LOAD ON OFFSHORE STRUCTURES

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Contents

- Gravity Loads.
- Live Loads
- Environmental Loads
- Extreme and Operating Conditions
- Wind Loads
- Wave and Current Loads
- Inplace Analysis
- Basic Loads
- Load Combinations
- Analysis Methods

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Types of Loads

- **Gravity Loads**
  - Structural Dead Loads
  - Facility Dead Loads
  - Fluid Loads
  - Live Loads
- **Environmental Loads**
  - Wind Loads
  - Wave Loads (Indirectly on Vessel)
  - Current Loads (Indirectly on vessel)
- **Inertia Loads**
- **Blast Loads**
- **Deflection Induced Loads**
- **Fatigue Loads**
- **Seismic Loads (only for fixed structures)**

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Gravity Loads

- **Dead Loads**
  - Dead loads includes the all the fixed items in the structures. It includes all primary steel structural members, secondary structural items etc.
- **Facility Loads**

  The equipment and facilities includes the following.
  - Mechanical equipment
  - Electrical equipment
  - Piping connecting each equipment
  - Electrical Cable trays
  - Instrumentation items

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Live loads

Live loads are defined as movable loads and will be temporary in nature. This load vary in nature from owner to owner but a general guideline on the magnitude of the loads is given below.

S.No.	Location	Load (kN/m^2)
1	Storage / laydown	20
2	Walkway	5
3	Access Platform	5
4	Galley	10

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Environmental Loads

- **Wind Loads**

  Wind Loads act on super structure whether it is a FPSO or fixed structure.

- **Wave and Current Loads**

  Wave and current loads act on the structure directly for fixed offshore platforms where as for the FPSO and floating structures, it act on the hull and induces motion of the floating structure. Due to the motion of the structure, the inertia forces on the FPSO topsides shall be evaluated.

- **Seismic Loads**

  Seismic loads are only applicable for fixed structures and is due to seismic acceleration and its structure mass

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Extreme and Operating Condition

- **Operating Condition**

  Operating Condition a set of environmental load scenario associated with the normal operation of the facility and it can be a fixed or floating structure. This is associated with a load condition that may occur more often or the occurrence interval is small. i.e. 1 year or 10 year

- **Extreme Condition**

  Extreme Condition a set of environmental load scenario associated with the shut down of the facility for a fixed structure or a survival case for a floating structure. In case of floating structure it may change its draft or towed away to a safer location. This is associated with a load condition which occur very rarely or with a large occurrence interval. i.e. 100 year or 200 year

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WIND LOADS

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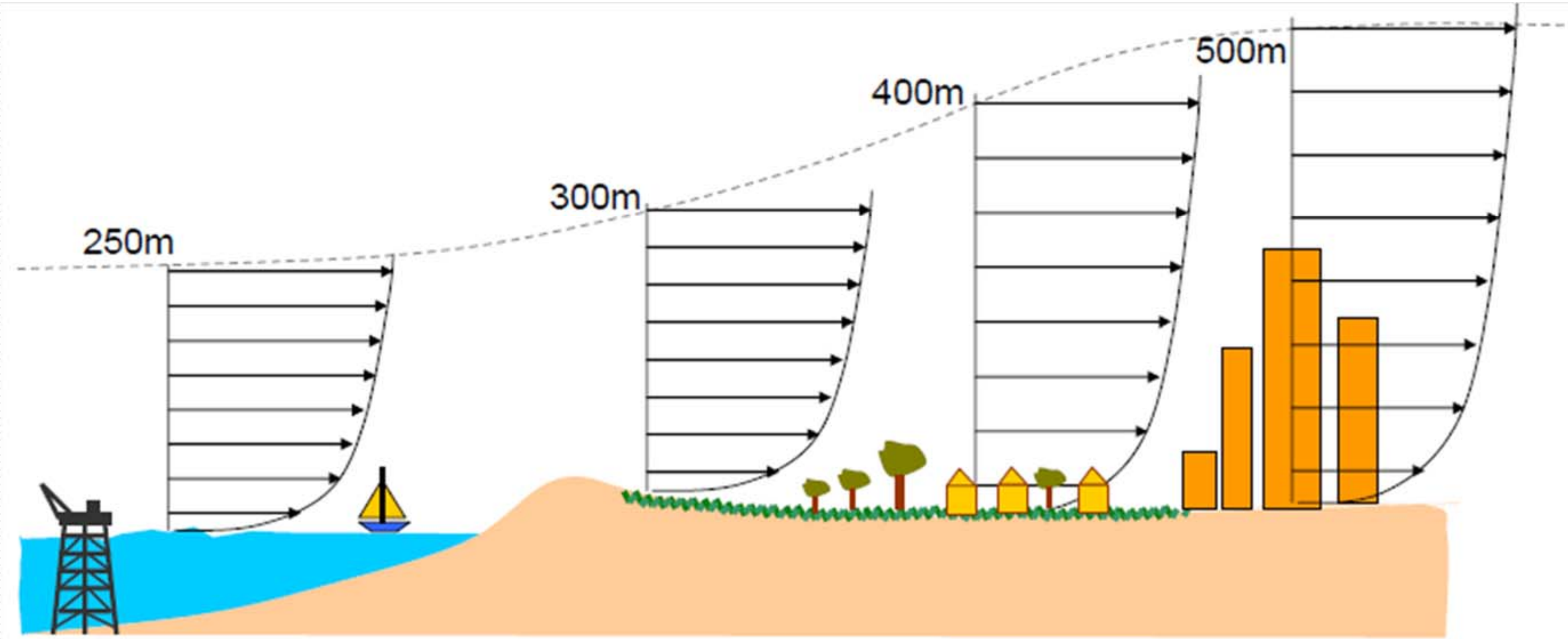
WIND SPEED VARIATION WITH HEIGHT AND TERRAIN



Variation of Mean wind speed with height

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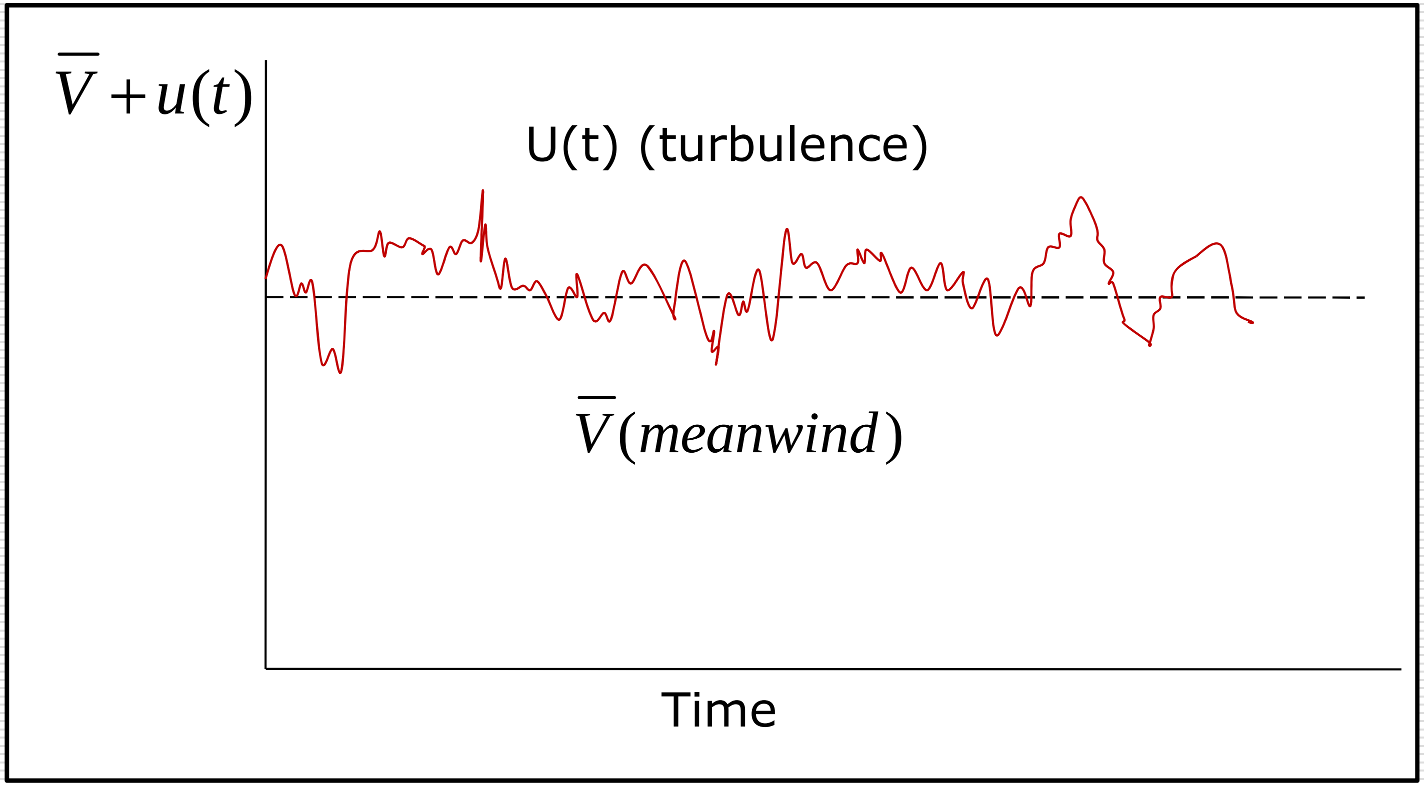
Wind Loads

Wind profiles and Gusts.



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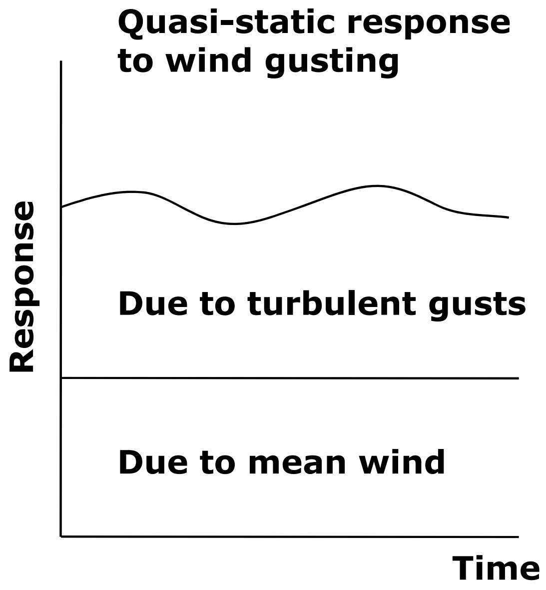
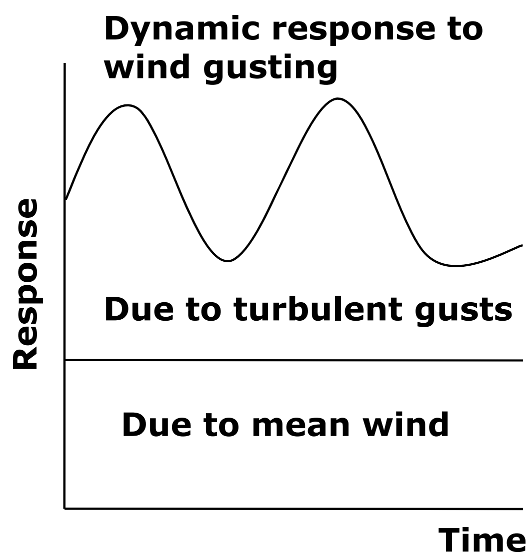
RESPONSE TO WIND GUSTING



(a) Short period structures



(b) Long period Structures

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Wind Gust and Profile

For strong wind conditions the design wind speed u (z,t) (ft/s) at height z (ft) above sea level and corresponding to an averaging time period t(s) [where $t \le t_0$; $t_0 = 3600$ sec] is given by:

$$u(z,t) = U(z) \times \left[1 - 0.41 \times I_u(z) \times ln\left(\frac{t}{t_0}\right)\right]$$

Where the 1 hour mean wind speed U(z) (ft/s) at level z(ft) is given by:

$$U(z) = U_0 \times \left[1 + C \times \ln\left(\frac{z}{32.8}\right)\right]$$

$$C = 5.73 \times 10^{-2} \times (1 + 0.0457 \times U_0)^{1/2}$$

And the turbulence intensity Iu(z) at level z is given by:

$$I_u(z) = 0.06 \times [1 + 0.0131 \times U_o] \times \left(\frac{z}{32.8}\right)^{-0.22}$$

Where U_o (ft/s) is the 1 hour mean wind speed at 32.8 ft.

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Wind averaging period

In applying design wind load on to the offshore structures, the averaging time period plays a major role. Following averaging periods are normally used

- 1 hour average
- 30 minute average
- 10 minute average
- 1 minute average
- 15 sec gust
- 5 sec gust
- 3 sec gust

Depending on the type of structure, any one of the above will be applied.

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Typical Calculation

All units shall be in ft and sec and the specified wind at 32.8m from MSL, one hour average

$$z_o := 32.8 \qquad U_o := 26 \qquad t_o := 3600$$

$$C := 5.73 \cdot 10^{-2} \cdot \sqrt{1 + 0.0457 \cdot U_o}$$

$$U(z) := U_o \cdot \left(1 + C \cdot \ln\left(\frac{z}{z_o}\right)\right)$$

$$I_u(z) := 0.06 \cdot \left(1 + 0.0131 \cdot U_o\right) \cdot \left(\frac{z}{z_o}\right)^{-0.22}$$

$$U(z,t) := U(z) \cdot \left(1 - 0.41 \cdot I_u(z) \cdot \ln\left(\frac{t}{t_o}\right)\right)$$

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Variation with averaging period

Wind Speed at 150 ft, 3 sec gust	$U(150,3) = 34.3$
Wind Speed at 150 ft, 5 sec gust	$U(150,5) = 33.9$
Wind Speed at 150 ft, 15 min ave	$U(150,90) = 31.9$
Wind Speed at 150 ft, 30 min ave	$U(150,180) = 31.4$

Variation with Height

Wind Speed at 50 ft, 3 sec gust	$U(50,3) = 32.7$
Wind Speed at 100 ft, 3 sec gust	$U(100,3) = 33.7$
Wind Speed at 150 ft, 3 min ave	$U(150,3) = 34.3$
Wind Speed at 200 ft, 3 min ave	$U(200,3) = 34.7$

Wind averaging period

Structure	Wind Speed	Load	Dynamic
Smaller elements in structure	3 sec gust	Static or dynamic	
Structures smaller than 50m	5 sec gust	Dynamic	
Structures larger than 50m	15 sec gust	Total Static Load	
Large Super Structure (Deck)	1 minute Sustained		Dynamically sensitive
Substructure (jacket)	1 hour sustained	Total Static Load	Dynamically insensitive

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Wind Pressure

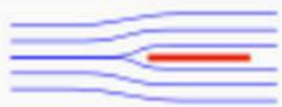
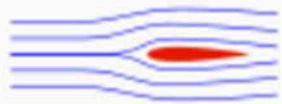
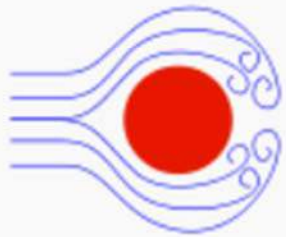
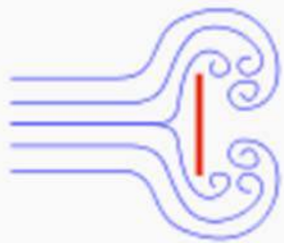
The wind pressure can be calculated as

$$f_w = \frac{1}{2}\frac{\rho_a}{g}V^2$$

$$f_w = 0.6V^2 \qquad N/m^2$$

where

ρ_a is the weight density of air = 0.01225 kN/m^3
g is the acceleration due to gravity (m/sec^2)
V is the velocity of wind (m/sec)

Shape and flow	Form Drag	Skin friction
	0%	100%
	~10%	~90%
	~90%	~10%
	100%	0%

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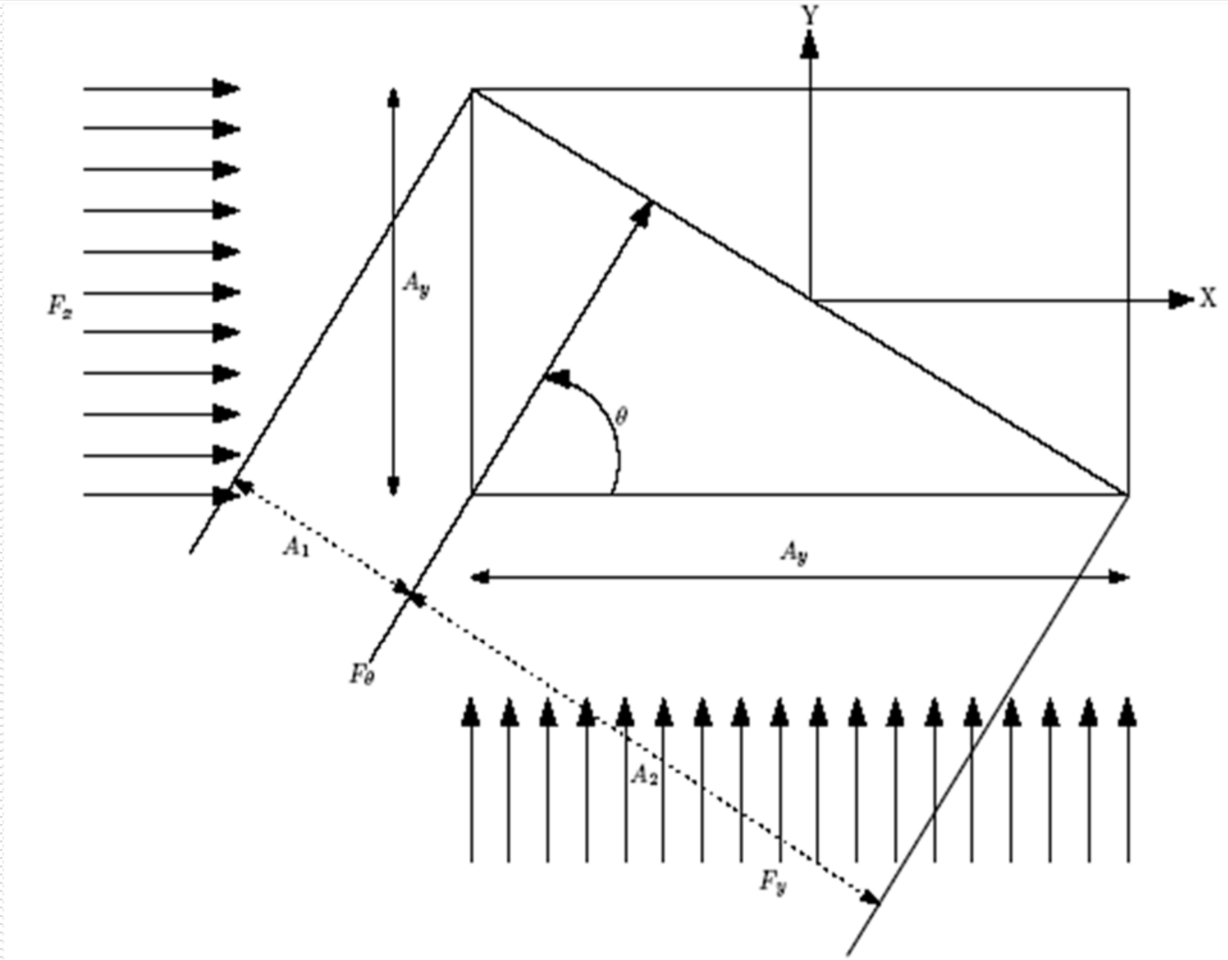
- The total force on the platform can be calculated as

$$F_x = f_w A_x C_s$$

$$F_y = f_w A_y C_s$$



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- Wind load on oblique directions can be calculated using following relationship.

$$F_\theta = F_x \cos(\theta) + F_y \sin(\theta)$$

- The projected areas can be calculated as *A1 = A_x cos(θ) and A_2 = A_y sin (θ)*

$$F_\theta = f_w (A_1 + A_2)$$

$$F_\theta = f_w (A_x \cos(\theta) + A_y \sin(\theta))$$

$$F_{\theta x} = f_w (A_x \cos(\theta) + A_y \sin(\theta)) \cos(\theta)$$

$$F_{\theta y} = f_w (A_x \cos(\theta) + A_y \sin(\theta)) \sin(\theta)$$

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Where $F_{\theta x}$ and $F_{\theta y}$ are the components of F_e in x and y directions respectively. Ratio between $F_{\theta x}$ and F_x can be expressed as

$$\frac{F_{\theta x}}{F_x} = \frac{f_w(A_x\cos(\theta) + A_y\sin(\theta)\cos(\theta)}{f_w A_x}$$

$$\frac{F_{\theta x}}{F_x} = \cos^2(\theta) + (A_y / A_x)\sin(\theta)\cos(\theta)$$

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Similarly, ratio between $F_{\theta y}$ and F_y can be expressed as

$$\frac{F_{\theta y}}{F_y} = \frac{f_w (A_x \cos(\theta) + A_y \sin(\theta) \sin(\theta)}{f_w A_y}$$

$$\frac{F_{\theta y}}{F_y} = \sin^2(\theta) + (A_x / A_y) \sin(\theta) \cos(\theta)$$

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Wave and Current Loads

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Difference between Waves and Tsunami

Waves

A **wave** is a disturbance that propagates through space and time, usually with transference of energy.

Ocean surface waves are surface waves that occur in the upper layer of the ocean. They usually result from wind, and are also referred to as **wind waves**.

Wind energy is imparted to water leading to the growth of waves.
The growth of wind generated wave are not indefinite. The point when the waves stop growing is termed as ***fully developed sea condition.***

Tsunamis

Tsunamis are a specific type of wave not caused by wind but by geological effects. In deep water, tsunamis are not visible because they are small in height and very long in wave length. They may grow to devastating proportions at the coast due to reduced water depth

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Short Crested Waves

The wind generated waves are not infinitely long. Depending on the width of the fetch, the length is finite. During the progress of the wave growth, the waves from different directions mix together and form the waves of limited length (length of crest).

The real ocean waves represent these limited length are called “Short Crested Waves”

The water particle kinematics and the behaviour will not be two dimensional.

Long Crested Waves

To the contrary, if the length of crest or trough is infinitely long, these are called “Long crested waves.

The water particle kinematics and the behaviour will be truly two dimensional.

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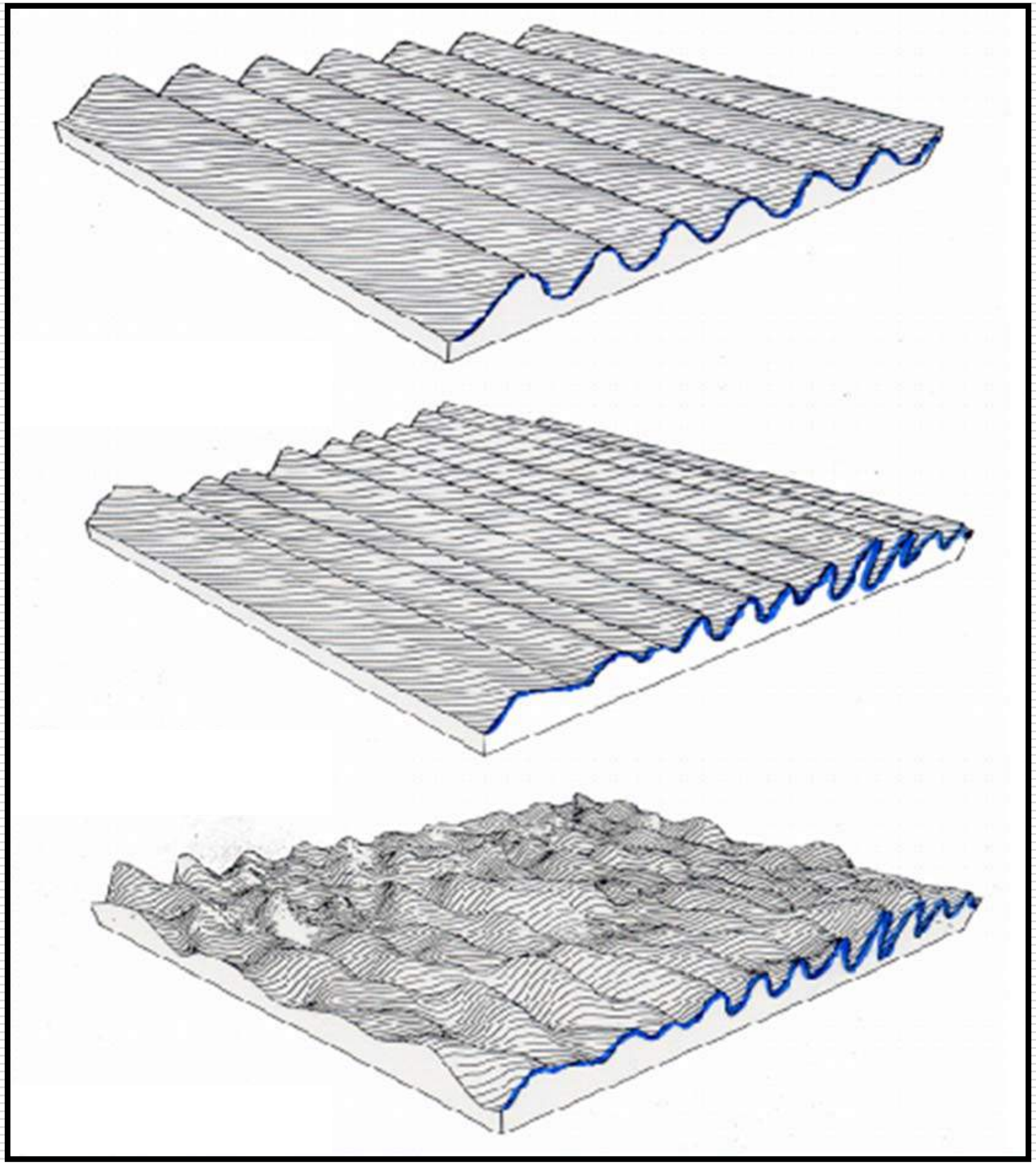
Long Crested
Regular Wave

Long Crested
Random Wave

Short Crested
Random Wave



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Regular Waves

A **sinusoidal wave train of regular shape is called "*regular waves*"**

Irregular Waves

The irregular wave will not be having regular shape and height but will be repetitive of some irregularity. These waves are called "***Irregular Waves***"

Random Waves

The real wave in ocean is the elevation of surface changes. This will not of definitive shape or pattern and will be irregular. These real waves are called "***Random Waves***"

SWELLS

The waves generated during a storm far away from the coast travels to a greater distance. These waves will appear to be more regular, with height and direction with limited variability are called "***Swells***".

The swells are mostly long crested and behave like regular waves.

The period of the swells will be greater than 10 sec.

