ENGINEERING IN THE OCEAN

Loads, Environment & Structural Behaviour

Offshore Wind — Engineering Perspective

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Bird View of the Talk

Six interconnected topics — from offshore wind basics to the mathematics of wave forces on structures.

PART A — The System

1 **Onshore and Offshore Wind Resources**
Why go offshore?

2 **OWF Arrangement**
Dogger Bank case study

3 **OWT Components**
Substructure types

PART B — The Physics & Mathematics

4 **Marine Environment**
Wind, wave, current loads

5 **Dynamic Loads & Statistical Methods**
Spectra · distributions

6 **Potential Flow & Environmental Load Predictions**
Morison · Diffraction · BEM

OWF – Offshore Wind Farm · OWT – Offshore Wind Turbine · BEM – Boundary Element Method

ONSHORE vs OFFSHORE WIND

ONSHORE

- Primary Load: Wind (aerodynamic)
- Foundation: Shallow spread footing / pile on firm ground
- Dynamics: 1P/3P rotor excitation — well characterised
- Environment: Wind only; terrain effects manageable
- No hydrostatic pressure, no buoyancy interaction
- Corrosion: Atmospheric only
- Fatigue: Relatively predictable loading cycles

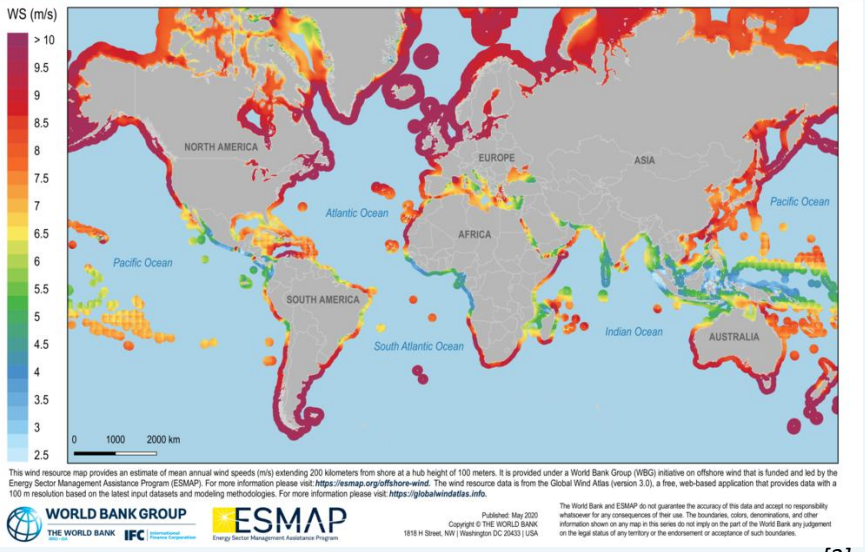
OFFSHORE

- Multi-hazard: Wind + Wave + Current + Seabed
- Foundation in saturated, uncertain soil — scour critical
- Coupled aero-hydro-elastic-soil dynamics
- Stochastic environment: wave climate is probabilistic
- Hydrostatic + hydrodynamic pressure on substructure
- Corrosion: Splash zone, immersion zone, cathodic protection
- Fatigue governs over ULS in many cases (10^8 cycles)

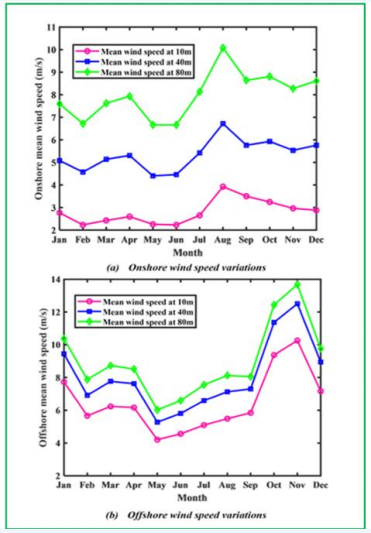
Note : ULS is Ultimate Limit state Design, i.e., design condition where structure reaches its maximum load-carrying capacity, for fatigue we are asking a question that does structure survive next 25 yrs of continuous cyclic loads

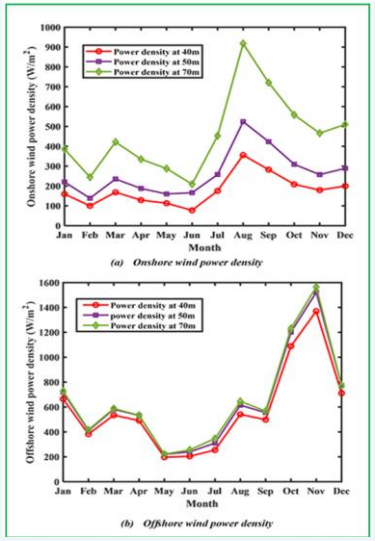
Why OFFSHORE Wind

Global Offshore Wind Speeds



[3]





[1]

Benefit outweigh the risks

- Strong and More Consistent Wind → Higher Capacity Factor and More predictable power generation
- Space Availability → No Land Acquisition , Huge Open Areas, Gigawatts of wind farm can be deployed
- Less Social Resistance → No Noise complaints, Located far from population
- Higher Energy Yields → CAPEX is high and Installation is Complex but higher energy production over Life, Better LCOE (Levelized Cost of Energy) over time
- Bigger turbines can be deployed offshore → transport is easier using vessels, and buoyancy reduces effective loads, allowing many components to be floated and installed at site.

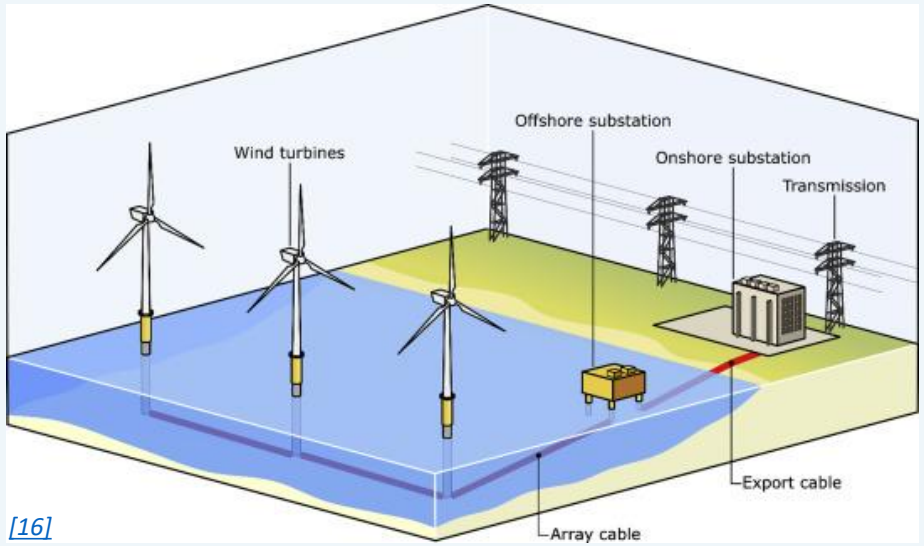
$$Wind\ Power = 0.5 * \rho * A\ * v^3 * C_p * CF\ * NG\ * NB$$

