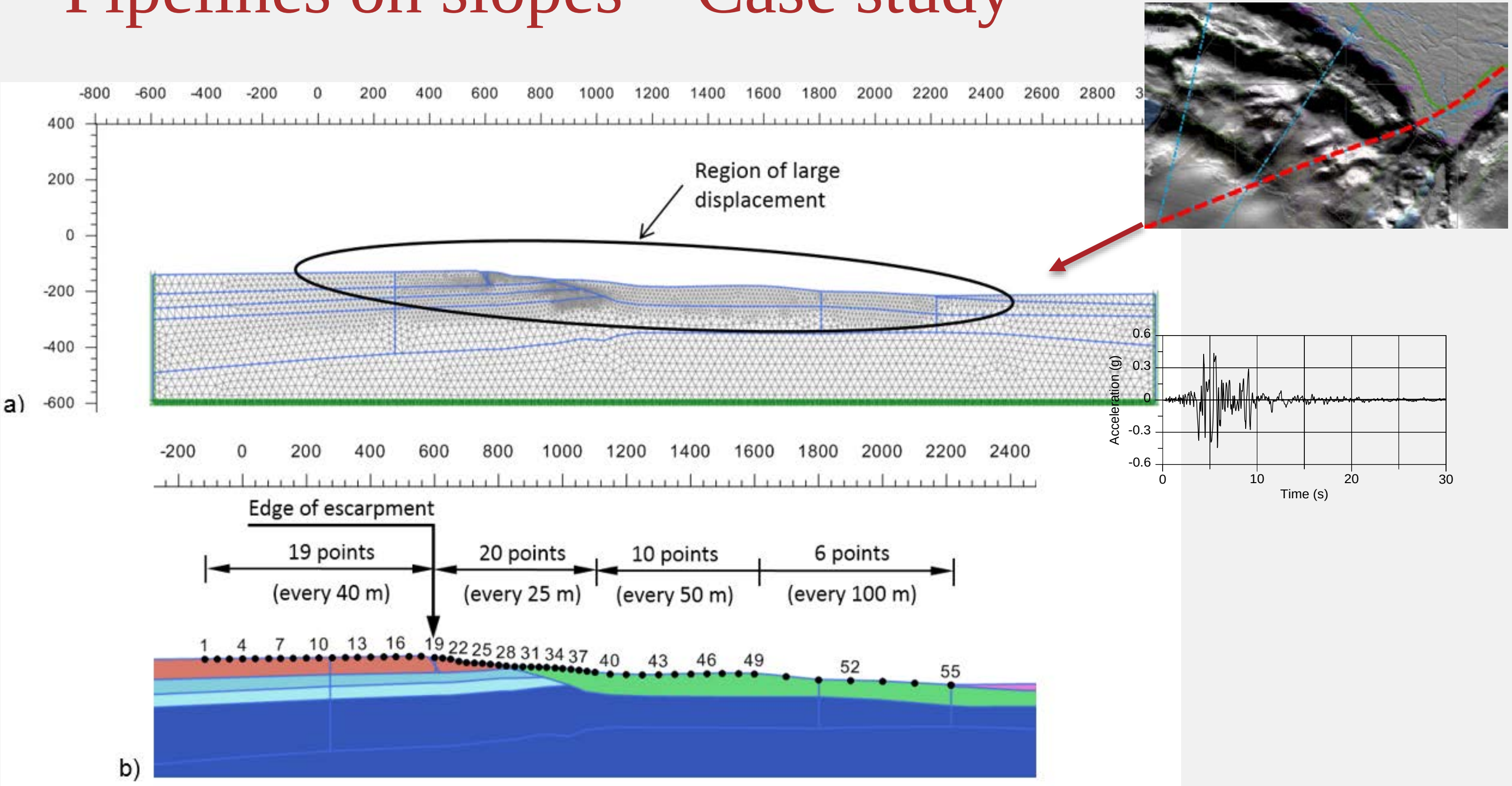
1) computation of earthquake accelerations on slope - for this step, one could use available 2D/3D FE/FD codes

2) response of pipeline on pipe-soil springs and subjected to seabed accelerations (using for example *QUIVER_pipe (Kaynia, 2012)*)