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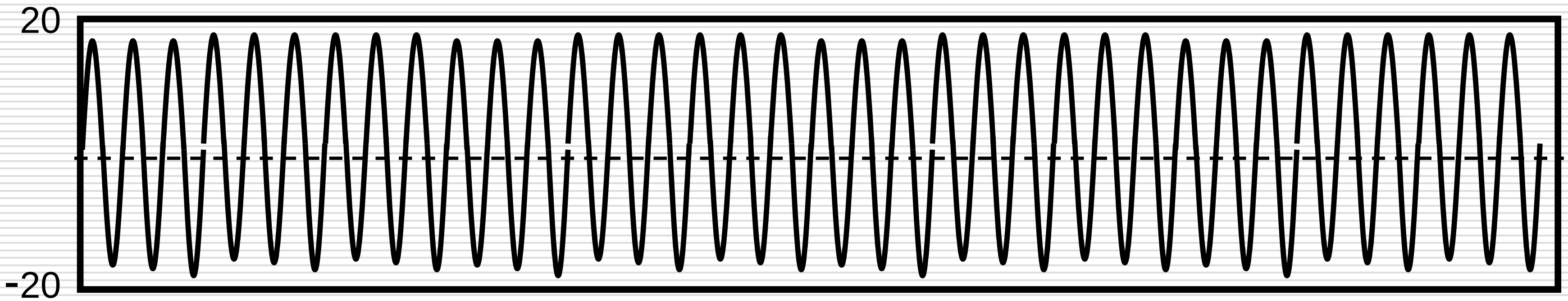
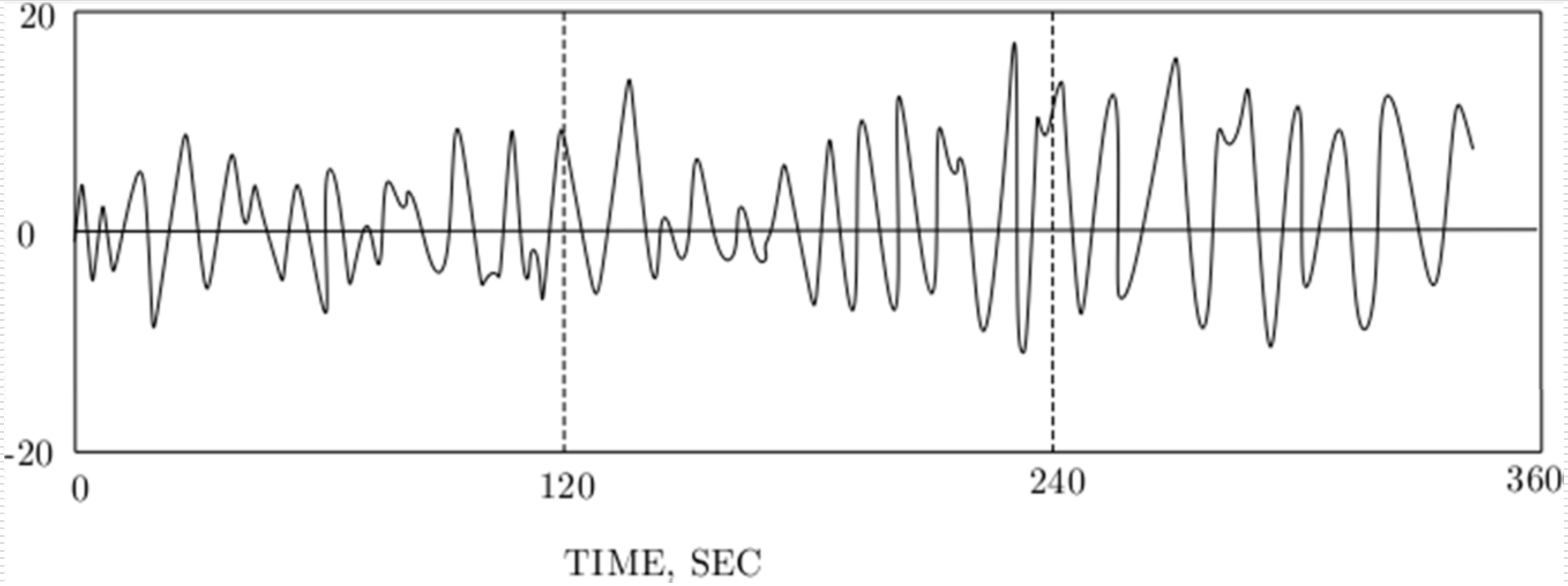
Regular Wave



Random Wave



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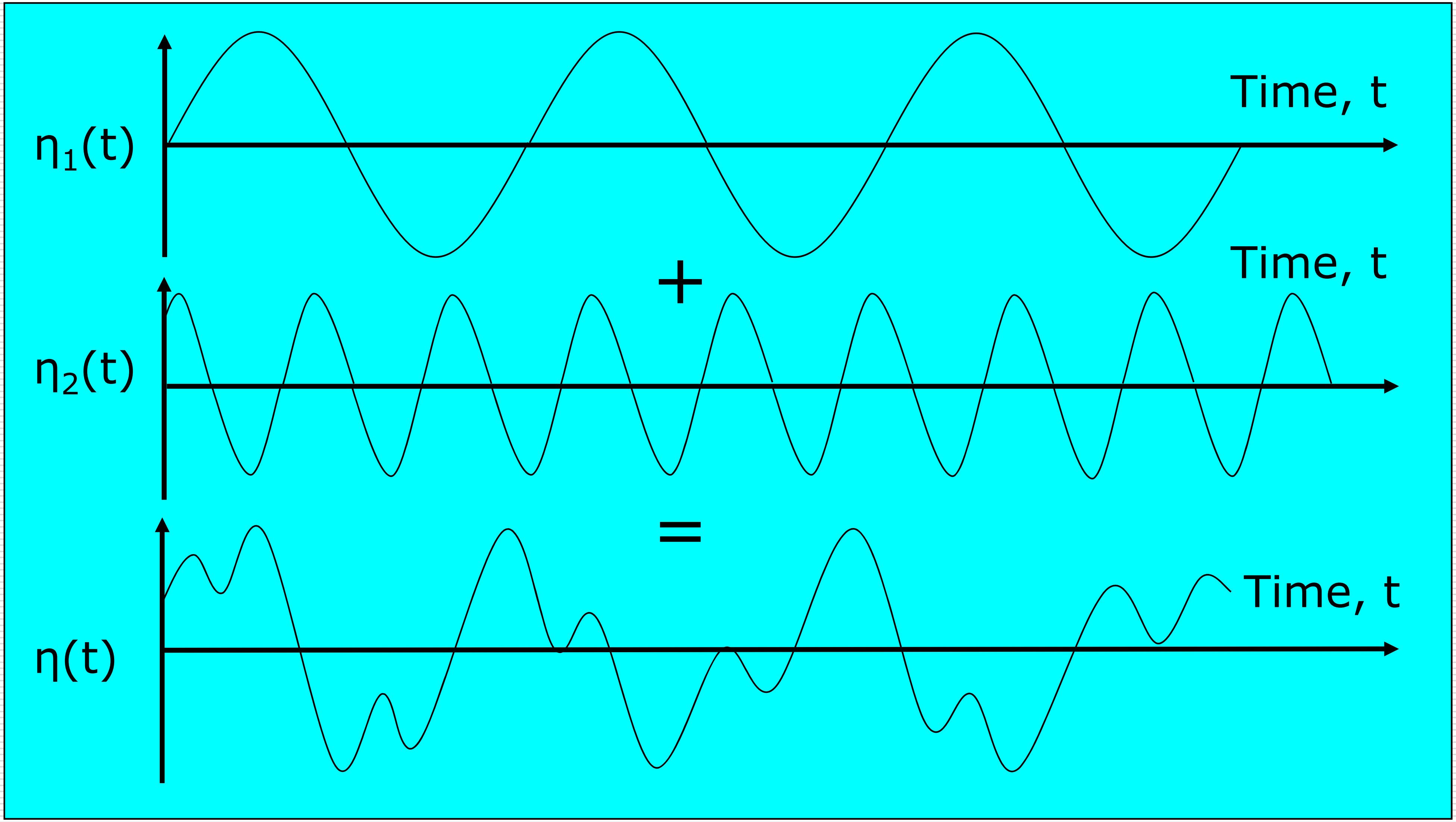
Summation of simple wave forms



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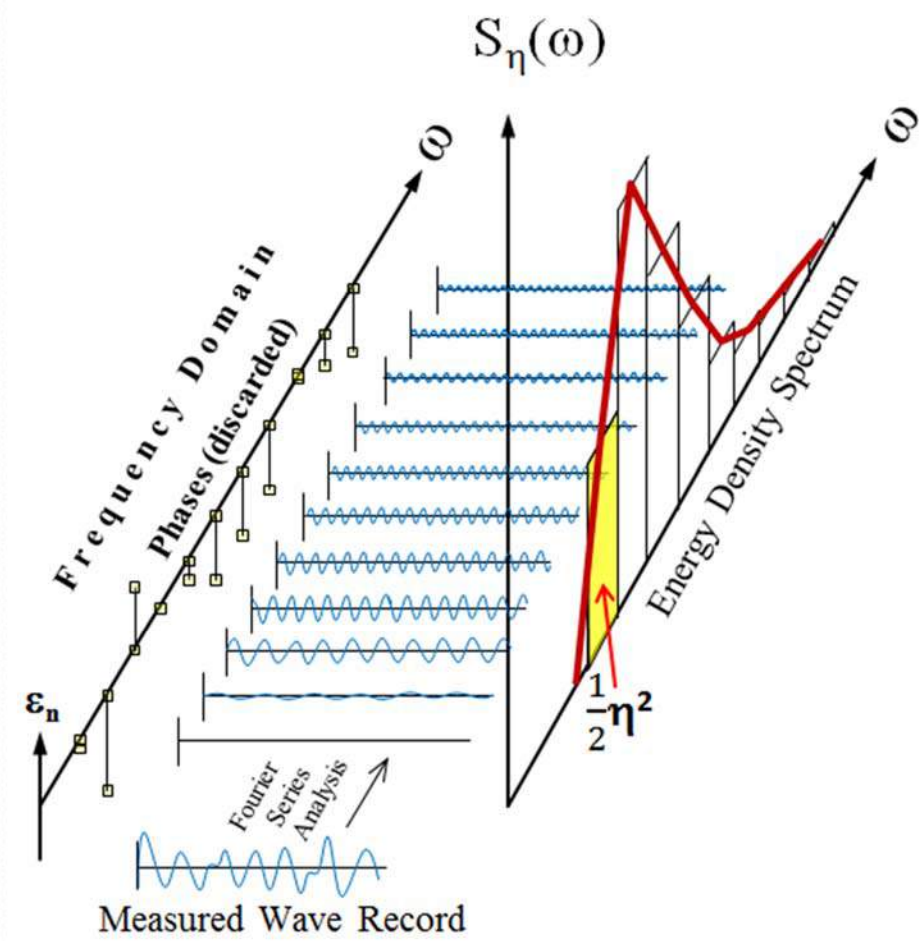
Wave Components

The wave elevation of irregular wave propagating along x axis can be written in terms of large number of wave amplitude components with random phase



$$\eta(t) = \sum_{n=1}^{N} \eta_{an} \cos(k_n x - \omega_n t + \varepsilon_n)$$

η_{an} = wave amplitude component (m)
ω_n = circular frequency component (rad/s)
k_n = wave number component
ε_n = random phase angle component (rad)

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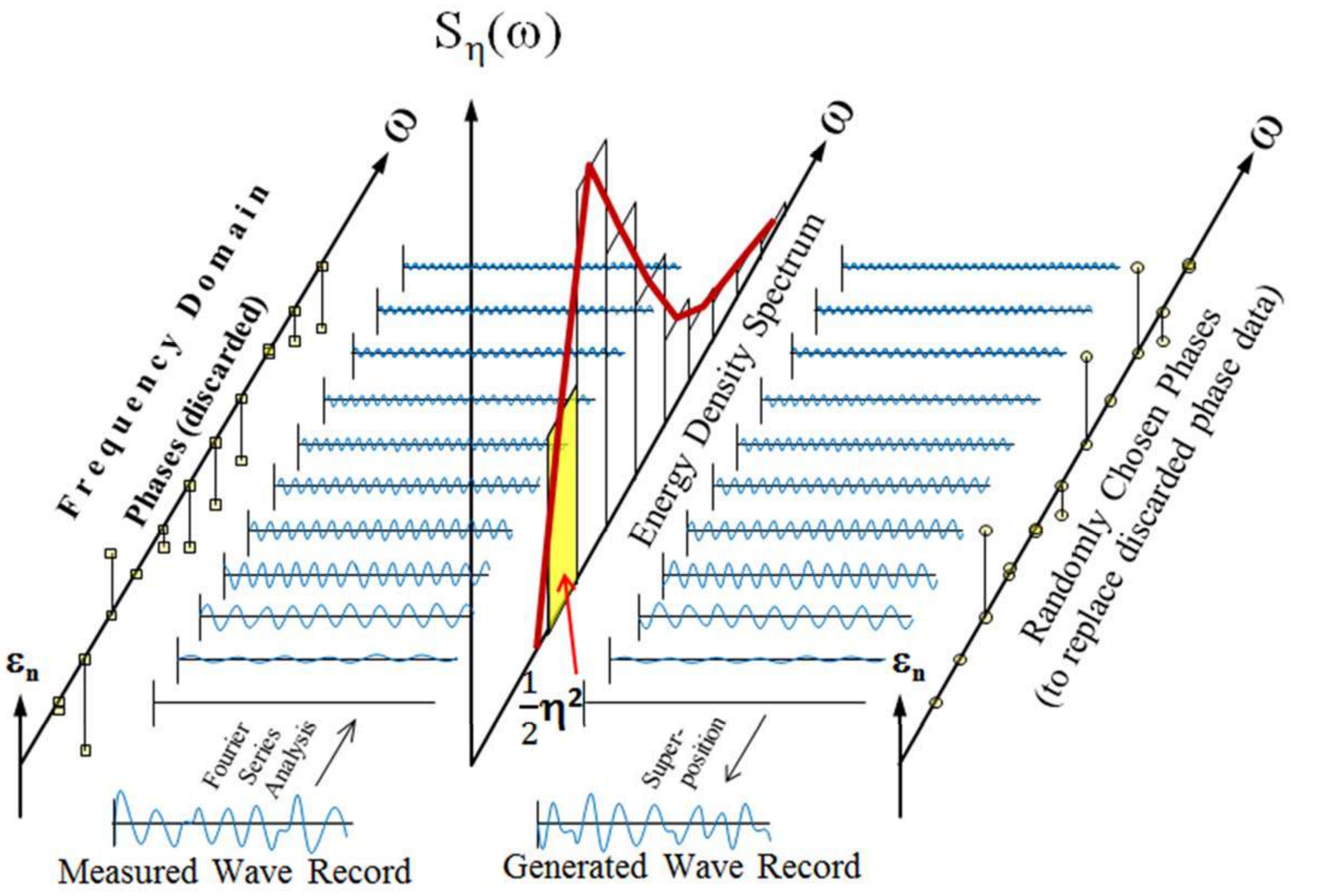
Regeneration of time history from wave spectra



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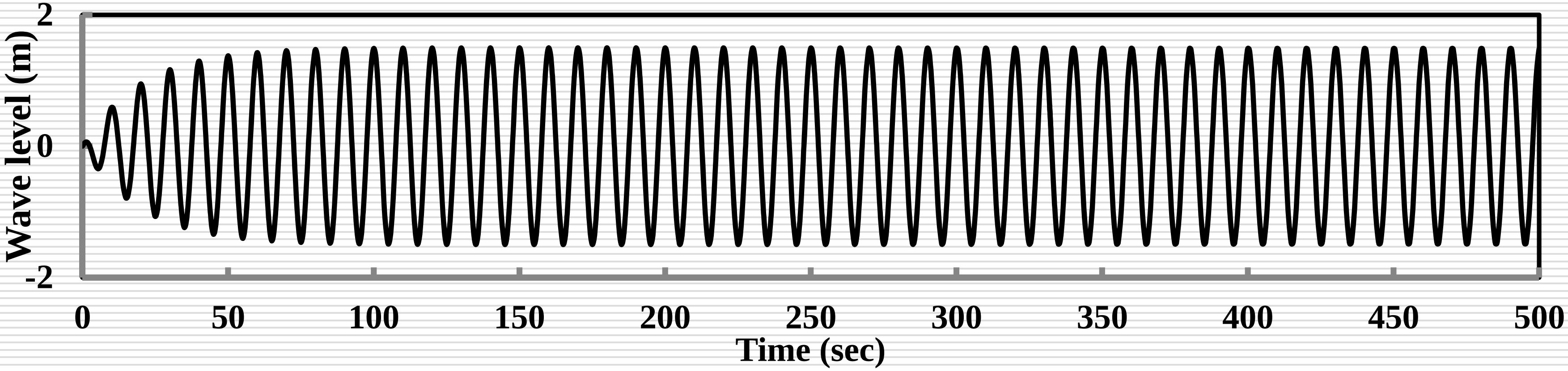
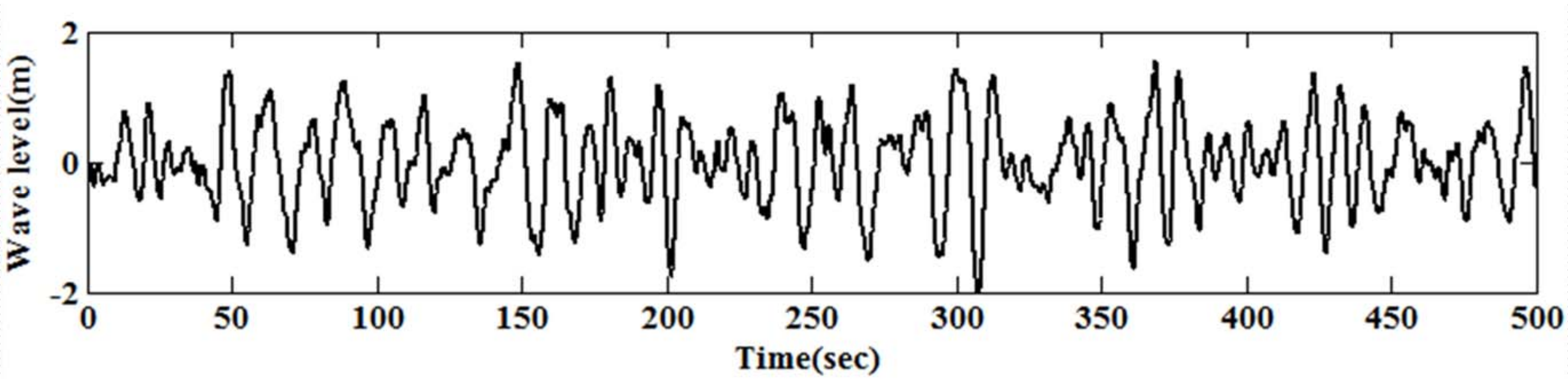
Example of a recorded Wave Forms

Regular Wave



Random Wave



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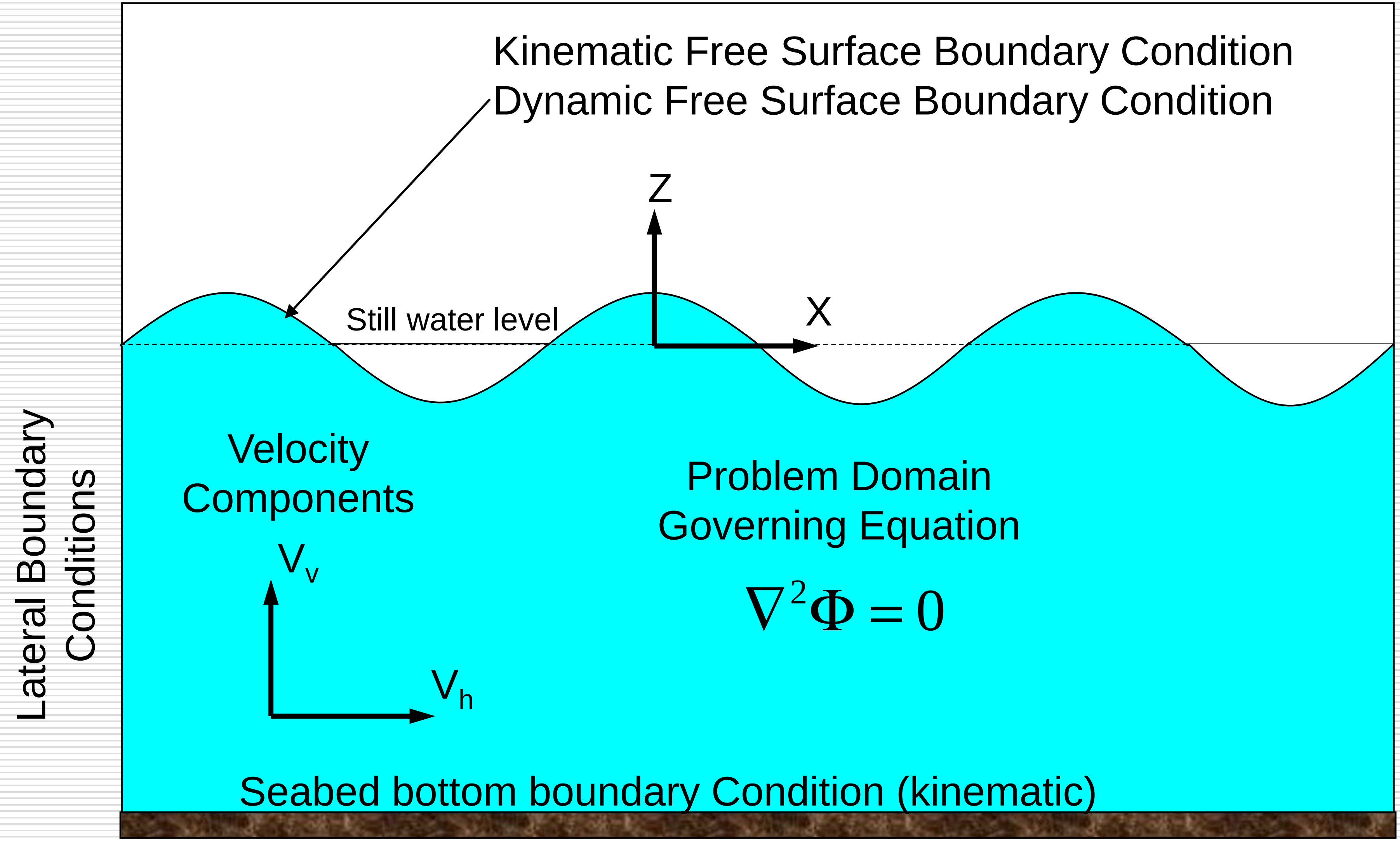
BOUNDARY VALUE PROBLEM



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Velocity Potential

- Considering irrotational flow curl (rotation) of the velocity vector =zero. ie $\nabla \times u = \omega = 0$

- According to vector algebra if the curl of a vector is zero, the vector can be expressed as the gradient of a scalar function, Φ called the **potential function.**

- Hence velocity u can be expressed as $u = \nabla \Phi$

  Φ is called **velocity potential function.**

- **Velocity Potential is a scalar function of space and time such that its derivative with respect to any direction yields velocity in that direction.**

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Wave Theories

Wave theories for the calculation properties of the water particle motion is classified in to following based on the application. The classification is based on the approximation made on the expression for the velocity potential.

$$\phi = \phi_1 \varepsilon + \phi_2 \varepsilon^2 + \phi \varepsilon^3 + \ldots.$$

In which ϕ_1 is the first order velocity potential and ϕ_2 and ϕ_3 are higher order terms and ε is the perturbation parameter = **ka**, where **a** is the wave amplitude and the various wave theory used in practice are listed below

- Linear wave theory (Airy's)
- Stoke's wave theory (Higher order)
- Cnoidal wave theory
- Stream function wave theory

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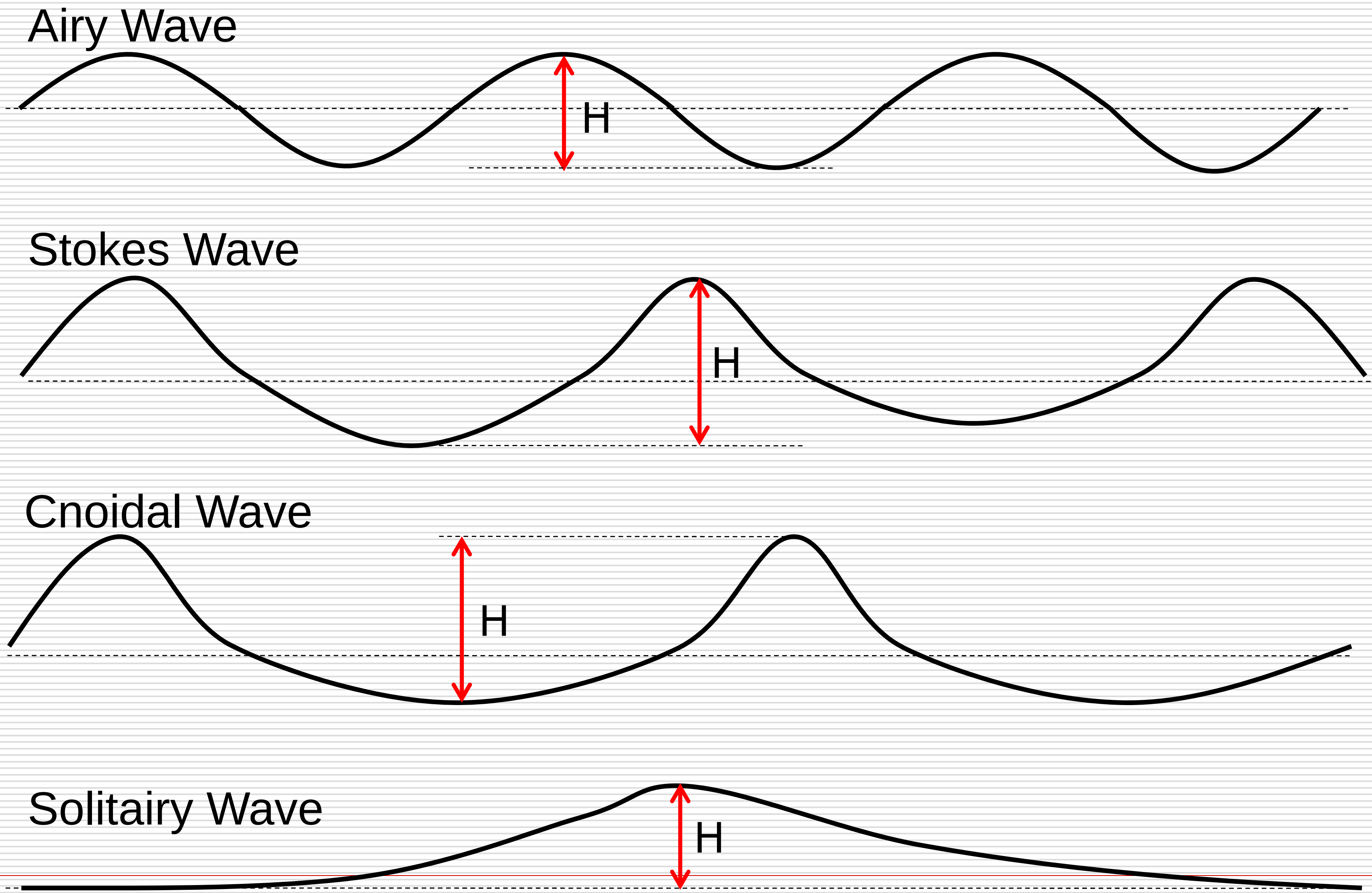
Wave forms



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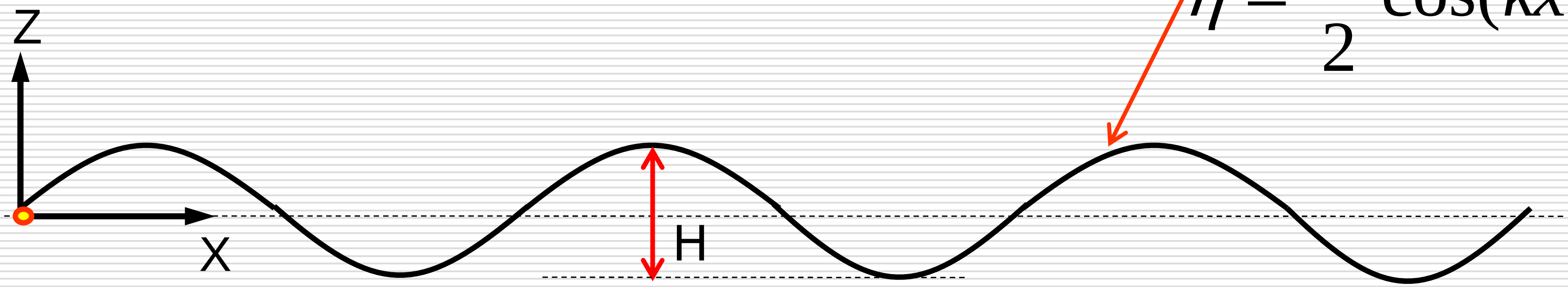
Linear Wave Theory

Airy wave theory is considered in the calculation of wave kinematics. Consider a progressive wave with water surface elevation depicted by cosine curve,

$$\eta = \frac{H}{2}\cos(kx - \omega t)$$



and the corresponding velocity potential is given by:

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

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Water Particle kinematics

The horizontal and vertical velocity and acceleration of water particle can be calculated using the following equations.