Here, A – Area, v – Wind velocity, Cp – Power coefficient , CF – Capacity factor, NG – generator efficiency , NB – gearbox efficiency

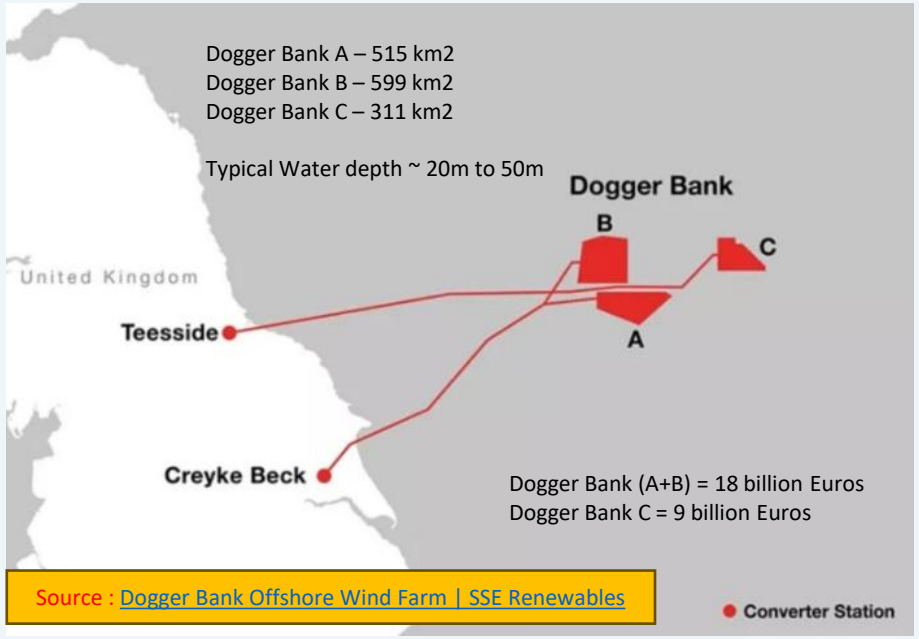
$$LCOE = \frac{C_{dev} + C_{cap} + C_{O\&M}}{E_A}$$

Here, C_{dev} is annual start-up development cost , C_{cap} = annual capital cost, $C_{O\&M}$ = annual operation and maintenance cost , E_A is annual average energy generation

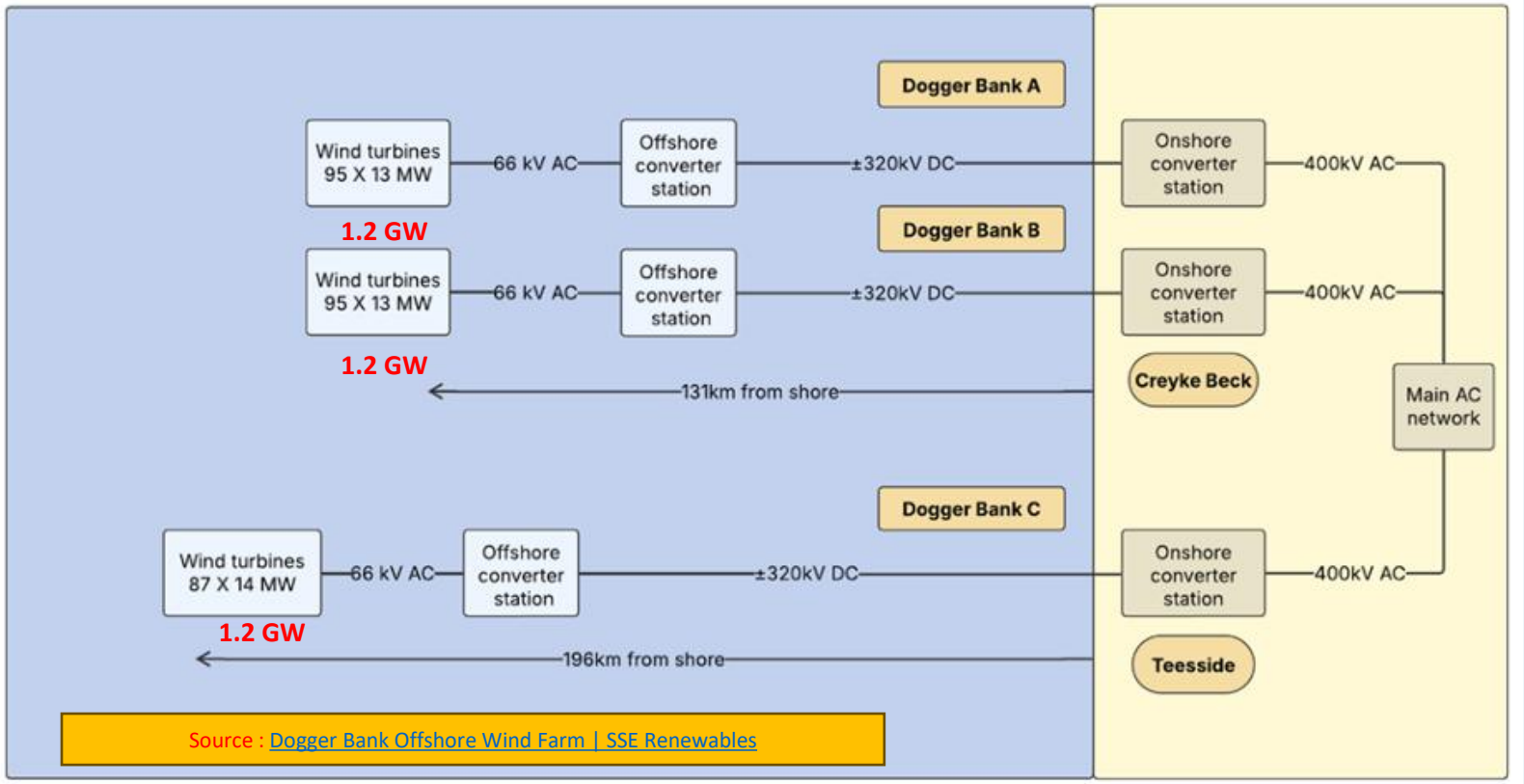
General Arrangement of Offshore Wind Farms



