Wave Energy: Introduction

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Overview

- The potential for wave energy
- Wind waves in the ocean environment
- Wave mechanics
- Wave energy and its propagation
- WECs: some history
- WECs: basic features and main types
- Recent trends and perspectives
- References (for further and deeper studies)

The potential for wave energy

- The potential for wave energy harnessing has long been known..

- Recent estimation of total world wide wave power [1]:

Total power ~ 2.7 TW

The potential for wave energy

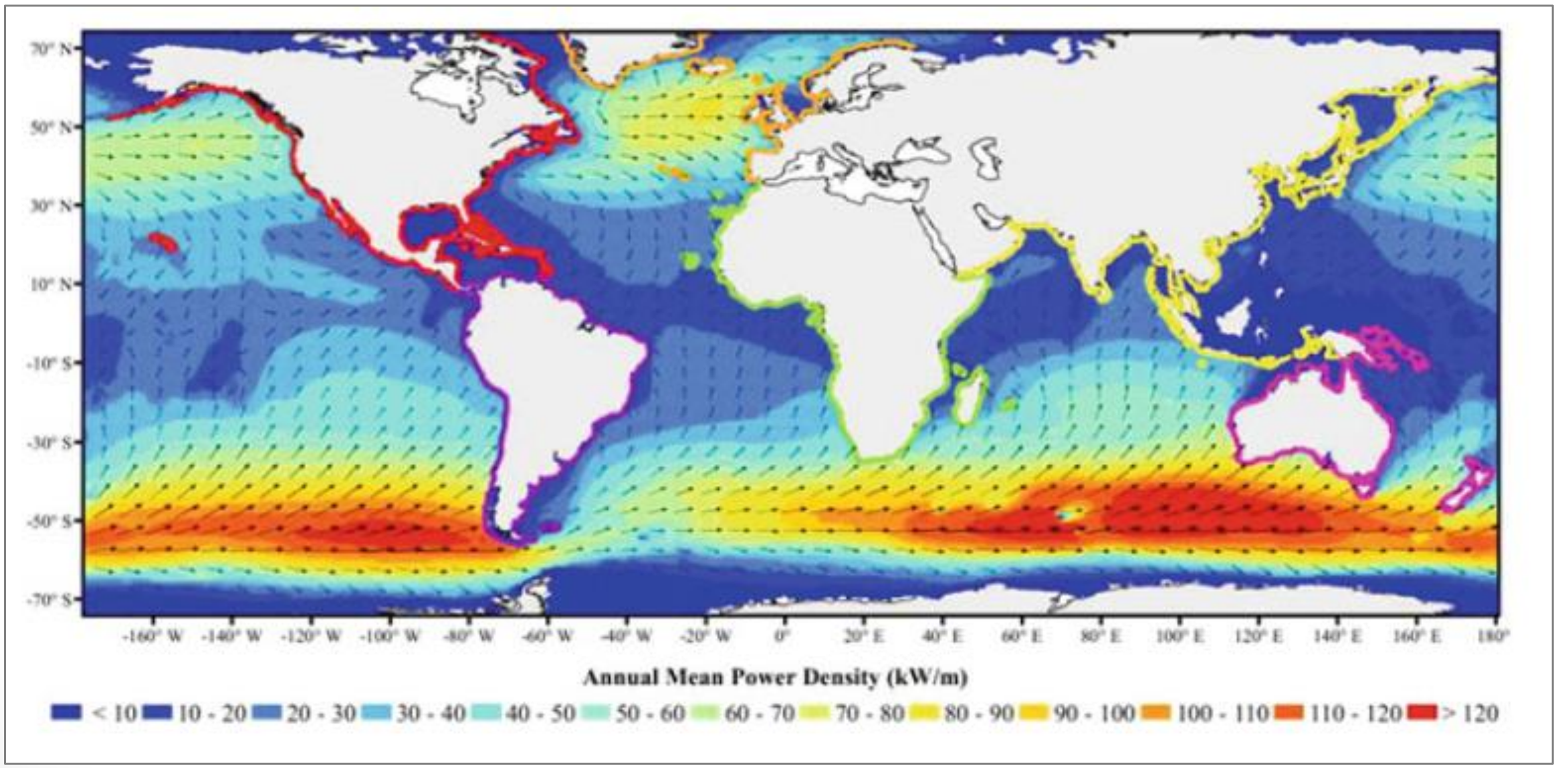
- This is only a fraction of the estimated total wind power, which in turn is only a fraction of the estimated total solar power, but the wave energy *density* is much *higher* (Power/surface area – W/m^2)

