INFRASTAR

FATIGUE IN GROUTED CONNECTIONS FOR OFFSHORE WIND FOUNDATIONS

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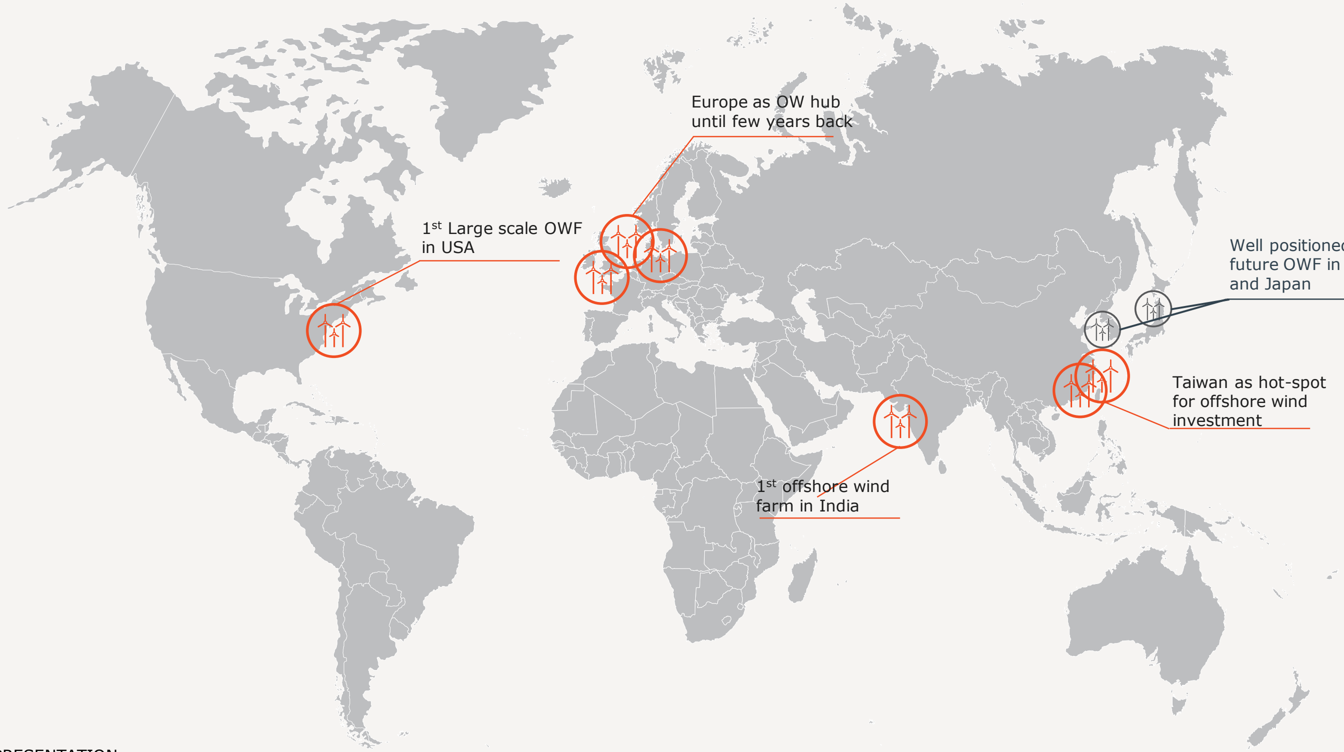
COWI's imprint on the offshore wind market



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SITE SPECIFIC CHALLENGES

- Soil characteristics
  - Site investigation - key to uncertainty level
  - Data available - benchmark investigations
  - New sites - not as much experience
- Environmental loading
  - Quality and quantity of current & historical records
  - Adjustment of numerical models to site specific sea and wind states
  - Extreme events and occurrence - patterns