[16]



Source : Dogger Bank Offshore Wind Farm | SSE Renewables



Source : Dogger Bank Offshore Wind Farm | SSE Renewables

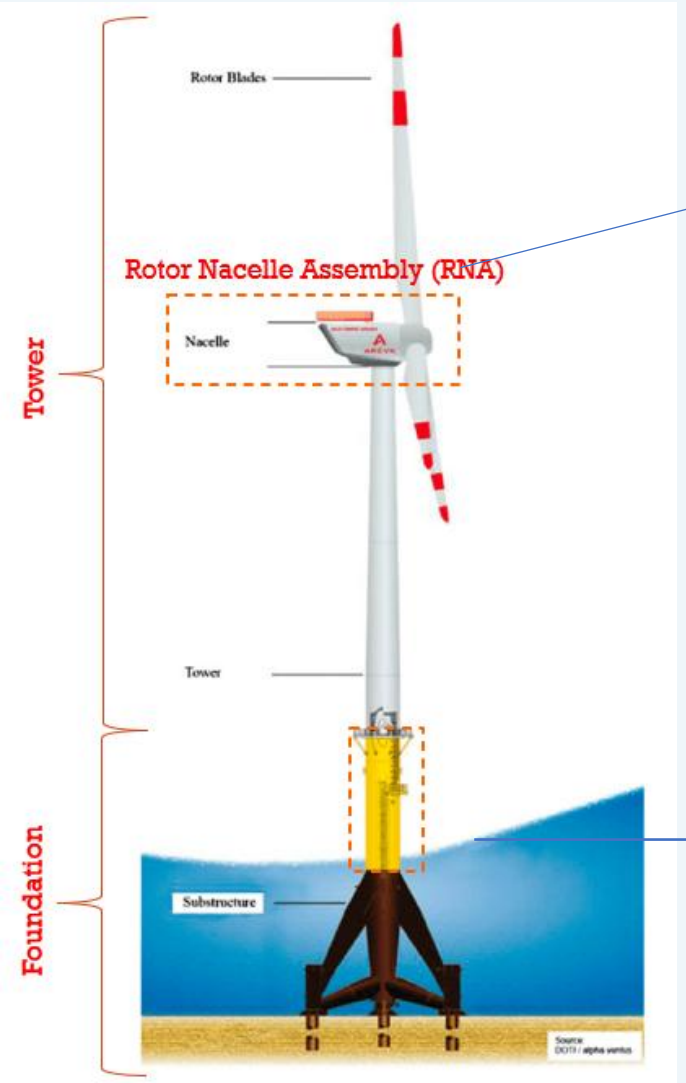
Perspective on what 3.6 GW means

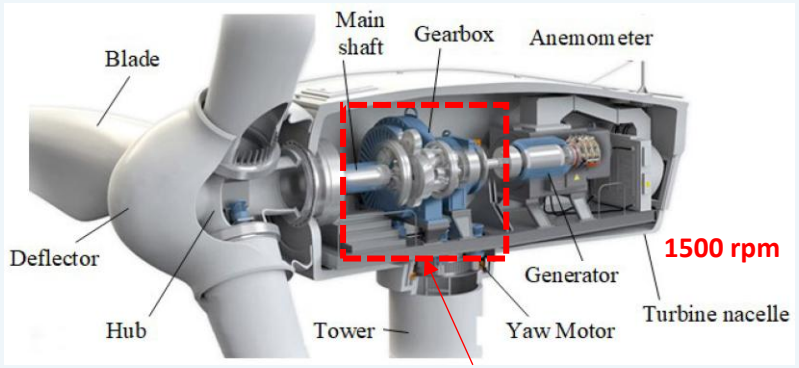
Capacity factor of offshore wind farms are 40-50% , For Land (Onshore) it is 25-35%

Average power production = 0.45 3.6 GW = 1.62 GW (average) , i.e., Annually 1.6224365 = 14,200 GWh/year
Average power consumption in urban cities in India is 200-300 units/months (assume 250 kWh/month), so yearly 3000 kWH/year per house

Total house that will get electricity = (14200 10^6) / 3000 = 4.7 million house , average population of Chennai city 7 Million

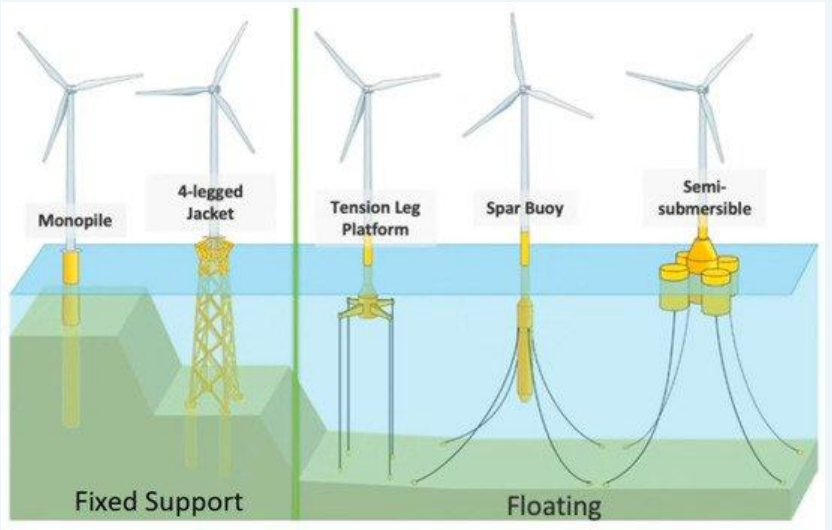
Different Parts of Offshore Wind Turbine