Horizontal Velocity
$$V_h = \frac{\partial \phi}{\partial x} = \frac{H}{2}\omega \frac{\cosh k(h+z)}{\sinh kh}\cos(kx - \omega t)$$

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

Horizontal acceleration (Local)
$$a_h = \frac{\partial V_h}{\partial t} = \frac{H}{2}\omega^2 \frac{\cosh k(h+z)}{\sinh kh}\sin(kx - \omega t)$$

Vertical acceleration (Local)
$$a_v = \frac{\partial V_v}{\partial t} = \frac{H}{2}\omega^2 \frac{\sinh k(h+z)}{\sinh kh}\cos(kx - \omega t)$$

Where **k** is the wave number defined by $2\pi/$**L**, **ω** is the wave circular frequency defined by **2π/T**, **L** is the wave length, and x is the distance of the point in consideration from origin.

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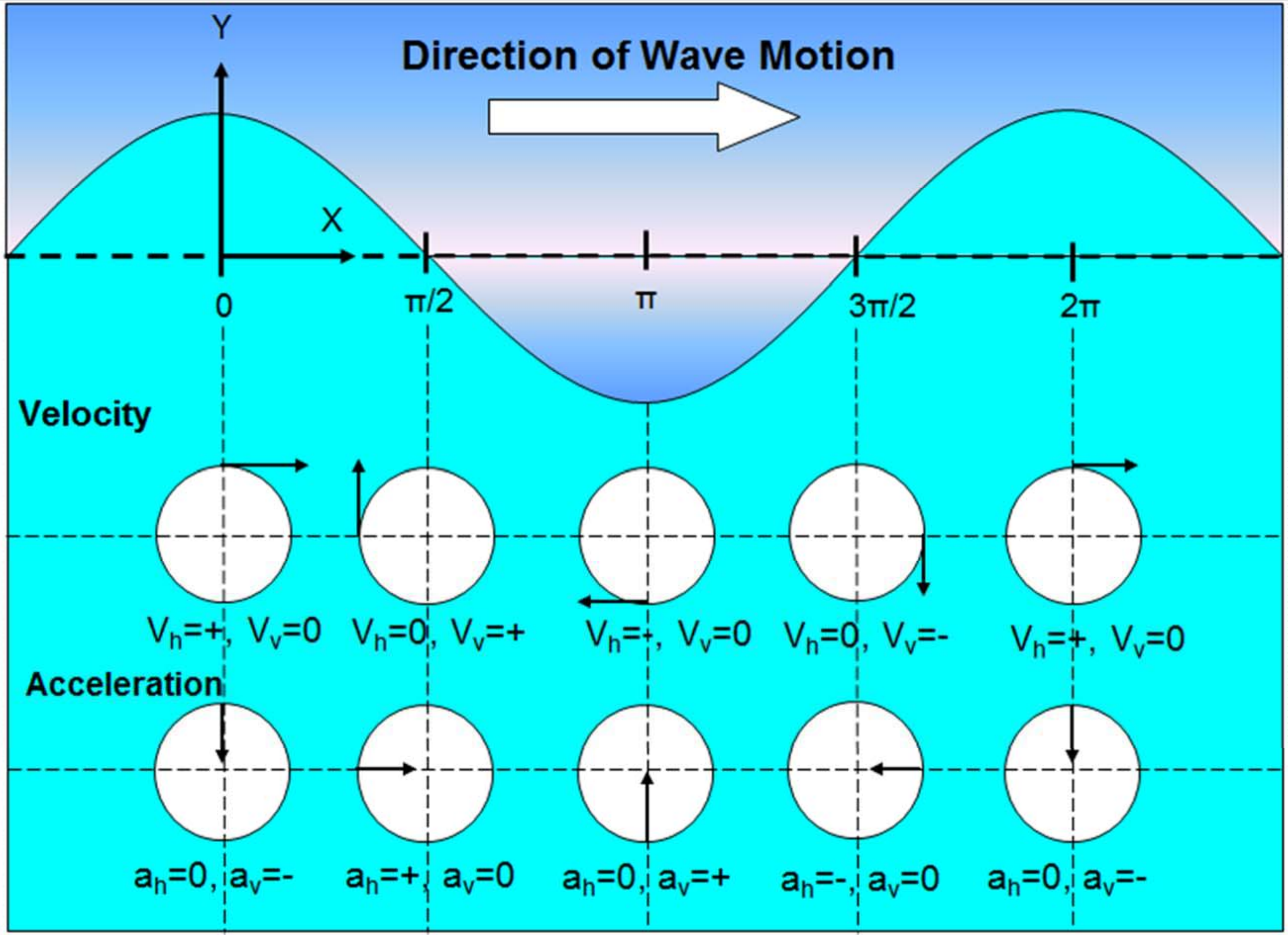

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Method of Hydrodynamic Analysis

In applying design waves load on to the offshore structures, there are two ways of applying it

- Design Wave method
- Spectral Method

In design wave method, a discrete set of design waves (maximum) and associated periods will be selected to generate loads on the structure. These loads will be used to compute the response of the structure.

In the spectral method, a energy spectrum of the sea-state for the location will be taken and a transfer function for the response will be generated. These transfer function will be used to compute the stresses in the structural members

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Design Wave Method

The forces exerted by waves are most dominant in governing the jacket structures design especially the foundation piles. The wave loads exerted on the jacket is applied laterally on all members and it generates overturning moment on the structure.

Period of wind generated waves in the open sea can be in the order of 2 to 20 seconds. These waves are called gravity waves and contain most part of wave energy.

Maximum wave shall be used for the design of offshore structures. The relationship between the significant wave height (H_s) and the maximum wave height (H_{max}) is

$$H_{max} = 1.86\ H_s$$

The above equation correspond to a computation based on 1000 waves in a record.

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Design Wave Heights

The design wave height for various regions is tabulated below

Region	1 year	100 year
Bay of Bengal	8	18
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

Maximum design waves in various regions

API RP2A requires both 1 year and 100 year recurrence wave shall be used for the design of jacket and piles. Appropriate combination of loads with these waves shall be used in the design. A one-third increase in permissible stress is allowed for 100 year storm conditions.

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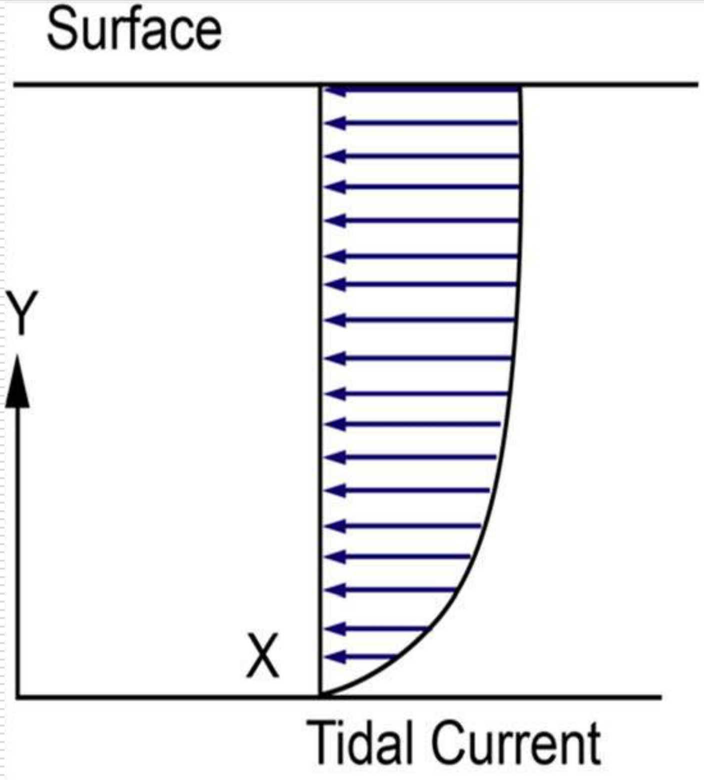
Tidal Current Profile

The wind driven current variation with depth can be expressed as:

$$V_T = V_{oT}\left(\frac{y}{h}\right)^{\frac{1}{7}}$$



Where V_T is the tidal current at any height from sea bed, V_{oT} is the tidal current at the surface, y is the distance measure in m from seabed and *h* is the water depth

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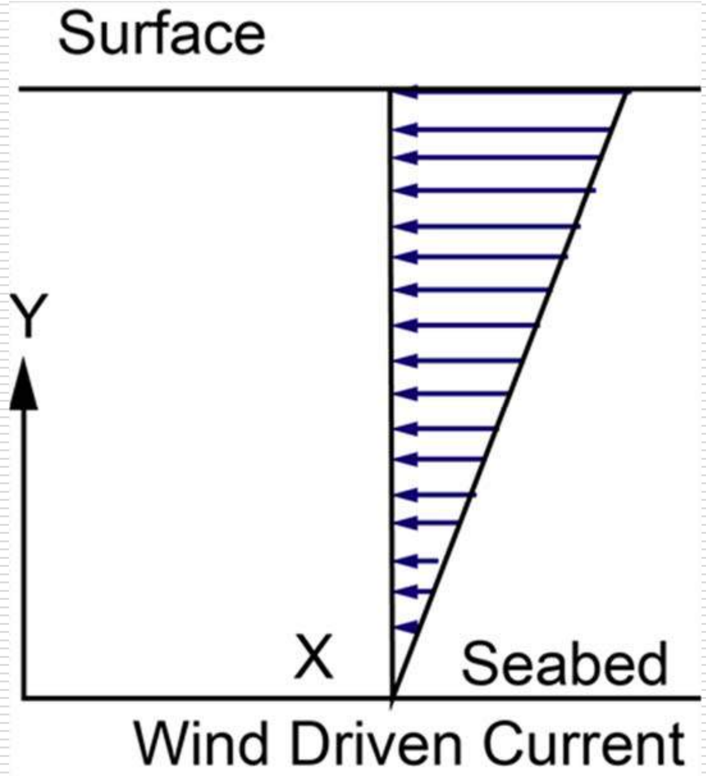
Wind Driven Current Profile

The current variation with depth can be expressed as:

$$V_W = V_{oW}\,\frac{y}{h}$$

Where V_W is the wind driven current at any height from sea bed, V_{oW} is the wind driven current at the surface, y is the distance measure in m from seabed and *h* is the water depth



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Basis of Morison Equation

Morison Equation is based on following assumptions

- Flow is assumed to be not disturbed by the presence of the structure
- Force calculation is empirical calibrated by experimental results
- Suitable Coefficients need to be used depending on the shape of the body or structure
- Validity range shall be checked before use and generally suitable for most jacket type structures where D/L << 0.2 where D is the diameter of the structural member and L is the wave length

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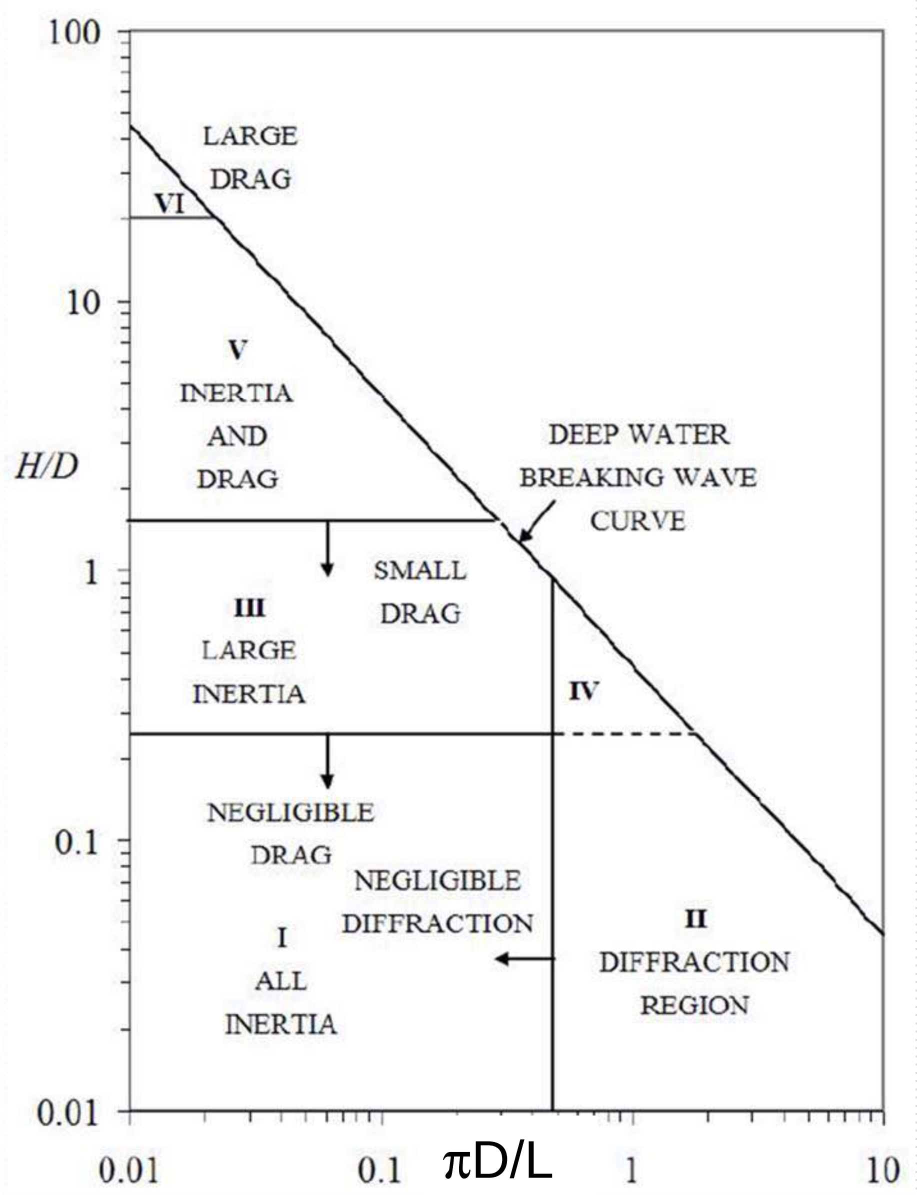
Force Regime

Parameters relating the force regime are

- ❑ Relative wave height (H/D)
- ❑ Relative size of structure (D/L)



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Morison Equation

Wave and current loading can be calculated by Morison equation as described below:

$$F_T = \frac{1}{2} C_D \rho_w \; D \; V \left| V \right| + \frac{\pi D^2}{4} C_M \rho_W a$$

Where $\mathbf{F_T}$ is the total force, $\boldsymbol{\rho_w}$ is the density of water, $\mathbf{C_D}$ and $\mathbf{C_M}$ are the drag and inertia coefficients respectively, **D** is the diameter of the member including marine growth, **V** is the velocity and **a** is the acceleration.

The first term in the equation is drag component ($\mathbf{F_D}$) and the second term is the inertia component ($\mathbf{F_I}$). This can be expressed as:

$$\mathbf{F_T = F_D + F_I}$$

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Estimation of Wave Load on a Member

Morison equation is a general form and can not be applied to all members in the offshore structure. It was developed specifically for a surface piercing cylinder like pile of a structure. But in reality, the members of the offshore structure may be horizontal or inclined in space and can not used without modification

- Establish Wave Height, Period and Current Distribution along the depth
- Establish Wave Theory applicable for H,T,d
- Estimation of Water particle kinematics including wave current interaction
- Establish Cd and Cm
- Establish Marine Growth
- Establish Wave Kinematics factor
- Conductor Shielding (if applicable)
- Current Blockage factor
- Morison Equation used to estimate the forces

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Wave load estimation procedure

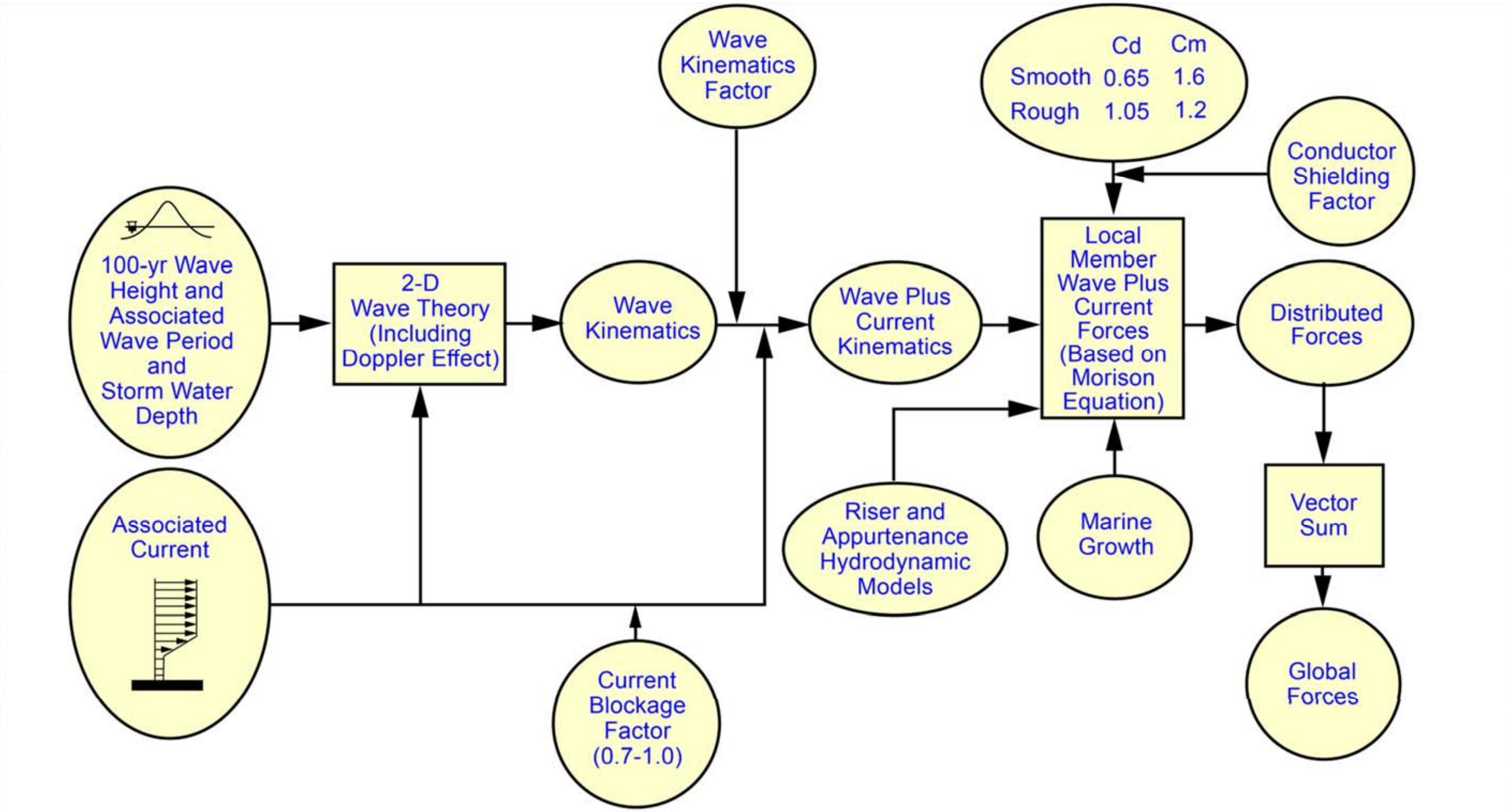

Figure 2.3.1-1 Procedure for calculation of Wave Plus Current Forces for Static Analysis

Source : API RP 2A

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Selection of wave theory

Suitable wave theory shall be selected depending on the water depth, wave height and wave period.

The chart show in the figure is sued to select the wave theory based H/gT^2 and d/gT^2

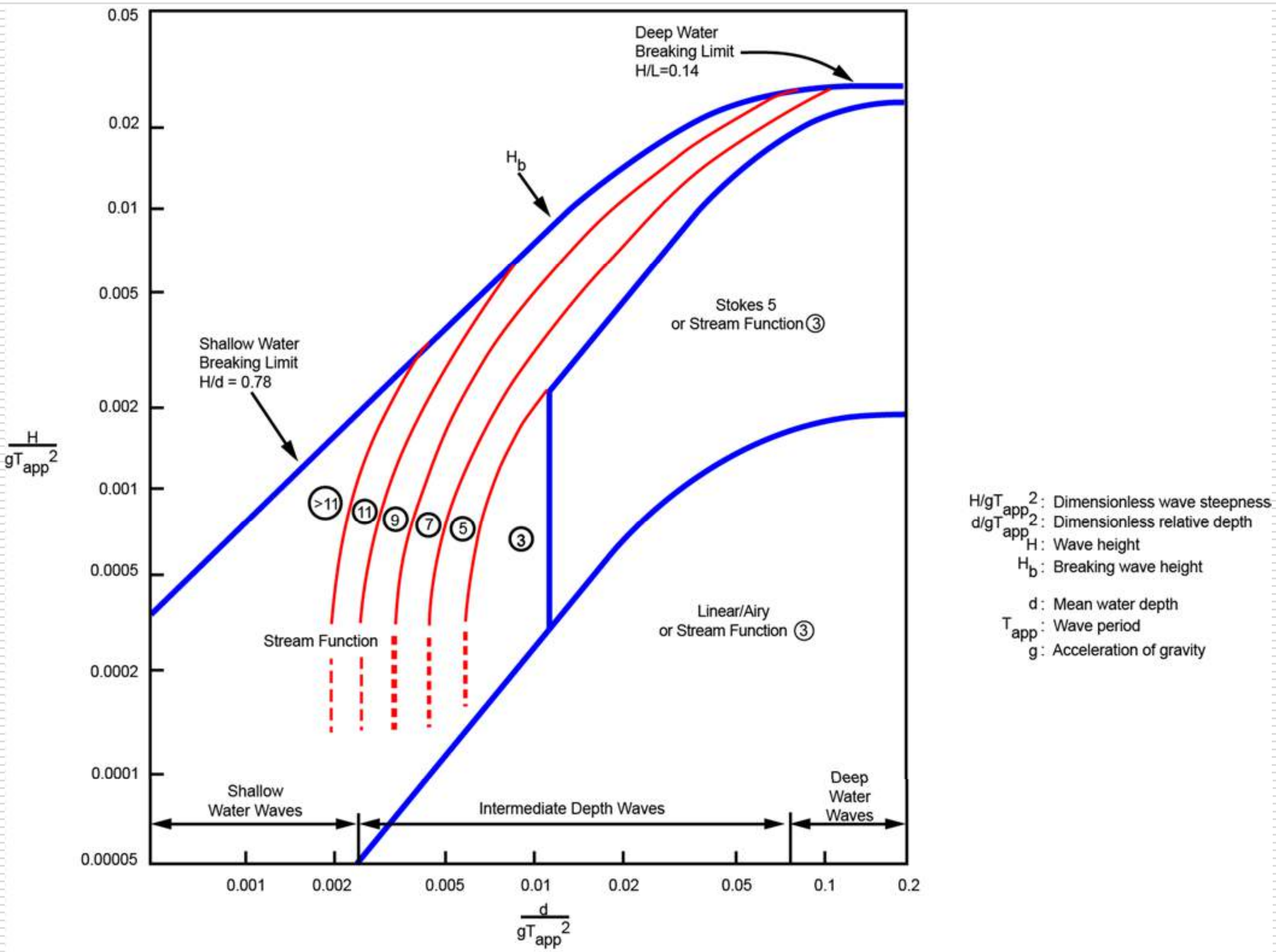

Figure 2.3.1-3—Regions of Applicability of Stream Function, Stokes V, and linear Wave Theory (From Atkins, 1990; Modified by API Task Group on Wave Force Commentary)

Source : API RP 2A

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SELECTION OF SUITABLE WAVE THEORY

- Water Depth d= 60m
- Wave height H= 12m
- Wave Period T_{app}= 10 Sec
- Calculate H/gT_{app}^2 =0.012
- Calculate d/gT_{app}^2 =0.06

For the calculated values of

H/gT_{app}^2 =0.012

d/gT_{app}^2 =0.06

Stokes Fifth Order wave theory is selected

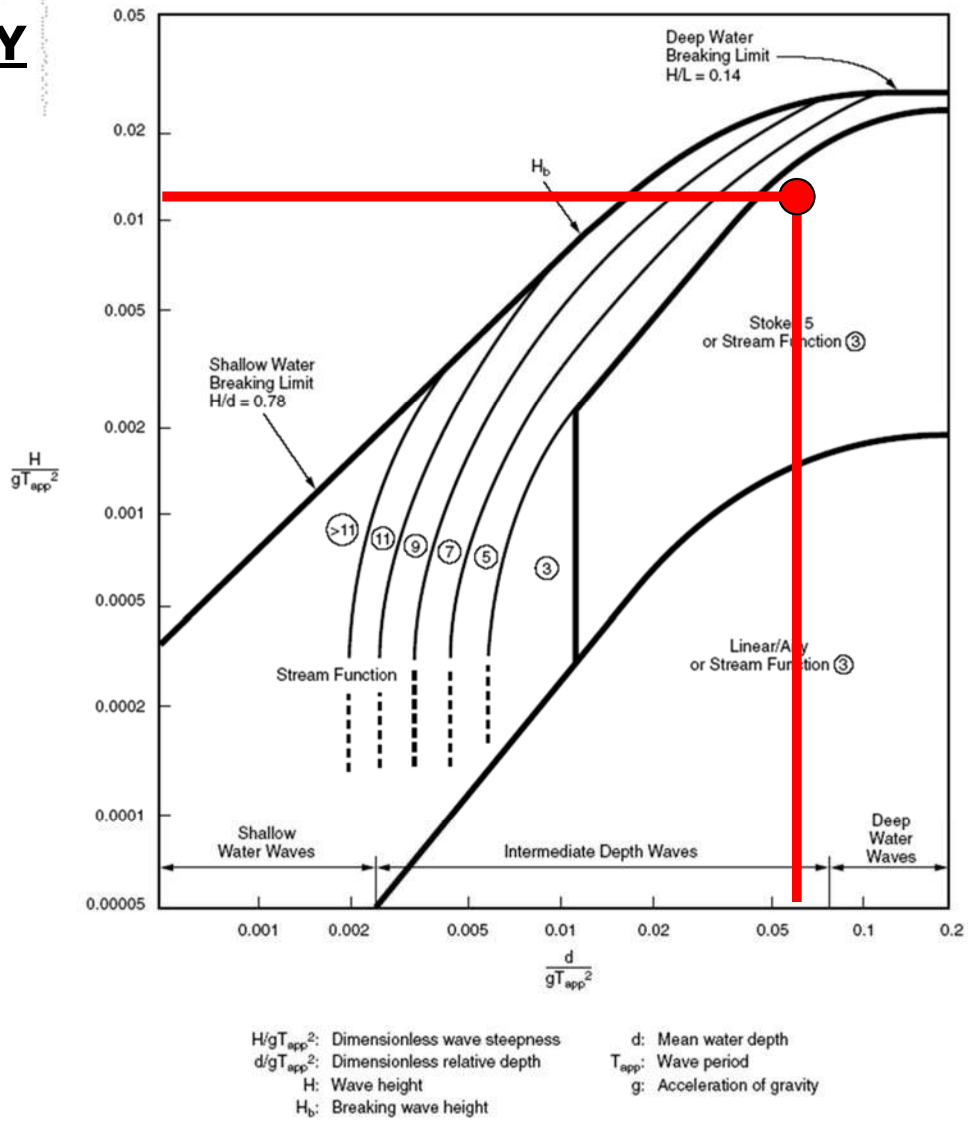

Figure 2.3.1-3—Regions of Applicability of Stream Function, Stokes V, and Linear Wave Theory (From Atkins, 1990; Modified by API Task Group on Wave Force Commentary)