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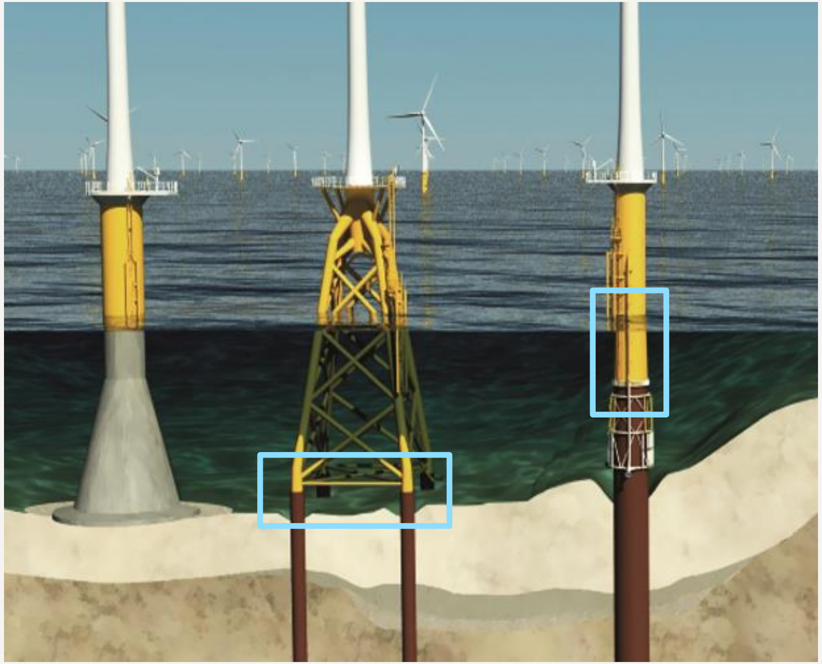
CHOICE OF FOUNDATIONS

Principal factors in decision making:

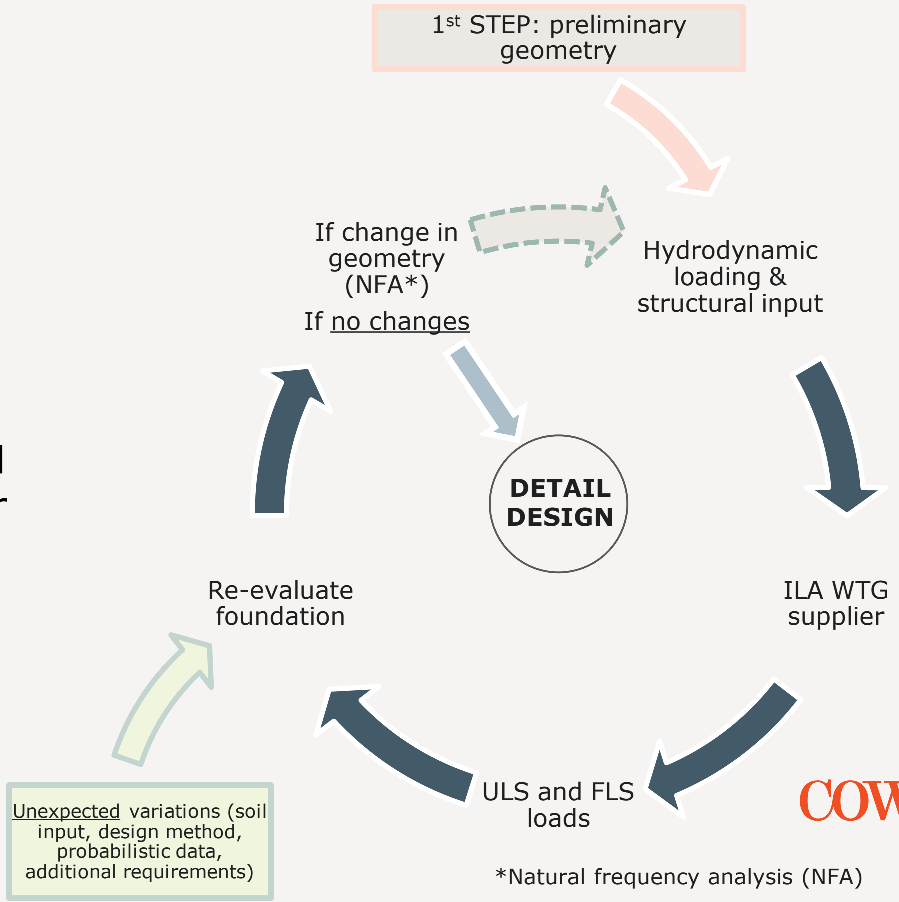
- Water depth
- Soil condition
- Severity of environmental hazards (i.e. seismic events and liquefaction)
- Fabrication yard capabilities/proximity
- Client preferences



LOAD ITERATIONS

Integrated load analysis, ILA

- The split between foundation designer and wind turbine generator (WTG) supplier requires an iterative design process.
- Different set-ups depending on the WTG supplier.
- Result, the ultimate limit state (ULS) and fatigue limit state (FLS) loads to consider for final detail design of the complete structure.