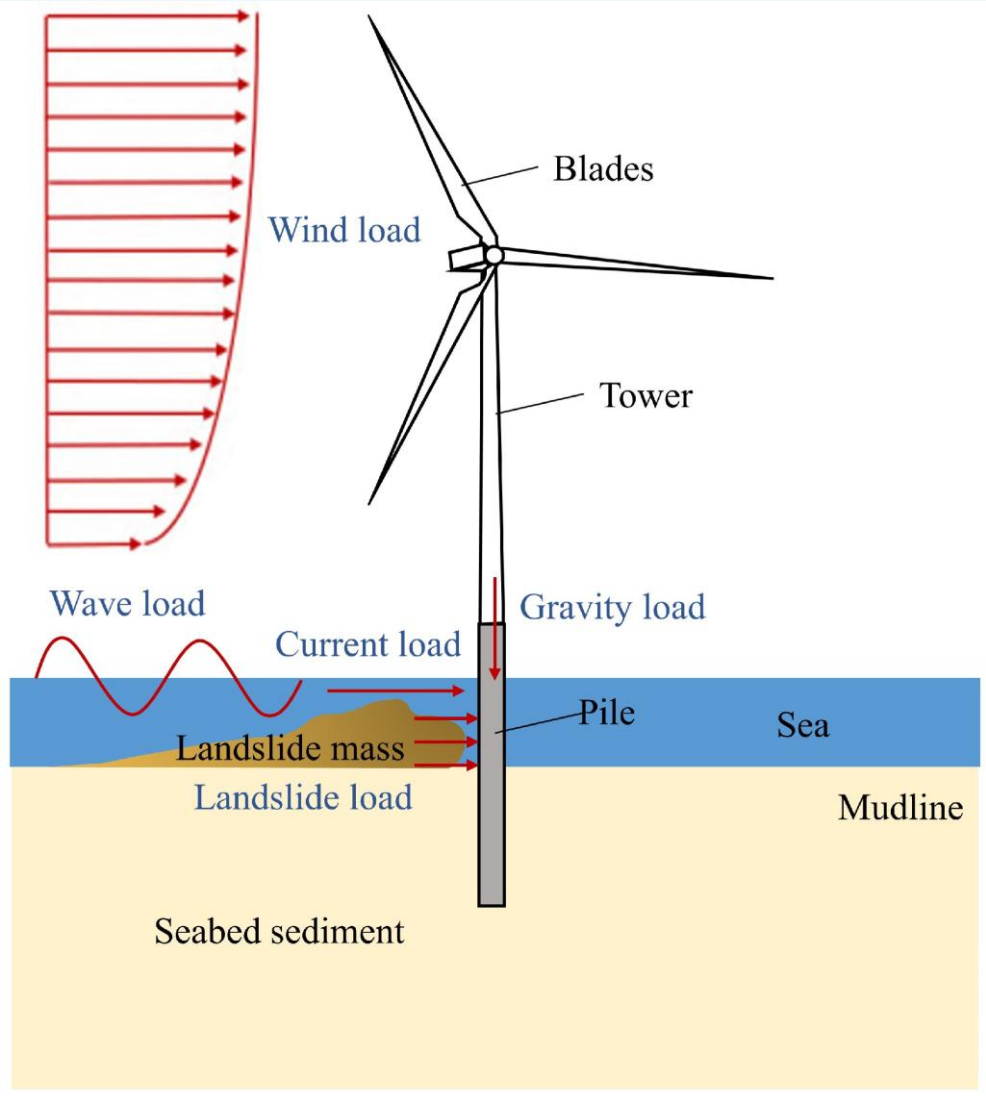


Substructure
Foundation

- Fixed (Water depth up-to 60m)
  - Proven at scale (Dogger Bank – 3.6 GW)
- Floating (up to 1000+ m)
  - Emerging, Opens up Vast Ocean
  - Hywind Scotland project (30 MW)



OFFSHORE ENVIRONMENT



STATIC LOADS

Dead Weight

Self-weight of tower, nacelle, blades & foundation

Current Load

Steady drag from tidal & ocean current flow

DYNAMIC LOADS

Primary

Wave Loads

Cyclic pressure from passing wave crests & troughs

Primary

Wind Loads

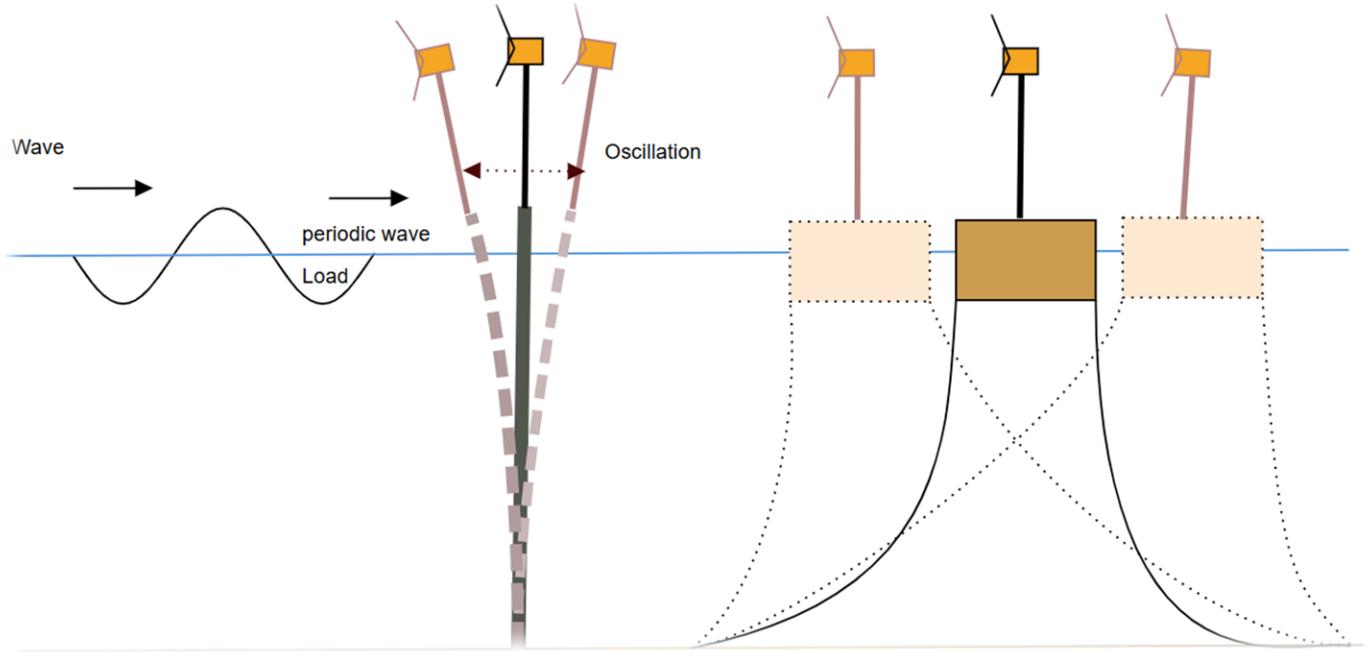
Turbulent thrust on rotor & drag on tower