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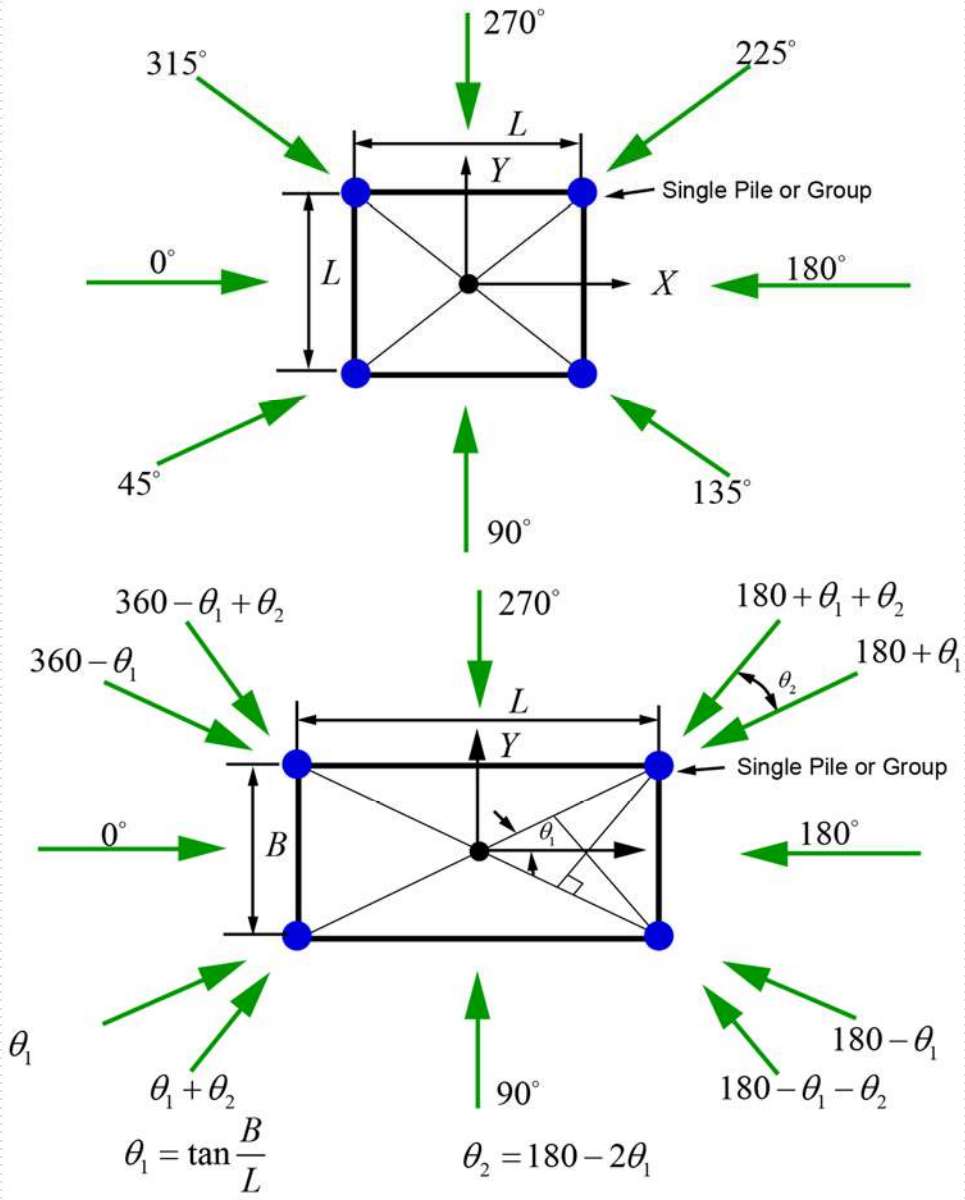
Wave / Current Direction

- Wave / Current assumed to be acting in same direction
- Wave Directions shall be set to maximize the total loads and pile loads
- Minimum 8 directions for 4 or 8 legged jackets and 12 for tripods
- Directional or Omni-directional depending on the design requirement



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WAVE CURRENT INTERACTION

Presence of current either stretches the wave or shortens it depending on the direction of current. This is called Doppler shift. The apparent wave period need to be calculated to use in the load calculation. Drag term is nonlinear and hence the water particle velocities due to wave and current needs to be added vectorialy before using it in Morison equation.

Apparent Wave Period

Following three equations needs to be solved to obtain the T_{app}

$$\frac{L}{T} = \frac{L}{T_{app}} + V_w \qquad T_{app}^{\;2} = \frac{2\pi L}{g \tanh(\frac{2\pi}{L} d)} \longleftarrow L = \frac{g T_{app}^{\;2}}{2\pi} \tanh(\frac{2\pi}{L} d)$$

$$V_w = \frac{(4\pi / L)}{\sinh(4\pi d / L)} \int_{-d}^{0} U_c(z) \cosh(4\pi (z+d)/L) dz$$

$U_c(z)$ – is the current profile elevation z

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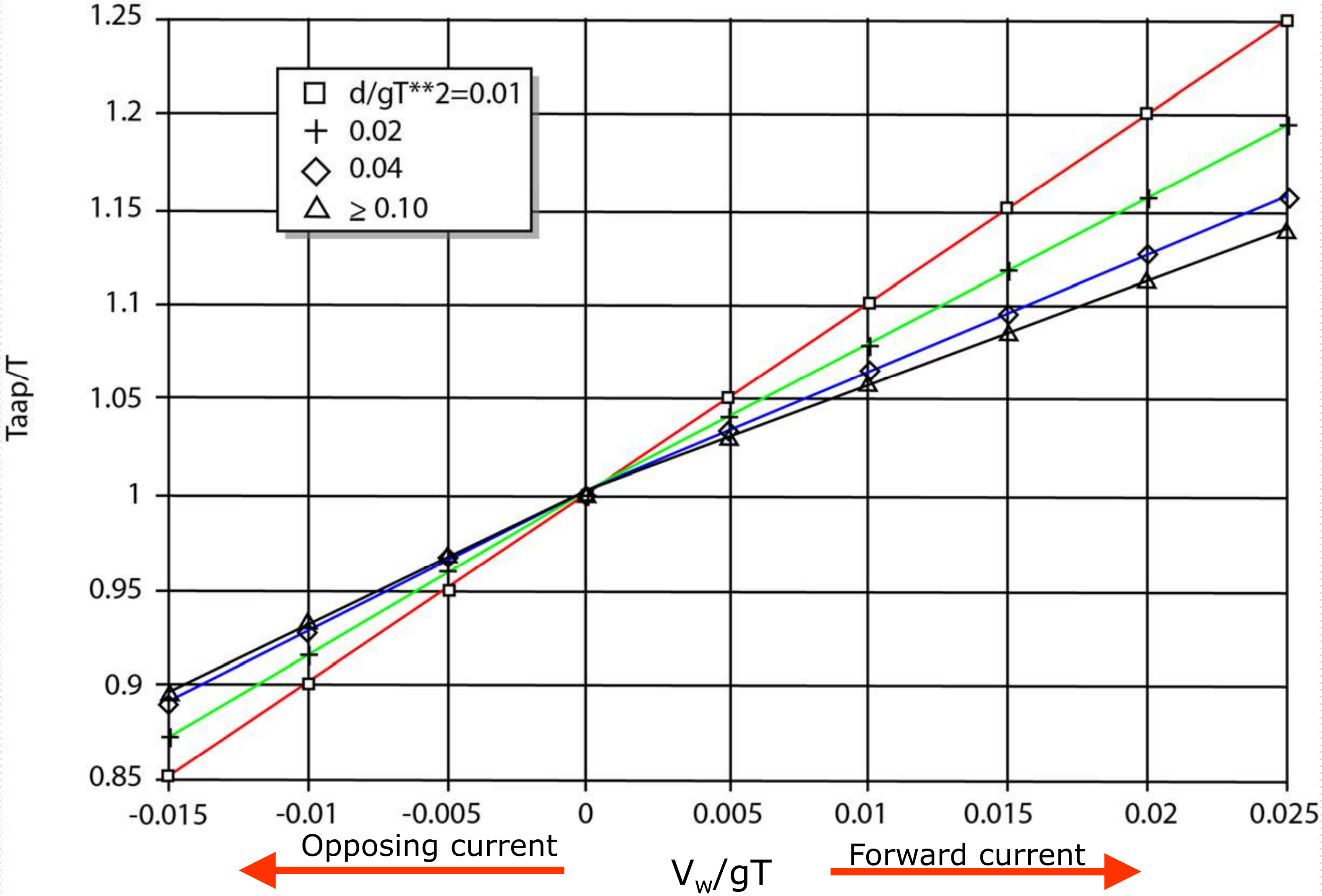

Figure 2.3.1-2—Doppler Shift Due to Steady Current

Source : API RP 2A

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Nonlinear Drag Term in Morison equation

$$F_T = \frac{1}{2} C_D \rho_w \; D \; V \left| V \right| + \frac{\pi D^2}{4} C_M \rho_W a$$

$$V = Vc + Vw$$

Vc = Current Velocity

Vw = Wave Water Particle Velocity

Example

Lets assume Vc=2m/sec, Vw=3m/sec

If we calculate the drag forces separately, add, we will get 2*2 + 3*3 = 13

If we add the velocities first and compute the loads, we get (2+3)*(2+3) = 25

It under predicts the forces as much as by 50%

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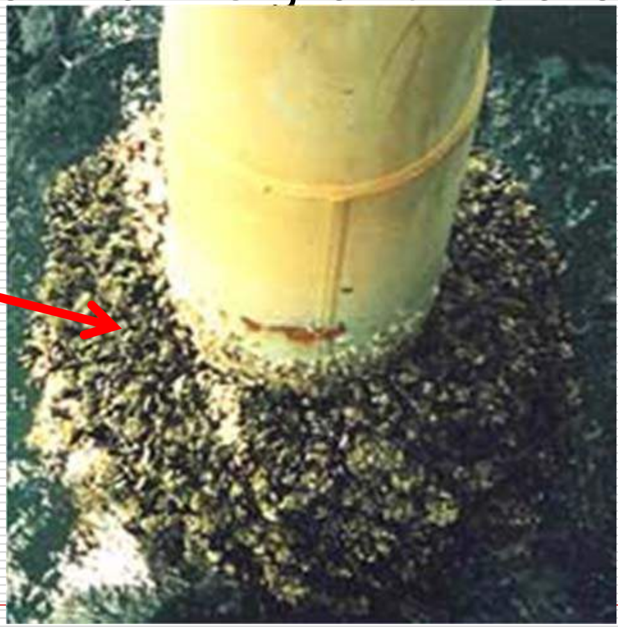
Marine Growth

- Marine growth around submerged structural members increases the wave/current loads as the diameter is increased
- It varies from 50mm to 150mm thickness along the depth from seabed. The thickness reduces as the depth increases as the algae could not live due to lack of oxygen.
- At also adds to additional weight
- This is to be modeled such that the above is taken in to account
- Density of marine growth is around 1300 kg/m^3

Marine growth



Marine growth preventer

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Modification factors for wave load estimation

Following factors shall be applied to the calculated wave load

Wave kinematic factor

The wave kinematics factor is applied to reduce the wave load on the structural members since the real ocean wave has three dimensional spreading and may induce lesser loads than the theoretical wave theory. This shall be less than 1.0. For most applications it shall be between 0.8 to 0.9.

Current blockage factor

This factor is to consider reduction in the free stream current velocity due to obstruction by structural members in the jacket.

Conductor shielding factor

This factor is to consider the shielding provided by the vertical members in close vicinity

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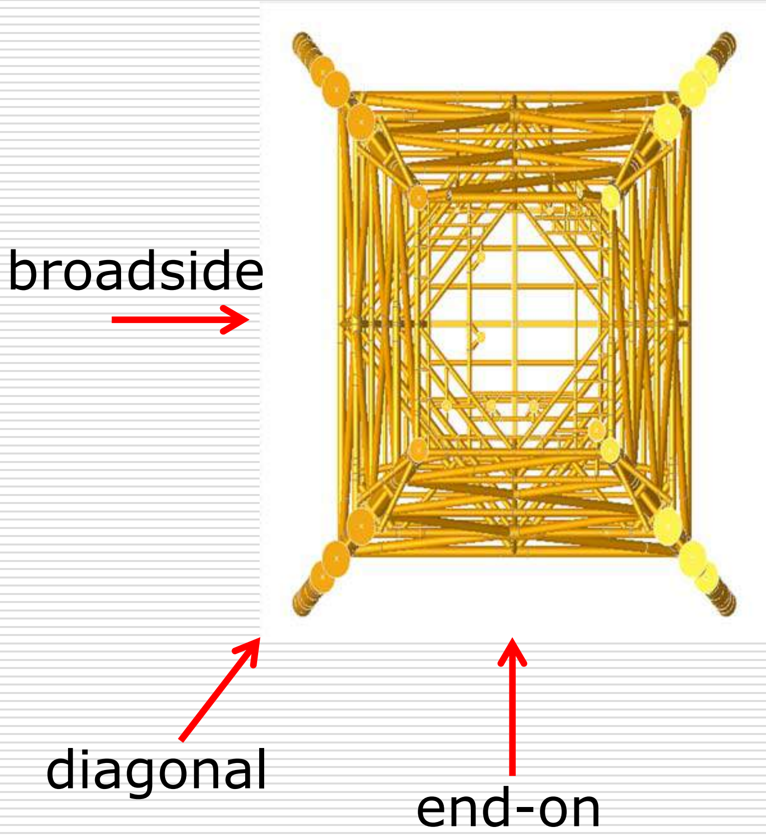
Current Blockage Factor

Current blockage factor is calculated to account for the reduction in free stream current due to the presence of the jacket members.



# of Legs	Heading	Factor
3	all	0.90
4	end-on	0.80
	diagonal	0.85
	broadside	0.80
6	end-on	0.75
	diagonal	0.85
	broadside	0.80
8	end-on	0.70
	diagonal	0.85
	broadside	0.80

Source : API RP 2A

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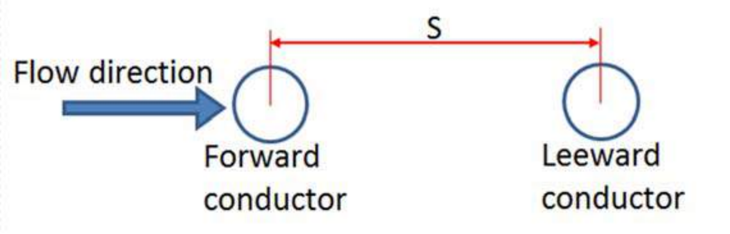
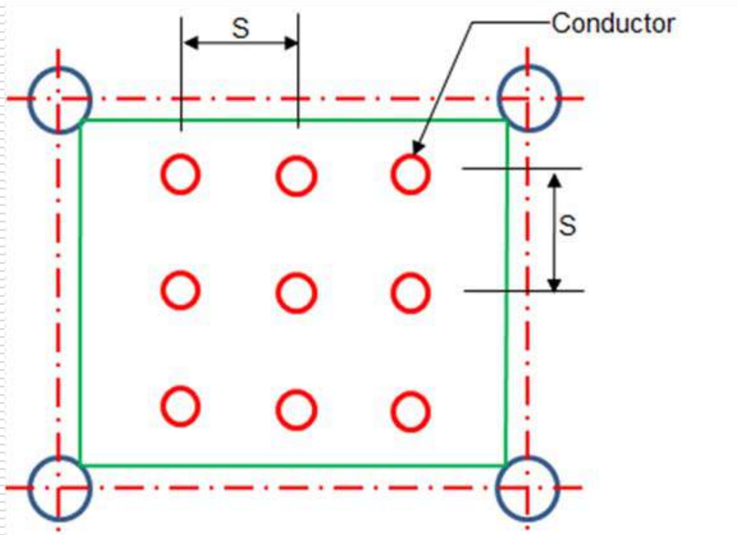
Conductor Shielding Factor

The conductor shielding factor is applied to account for reduction in wave and current load due to shielding effect of forward conductor on the leeward conductor. The effect of spacing ratio (S/D) on wave load is given in API RP 2A in which S is the spacing of conductor and D is the diameter of conductor.





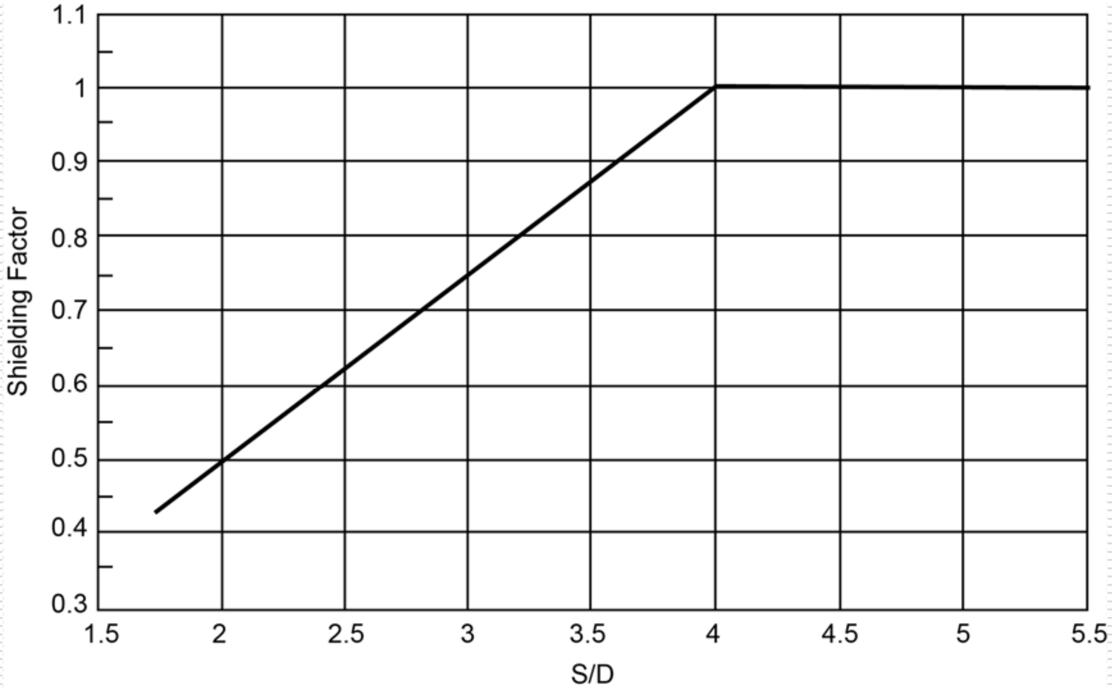


Figure 2.3.1-4—Shielding Factor for Wave Loads on Conductor Arrays as a Function of Conductor Spacing

Source : API RP 2A

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Selection of C_D and C_M

- These are empirical Coefficients to be used in Morison equation and they have been correlated with experimental data
- These coefficients vary due to shape of the structure, surface roughness, flow velocity and direction of flow
- Extensive research on various shapes available
- API RP 2A has enough information for circular cylinders
- DNV recommendation can be used for non-circular shapes

C_D and C_M for Storm waves

- For Smooth cylinders C_D = 0.65, C_M=1.6
- For rough cylinders C_D = 1.05, C_M=1.2

- The values shall be used only if UT/D > 30
- For other region of flow, charts available in literature shall be used

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Keulegan-Carpenter Number

$$K = \frac{2U_m T_2}{D}$$

Where **K** is Keulegan-Carpenter Number, $\mathbf{U_m}$ is the maximum velocity including current and $\mathbf{T_2}$ is the duration of half wave cycle and **D** is the diameter of the member

Reynold’s Number

$$\mathrm{Re} = \frac{U_m D}{\nu}$$

Where **Re** is Reynold’s Number, $\mathbf{U_m}$ is the maximum velocity including current and **D** is the diameter of the member

v is the kinematic viscosity

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Inertia Coefficient (C_M)

Varies between 1.6 to 2.0

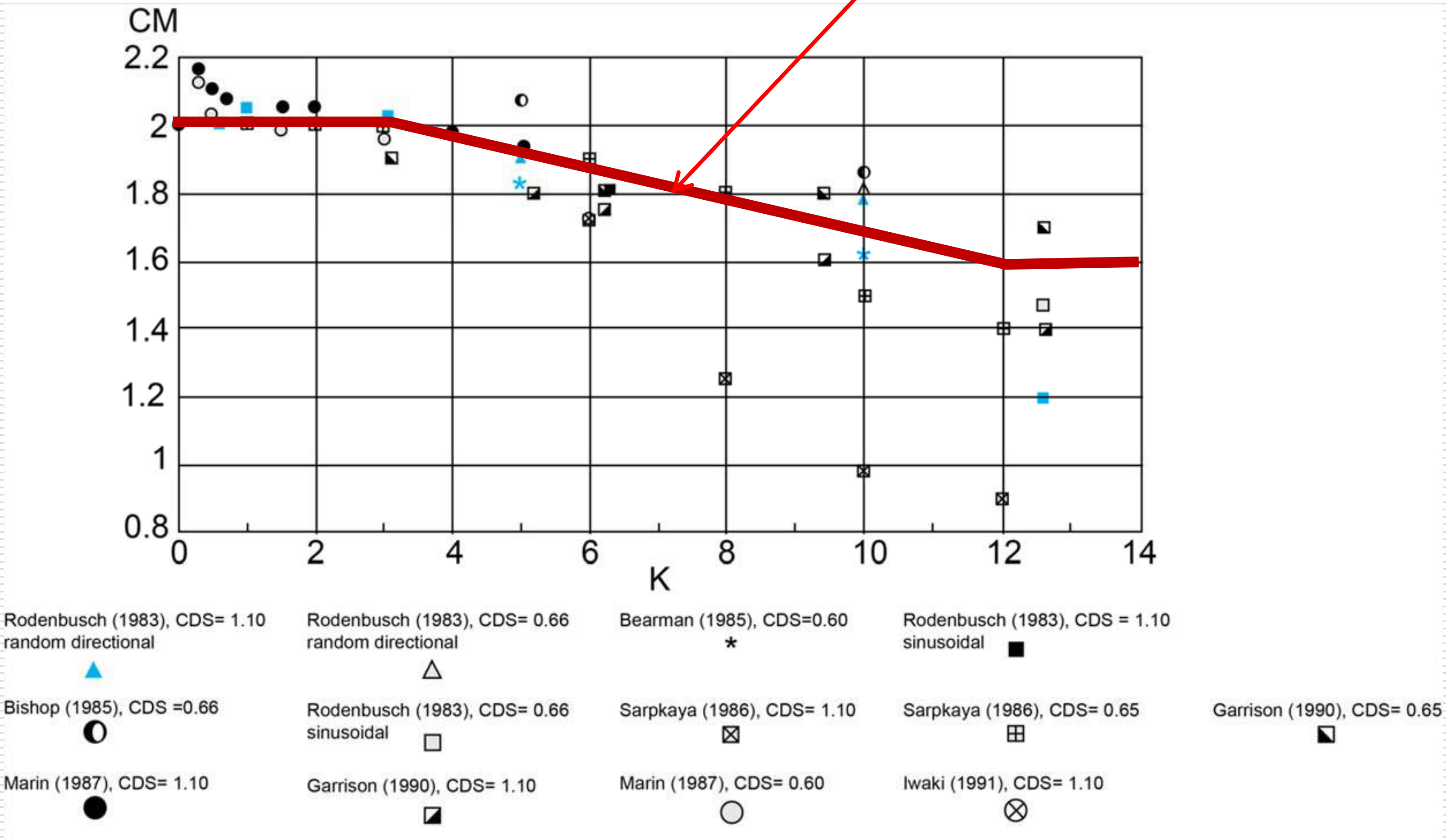

Figure C2.3.1-7 — Inertia Coefficient as a Function of *K*

Source : API RP 2A

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Drag Coefficient (C_D)

Varies between 0.5 to 1.5

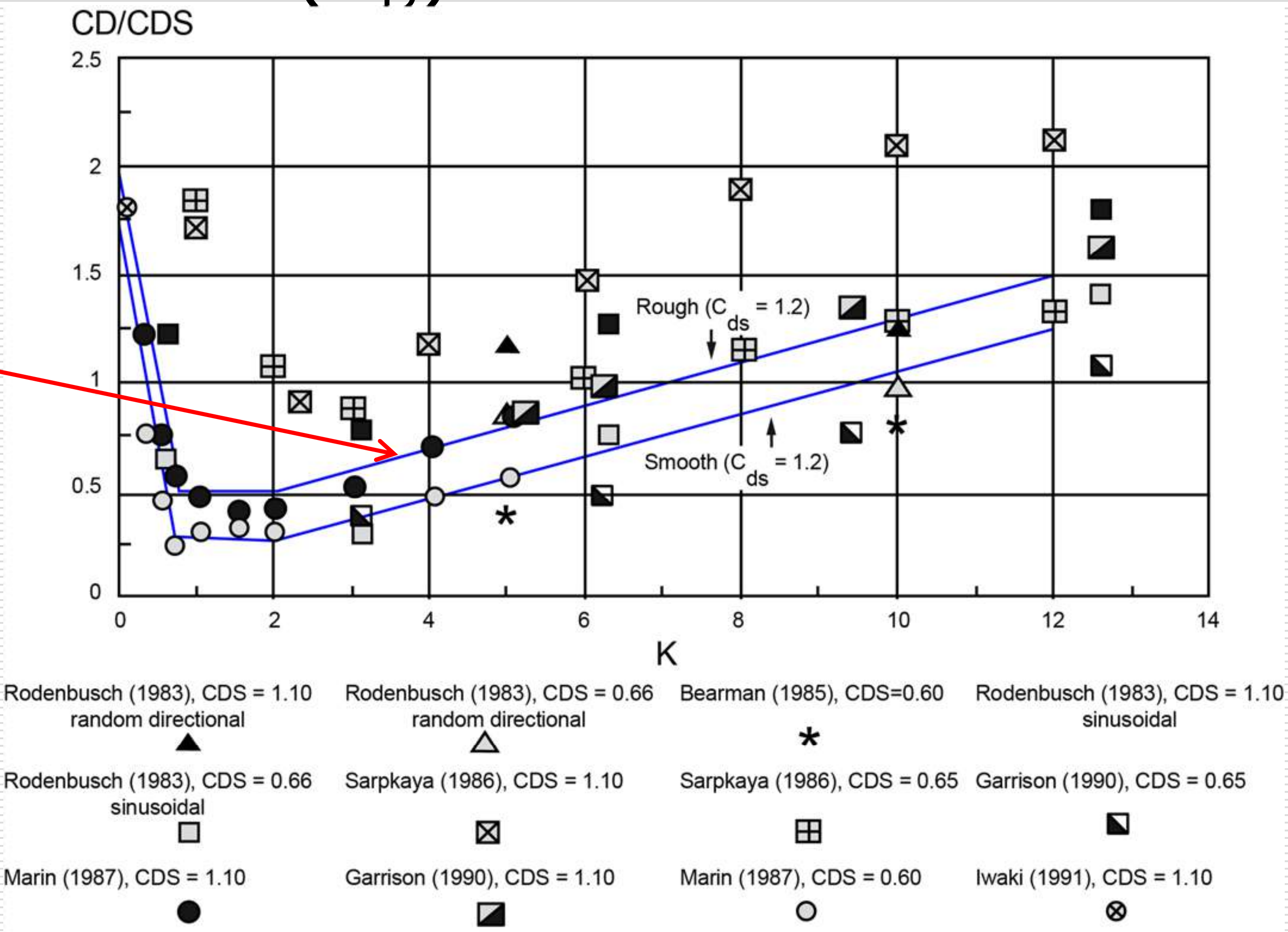

Figure C2.3.1-6 Wake Amplification Factor for Drag Coefficient as a Function of K