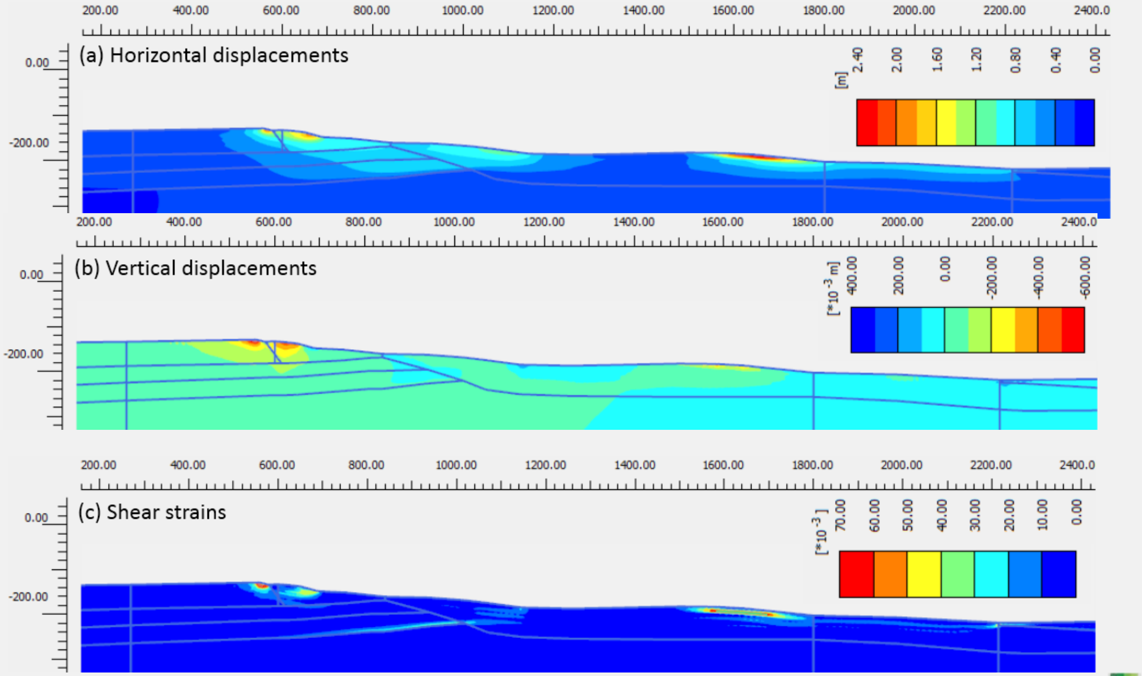


Pipelines on slopes – Case study



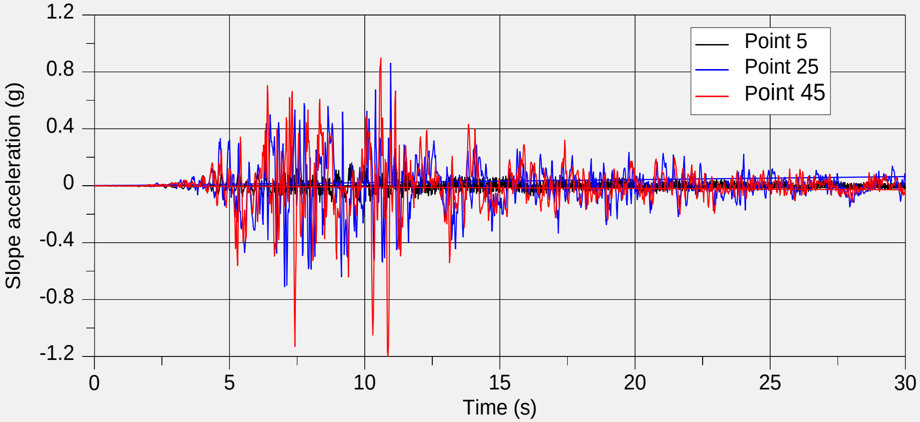
Pipelines on slopes – Case study

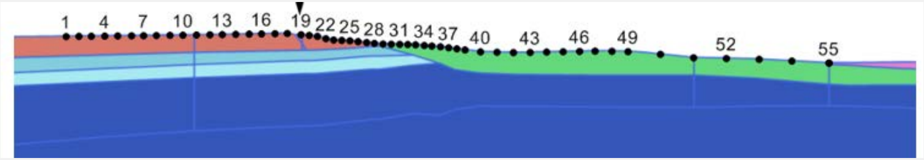
Results of 2-D FEM analyses of slope



Pipelines on slopes – Case study

- Typical results – acceleration time histories at several points: large variations along slope





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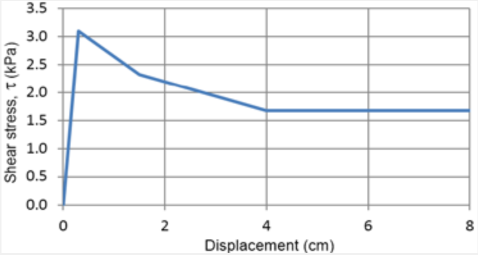
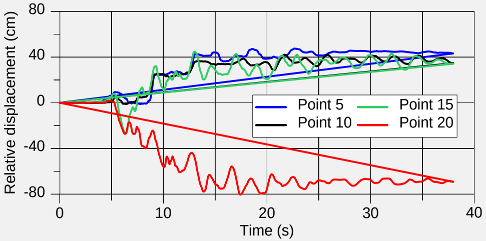
Pipelines on slopes – Case study

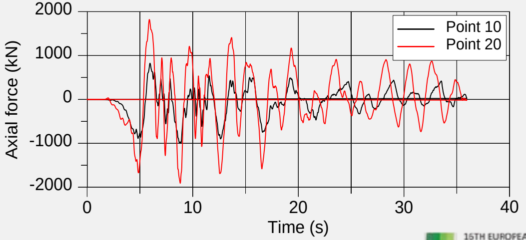
- Pipe-soil interaction spring in axial direction established based on model tests in laboratory.



- Time histories of displacements of pipeline relative to soil at selected points on seabed

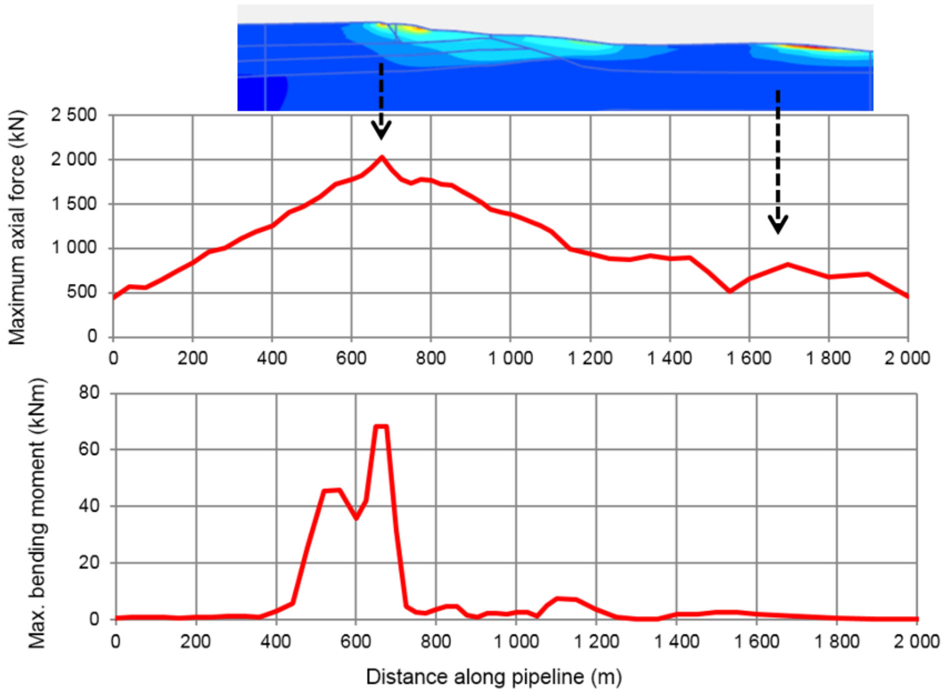


- Time histories of axial force in pipeline at selected points on seabed (note both tension and compression).