Fatigue

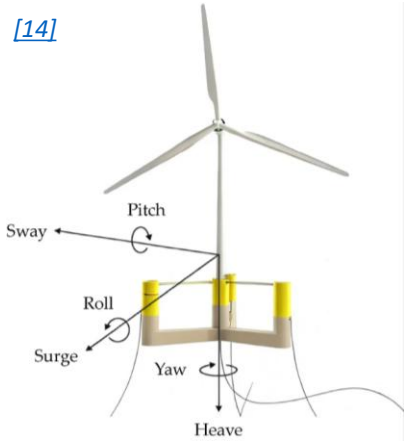
Vortex-Induced Vibrations

Oscillation from wake shedding at resonance

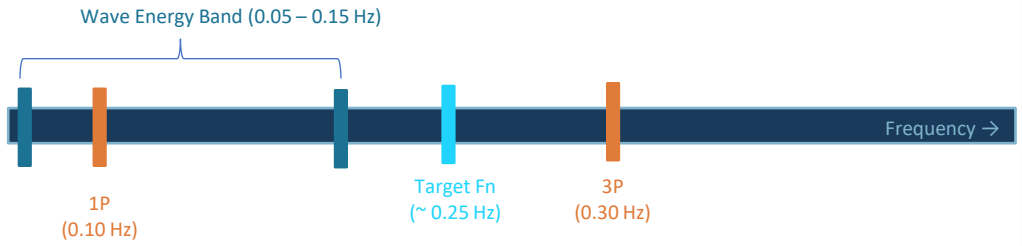
Structural Response under dynamic loads



[14]



FREQUENCY SEPARATION



Wave Loads

Hydrodynamic · cyclic pressure

Mechanism

As a wave crest passes the pile/floating platform, it pushes. As the trough follows, it pulls back. This creates a back-and-forth force that the structure must resist millions of times.

Frequency range of waves

0.05 – 0.15 Hz (6 to 20 second wave periods)

← *Wave frequency band*

Wind Loads

Aerodynamic · turbulent thrust

Mechanism

Wind pushes on the rotor blades (thrust) and drags on the tower. Offshore wind is never steady — it gusts, creating a continuously fluctuating force on the structure.

Frequency range

0.001 – 0.10 Hz (10 s to 15 min gusts) plus 1P/3P rotor harmonics

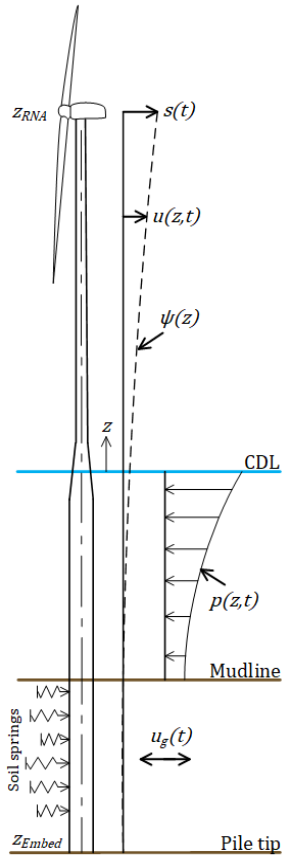
Consequence

The 3P (blade-passing) frequency is the critical design constraint — the monopile's natural frequency must sit above 1P and below 3P to avoid resonance during operation.

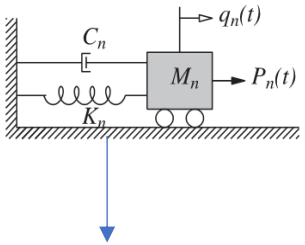
← *Wind frequency band (wider)*

Each load acts at a different frequency. The danger comes when one of them matches the structure's natural frequency

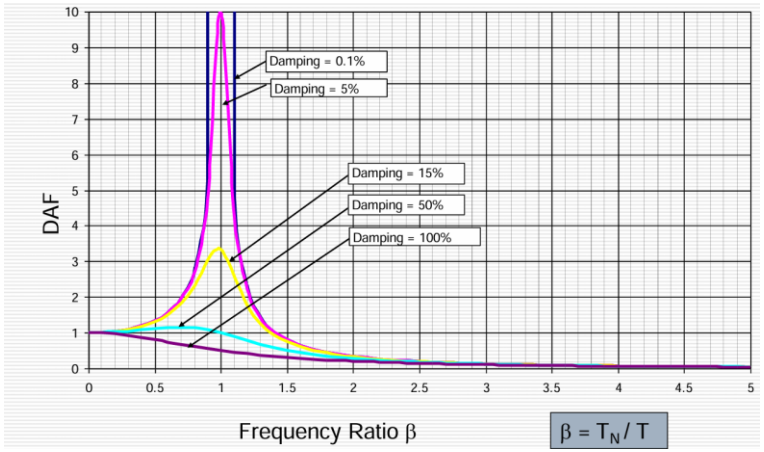
Understanding Structural response using SDOF



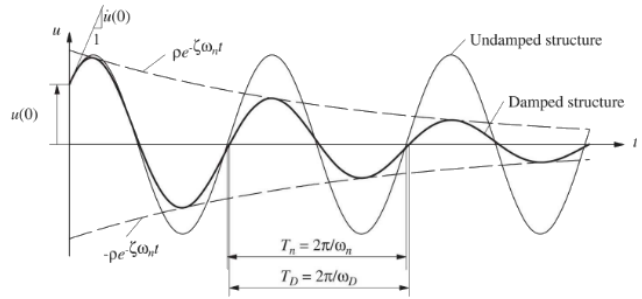
$\psi(z)$: Shape function (mode shape) wrt. elevation.
u_g: ground displacement (seismic) wrt. time
$u(z,t)$: displacement wrt. Elevation and time.
q_n: modal displacement
$p(z,t)$: external load wrt. Elevation and time. (wave and wind)