$$energy\ density = \frac{Power}{area} \left(\frac{\mathrm{W}}{m^2}\right)$$

- According to Falnes (2007) [2]:
  - Solar: ~ **0.1 – 0.3** kW/m^2 (earth surface)
  - Wind: typically **0.5** kW/m^2 (perpendicular to wind)
  - Waves: typically **2 – 3** kW/m^2 (perpendicular to waves)

The potential for wave energy

- Estimates of mean wave energy distribution around the globe can also be found (see, for instance, [3]):



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy, Springer Open, Ocean Eng. and Oceanography Series V.7, 2017* [4]

The potential for wave energy

- However, the problems for economically harvesting such energy are **MANY**, such as:
  - There is a large **seasonal variability** of the mean energy in any location (typically around 50% !).
  - In any spot and any season, there is also a **large variability of wave energy in time** (related to local wind conditions and swells coming from distant locations).
  - In a real sea condition, there is always some level of **energy spread regarding wave direction** (more intense in deep water areas).
  - The need for mechanical devices operating in a **hostile environment** (current and wind loads, corrosion, etc.), requiring intensive maintenance.
  - Wave energy is better offshore, but this requires floating systems, with large economical impacts from **moorings and power cables to the shore**…

The potential for wave energy

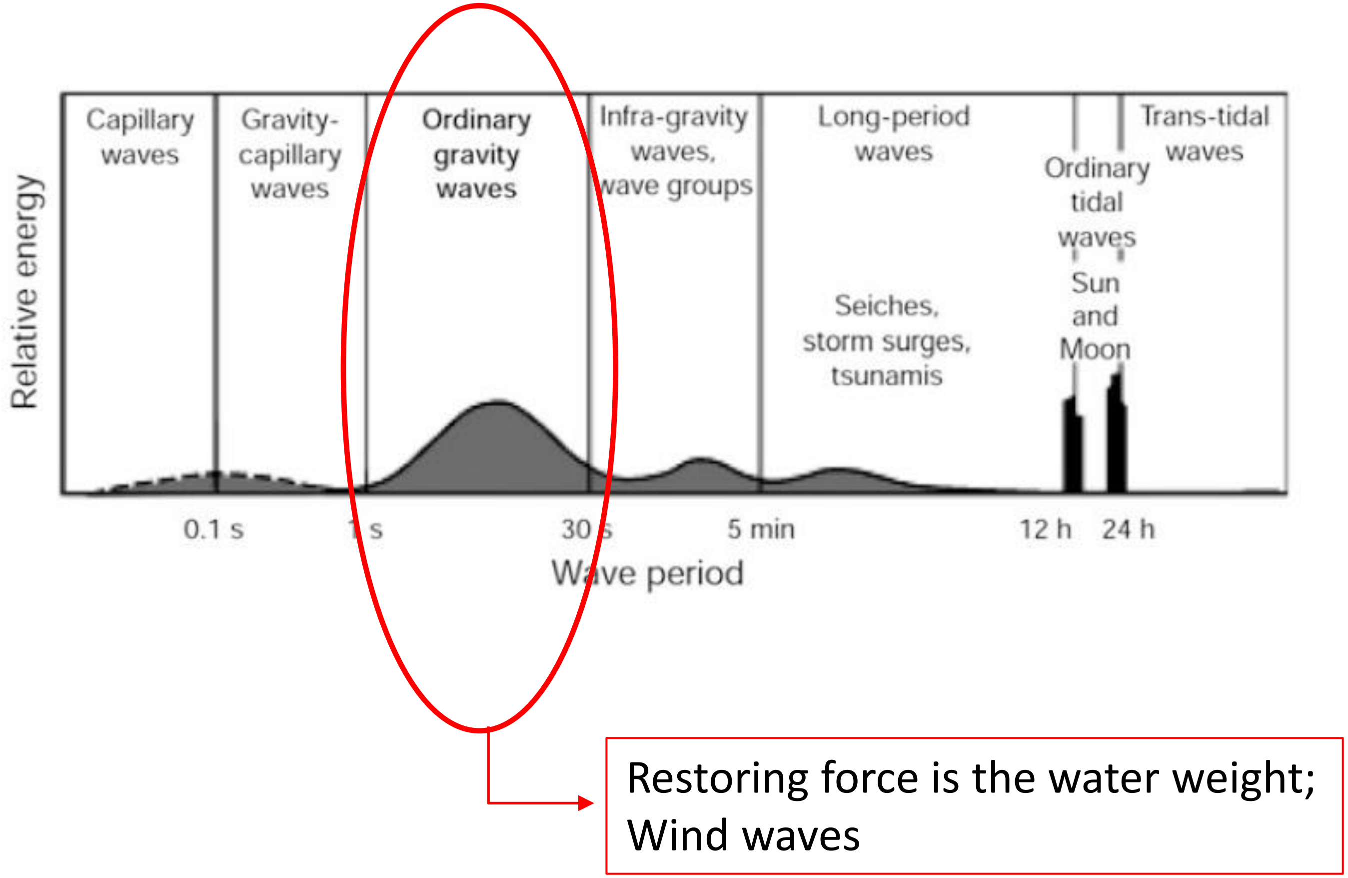
- All these problems, ultimately…

Prevent (so far) the economical feasibility of wave energy conversion devices (WECs) designed for large-scale and long-term commercial electrical power production, but…

there is always opportunity for small-scale energy production for specific sites/applications, and the economics change depending on many variables (environmental constraints, oil/gas prices, development of smart-grids, etc…)

Wind waves in the ocean environment

- There are many oscillatory phenomena in the ocean:



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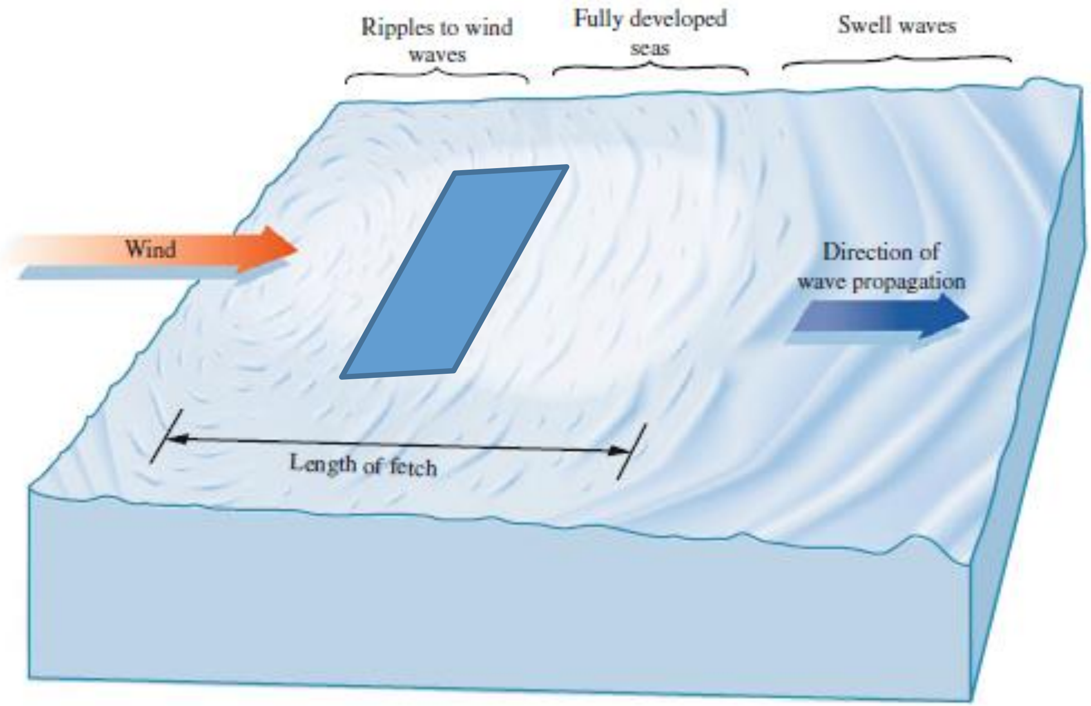
Wind waves in the ocean environment