*Natural frequency analysis (NFA)

DESIGN LIFE AND FATIGUE LOADING

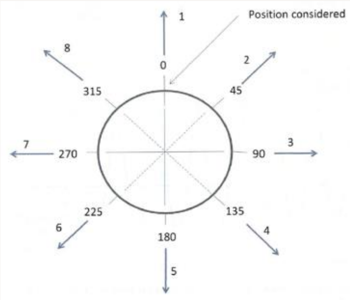
- FLS loads are the result of the combination of load case scenarios, scaled to the design life span of the infrastructure and limited to a probability of occurrence.
- Usually summarized in Markov Matrixes
- Simplistic representation by damage equivalent loads (DEL)
- Extreme events related to low fatigue cycles, might not be included in the long-term load considered.

Structure of Markov matrices where i=1N and j=1M

	$M_{mean,1}$	…	$M_{mean,j}$	…	$M_{mean,M}$
$M_{range,1}$	$n(1,1)$	…	$n(1,j)$	…	$n(1,M)$
…	…	…	…	…	…
$M_{range,i}$	$n(i,1)$	…	$n(i,j)$	…	$n(i,M)$
…	…	…	…	…	…
$M_{range,N}$	$n(N,1)$	…	$n(N,j)$	…	$n(N,M)$

Table above would be replaced with axial loading for a jacket GC

Loads projected to at least 6 directions



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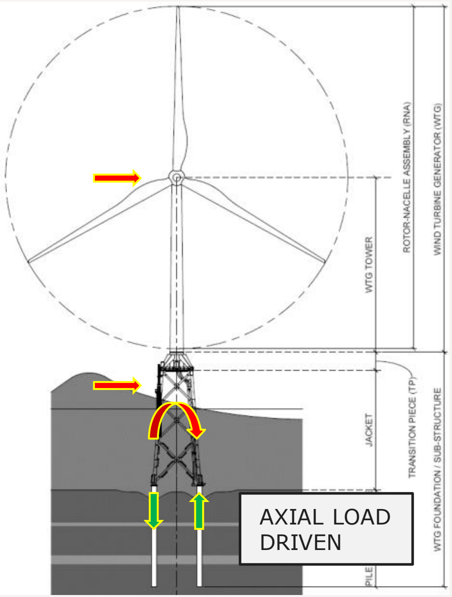
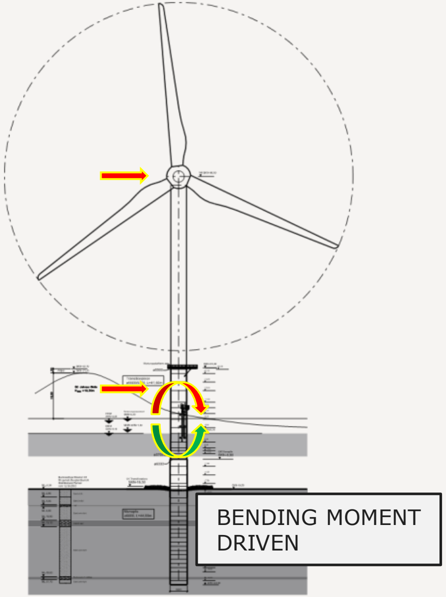
GROUTED CONNECTIONS AS PRIMARY STRUCTURE

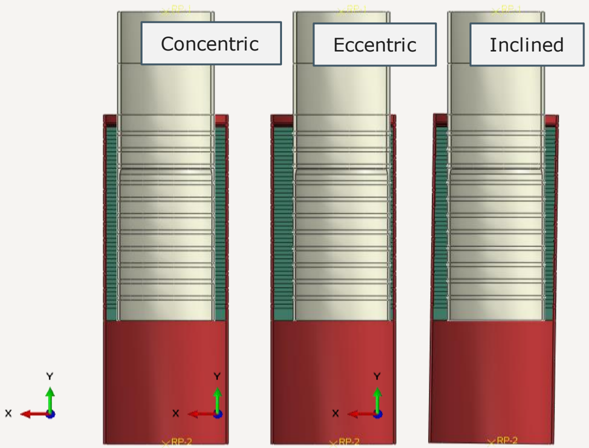
- Grouted connections transfers the loads to the support medium
  - Jacket: driven piles at mudline interface (>2 connections)
  - MP-TP: monopile at the sea surface interface (1 connection)
- A failure can jeopardize the operability & integrity of the infrastructure
- High risk item