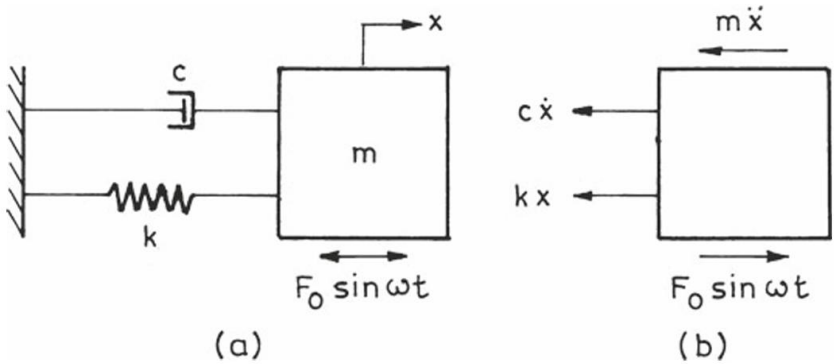
k_n: WTG-FOU stiffness incl. Soil stiffness
c_n: Aerodynamic damping, structural damping, additional damping
m_n: Structural and added mass
q_n: modal displacement
p_n: external load

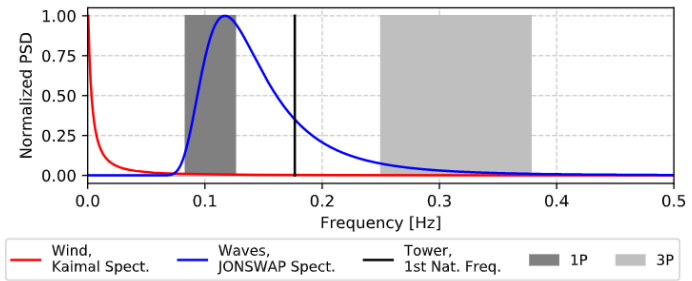


T_N = Natural period of structure, T = Wave period



Response – Damped free Vibration





Dynamic equilibrium equation

SDOF –spring mass system

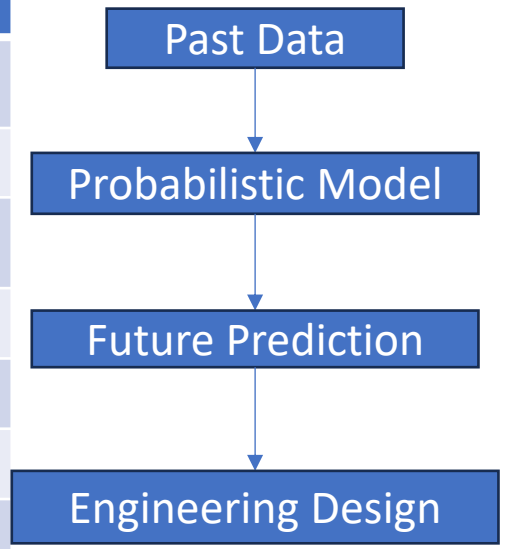
$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t$$

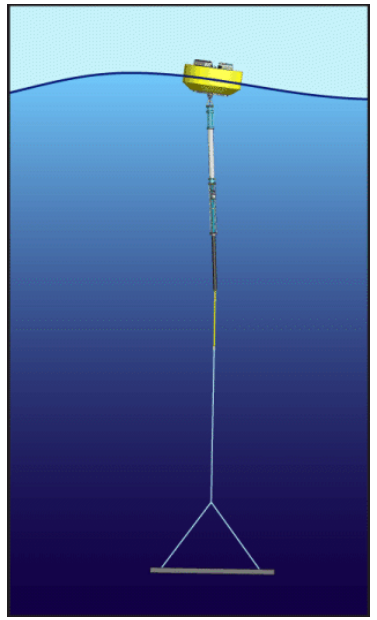
[15]

SDOF – Single degree of freedom

STATICTICAL MODELLING OF WAVES

Step	Action	Detail
1	Deploy wave sensors at site	Record X(t) — surface elevation. Measure how sea level changes with time
2	Extract wave properties	Find wave crests, troughs, heights and periods
3	Compute empirical crossing intensity	Count how often waves reach different heights
4	Estimate the transformation g	Convert real irregular waves into an equivalent Gaussian form
5	Estimate spectral density S(f)	Find which wave frequencies contain most energy
7	Compute wave distributions	Calculate probability of different wave heights and periods
8	Predict extremes	Estimate rare extreme waves like 100-year or 1000-year waves

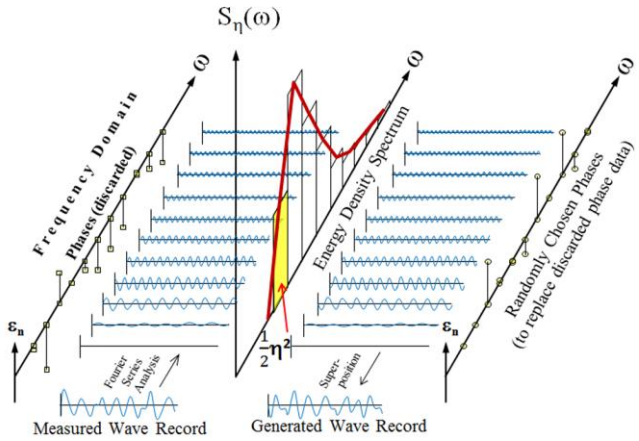




Variable	Distribution	Remark
Wave surface elevation	Gaussian	Zero-mean narrow-band sea surface process
Wave Amplitude	Rayleigh	Valid for linear Gaussian sea states
Wave Height	Rayleigh	Common approximation for narrow-band seas
Wave period	Weibull/Lognormal	Depends on sea state and definition used
Extreme wave height	Gumbel / Weibull / Generalized Extreme Value (GEV)	Used for long-term extreme analysis