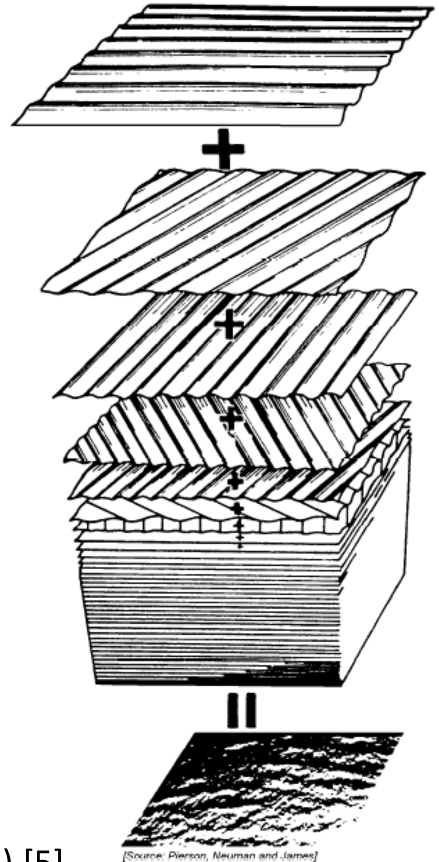
- Waves generated by wind action:
  - **Quite efficient mechanism of energy transmission**
  - **Different characteristics as move away from generation zone**



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

Wind waves in the ocean environment

- In or close to the generation zone: "Sea waves"
  - **Waves of various frequencies, amplitudes and directions coexist**



Source: Journée & Massie (2001) [5]

Wind waves in the ocean environment

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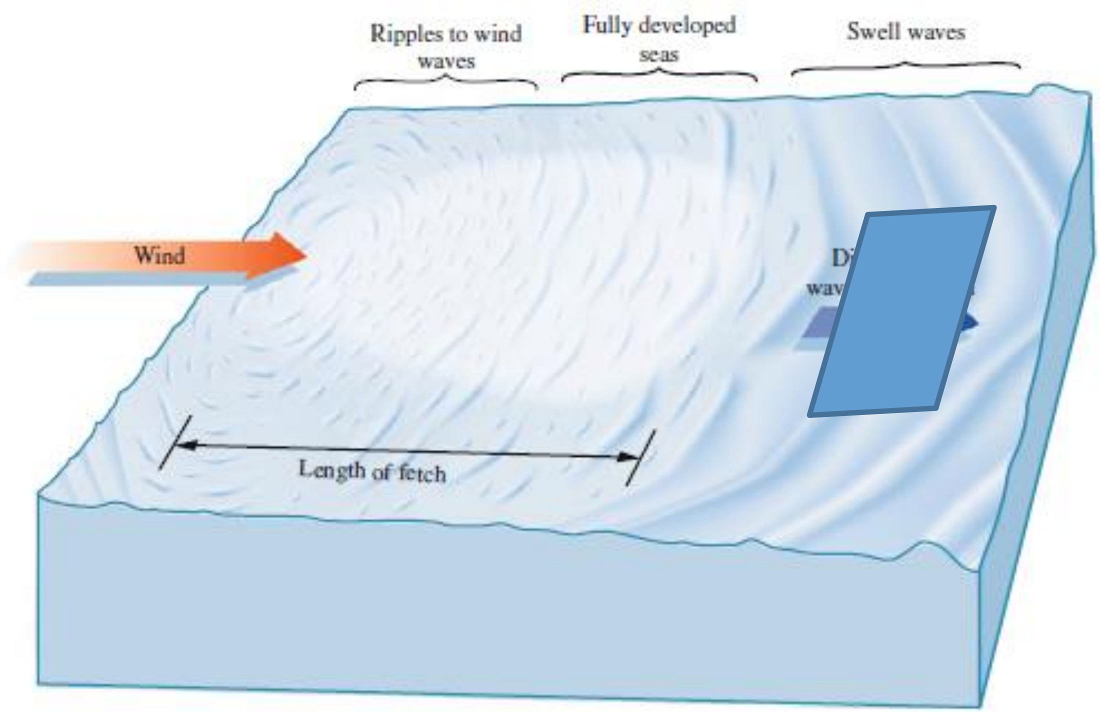