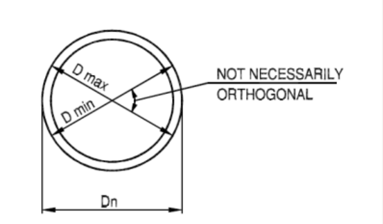


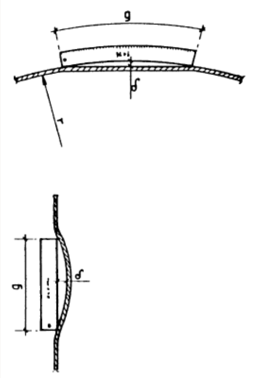


FUNCTIONALITY OF GROUTED CONNECTIONS

- Flexibility accommodating and correcting tolerances
  - Fabrication
    - Circumference
    - Out of roundness
    - Local roundness and straightness
  - Installation
    - Pile/monopile out of verticality
    - Horizontal precision from driving (jackets)
- Limited inspection/maintenance required







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GROUT MATERIALS

› Very high strength no shrinkage materials

Table 2 TAC Operational Limitations for Application of

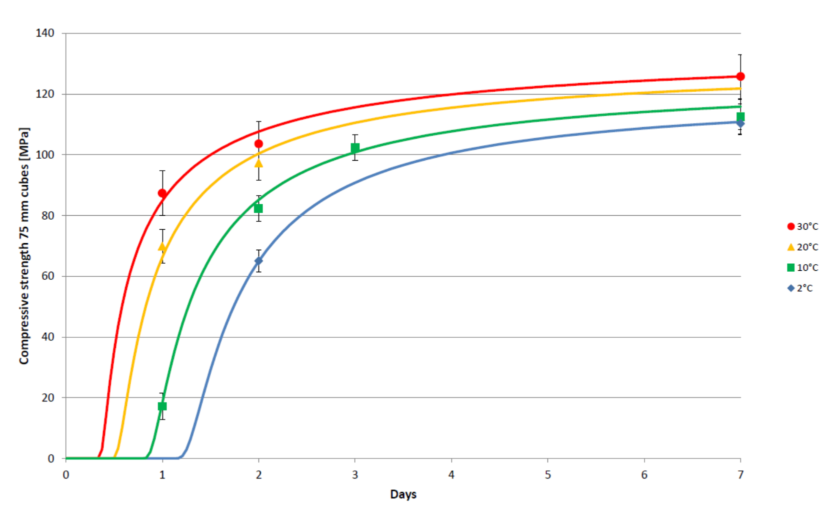
Description	Unit	Limitations
Nominal Bore (NB) for grout hoses/lines	inch	NB ≥ 2[1)]
Grout annulus thickness[2)]	mm	40 ≤ t ≤ 1000
Pumping length through 2" NB flexible hoses[3)]	m	L ≤ 150
Pumping length through 3" & 4" NB flexible hoses[3)]	m	L ≤ 250
Pumping length through 5" NB flexible hoses[3)]	m	L ≤ 435
Pumping elevation head using 2" to 5" NB flexible hoses[3)]	m	H ≤ 20
Minimum application temperature ($t_{app,min}$)	°C	0[4)]
Maximum application temperature ($t_{app,max}$)	°C	30

Table 5 Characteristic 28-days strengths for acc. to EN 1990

Material Property	Test Specimen	Curing/Testing Temperature [°C]	Notation	Characteristic Value [MPa]
Compressive Strength	150 x 300 mm cylinders	20	f_{cck}	115.9
	75 mm cubes	20	f_{ck}	127.4
	40 x 40 x 160 mm prisms	20	$f_{ck,prisms}$	108.9[1)]
Flexural Strength	40 x 40 x 160 mm prisms	20	$f_{ctk,fl}$	14.9
Tensile Splitting Strength	150 x 300 mm cylinders	20	$f_{ctk,spl}$	7.3