Pipelines on slopes – Case study

Maximum axial forces and bending moments in pipeline



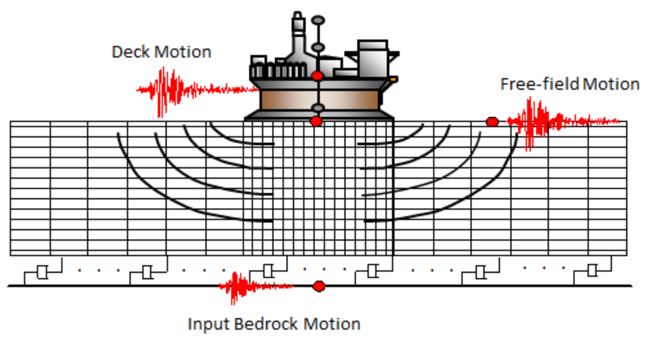
SSI response of gravity based structures (GBS)

Pictures: Various websites

Earthquake SSI analyses

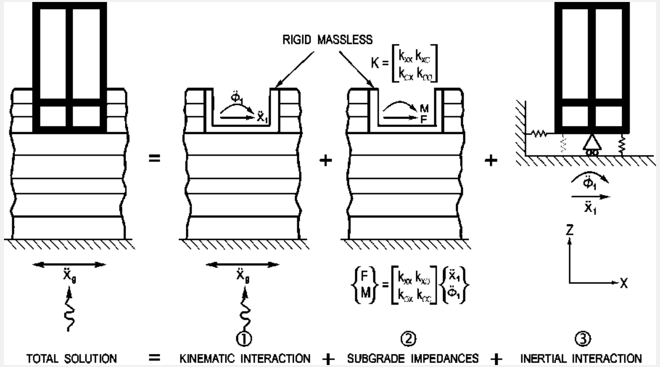
1. Integrated FE analyses of soil/structure interaction
   - One could use most advanced commercial programs; however, not all of them can satisfactorily handle lateral soil boundaries

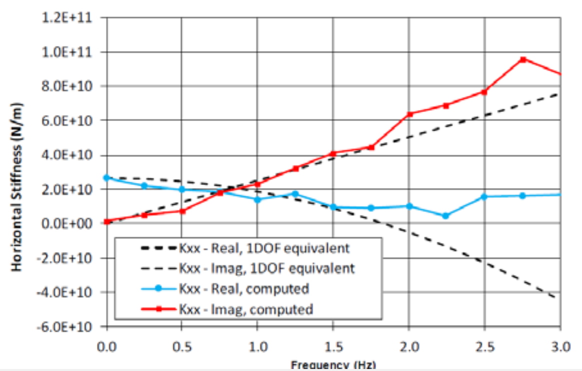
- Practical disadvantages of integrated solutions:
  - the required state-of-the-art SSI software is rarely used by structural designers
  - engineering usually involves several EPC contractors, each with their own set of tools. Therefore, project owner has to manage various EPC contractor models while ensuring proper SSI behavior in each model.



Earthquake SSI analyses

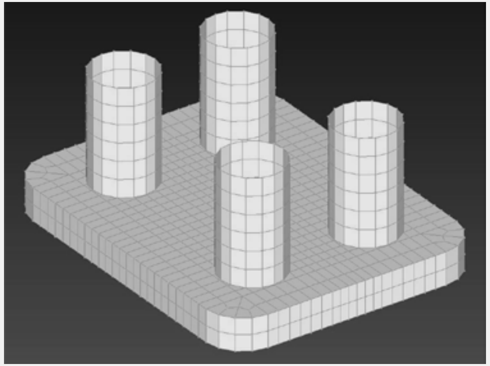
2. Sub-structuring analyses
   - For example, 3-step method using concept of soil spring/dashpot/added mass
   - Main advantage is separation of soil and structure and running smaller models

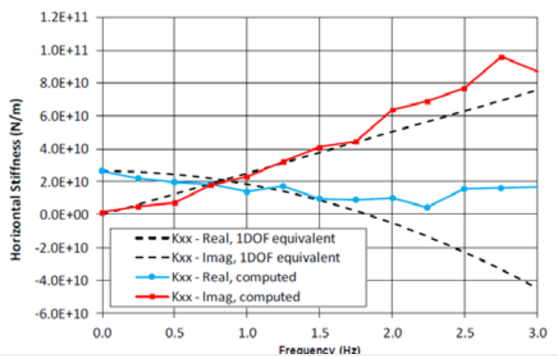




Distributed lumped-parameter foundation model => large foundation base (e.g. Tabatabaie, 2006)

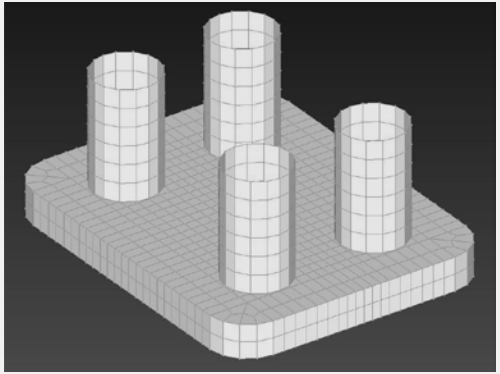
- Apply load at different frequencies and compute stresses/loads and corresponding displacements at selected base nodes
- Divide load by displacement to compute localized subgrade impedance
- Use real and imaginary parts to compute stiffness, added mass and dashpot constants