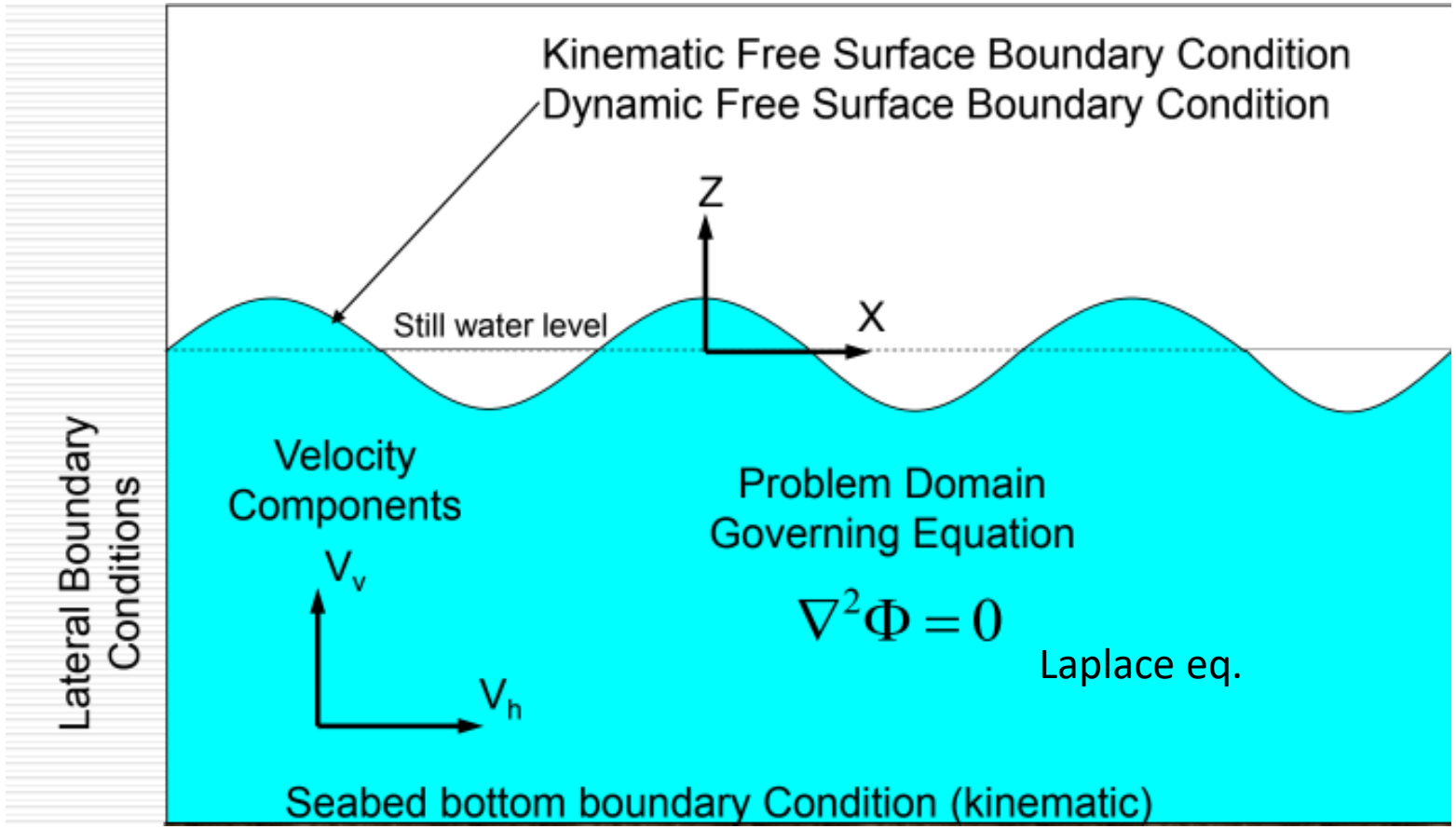
Region	1 year	100 year
Bay of Bengal	11	23
Gulf of Mexico	12	24
South China Sea	11	24
Arabian Sea	8	18
Gulf of Thailand	6	12
Persian Gulf	5	12
North sea	14	22

Source



Additional Reading

Potential Flow Theory



Velocity Potential

U = ∇Φ, Here Φ, velocity potential function

$$\phi = -\frac{H}{2}\frac{\omega}{k}\frac{\cosh k(h+z)}{\sinh kh}\sin(kx-\omega t)$$

Key Assumptions of potential flow theory:

Ideal Fluid – Inviscid (non viscous), Incompressible (Constant density), irrotational (no vortices formation)

This Helps in simplifying the solution and different geometry can be solved using Numerical techniques or analytically

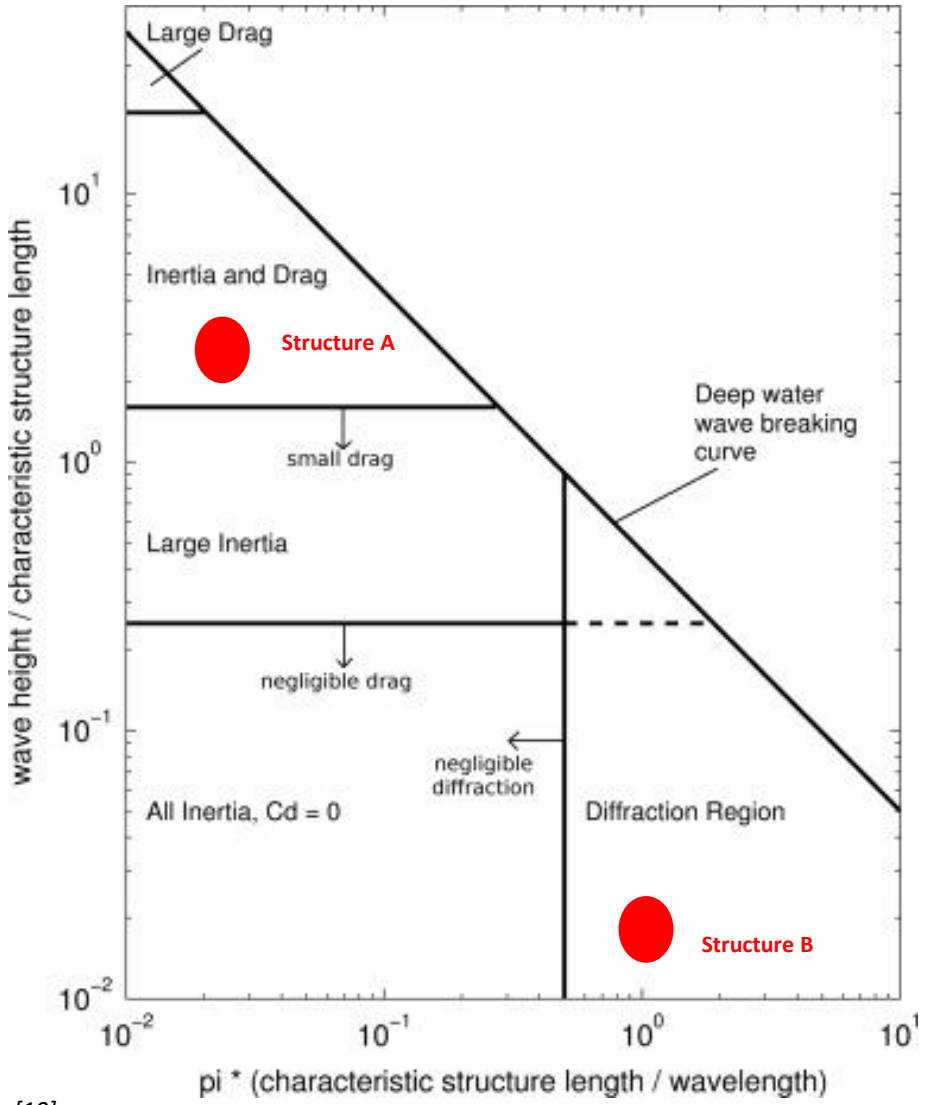
Industry tools - WAMIT, Ansys AQWA, OrcaFlex