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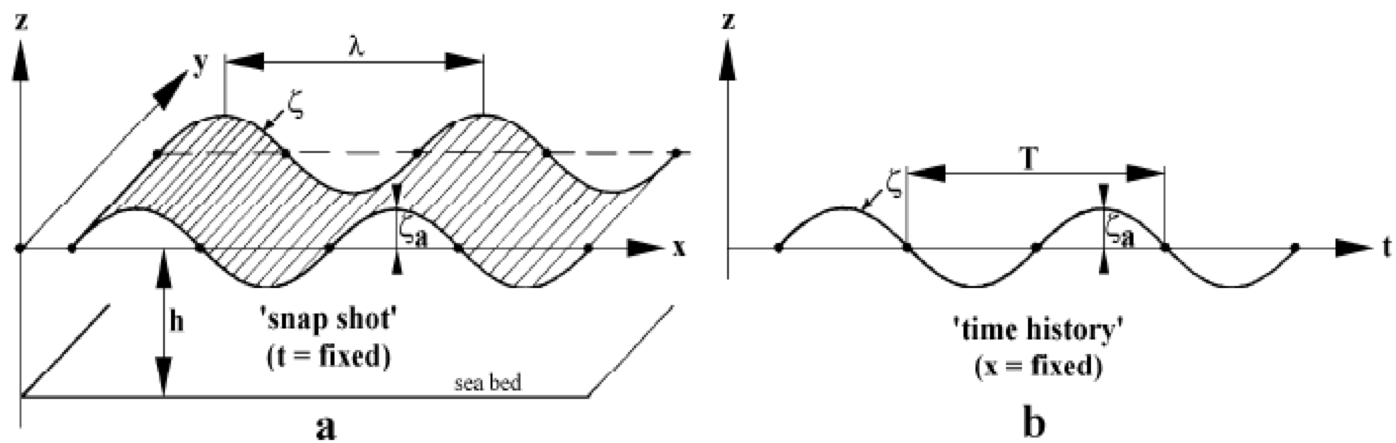
Wind waves in the ocean environment

- Far from the generation zone: "Swell waves"
  - **Only waves of approx. equal frequencies coexist in each location**

Wave Mechanics

- Let us examine the mechanics of wind waves:
- **Suppose a “regular” progressive wave:**



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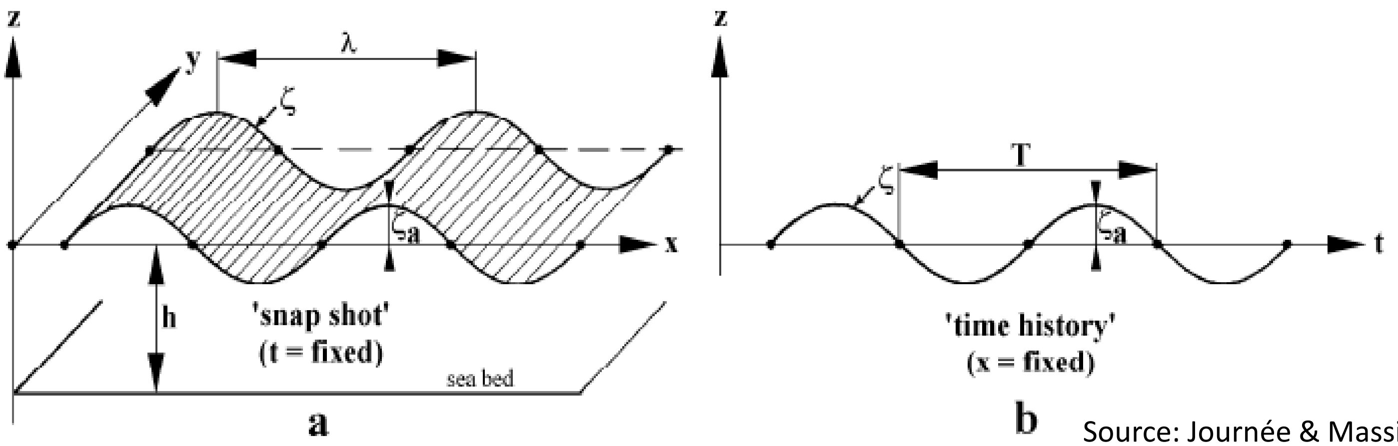
- 3 parameters define the wave:
  - Amplitude (m): A
  - Wavelength (m): λ
  - Period (s): T