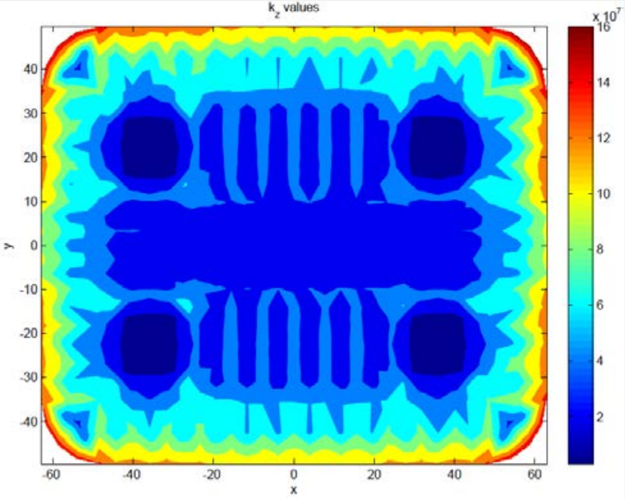


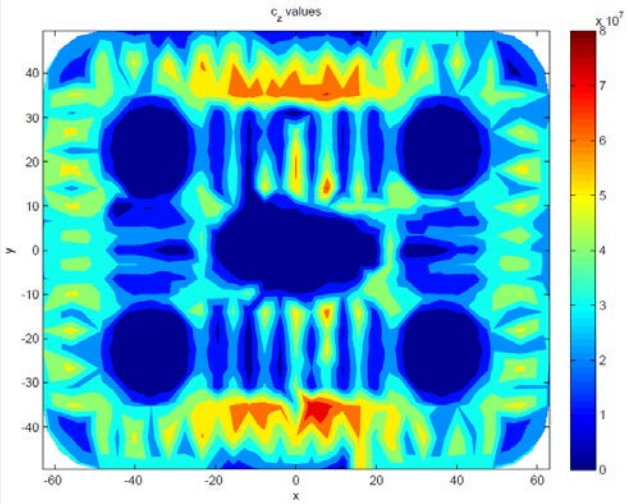


Distributed lumped-parameter foundation model

Figures show values of distributed springs and dashpots







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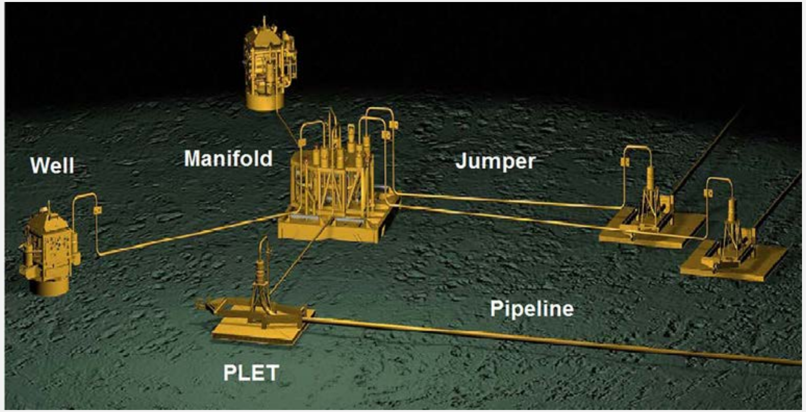
Subsea facilities

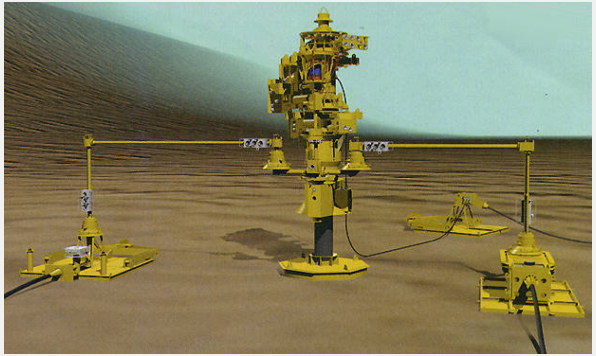
- Development of offshore fields in deep water is made possible by a large variety of complex subsea facilities, for example
  - Manifolds (have different functions, and vary largely in size - can reach 30 m in height and larger in base dimensions)
  - Templates (often large steel structures used to support/protect manifolds)
  - PLEM (Pipeline End Manifold)
  - PLET (Pipeline End Termination)
  - Wellhead structures
  - Pipelines



Subsea Facilities

Large manifold, FMC Technologies

PLEM, Statoil/Kongsberg



Wellhead (with seabed tree)

Different types of templates

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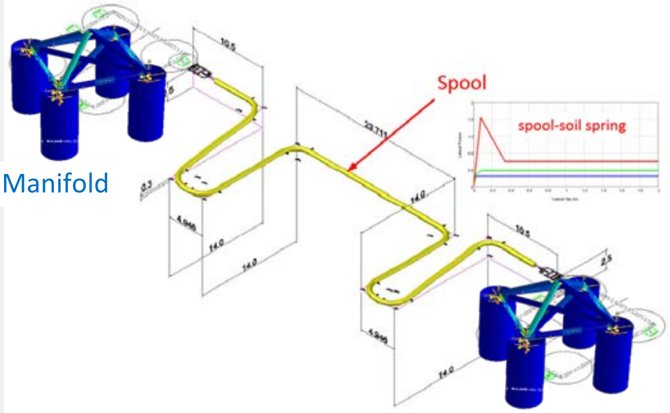
Pictures: Various websites