Source : API RP 2A

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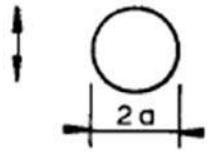
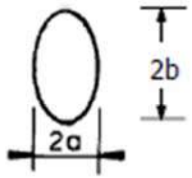
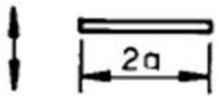
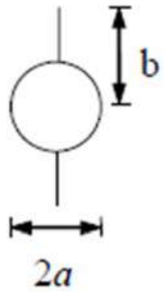
Added mass coefficients (DNV RP C205)

Section through body	*Direction of motion*	C_A	A_R	*Added mass moment of inertia* $[(\mathrm{kg/m}) \times \mathrm{m}^2]$
		1.0	πa^2	0
	Vertical	1.0	πa^2	$\rho \frac{\pi}{8}(b^2 - a^2)^2$
	Horizontal	1.0	πb^2	
	Vertical	1.0	πa^2	$\rho \frac{\pi}{8} a^4$
 Circular cylinder with two fins	Vertical	1.0	πa^2	$\rho a^4 (\csc^4 \alpha\, f(\alpha) - \pi^2)/2\pi$ where $f(\alpha) = 2\alpha^2 - \alpha \sin 4\alpha$ $+ 0.5 \sin^2 2\alpha$ and $\sin \alpha = 2ab/(a^2 + b^2)$ $\pi/2 < \alpha < \pi$
	Horizontal	$1 - \left(\frac{a}{b}\right)^2 + \left(\frac{a}{b}\right)^4$	πb^2	

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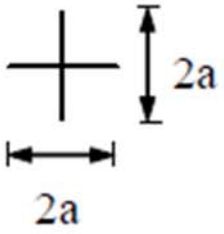
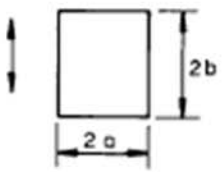
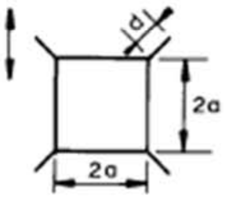
Added mass coefficients (DNV RP C205)

		Horizontal or Vertical	1.0	πa^2	$\frac{2}{\pi}\rho a^4$
	a / b = ∞ a / b = 10 a / b = 5 a / b = 2 a / b = 1 a / b = 0.5 a / b = 0.2 a / b = 0.1	Vertical	1.0 1.14 1.21 1.36 1.51 1.70 1.98 2.23	πa^2	$\beta_1 \rho \pi a^4$ or $\beta_2 \rho \pi b^4$ *a/b* ; β_1 ; β_2 0.1 ; - ; 0.147 0.2 ; - ; 0.15 0.5 ; - ; 0.15 1.0 ; 0.234 ; 0.234 2.0 ; 0.15 ; - 5.0 ; 0.15 ; - ∞ ; 0.125 ; -
	d / a = 0.05 d / a = 0.10 d / a = 0.25	Vertical	1.61 1.72 2.19	πa^2	$\beta \rho \pi a^4$ *d / a* ; β 0.05 ; 0.31 0.10 ; 0.40 0.10 ; 0.69

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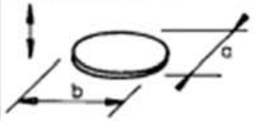
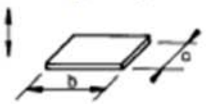
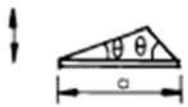
Added mass coefficients (DNV RP C205)

Body shape		Direction of motion	C_A				V_R
Flat plates	Circular disc 	Vertical	$2/\pi$				$\frac{4}{3}\pi a^3$
	Elliptical disc 	Vertical	b/a	C_A	b/a	C_A	$\frac{\pi}{6} a^2 b$
			∞	1.000	5.0	0.952	
			14.3	0.991	4.0	0.933	
			12.8	0.989	3.0	0.900	
			10.0	0.984	2.0	0.826	
			7.0	0.972	1.5	0.758	
			6.0	0.964	1.0	0.637	
	Rectangular plates 	Vertical	b/a	C_A	b/a	C_A	$\frac{\pi}{4} a^2 b$
			1.00	0.579	3.17	0.840	
			1.25	0.642	4.00	0.872	
			1.50	0.690	5.00	0.897	
			1.59	0.704	6.25	0.917	
			2.00	0.757	8.00	0.934	
			2.50	0.801	10.00	0.947	
			3.00	0.830	∞	1.000	
	Triangular plates 	Vertical	$\frac{1}{\pi}(\tan\theta)^{3/2}$				$\frac{a^3}{3}$

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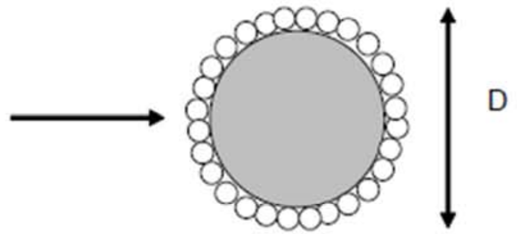
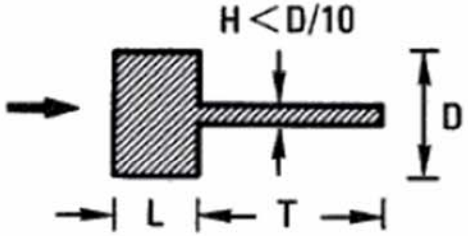
Drag coefficients (DNV RP C205)

Geometry	Drag coefficient, C_D	
1. Wire and chains	Type ($R_e = 10^4$ - 10^7)	C_D
	Wire, six strand	1.5 - 1.8
	Wire, spiral no sheating	1.4 - 1.6
	Wire, spiral with sheating	1.0 - 1.2
	Chain, stud (relative chain diameter)	2.2 - 2.6
	Chain studless (relative chain diameter)	2.0 - 2.4

Geometry	L/D	T/D		
2. Rectangle with thin splitter plate		0	5	10
	0.1	1.9	1.4	1.38
	0.2	2.1	1.4	1.43
	0.4	2.35	1.39	1.46
	0.6	1.8	1.38	1.48
	0.8	2.3	1.36	1.47
	1.0	2.0	1.33	1.45
	1.5	1.8	1.30	1.40
	2.0	1.6	-	1.33
	$R_e \sim 5 \times 10^4$			

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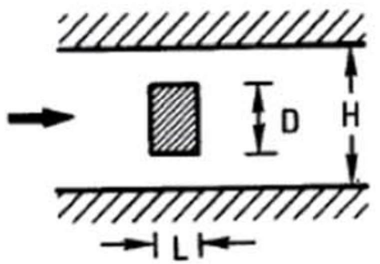
Drag coefficients (DNV RP C205)

3. Rectangle in a channel



$$C_D = (1-D/H)^{-n} C_D|_{H=\infty} \quad \text{for } 0 < D/H < 0.25$$

L/D	0.1	0.25	0.50	1.0	2.0
n	2.3	2.2	2.1	1.2	0.4

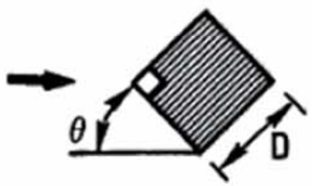
$R_e > 10^3$

4. Rectangle with rounded corners

L/D	R/D	C_D	L/D	R/D	C_D
0.5	0 0.021 0.083 0.250	2.5 2.2 1.9 1.6	2.0	0 0.042 0.167 0.50	1.6 1.4 0.7 0.4
1.0	0 0.021 0.167 0.333	2.2 2.0 1.2 1.0	6.0	0 0.5	0.89 0.29

$R_e \sim 10^5$

5. Inclined square



θ	0	5	10	15	20	25	30	35	40	45
C_D	2.2	2.1	1.8	1.3	1.9	2.1	2.2	2.3	2.4	2.4

$R_e \sim 4.7 \times 10^4$

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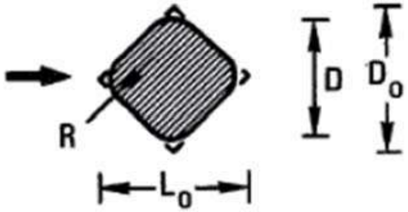
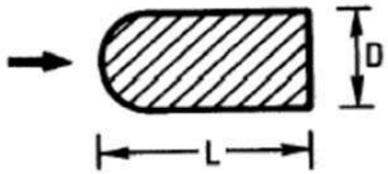
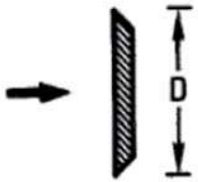
Drag coefficients (DNV RP C205)

Geometry	Drag coefficient, C_D			
6. Diamond with rounded corners	L_0/D_0	R/D_0	C_D	
	0.5	0.021 0.083 0.167	1.8 1.7 1.7	Fore and aft corners not rounded
	1.0	0.015 0.118 0.235	1.5 1.5 1.5	
	2.0	0.040 0.167 0.335	1.1 1.1 1.1	Lateral corners not rounded
	$R_e \sim 10^5$			
7. Rounded nose section	L/D		C_D	
	0.5 1.0 2.0 4.0 6.0		1.16 0.90 0.70 0.68 0.64	
8. Thin flat plate normal to flow 	$C_D = 1.9,\ R_e > 10^4$			

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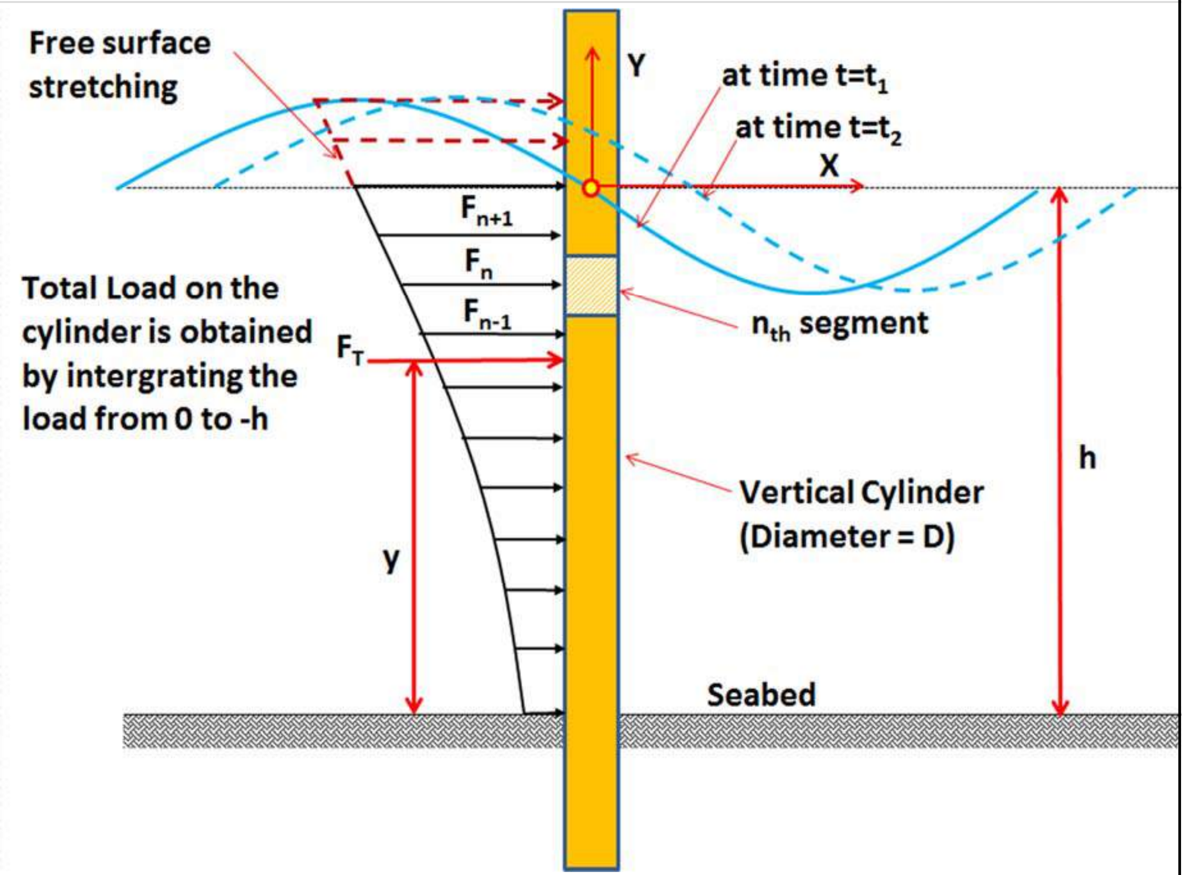
Maximum base shear method

This method is used to determine the maximum horizontal shear during the propagation of the wave across the structure. Since the water particle kinematics such as velocity and acceleration varies with space and time, the total force also varies with time.

- Divide the wave in to several time steps.
- Divide the submerged portion of the structure into sub-segments
- Apply Morison equation determine the wave load on each segment
- Carry out a numerical integration of calculated force on all segments to obtain for this time step.
- Repeat the above for each time step
- Maximum of all the above time step is the absolute maximum force



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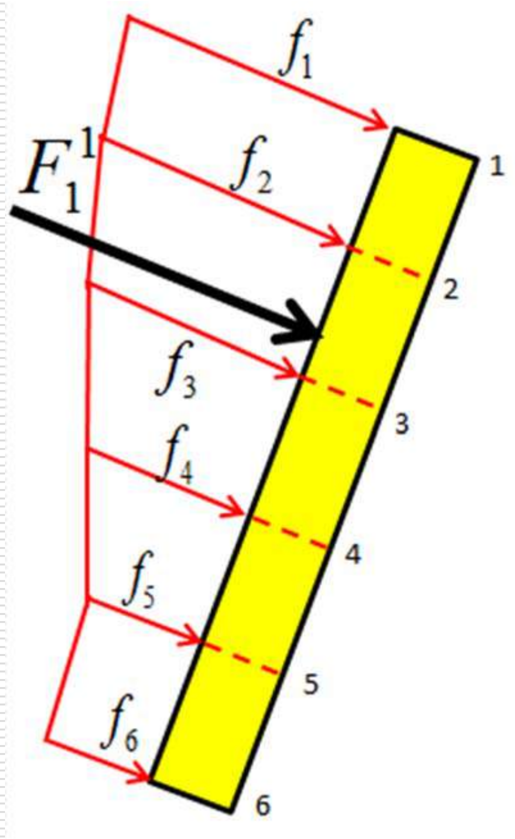
Integration of force in each member

Wave load at any instant in a wave cycle on a typical element of a structure can be calculated using Morison equation. The steps involved are listed below.



- The element is divided in to n number of sub segments as shown in figure.

- The water particle velocity and acceleration can be computed using the x, y coordinates of these points 1, 2 … and the time of each step in the wave cycle(or phase angle as below).

- The normal force on each point can be computed using the Morison equation as be equation below

$$\vec{f}\,_1^n = \frac{1}{2} C_D^n D \rho \vec{V}_n \left|\vec{V}_n\right| + \frac{1}{4} \pi D^2 C_M^n \rho \vec{a}_n$$

- The total force on the element is found by numerical integration using trapezoidal or other schemes

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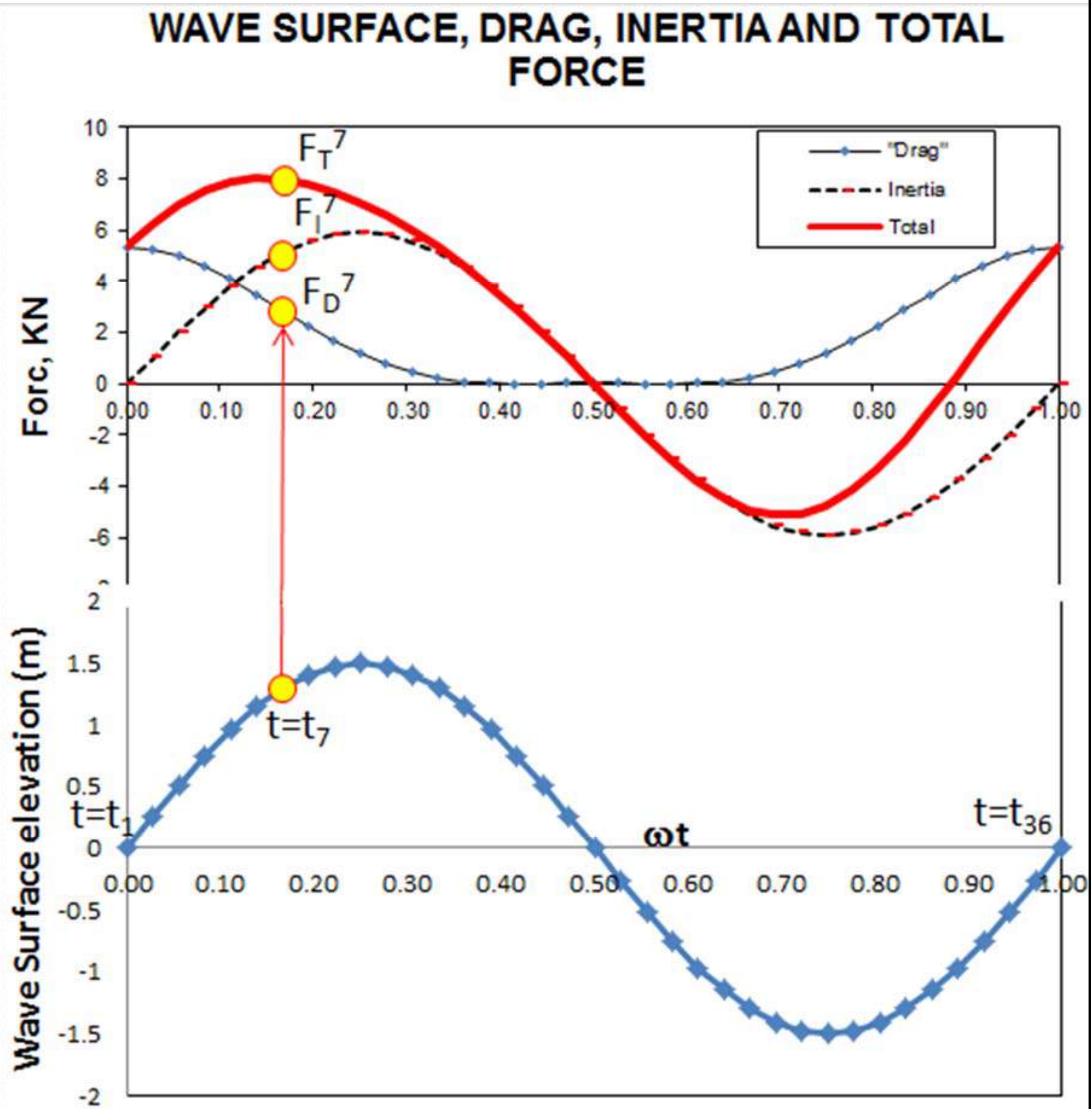
Computation for one wave cycle

- One wave cycle is divided into steps of 36 or more either in time domain or in wave length.
- For each time step, compute the drag, inertia and total force for the structure using the steps involved earlier.
- Repeat the step to complete one wave cycle.
- The maximum force obtained from various steps is the design force.
- This procedure can be adopted to determine the following.
  - Maximum positive force
  - Maximum negative force
  - Maximum positive moment
  - Maximum negative moment



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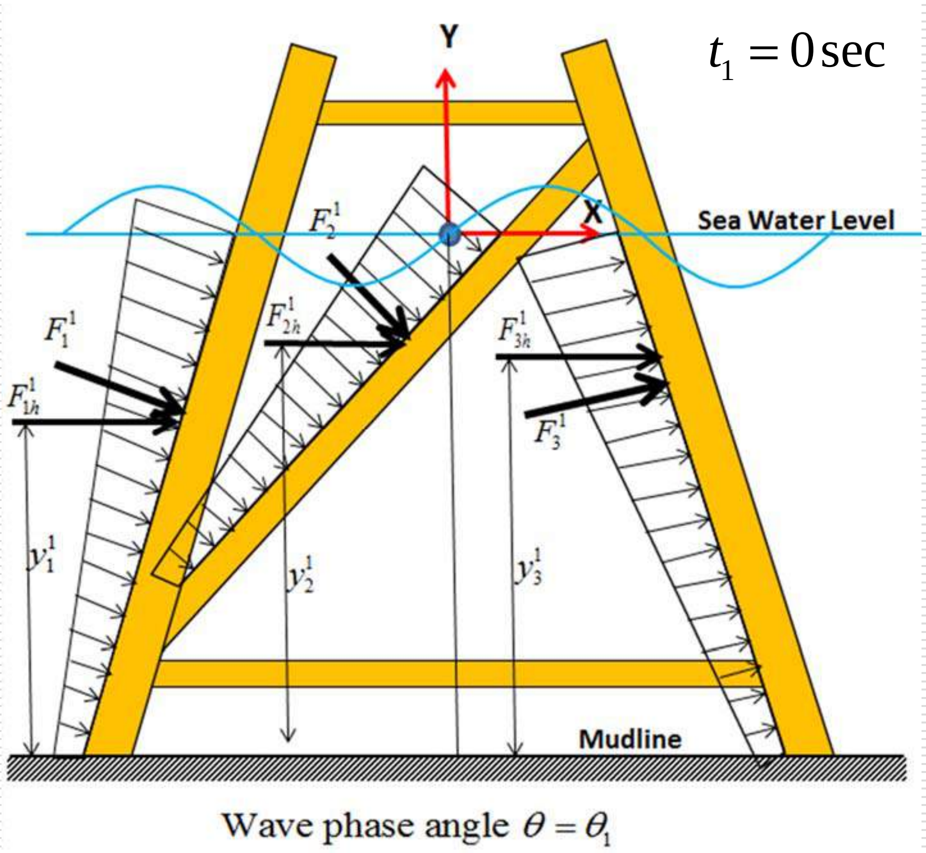

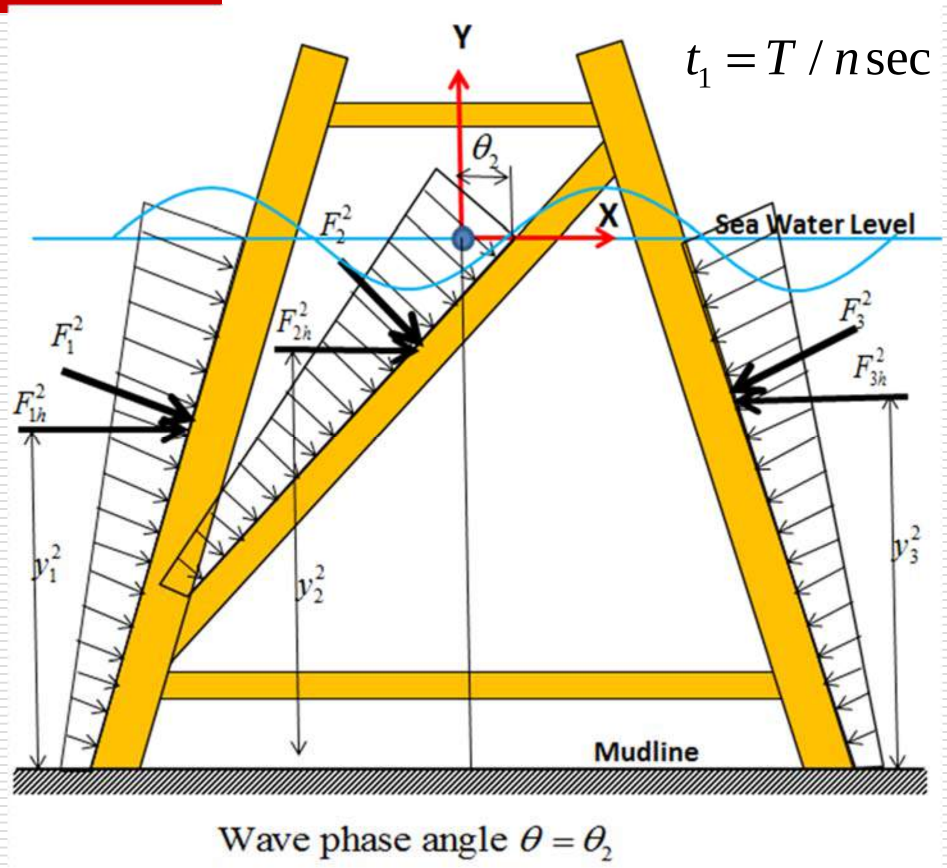

$$\eta_1 = \frac{H}{2}\sin(\theta_1) \quad when \quad \theta_1 = kx - \omega t_1$$

$$\eta_1 = \frac{H}{2}\sin(\theta_2) \quad when \quad \theta_2 = kx - \omega t_2$$

$x =$ x coordinate of the member location

$\omega =$ wave frequency

$k =$ wave number

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Summation for whole structure

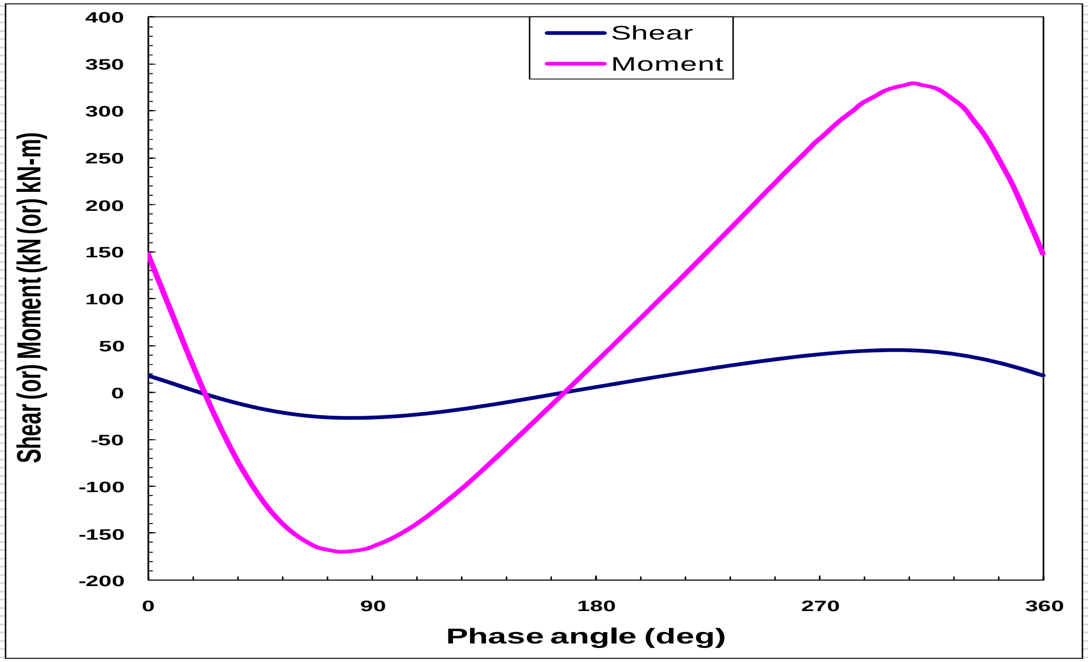
Total Wave load on the structure at time t=t_1 (phase angle $\theta=\theta_1$)

$$F_S^1 = \sum_1^N F_{1h}^1 + F_{2h}^1 + F_{3h}^1 \ldots\ldots + F_{Nh}^1$$

Total Wave load on the structure at time t=t_2 (phase angle $\theta=\theta_2$)

$$F_S^2 = \sum_1^N F_{1h}^2 + F_{2h}^2 + F_{3h}^2 \ldots\ldots + F_{Nh}^2$$

The above procedure is repeated until one wave cycle is completed such that the wave forces on the full structure is available and it can be plotted as shown in figure.