Tools for Navier-strokes (without above assumptions) – Ansys Fluent, Open Foam (Open-source), Star-CCM+

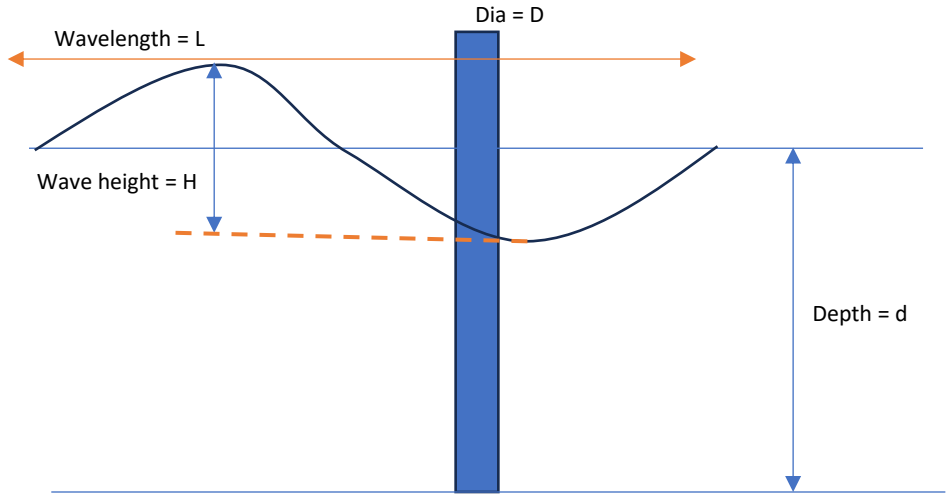
⚠ Without these assumption, Modelling will require solving Navier-Strokes equations (Non-linear partial differential equations with no general closed-form solution) – Evern simple geometry will require heavy computing
For most of the wave-structure scenarios, these assumptions give remarkably accurate results

Wave Loads

Detailed Wave Loads estimation method - Theory and Example

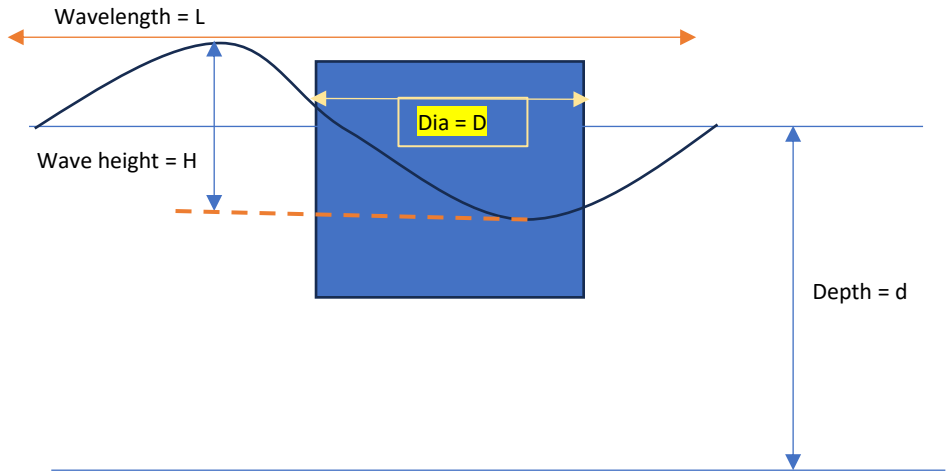


[10]



Structure A – Typical small diameter Monopile/Jacket

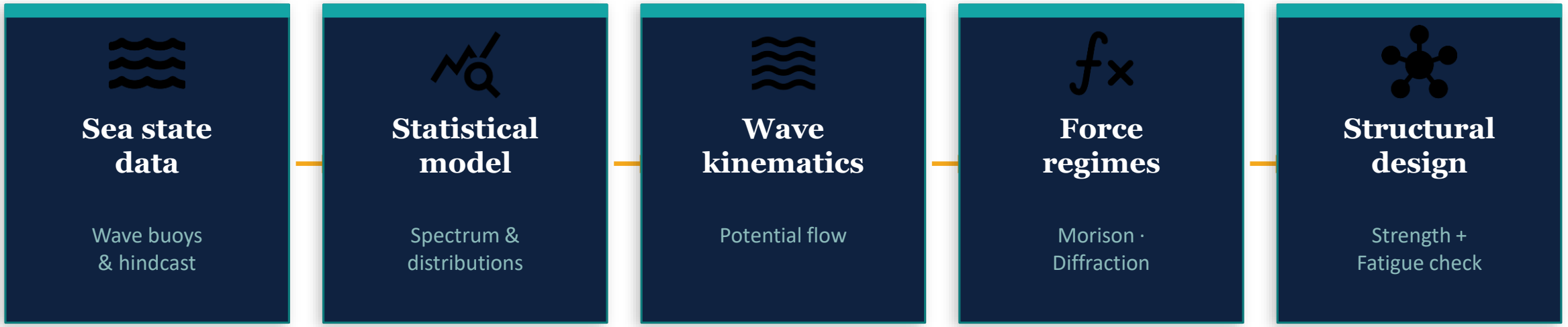
L >> D, D/L≪1
- Morisson regime i.e., inertia dominated



Structure B – Typical Floating structure – Ships, Semi-submersibles

L ~ D,
D/L≈1
Waves will be strongly disturbed
- Diffraction regime

The chain that connects it all



References and Reading Materials

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Thank You

GitHub link for additional reading material : https://github.com/singhdeveshkr/offshore_wind_talk_XKDR

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