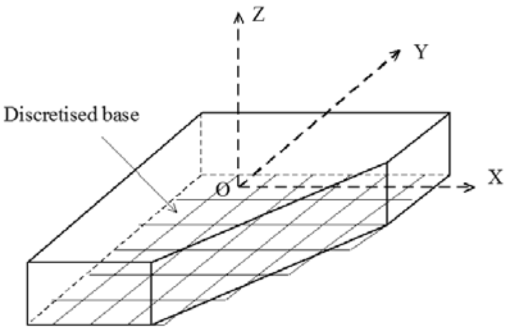
Challenges <u>and</u> potentials

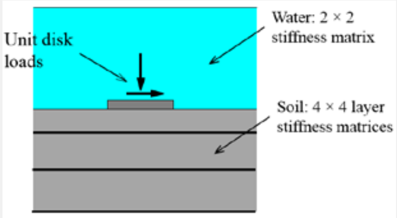
- Because of large stiffness and relatively light weight, natural frequencies of most subsea facilities are high (typically 2-4 Hz).
- Added soil mass, which contributes to dynamic response, could be large; therefore, it should be properly computed
  - NB: Added soil mass is often arbitrarily selected, for example, mass of soil plug in piles, or mass of soil trapped between skirts in mudmats
- Radiation damping is potentially high which is a positive factor in reducing earthquake response, but very often ignored in practice
- Interaction with other facilities, such as pipelines and spools, is crucial for their design
  - NB: Above topics are almost independent of SSI model, and are equally applicable to for example p-y curves



Numerical tools in this study

- To properly capture dynamic characteristics of foundations (mainly added soil mass and radiation damping), one should use frequency- domain numerical tools
  - PILES (Kaynia, 1982) for multiple piles or anchor piles
  - Model by Tassoulas (1981) for large-diameter bucket foundations
  - LAYSAC (Green's function) + IMPED (Kaynia, 1998) for mudmats

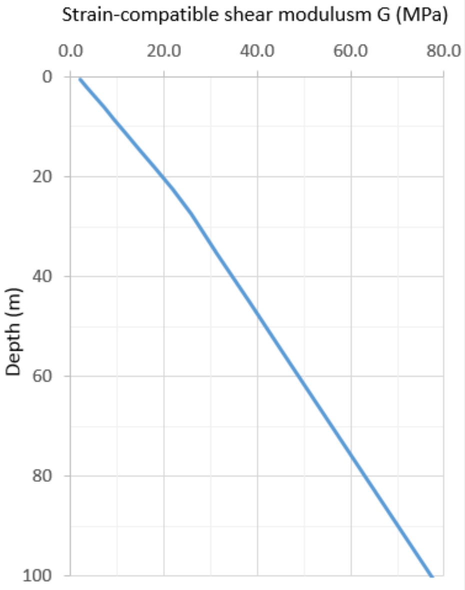


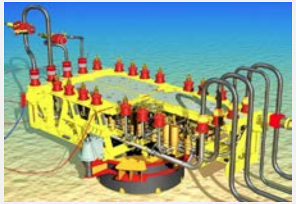


$$u_Z(r,z,\omega) = \frac{1}{\pi}\int_0^\infty \bar{u}_2 J_0(kr)\,\frac{J_1(kR)}{kR}\,k\,dk$$

Demonstration example

- Soil condition: soft clay with strain-compatible small-strain shear modulus as shown in figure
- Manifold, m = 500 tons, on three foundation types
  - 4-pile foundation: Diameter, length and wall thickness, D = 3 m, L= 12 m, t = 15 mm, center spacing of piles 9 m
  - Bucket foundation: D = 8 m, L = 9 m, t = 25 mm
  - Mudmat: Plan dimensions and length, 17 m × 17 m × 1.0 m
  - The foundations have about the same capacity and vertical stiffness

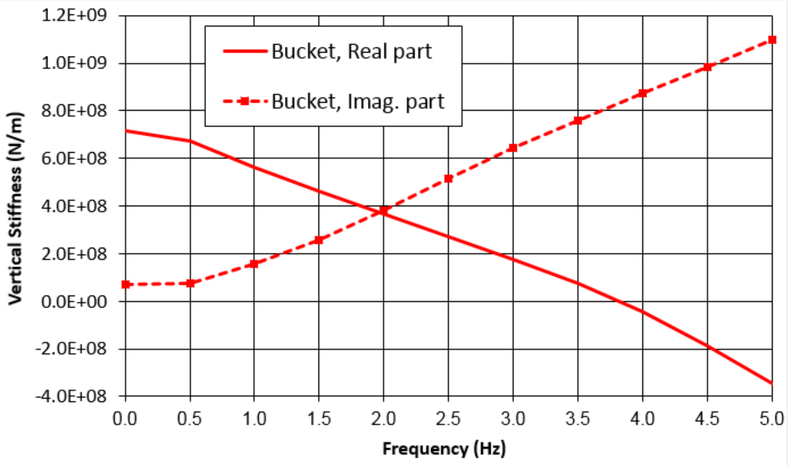




Pictures: Various websites

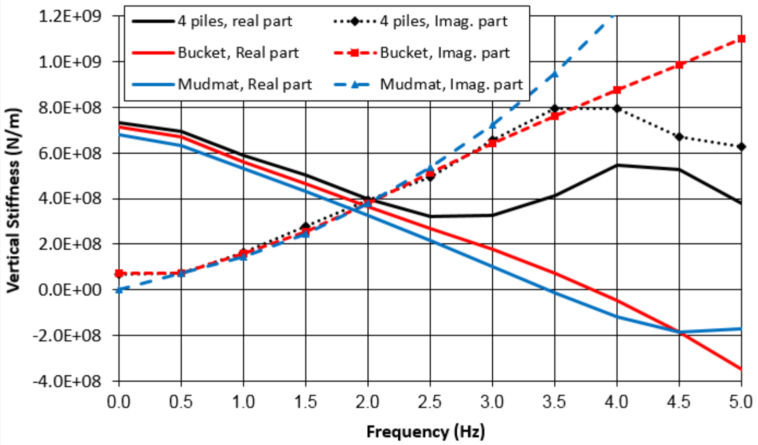
Foundation impedances – General features