The maximum value as it can be read from the plot is the maximum value for the base shear (F_{max})

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Closed form solution – Vertical Surface piercing cylinder

Consider a case of a surface piercing cylinder such as pile of a structure or a leg of a jacket, the combined drag and inertia force (total force) varies with time and will be maximum only at one occasion. In order find the maximum force, phase angle at which the maximum force occurs shall be found first.

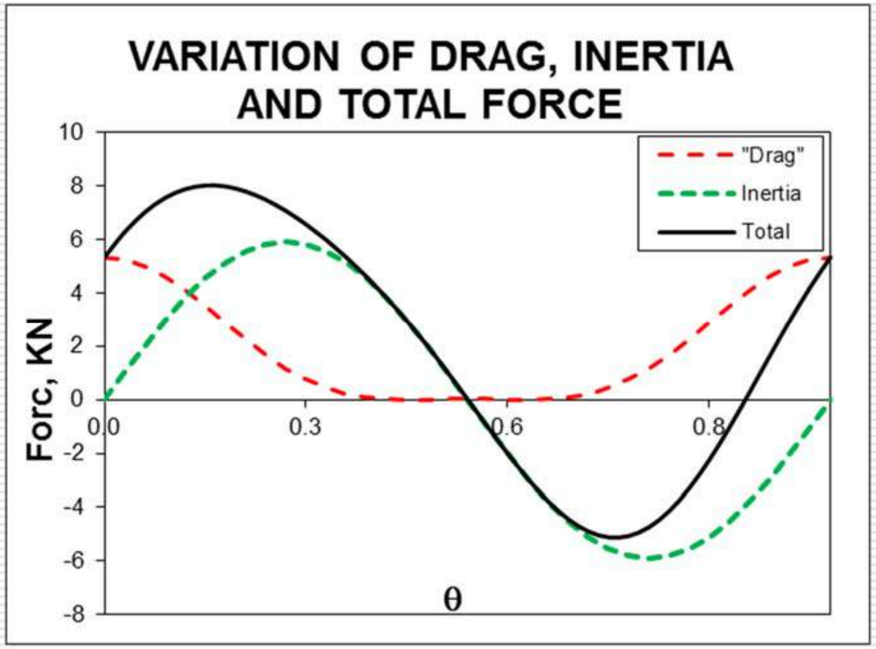
Let us express the total force on the pile by substituting the velocity and acceleration components and integrating between the limits (from surface to seabed, i.e. 0 to –h)

$$F_T = \frac{1}{2} C_D \rho D \frac{\pi^2 H^2}{T^2} \frac{\cos\theta|\cos\theta|}{\sinh^2 kh} \left[\frac{\sinh(2kh)}{4k} + \frac{h}{2} \right]$$

$$- C_M \rho \frac{\pi D^2}{4} \frac{2\pi^2 H}{T^2} \frac{\sin\theta}{k}$$

The total force will be maximum when, $\frac{\partial F_T}{\partial \theta} = 0$

$$\theta_{\max} = \cos^{-1}\left[-\frac{\pi D}{H} \frac{C_M}{C_D} \frac{2\sinh^2 kh}{(\sinh 2kh + 2kh} \right]$$



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Closed form solution – Horizontal member

Consider a case of horizontal cylinder such as brace of a jacket, the combined drag and inertia force (total force) varies with time and will be maximum only at one occasion. In order find the maximum force, phase angle at which the maximum force occurs shall be found first. Let us express the total force on the pile by substituting the velocity and acceleration,

$$F_T = \frac{1}{2} C_D \ \rho \ D \ \frac{H^2 \omega^2}{4} \cos\theta \left| \cos\theta \right| \left[\frac{\cosh^2 k(z+h)}{\sinh kh} \right]$$

$$-C_M \ \rho \frac{\pi D^2}{4} \frac{H\omega^2}{2} \sin\theta \left[\frac{\cosh^2 k(z+h)}{\sinh kh} \right]$$

The total force will be maximum when, $\dfrac{\partial F_T}{\partial \theta} = 0$

$$\theta_{\max} = \sin^{-1}\left[-\frac{\pi D}{2H} \frac{C_M}{C_D} \frac{\sinh kh}{(\cosh k(h+z)} \right]$$

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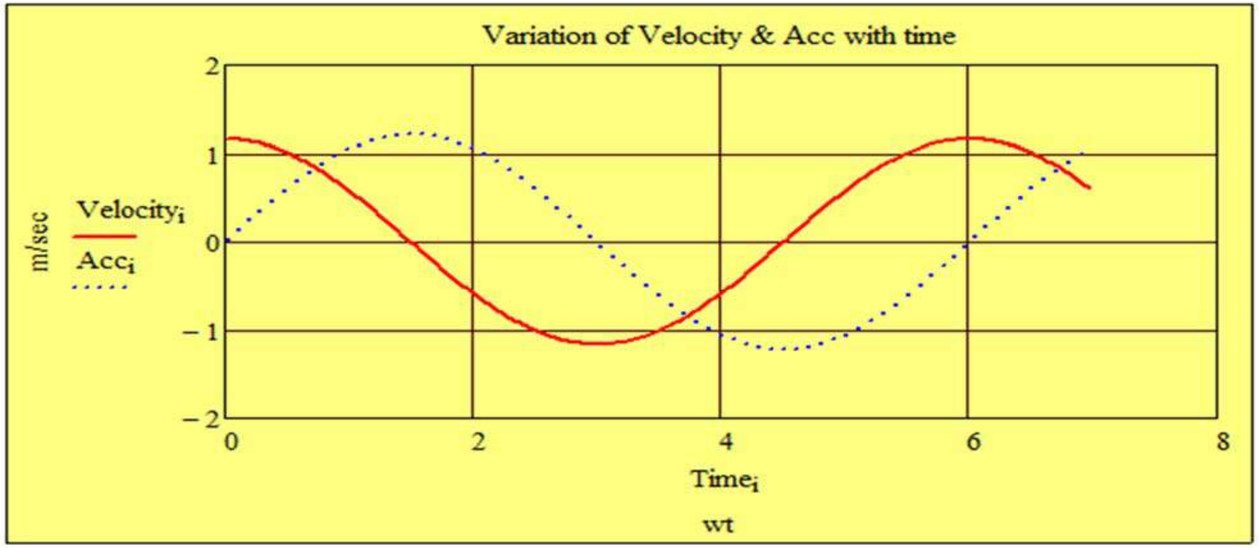

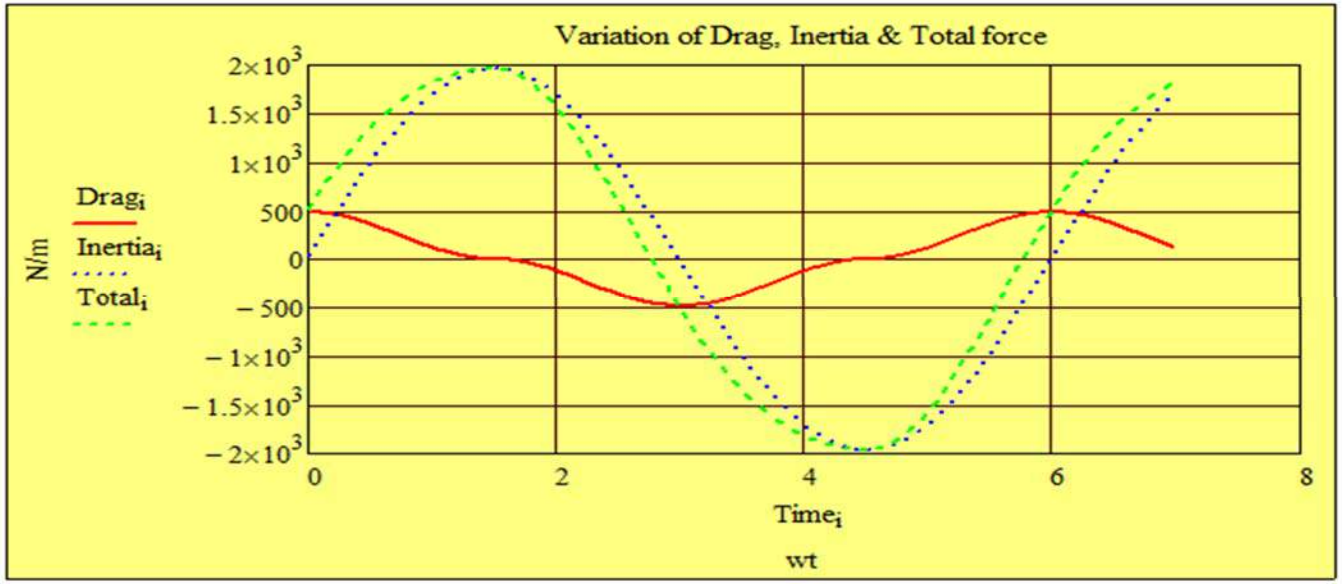

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Submerged member in 3D space

The resultant force on a arbitrarily oriented circular cylinder in water waves can be calculated using vector analysis combined with Morison equation

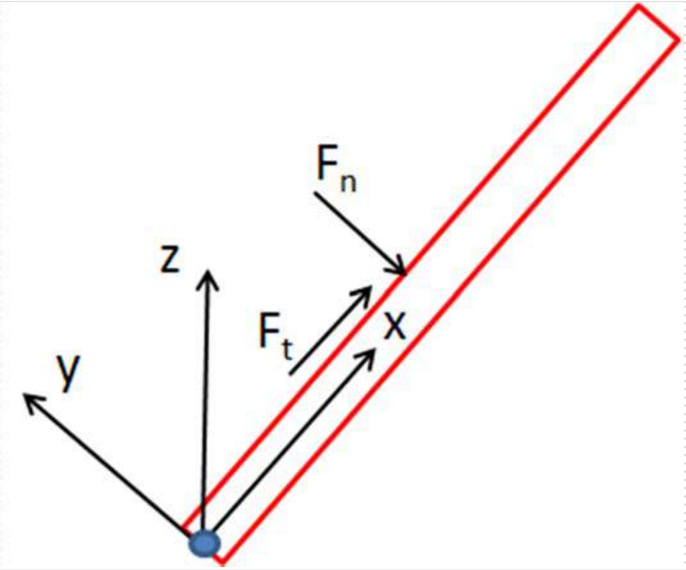
The total force per unit length of the cylinder can be written as

$$\vec{F} = \vec{F}^{n} + \vec{F}^{t}$$

The force in normal direction an be expressed as:

$$\vec{F}^{n} = \vec{F}^{n}_{D} + \vec{F}^{n}_{I}$$

where F_D^n and F_I^n are the drag and inertia forces respectively.



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These forces expressed as:

$$\vec{F}^{\,n}_{D} = \frac{1}{2} C^n_D D \rho_w \vec{V}_n \left| \vec{V}_n \right|$$

$$\vec{F}^{\,n}_{I} = \frac{1}{4} \pi D^2 C^n_M \, \rho a^{\rightarrow}_n$$

where

C^n_D = Drag coefficient for flow normal to the cylinder

C^n_M = Inertia coefficient for flow normal to the cylinder

D = Diameter of cylinder

ρ_w = Density of seawater

$\vec{V}_n$ = Velocity of fluid particle normal to the cylinder axis

$a^{\rightarrow}_n$ = Acceleration of fluid particle normal to the cylinder axis

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The equation for tangential force can be written as

$$\vec{F}^{t} = \vec{F}_{D}^{t}$$

$$\vec{F}_{D}^{t} = \frac{1}{2} C_{D}^{t} D \rho \vec{V}_{t} \left| \vec{V}_{t} \right|$$

C_{D}^{n} = Drag coefficient for flow tangential to the cylinder

$\vec{V}_{t}$ = Velocity of fluid particle tangential to the cylinder axis

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These forces can be summed and expressed in terms of cylinder local axis as below:

$$\vec{F}_x = \frac{1}{2} C_D^t D \rho_w \vec{V}_t \left| \vec{V}_t \right|$$

$$\vec{F}_y = \frac{1}{2} C_D^n D \rho_w \vec{V}_n \left| \vec{V}_y \right| + \frac{1}{4} \pi C_M^n l D \rho_w \vec{a}_y$$

$$\vec{F}_z = \frac{1}{2} C_D^n D \rho_w \vec{V}_n \left| \vec{V}_z \right| + \frac{1}{4} \pi C_M^n l D^2 \rho_w \vec{a}_z$$

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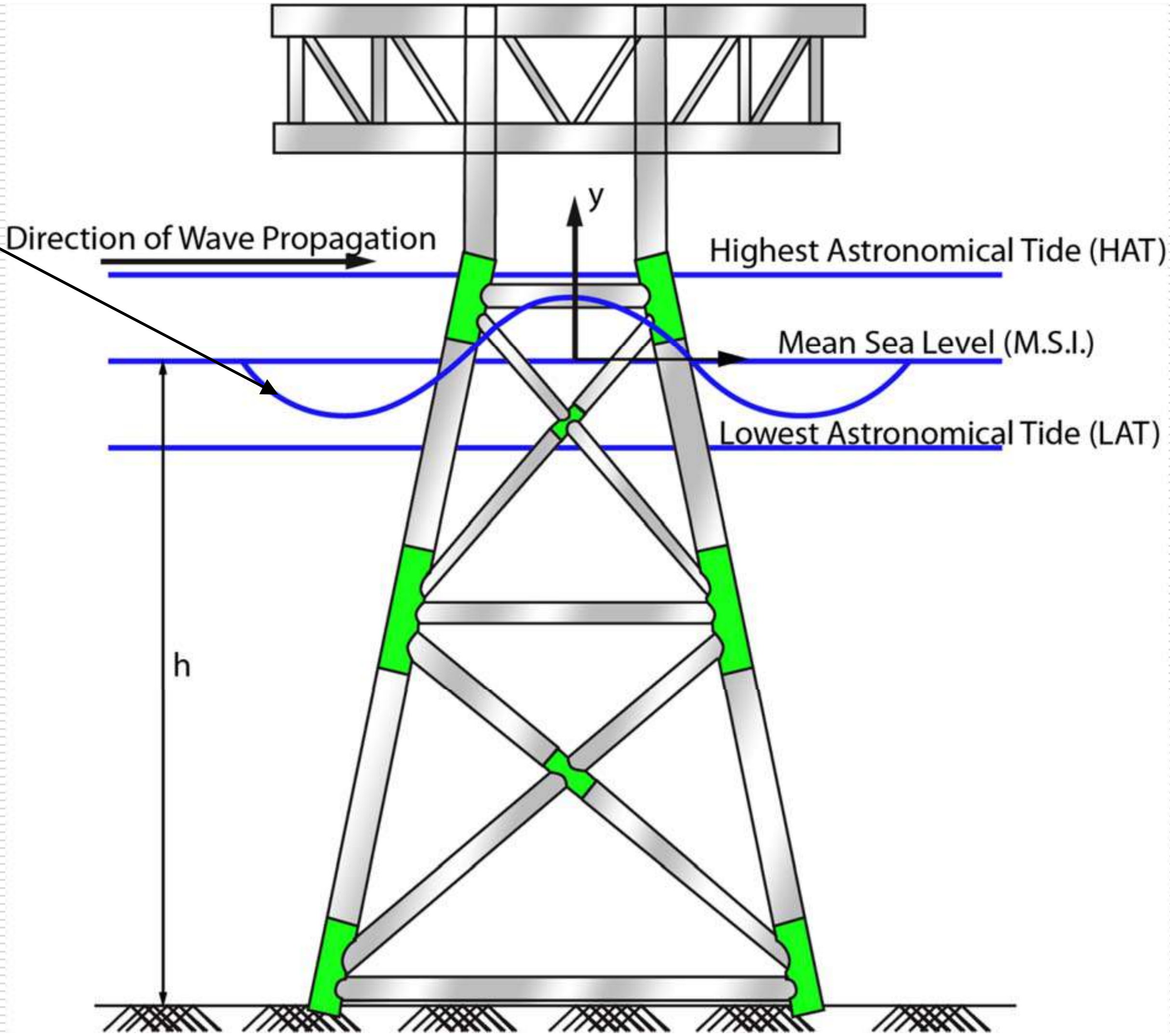
Wave Loads on Jacket Structure

Storm Wave



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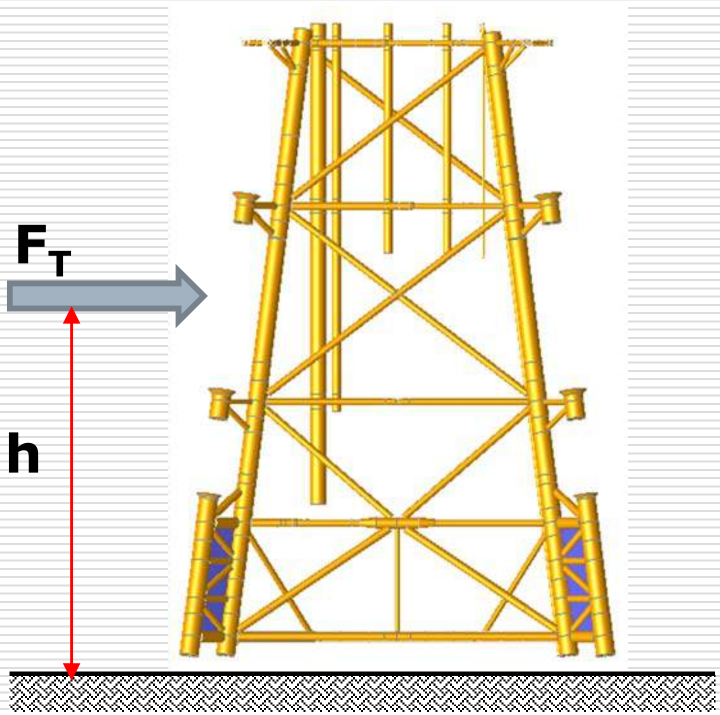
Maximum Global Loads

Maximum global loads on a platform can be calculated using two principles

Maximum Base Shear Method

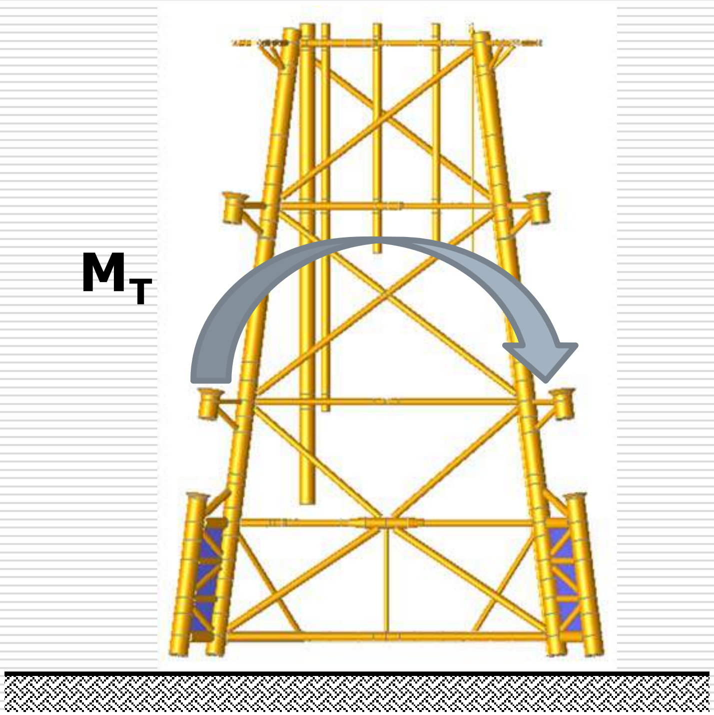
$$F_T = \Sigma F_i$$



Maximum Overturning Moment Method

$$M_T = \Sigma F_i \times h_i$$

$$M_T = F_T \times h$$



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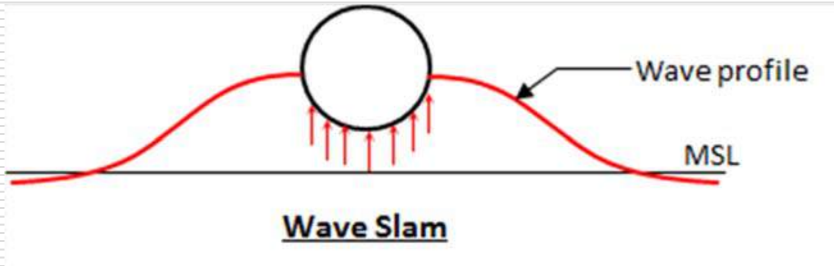
Wave slam Load

- Wave slamming is predominant in horizontal members of the jacket and this force acts upwards against the gravity.
- Needs to be taken in to account together with global loads.
- Wave Slamming is computed similar to drag force using the horizontal crest velocity of the wave (V_{sm}).
- Slamming force coefficient (C_{sm}) is to be taken as 5.5 as recommended by API RP 2A.
- D is the diameter of the cylinder and ρ_w is the density of water

$$F_{SM} = \frac{1}{2} C_{sm} \rho_w \; D \; V_{sm} \left| V_{sm} \right|$$



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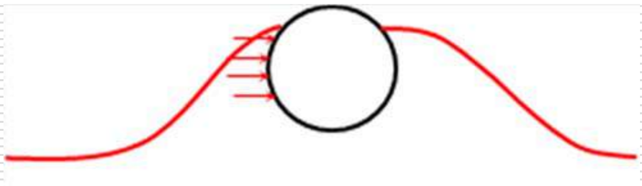
Wave slap Load

- Wave slap is predominant in horizontal members of the jacket and this force acts horizontally.
- Needs to be taken in to account together with global loads.
- Wave Slap is computed similar to drag force using the horizontal crest velocity of the wave (V_{sp}).
- Slap force coefficient (C_{sp}) is to be taken same as the drag coefficient.

$$F_{SP} = \frac{1}{2} C_D \rho_w \; D \; V_{sp} \left| V_{sp} \right|$$



Wave Slap

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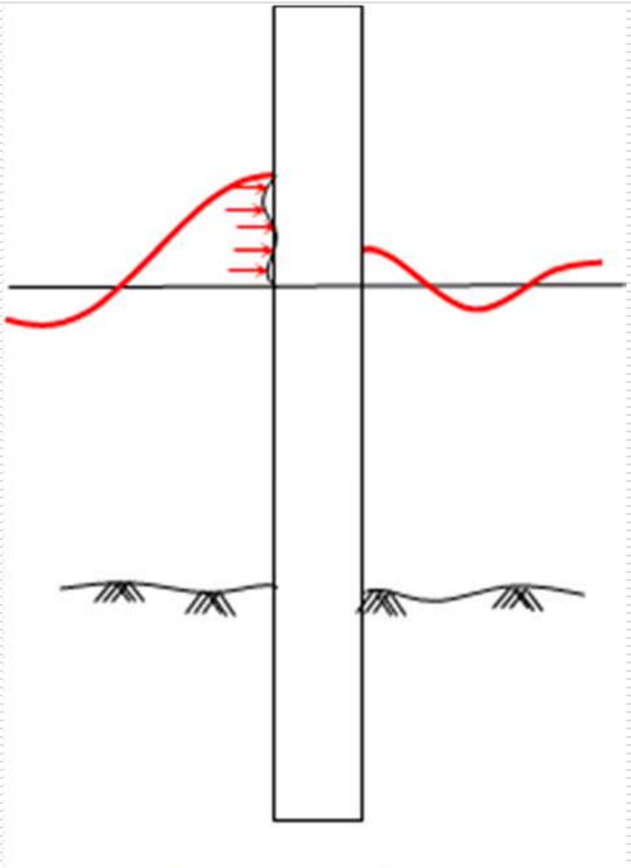
Wave Breaking Load

- Wave breaking is predominant in vertical members and vertical faces of coastal structures
- The wave breaking force coefficient C_s is to be taken as 5.98 for breaking wave and 2.74 for broken wave
- The coefficient β for calculating the impact velocity is to taken as 0.48 for breaking wave and 0.70 for broken wave
- C is the speed of breaking wave

$$V_b = \beta C$$

$$F_b = C_s \rho_w \, A V_b \left| V_b \right|$$

$$C = 1.092 \frac{gT}{2\pi}$$



Wave Breaking

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VORTEX SHEDDING FREQUENCY

Vortex-Shedding Frequency $$f_s = \frac{SU_c}{D}$$

f_s = vortex-shedding frequency
S = Strouhal Number
U_c = Design current Velocity
D = Pipe outside diameter

REYNOLDS NUMBER

Strouhal Number is the dimensionless frequency of the vortex shedding and is a function of the Reynolds Number. Reynolds Number Re is a dimensionless parameter representing the ratio of inertial force to viscous force:

$$\mathrm{Re} = \frac{U_c D}{\mu_k}$$

Where μ_k is kinematic viscosity of fluid (0.85×10^{-6} m^2/sec for water at 60° F)

REDUCED VELOCITY

The reduced velocity, V_R, is defined as:

$$V_R = \frac{U_c}{f_n D}$$

Where
f_n = Natural frequency for a given vibration mode
U_c = Mean current velocity normal to the cable (average from mud-line to bell mouth elevation)
D = Outer cable diameter.