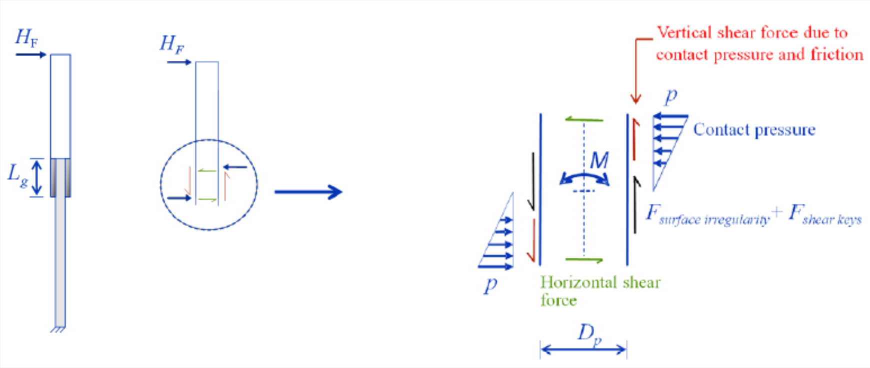
HG6A[1)]	Autogenous shrinkage strain after 28 days curing	ASTM C1698	20°C	-0.042 mm/m
HG6A[1)]	Autogenous shrinkage strain after 56 days curing			-0.052 mm/m
HG6A[1)]	Autogenous shrinkage strain after 91 days curing			-0.069 mm/m
HG6A[1)]	Autogenous shrinkage strain after 150 days curing			-0.077 mm/m

› Curing curves

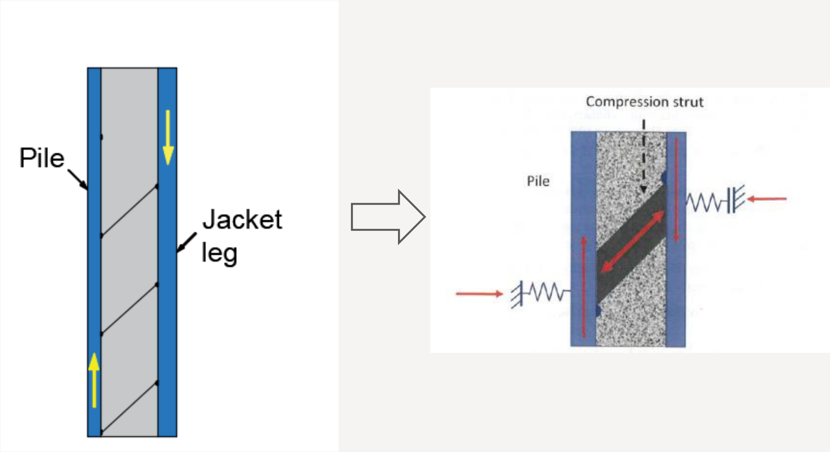


LOAD TRANSFER MECHANISM

› **Monopile** foundation: sectional forces transferred through contact pressure.



› **Jacket** foundation: sectional forces transferred through compression grout blocks.



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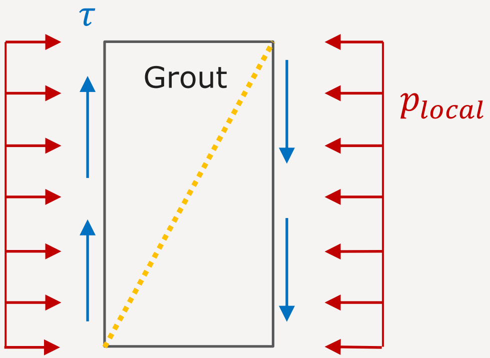
FAILURE MECHANISMS

- **Monopile** foundation: shear stress dominated.



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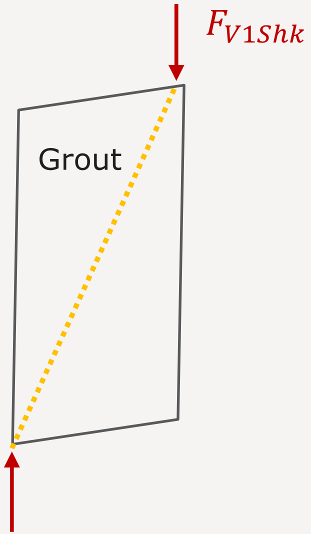