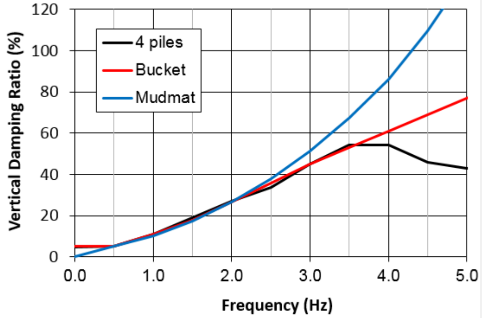
- Impedance is expressed in complex-number form $K = K_{real} + i\,K_{imag}$
- Real part represents combined effect of stiffness and added soil mass
- Imaginary part represents radiation damping (hysteretic damping at low frequencies)



Three Foundations – Vertical direction

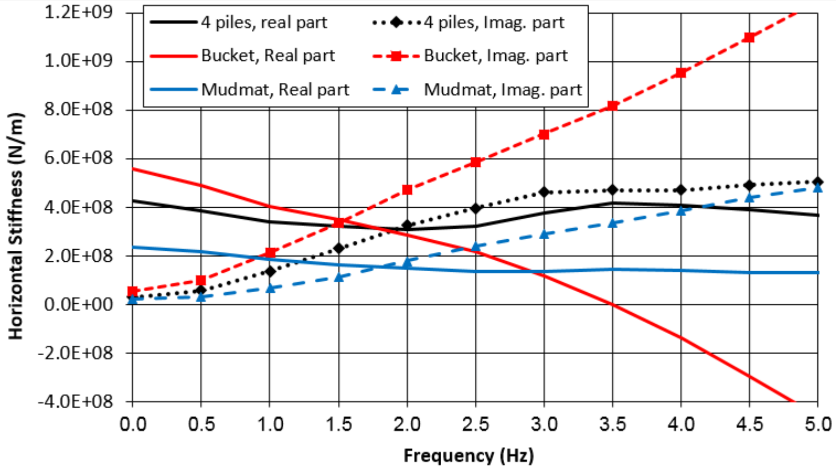
- Have fairly similar impedances => similar stiffness, added soil mass and damping, except 4-pile foundation that has lower added mass at higher frequencies.
- Added soil mass for bucket foundation is 1200 tons which is 1.5 times mass of soil plug.
- Large radiation damping for all cases – Only 5% is often used in practice => Large earthquake response - too conservative.





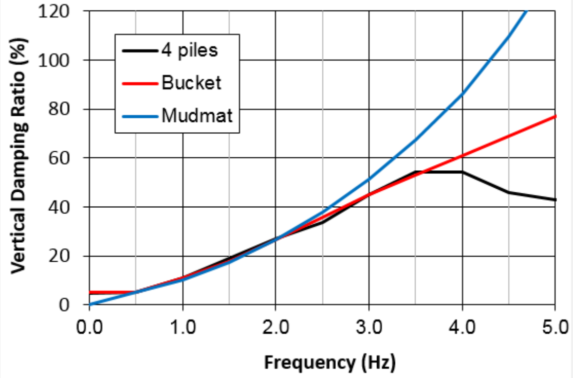
Three Foundations – Horizontal direction

- Bucket foundation has largest stiffness, added soil mass and damping.
- Horizontal stiffness of mudmat is small due to low soil modulus near surface.
- Added soil mass for 4-pile foundation is about 200 tons which is only 40% of plug mass! and this depends on manifold mass, soil profile, pile spacing, . .



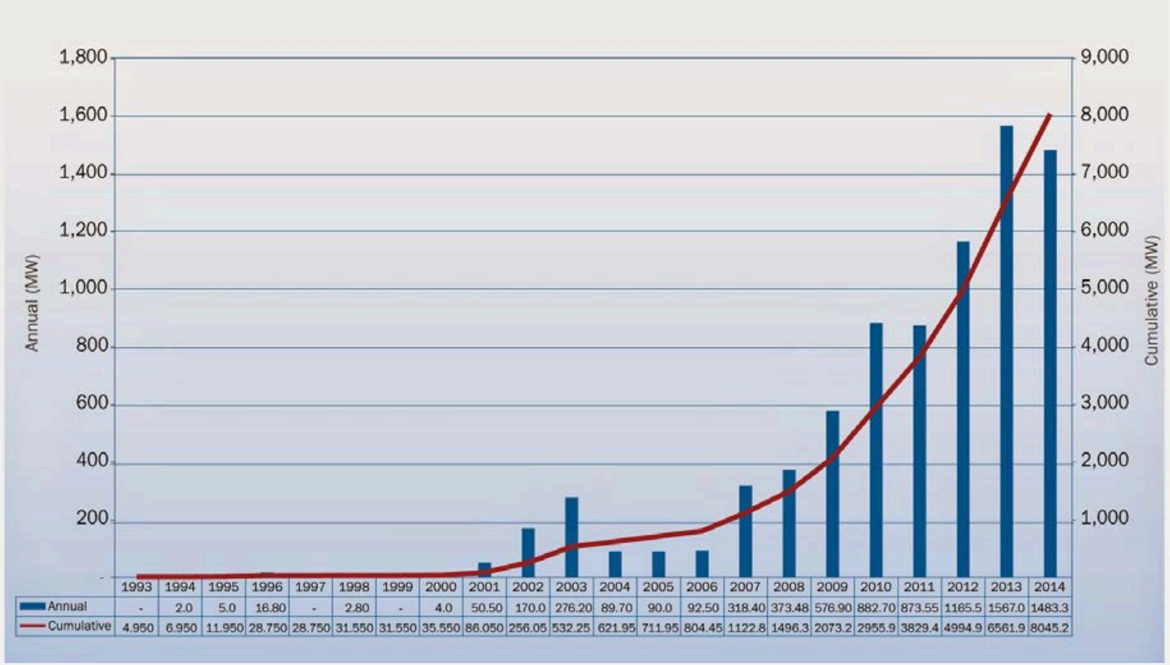
Impact of radiation damping on earthquake response

- Natural frequency depends on added soil mass. For the bucket foundation (considering other parameters including mass of manifold), natural frequency in vertical direction is about 3.3 Hz.
- This give a damping ratio of about 50% which results in at least 45% reduction of earthquake forces (compared to 5% damping often assumed in practice/design).