STABILITY NUMBER

The stability parameter, K_S, representing the damping for a given mode shape is given by:

$$K_S = \frac{4\pi m_e \zeta_T}{\rho D^2}$$

Where
ρ = Water density
ζ_T = Total modal damping ratio
m_e = Effective mass

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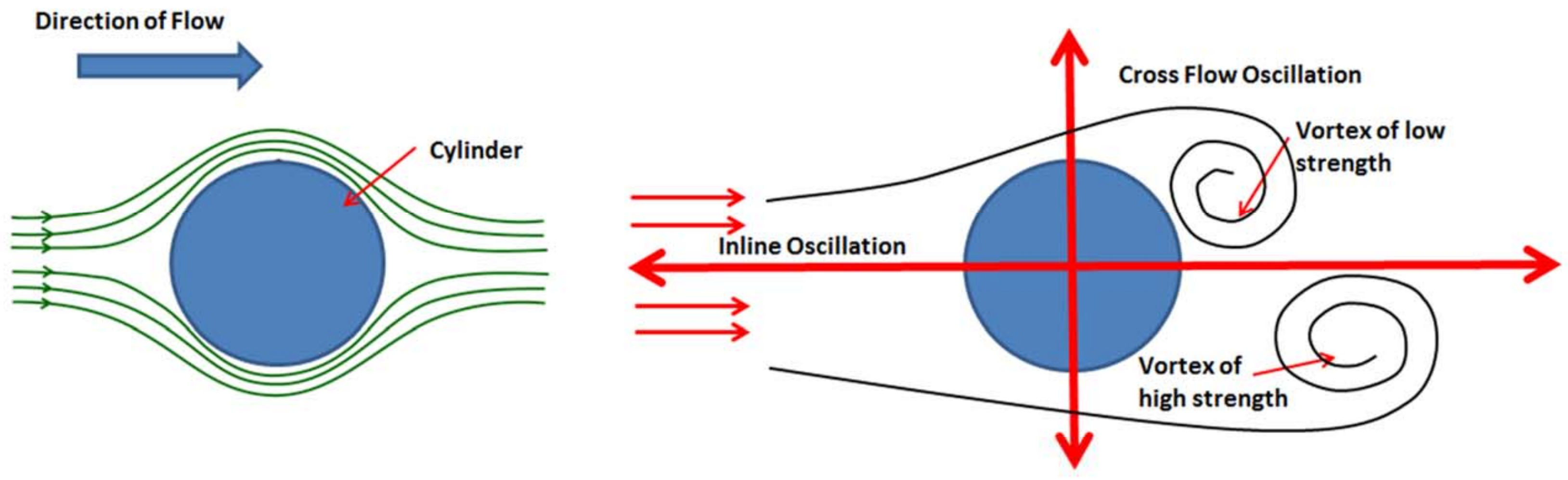
Vortex Shedding

- Vortex shedding is a phenomenon of formation of vortices at the downstream side of the pipe due to wave/current flow.
- This can be classified in two categories
  - Inline Oscillation
  - Cross flow Oscillation

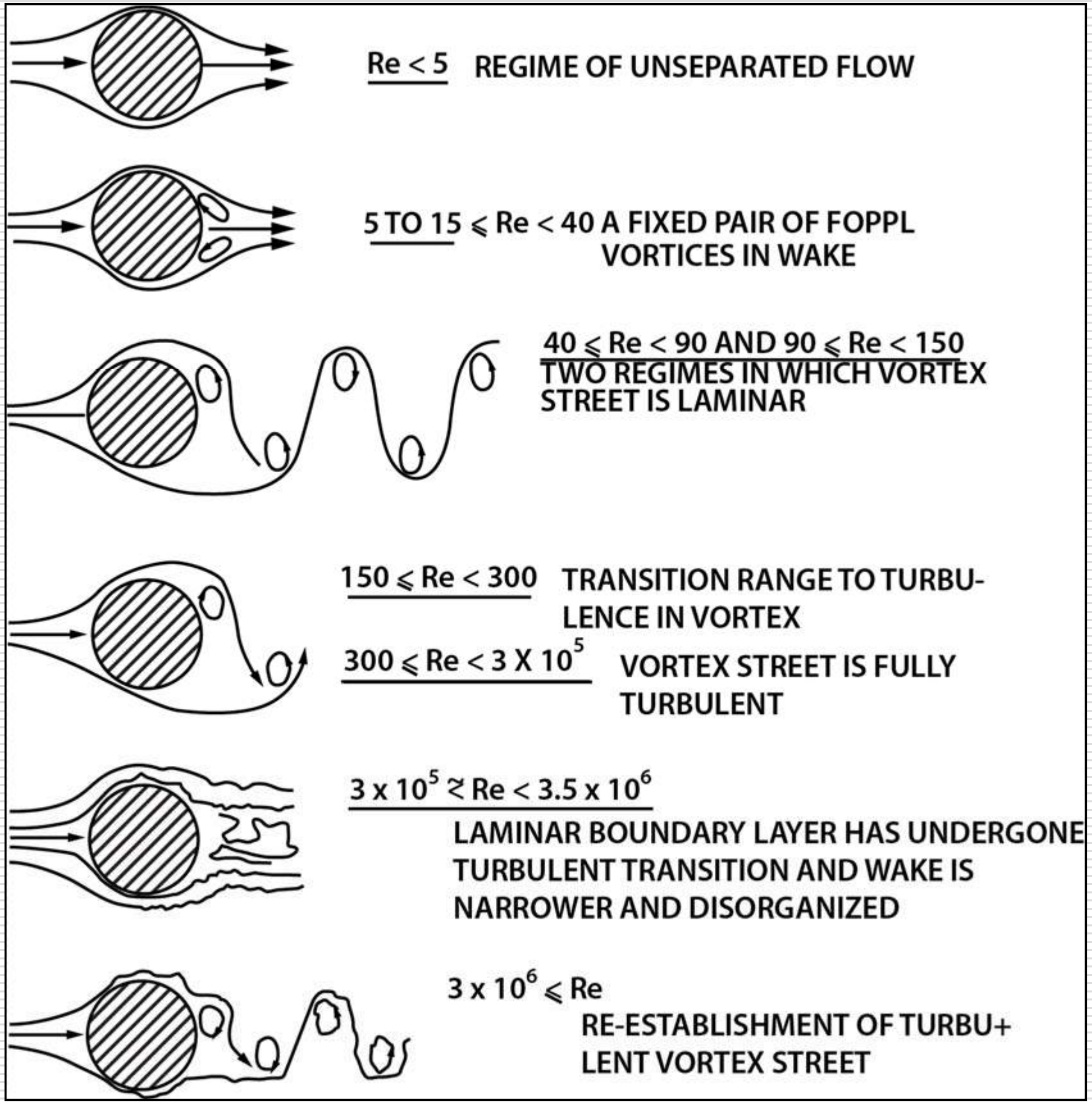


(a) Unseparated Flow

(b) Separate Flow with vortex shedding

FLOW REGIMES

The shedding of vortices depends on the diameter of cylinder, current velocity and surface roughness and viscosity of fluid. Figure 3.1 shows the types and regions of vortex shedding for different Reynolds (**Re**) number from 5 to 10^6. It can be observed that for low Re values, separated flow occurs. For increasing values of **Re** the flow becomes separated with shedding of vortices at the downstream of the cylinder.



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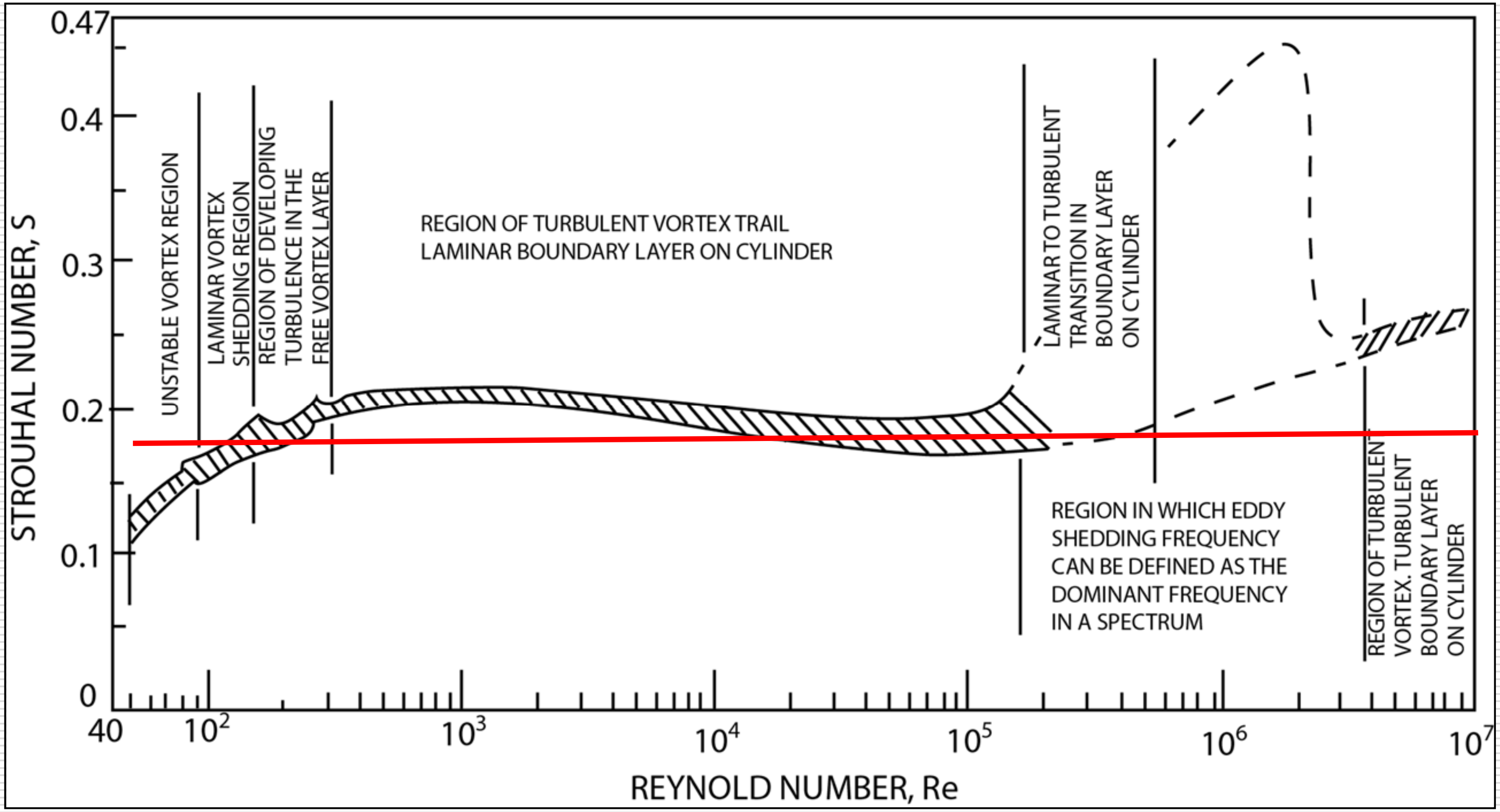
Strouhal Number

The frequency of this unbalanced force can also be estimated using the relationship between the Re value and Strouhal Number as shown in Figure below. For most practical problems of flow induced vibration in the field the Re values will be in the range of 10^3 to 10^5 and hence the Strouhal number can be taken approximately as 0.2.



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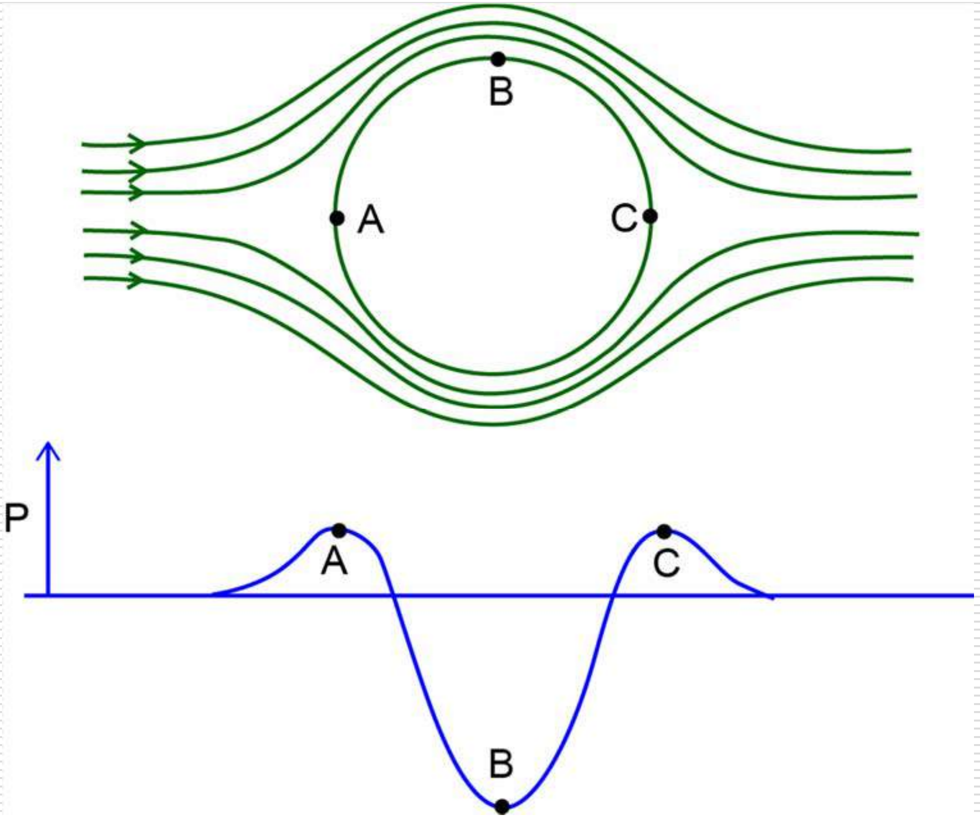
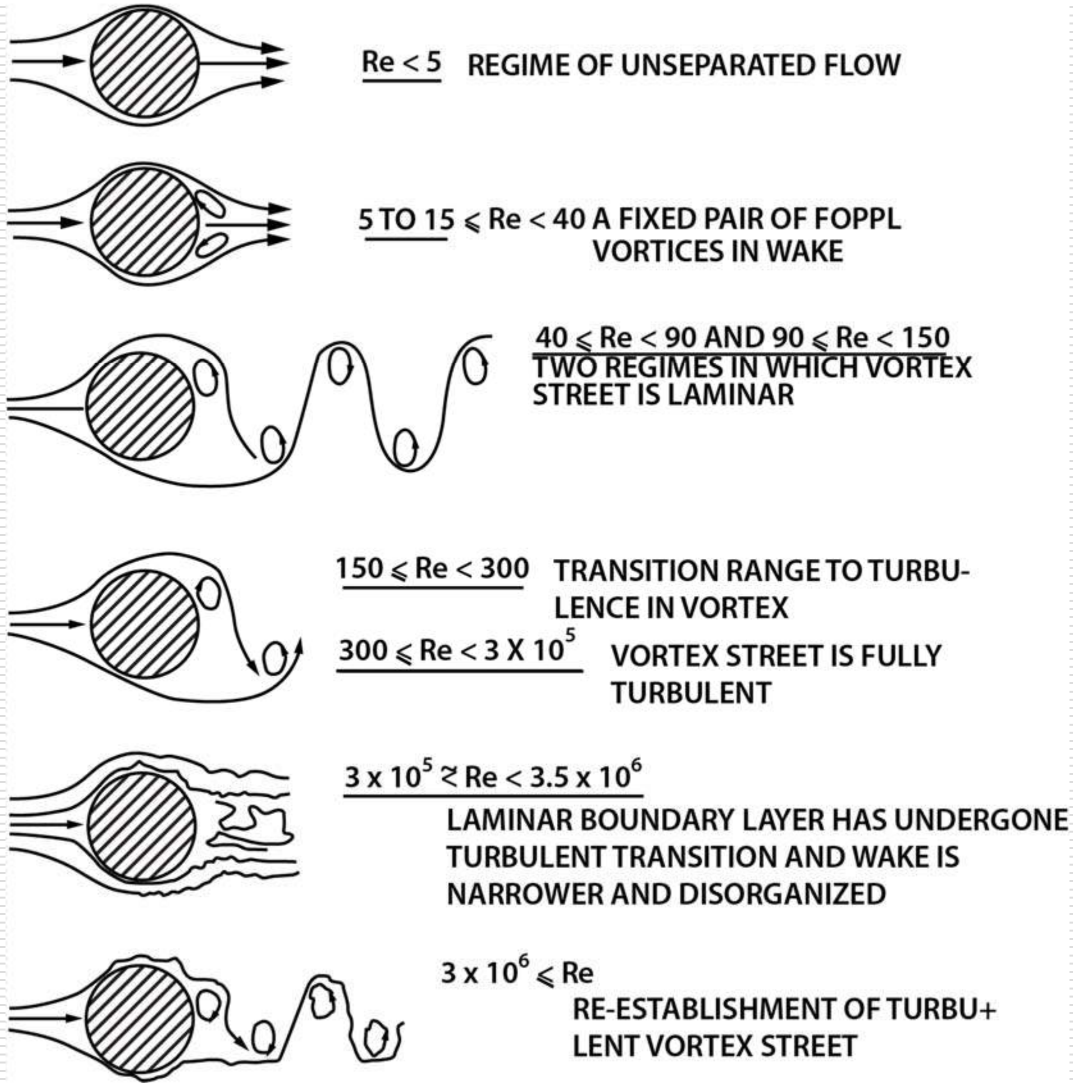
FLOW PAST HORIZONTAL CYCLINDER

Vortex Shedding Around Circular Cylinders





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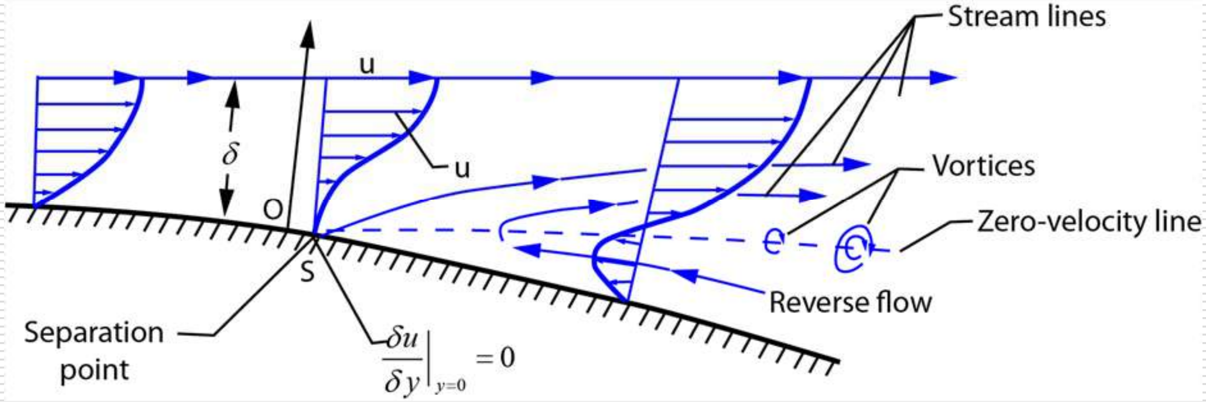
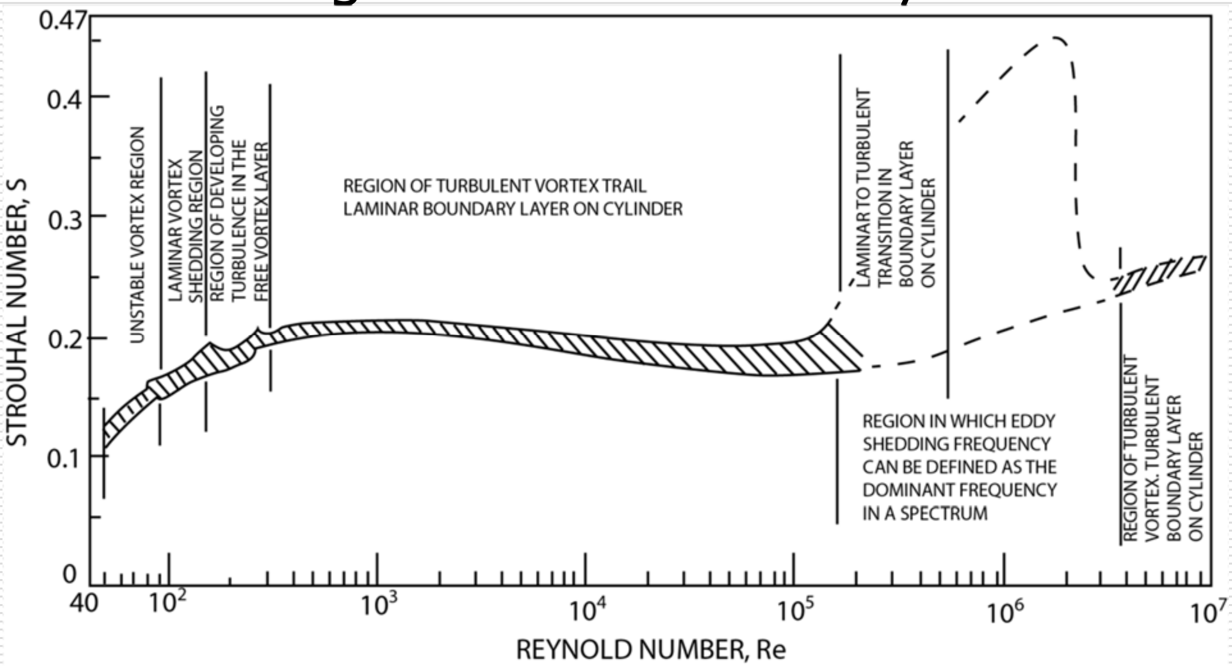
BOUNDARY LAYER



Flow Regimes for circular cylinder



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LIFT FORCES

- Lift forces are caused by unbalanced pressure forces arising from the asymmetric vortex shedding.
- This force can be calculated using the velocity and lift coefficient.
- The horizontal velocity at the cylinder axis shall be considered appropriate.
- Lift coefficient shall be takes and 70% of drag coefficient.

$$F_L = \frac{1}{2} C_L \rho_w \; D \; U_s \left| U_s \right|$$

$$C_L = 0.7 C_d$$

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Diffraction Forces

- Assumption of "No disturbance" is not valid if $D/L > 0.2$
- Part of Wave reflected once the wave touches the structure and part of it pass around
- This phenomenon is called diffraction
- These forces also can be measured experimentally
- Many research papers exist for different types and shapes of structures

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Calculate the wave force on a pile structure installed at a water depth of 100m subjected to regular wave of amplitude 1m with a wave period of 12 sec. The drag and inertia coefficients are 0.6 and 2.0 for respectively. The wind driven current at the surface is 2m/sec and the thickness of the marine growth is 100mm. The wave force needs to be computed at 2.5 sec from start of the wave.

Wave height	$H_w := 2 \cdot m$	
Water depth	$d := 100 \cdot m$	
Wave period	$T_w := 12 \cdot sec$	
Diameter of cylinder	$D_c := 1m$	
Thickness of marine growth	$T_{mg} := 100 \cdot mm$	
Hydrodynamic Coefficients	$C_D := 0.6$	$C_M := 2$
Density of water	$\rho_w := 1030 \cdot \frac{kg}{m^3}$	
Wind riven Current Velocity at surface	$V_{cs} := 2 \cdot \frac{m}{sec}$	

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Parameter for wave theory $\frac{H_w}{g \cdot T_w^{\,2}} = 0.001$

$\frac{d}{g \cdot T_w^{\,2}} = 0.071$

Airy Theory is applicable

Deep water wave length $L_o := \frac{g \cdot T_w^{\,2}}{2\pi} = 224.752\,m$

Wave frequency $\omega := \frac{2 \cdot \pi}{T_w}$ $\omega = 0.524 \cdot Hz$

Wave Number $k := \frac{2 \cdot \pi}{L_o}$ $k = 0.028 \frac{1}{m}$

Position of cylinder with respect to origin $x := 0.0 \cdot m$

Time at which force calculation is required $t := 2.5 \cdot sec$

Diameter for hydrodynamic force calculation $D := D_c + 2 \cdot T_{mg}$ $D = 1.2\,m$

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Calculation of Water particle velocity

Horizontal velocity at

$z0 := 0.0\cdot m \qquad V_{h0} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z0)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z0)}{d} \qquad V_{h0} = 2.137\frac{m}{s}$

$z1 := -10.0\cdot m \qquad V_{h1} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z1)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z1)}{d} \qquad V_{h1} = 1.904\frac{m}{s}$

$z2 := -20.0\cdot m \qquad V_{h2} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z2)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z2)}{d} \qquad V_{h2} = 1.679\frac{m}{s}$

$z3 := -30.0\cdot m \qquad V_{h3} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z3)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z3)}{d} \qquad V_{h3} = 1.46\frac{m}{s}$

$z4 := -40.0\cdot m \qquad V_{h4} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z4)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z4)}{d} \qquad V_{h4} = 1.246\frac{m}{s}$

$z5 := -50.0\cdot m \qquad V_{h5} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z5)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z5)}{d} \qquad V_{h5} = 1.036\frac{m}{s}$

$z6 := -60.0\cdot m \qquad V_{h6} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z6)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z6)}{d} \qquad V_{h6} = 0.828\frac{m}{s}$

$z7 := -70.0\cdot m \qquad V_{h7} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z7)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z7)}{d} \qquad V_{h7} = 0.623\frac{m}{s}$

$z8 := -80.0\cdot m \qquad V_{h8} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z8)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z8)}{d} \qquad V_{h8} = 0.419\frac{m}{s}$

$z9 := -90.0\cdot m \qquad V_{h9} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z9)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z9)}{d} \qquad V_{h9} = 0.217\frac{m}{s}$

$z10 := -100.0\cdot m \qquad V_{h10} := \frac{H_w}{2}\cdot\omega\cdot\frac{\cosh[k\cdot(d+z10)]}{\sinh(k\cdot d)}\cdot\cos(k\cdot x-\omega\cdot t)+\frac{V_{cs}\cdot(d+z10)}{d} \qquad V_{h10} = 0.017\frac{m}{s}$

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Calculation of Water particle acceleration

Horizontal acceleration at

$$a_{h0} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z0)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h0} = -0.267\,\frac{m}{s^2}$$

$$a_{h1} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z1)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h1} = -0.202\,\frac{m}{s^2}$$

$$a_{h2} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z2)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h2} = -0.154\,\frac{m}{s^2}$$

$$a_{h3} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z3)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h3} = -0.117\,\frac{m}{s^2}$$

$$a_{h4} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z4)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h4} = -0.09\,\frac{m}{s^2}$$

$$a_{h5} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z5)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h5} = -0.07\,\frac{m}{s^2}$$

$$a_{h6} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z6)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h6} = -0.055\,\frac{m}{s^2}$$

$$a_{h7} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z7)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h7} = -0.045\,\frac{m}{s^2}$$

$$a_{h8} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z8)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h8} = -0.038\,\frac{m}{s^2}$$

$$a_{h9} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z9)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h9} = -0.034\,\frac{m}{s^2}$$

$$a_{h10} := \frac{H_w}{2}\cdot\omega^2\cdot\frac{\cosh[k\cdot(d+z10)]}{\sinh(k\cdot d)}\cdot\sin(k\cdot x-\omega\cdot t) \qquad a_{h10} = -0.032\,\frac{m}{s^2}$$

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Calculation of Wave force using Morison equation

$$L_{seg} := \frac{d}{10} \qquad L_{seg} = 10\,m$$

$$F_{T0} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h0}\right| \cdot V_{h0} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h0}\right) \cdot \frac{L_{seg}}{2} \qquad F_{T0} = 5.355 \cdot kN$$

$$F_{T1} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h1}\right| \cdot V_{h1} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h1}\right) \cdot L_{seg} \qquad F_{T1} = 8.723 \cdot kN$$

$$F_{T2} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h2}\right| \cdot V_{h2} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h2}\right) \cdot L_{seg} \qquad F_{T2} = 6.868 \cdot kN$$

$$F_{T3} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h3}\right| \cdot V_{h3} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h3}\right) \cdot L_{seg} \qquad F_{T3} = 5.173 \cdot kN$$

$$F_{T4} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h4}\right| \cdot V_{h4} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h4}\right) \cdot L_{seg} \qquad F_{T4} = 3.662 \cdot kN$$

$$F_{T5} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h5}\right| \cdot V_{h5} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h5}\right) \cdot L_{seg} \qquad F_{T5} = 2.353 \cdot kN$$

$$F_{T6} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h6}\right| \cdot V_{h6} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h6}\right) \cdot L_{seg} \qquad F_{T6} = 1.262 \cdot kN$$

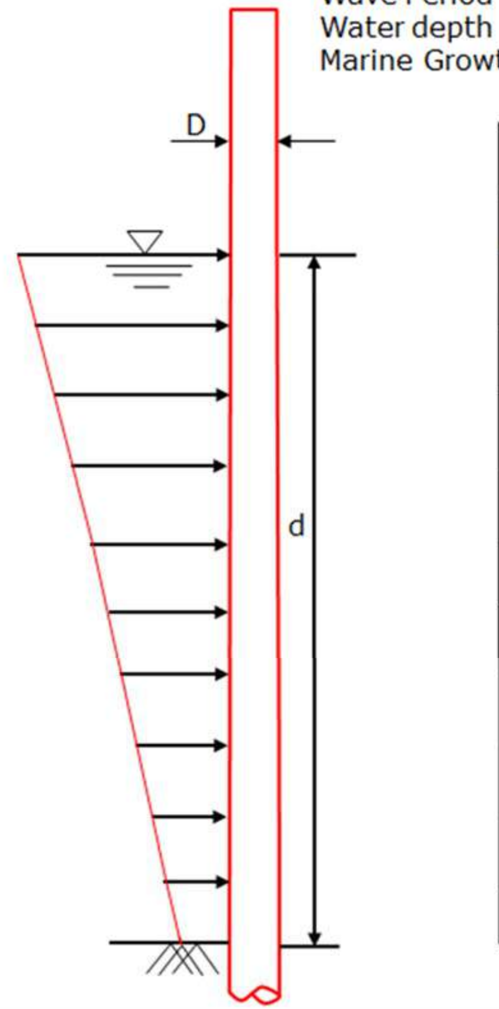
$$F_{T7} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h7}\right| \cdot V_{h7} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h7}\right) \cdot L_{seg} \qquad F_{T7} = 0.4 \cdot kN$$

$$F_{T8} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h8}\right| \cdot V_{h8} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h8}\right) \cdot L_{seg} \qquad F_{T8} = -0.226 \cdot kN$$

$$F_{T9} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h9}\right| \cdot V_{h9} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h9}\right) \cdot L_{seg} \qquad F_{T9} = -0.611 \cdot kN$$

$$F_{T10} := \left(0.5 \cdot C_D \cdot \rho_w \cdot D \cdot \left|V_{h10}\right| \cdot V_{h10} + \frac{\pi \cdot D^2}{4} \cdot \rho_w \cdot C_M \cdot a_{h10}\right) \cdot \frac{L_{seg}}{2} \qquad F_{T10} = -0.378 \cdot kN$$

Wave height H = 2m
Wave Period T = 12Sec
Water depth d = 100m
Marine Growth T_{mg} = 100m



V_h	α_h	F_T
2.137	-0.267	5.355
1.904	-0.202	8.723
1.679	-0.154	6.868
1.460	-0.117	5.173
1.246	-0.09	3.662
1.036	-0.07	2.353
0.828	-0.055	1.262
0.623	-0.045	0.4
0.419	-0.038	-0.226
0.217	-0.034	-0.611
0.017	-0.032	-0.378

AT t= 2.5 Sec

$$F_T := \frac{F_{T0} + F_{T1} + F_{T2} + F_{T3} + F_{T4} + F_{T5} + F_{T6} + F_{T7} + F_{T8} + F_{T9} + F_{T10}}{10} \qquad F_T = 3.258 \cdot kN$$

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INPLACE ANALYSIS - PURPOSE

- Structural analysis to simulate the behaviour of structure as close as possible and to obtain the response to all loads during its service
- To check the global integrity of the structure against premature failure
- To check the components (members and joints) against the loads that they are carrying and transmitting to the foundation
- To satisfy code requirements against safety of structure and supporting foundation
- Called In-service analysis or Inplace Analysis

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INPLACE ANALYSIS

- Jacket Geometry
- Member Sizes
- Wave Directions
- Hydrodynamic Coefficients
- Basic Loads and Combinations
- Pile-Soil Model (P-Y, T-Z and Q-Z Curves)
- Analysis Methods
- Dynamic Effects
- Pile capacity and Factor Of Safety
- Members and Joint Design
- Allowable Stress Modifiers

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Jacket Geometry

- Jacket Geometry depends on the space requirements of the topsides and water depth.
- Most of the jackets in shallow water is either 4 or 8 legged structure.
- Depending on whether the jacket in lift installed or launch installed, the arrangement may differ as additional launch truss will be added for the launch jackets.
- Jacket structure geometry differs also due to topside installation scheme such as modular installation or float-over installation.
- Jacket geometry is also influenced by the geotechnical conditions at the site. Depending on the soil strata, the number of legs may also be determined such that the pile arrangement becomes possible to design and install.