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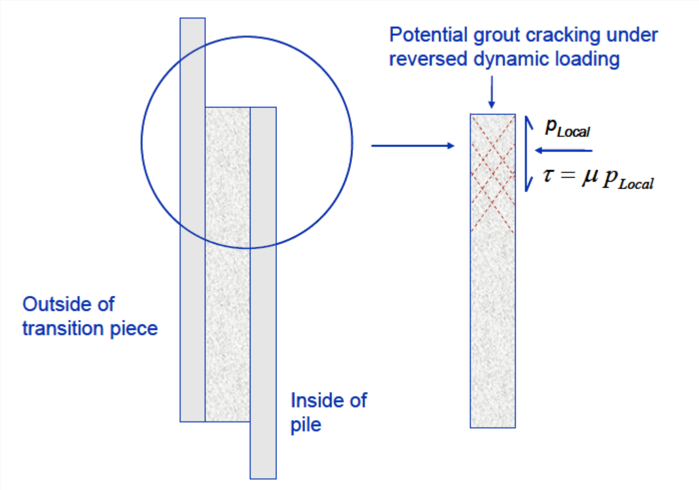

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FLS ASSESSMENT

› Monopile GC

$$\log_{10} N = C_1 * \left(1 - \frac{\sigma_{max}}{f_{rd}}\right) / \left(1 - \frac{\sigma_{min}}{f_{rd}}\right)$$

› Jacket GC

$$\log N = 5.400 - 8y \qquad for\ y \geq 0.30$$
$$\log N = 7.286 - 14.286y \qquad for\ 0.16 < y < 0.30$$
$$\log N = 13.000 - 50y \qquad for\ y \leq 0.16$$

$$y = \frac{F_{V1\,Shk}\gamma_m}{F_{V1\,Shk\,cap}}$$

Relative load level as input for SN curves

Safety level for GC FLS → Consequence of high uncertainty

	JACKET	MONOPILE
DFF	1.0	3.0
$\gamma_{m.FLS}$	1.5	1.5

This can be lower depending on the reference

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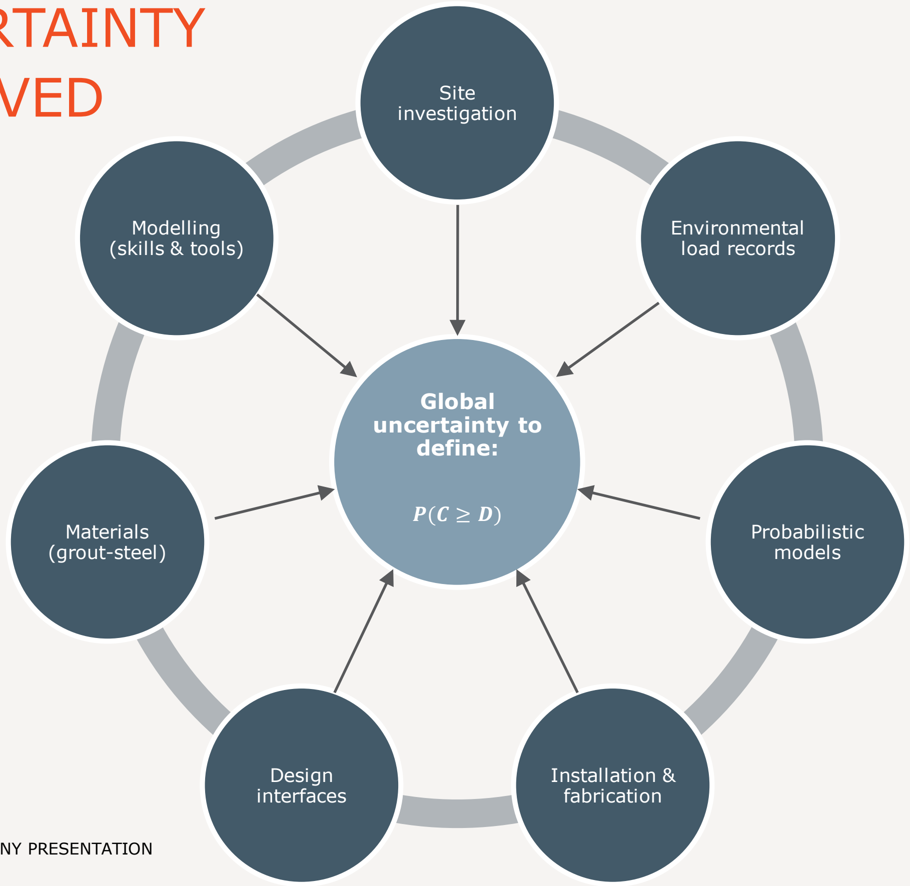
UNCERTAINTY INVOLVED



- Real life structures involve a high level of uncertainty.
- Feedback is needed. Am I right? Does it actually work?
- Theory must be benchmarked with empirical experience.
- Need to have structural health monitoring.

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