Offshore Wind Energy – global trends

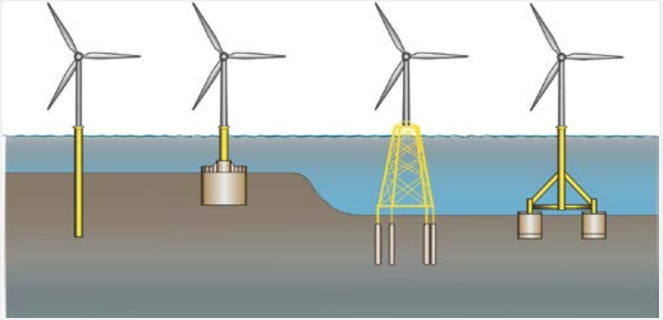
- UK is world's largest offshore wind market (~36% of installed capacity), followed by Germany (29%) and China (11%). The other nations in ranking: Denmark (9%), the Netherlands (8%) and Belgium (5%).
- First US offshore wind started in 2016, and now we see immense interest/ development in China and Taiwan.



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Annual	-	2.0	5.0	16.80	-	2.80	-	4.0	50.50	170.0	276.20	89.70	90.0	92.50	318.40	373.48	576.90	882.70	873.55	1165.5	1567.0	1483.3
Cumulative	4.950	6.950	11.950	28.750	28.750	31.550	31.550	35.550	86.050	256.05	532.25	621.95	711.95	804.45	1122.8	1496.3	2073.2	2955.9	3829.4	4994.9	6561.9	8045.2

Type of support structures

- Mono-piles (most common type): Water depths ~ 30 m, D ~ 6 m, L/D ~ 5 (next generation: water depth ~ 50 m, D ~ 11 m)
- Gravity-based foundation
- Monopod: D ~ 15 m
- Steel jacket on piles
- Jackets on suction caissons
- Floating turbines with anchors
- <u>Foundations constitute ~ 25% of costs</u>



Pictures: Various websites

OWTs on Monopiles

- Next generation of monopiles for Water depths ~ 50 m, D ~ 12 m in 3-5 years

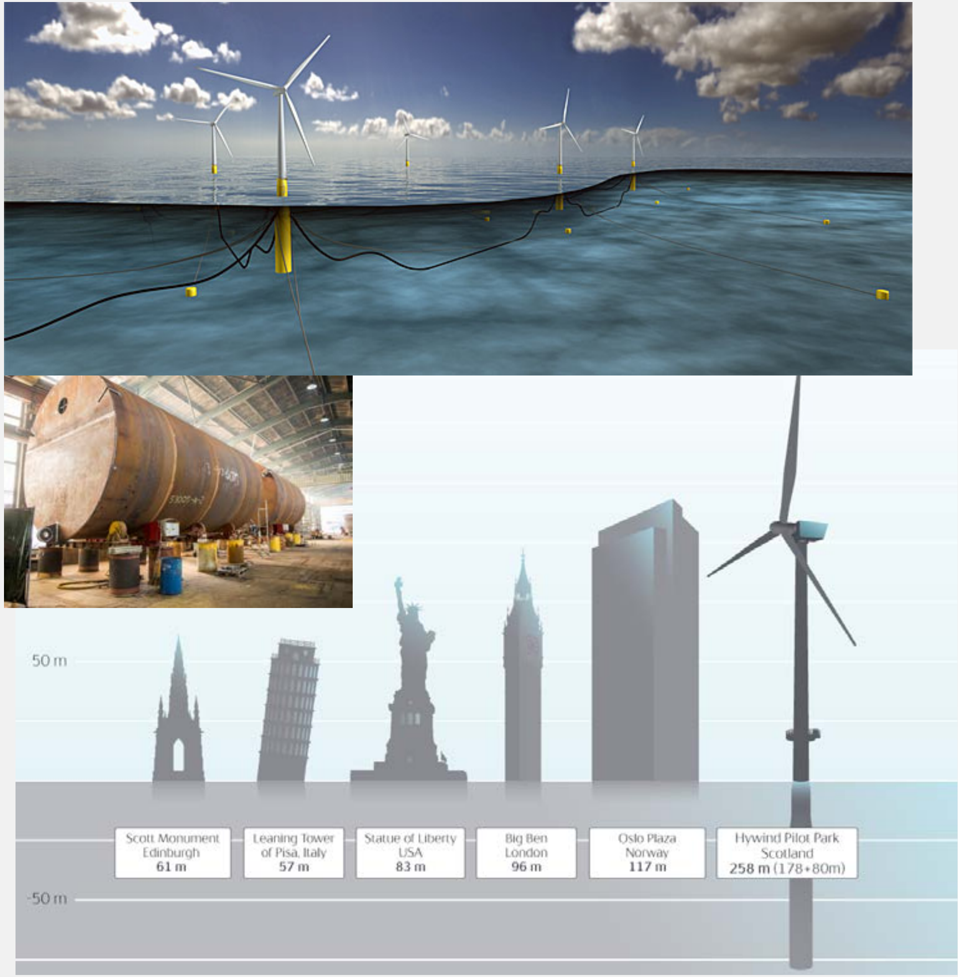
Pictures: Various websites

Jackets and tripods

- Piles and suction caissons

Pictures: Various websites

Floating OWT with anchors



Pictures: Various websites

Loads on OWTs

- Main loads:
  - Wind (mean and turbulent)
  - Wave loads
  - Harmonic load in connection with rotor rotation, “1P load”
  - Harmonic load due to blade passing/shadowing, “3P load”
  - Other loads, like earthquake, ship impact, ice, . .
- Earthquake loads are in most regions not governing due to their long natural period , however other aspects such as liquefaction of loose-medium dense sands and vertical earthquake motions are important issues