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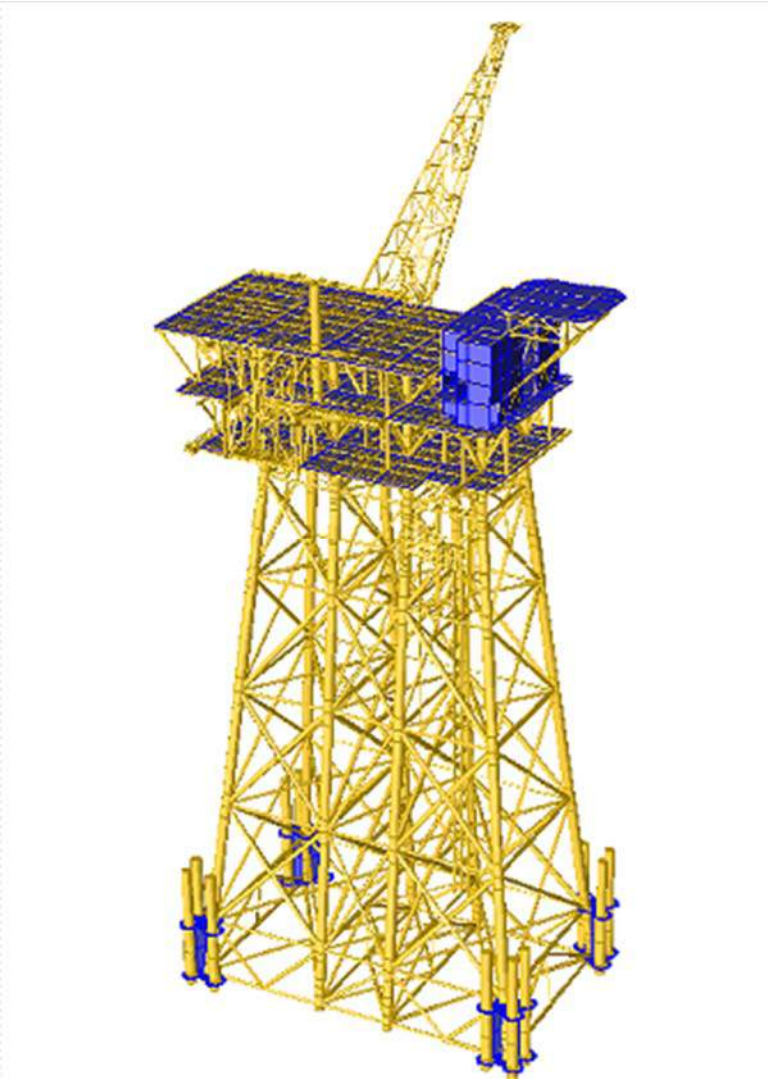
Modular installation



Float-over installation

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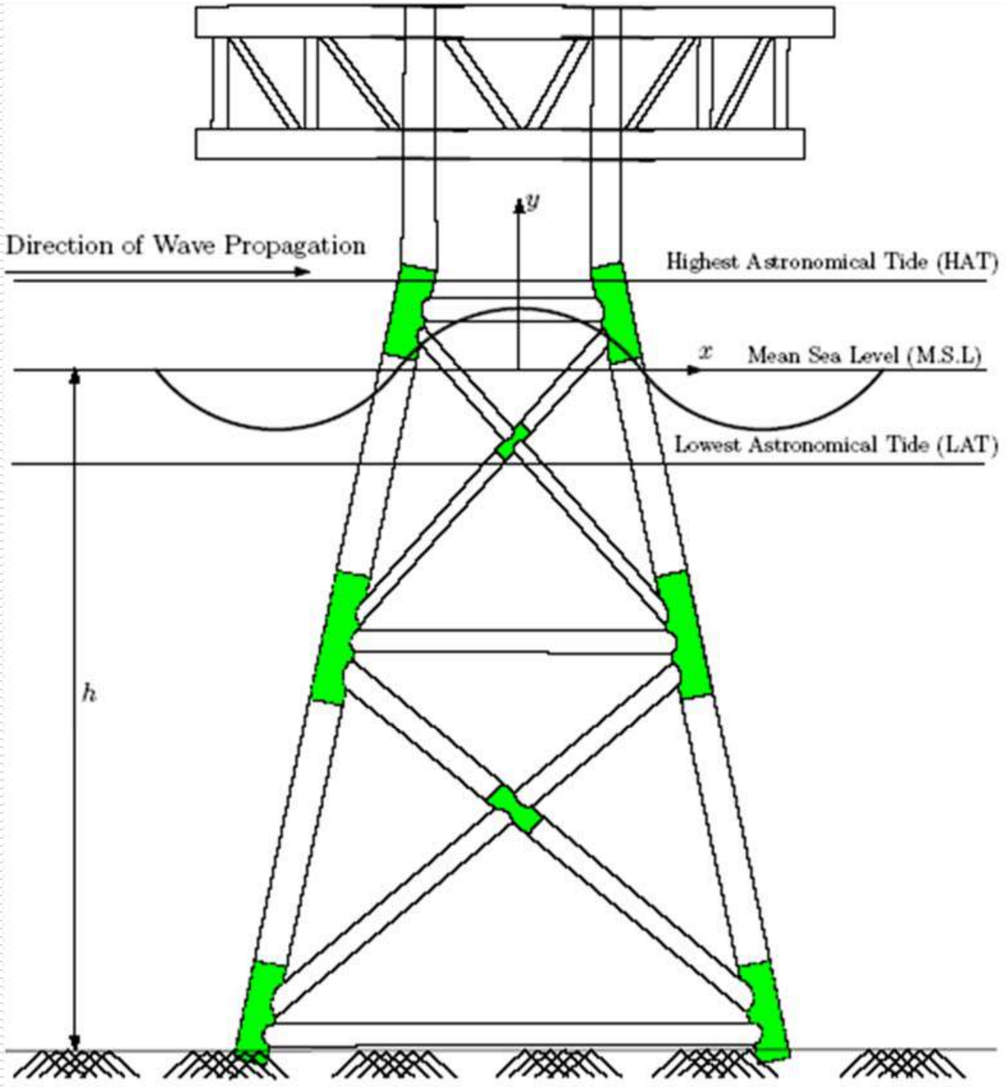
Modeling Techniques



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LOAD COMBINATIONS

- Typical Combinations are as below
  - Maximum Dead Load + Live Load + Environmental Load
  - Minimum Dead Load + Environmental Loads
  - Maximum Dead Loads + Live Loads + maximum Environmental Loads
- All the environmental loads shall be acting in the same direction
- The wave loads need to be calculated based on maximum wave period and height for the direction considered

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Maximum Environmental Loads

- When combining maximum environmental Loads following shall be noted
  - Maximum wave height and Period and associated wind speed shall be combined
  - Maximum wind speed and associated wave height and period shall be considered
  - Maximum wave height and wind speed need not be considered unless otherwise they coexist
  - Similarly, the associated current speed shall be considered for each case

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Design Wave Height / Period

- 1 year return period wave height and associated peak period shall be considered for operating cases
- 100 year return period wave height and associated peak period shall be considered for storm and pullout cases

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Design Wind speed

STRUCTURE / COMPONENTS	DESIGN WIND SPEED
Jacket global analysis	1 Hour average
Deck Global Analysis	1 minute average
Local Element Response	3 second gust

Typical design wind speed (1 hour average) in Bombay High field reaches as much as 192 km/hour (53.3 m/sec) for storm conditions (100 year return period) and 118 km/hour (32.7 m/sec) for operating cases (1 year return period)

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LOAD COMBINATIONS – WELLHEAD PLATFORMS

LOAD CATEGORY		DESIGN CONDITION		
		I	II	III
1.	**Dead Loads**	X	X	X
2.	**Equipment / Piping Bulk Loads**			
	(a) Operating	X		X
	(b) Dry		X	
3.	**Blanket Global Live Loads (unoccupied areas)**	X		X
4.	**Drilling Rig Reaction Loads**			
	(a) Operating	X		
	(b) Storm		X	X
5.	**Environmental Loads (Wind/Wave/Current)**			
	(a) Operating	X		
	(b) Storm		X	X

Design Condition I – Normal Operation (Production / Drilling)

Design Condition II – Pullout Condition (No Drilling and no blanket loads)

Design Condition III – Storm Condition (Drilling Not allowed but platform may produce remotely)

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LOAD COMBINATIONS – PROCESS PLATFORMS

LOAD CATEGORY		DESIGN CONDITION		
		I	II	III
1.	**Dead Loads**	X	X	X
2.	**Equipment / Piping Bulk Loads**			
	(a) Operating	X		X
	(b) Dry		X	
3.	**Blanket Global Live Loads (unoccupied areas)**	X		X
4.	**Crane Loads**			
	(a) Dead Loads	X	X	X
	(b) Lifting Loads	X		
5.	**Environmental Loads (Wind/Wave/Current)**			
	(a) Operating	X		
	(b) Storm		X	X

Design Condition I – Normal Operation (Production)

Design Condition II – Pullout Condition (No blanket loads)

Design Condition III – Storm Condition

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ANALYSIS METHODS

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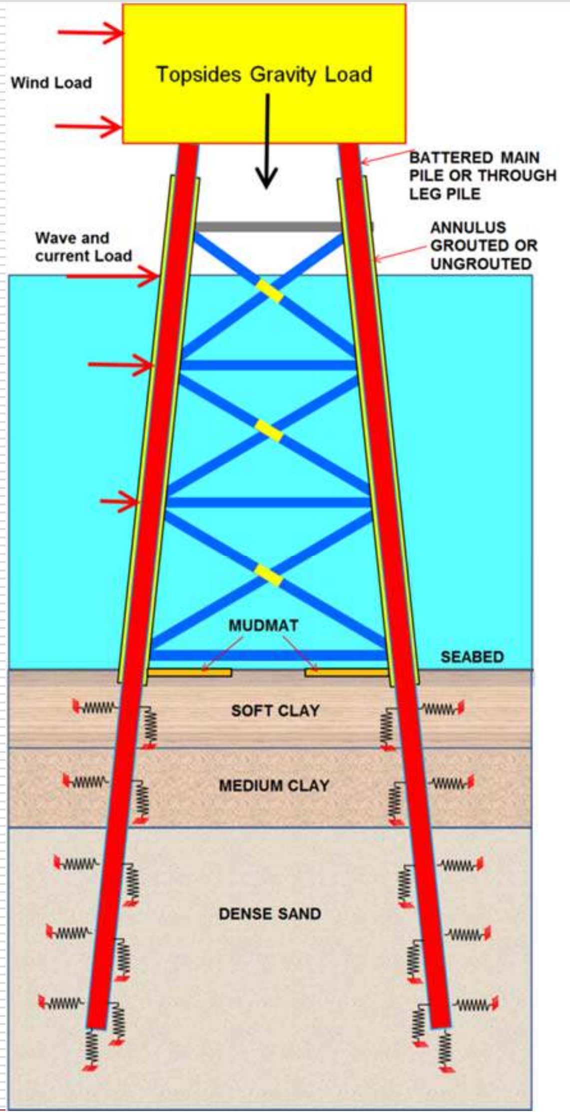
Jacket Structure – Pile foundation Interaction



- **An offshore jacket structure is a space frame supported by piles.**
- **The piles are often very long.**
- **Lateral/transverse deformation of the of the pile is very significant.**
- **Beam-column effect in the piles piles is very important.**
- ***The mechanical characteristics of the soil is (materially) nonlinear.***
- **A quasi-static model for the jacket-pile system is discussed in this lecture.**

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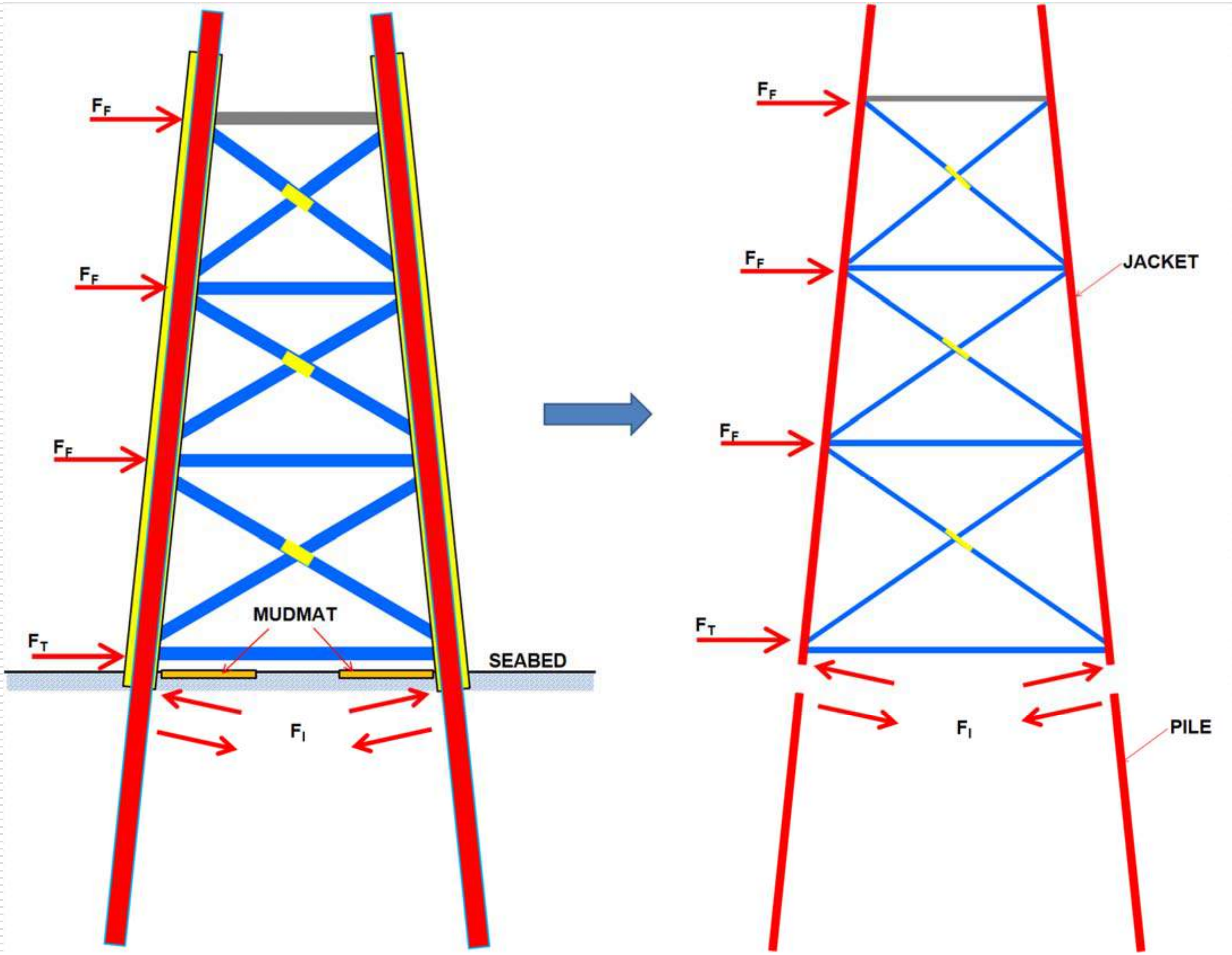
Jacket Structure – Pile foundation Interaction



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ANALYSIS METHODS

- Linear Static Analysis
- Linear Static Analysis (Pseudo-Static)
- Dynamic Wave Response Analysis (Frequency Domain)
- Dynamic Wave Response Analysis (Time Domain)
- Nonlinear Analyses (material or geometric)

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Structural Response – Static Analysis

- If the natural period of the platform is considerably away from fatigue waves, assumption of equivalent static analysis is acceptable
- Simple calculations for DAF using SDOF model for each of the wave period can be calculated and applied to the wave loads
- Simple Static Analysis either with Pile Soil Interaction or equivalent linearised foundation can be used.

$$[K]\{X\} = \{F * DAF\}$$

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DYNAMIC AMPLIFICATION FACTOR (SDOF)

$$\mathrm{DAF} = \frac{1}{\sqrt{\left(1 - \frac{T_N^2}{T^2}\right)^2 + \left(2\varsigma \frac{T_n}{T}\right)^2}}$$

T_N – Natural Period of the structure

T – Wave Period

ζ – Structural Damping Ratio

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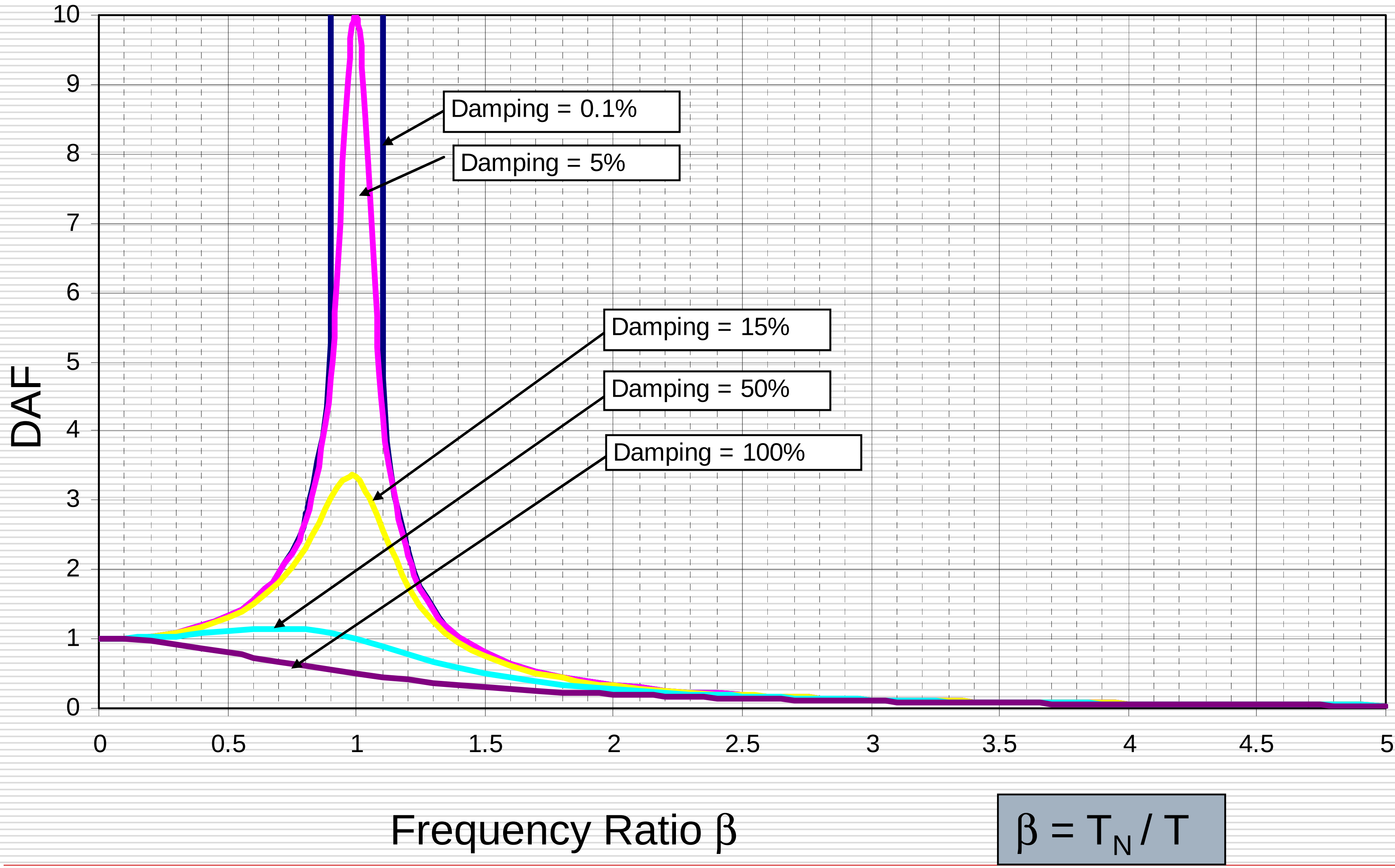
DYNAMIC AMPLIFICATION FACTOR (DAF)



$\beta = T_N / T$

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Structural Response – Wave Response analysis

- If the natural period of the platform is close to the fatigue waves, assumption of equivalent static analysis is not acceptable
- Simple calculations for DAF using SDOF model for will result in very conservative or non-conservative results depending on the assumptions made on average wave periods for the calculation of DAF
- Hence a Dynamic Wave Response analysis needs to be performed
- Due to iterative calculations in Free Vibration analysis, equivalent linearised Foundation is required

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Structural Response – Wave Response analysis

- The dynamic wave response analysis requires the dynamic characteristics
- The results of dynamic analysis will be used in Dynamic Wave Response analysis to generate structure response

Free Vibration Analysis

$$[K]\{X\}+[M]\{X''\}=0$$

Wave Response Analysis

$$[K]\{X\}+[C]\{X'\}+[M]\{X''\}=\{F\}$$

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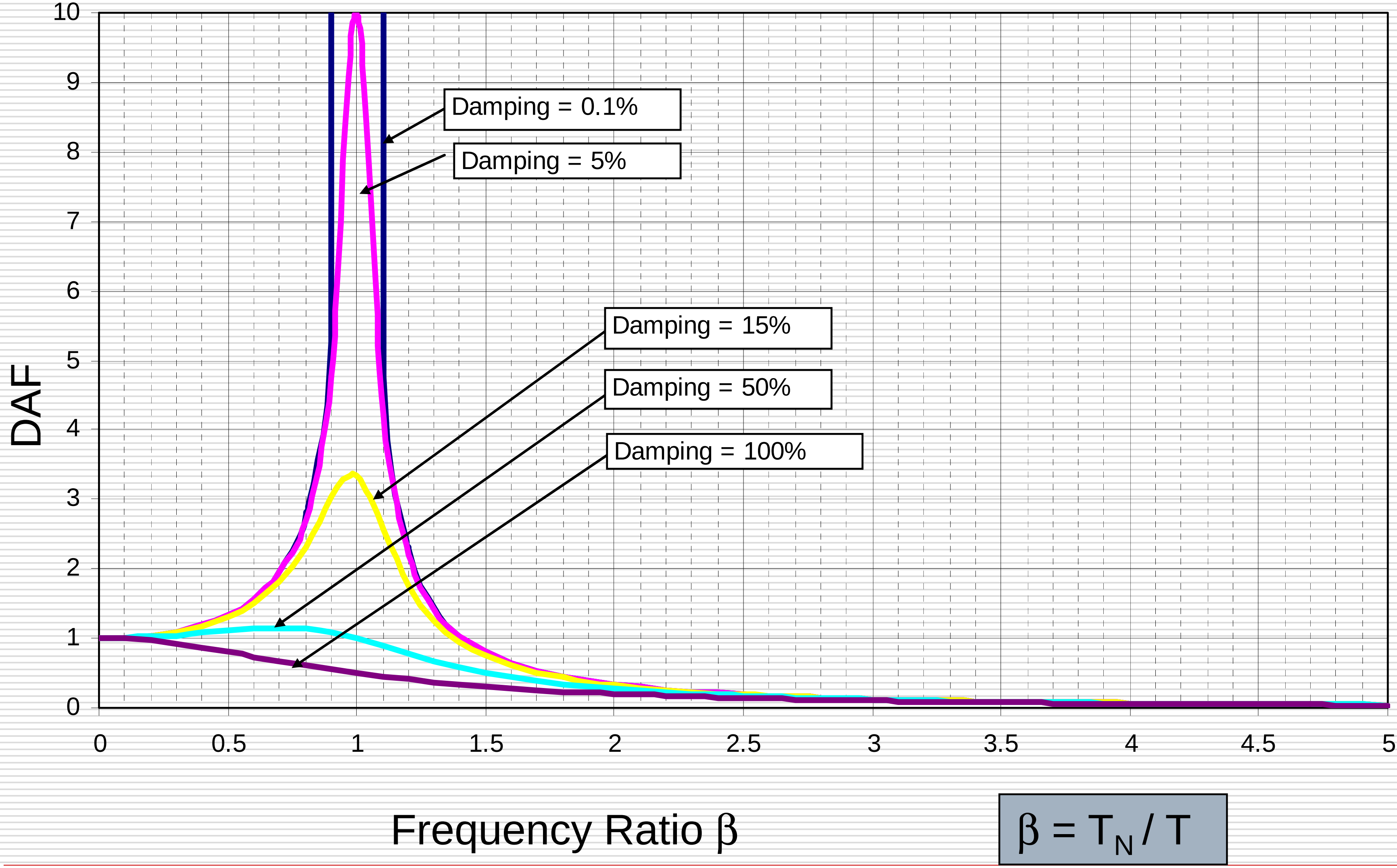

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