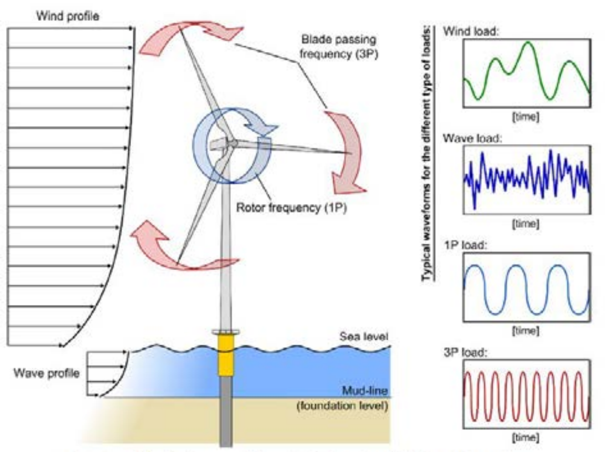
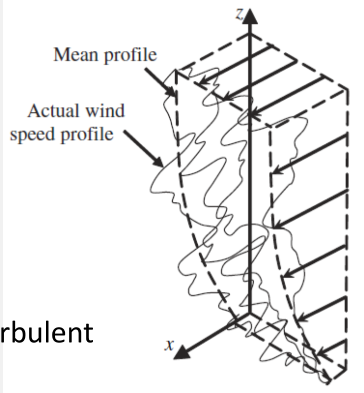


Fig. 1. External loads acting on an offshore wind turbine, along with their typical waveforms.

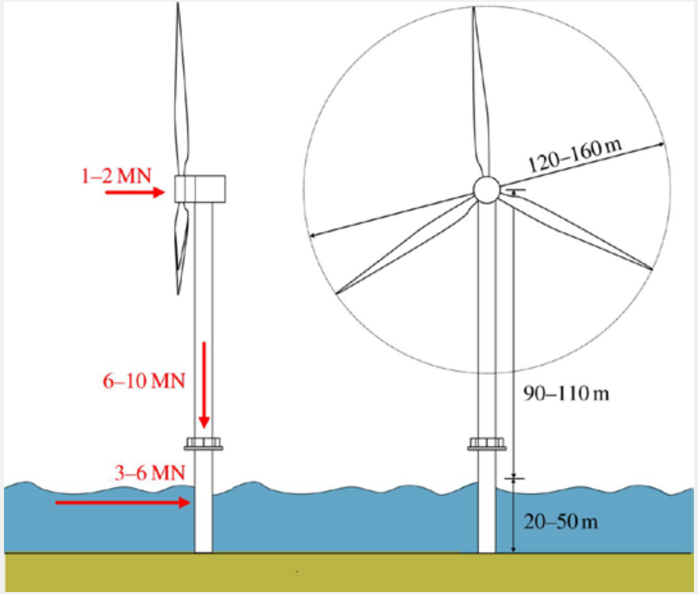


Mean and turbulent wind profiles

Pictures: Various websites/sources

Typical loads – complex aerodynamics

Wind wake made visible due to fog formation that includes three processes: cooling, moistening and vertical mixing of air parcels



Using a peak acceleration of about 0.05 – 0.1 g, one would expect typical horizontal earthquake loads in seismic regions ~ **0.5 - 1 MN** acting at hub level.

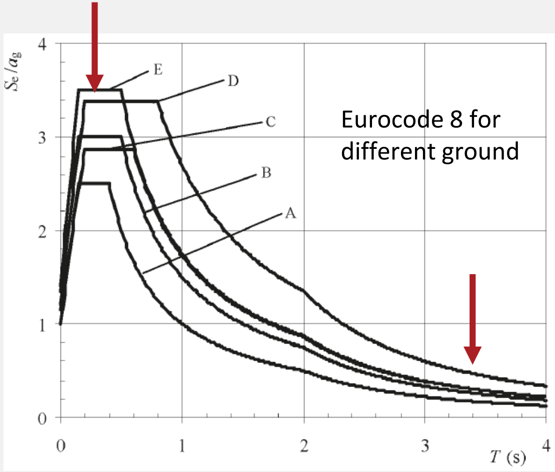
Pictures: Various websites

Some design differences to other structures

- For design earthquake (475-yr), foundation should not experience permanent tilt (more than 0.50°) due to strict performance criteria of turbines.
- Earthquake is considered simultaneously with other environmental loads (wind and wave) representing operational conditions.
- There is very little damping in tower structure (as low as 0.5%) in side-side direction, and equally low in fore-aft direction in stand-still condition.
- Monopiles are much larger than traditional piles used in other structures; therefore, classical solutions, such as p-y curves are not valid.
- The response of piles to liquefaction has not been adequately studied and it is not well understood.
- Kinematic pile interaction will result in larger rotations at pile head than in traditional (smaller diameter) piles.

Earthquake response of offshore wind turbines

- Modern, large OWTs have relatively high natural periods in lateral direction - typically 3.0-3.5 s. Therefore, they are not expected to be very vulnerable to horizontal earthquake shaking in areas with minor to moderate seismicity.
- On the other hand, they have low natural periods in axial direction which could result in large axial response under vertical earthquake shaking.
- Design of OWTs should be such that they do not undergo any major permanent deformation/tilt during the design earthquake and should satisfy the operational performance criteria after the earthquake.



Eurocode 8 for different ground

Summary and Conclusions

- Earthquake response of slopes is negatively impacted by strain softening, multi-directional shaking and 3D geometry all of which are often ignored.
- Pipelines traversing slopes are vulnerable to downslope movement of slopes during earthquake shaking and need special modelling.
- Consideration of foundation flexibility in SSI analysis of large platforms requires integrated analyses or distributed soil springs derived from such SSI analyses.
- Dynamic responses of subsea foundations, such as pile-groups, mudmats and buckets, are characterized by relatively large natural frequencies (~ 2-4 Hz) corresponding to large added soil masses and radiation damping. Radiation damping can be as high as 50% in practice that is positive for design.
- Considering strict performance requirements of OWTs, earthquake evaluation of OWTs should be based on performance-based design approaches.
- Use of advanced computational tools, which correctly account for dynamic stiffness and damping of foundations, could result in more realistic and economical foundation design of offshore structures including OWTs.

Thank you for your attention