Wave number (rad/m): $k = 2\pi/\lambda$

Wave frequency (rad/s): $\omega = 2\pi/T$

Wave Mechanics



Source: Journée & Massie (2001) [5]

- It progresses in the x+ direction with velocity (**celerity**):

$$c = \frac{\lambda}{T} = \frac{\omega}{k}$$

- and, if the ratio **A/λ** is small (typically below **3%**), the wave is considered **linear**, and the wave equation is given simply by:

$$\zeta(x,t) = A\cos(kx - \omega t)$$

Wave Mechanics

- Gravity waves are **dispersive waves**: there is a nonlinear relation between wavelength (λ) and wave period (T)
- For *linear waves in a constant depth* h, the dispersion relation is given by:

$$k = \frac{\omega^2}{g\tanh(kh)}$$

- Thus:

$$\lambda = \frac{gT^2\tanh(kh)}{2\pi}$$

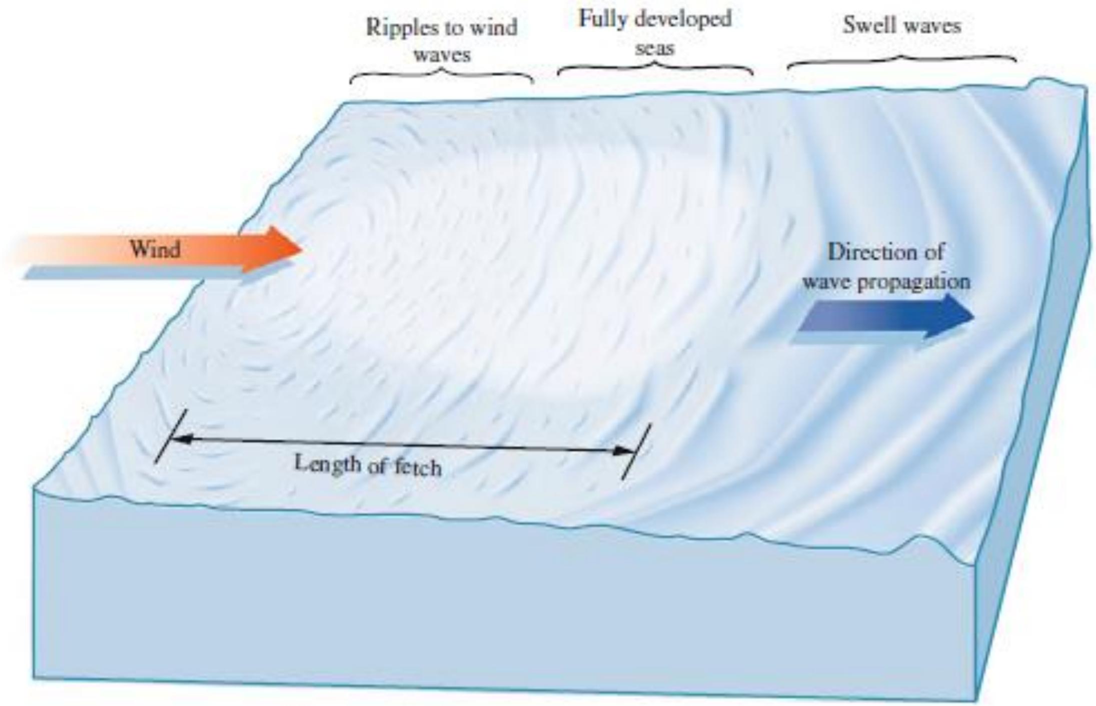
→ Longer waves have higher periods

$$c = \frac{gT\tanh(kh)}{2\pi}$$

→ Longer waves have **higher speeds**

Wave Mechanics

- This explains the *regularization process* the waves undergo as they move away from the generation zone: *each wave component has a different speed (dispersion)*



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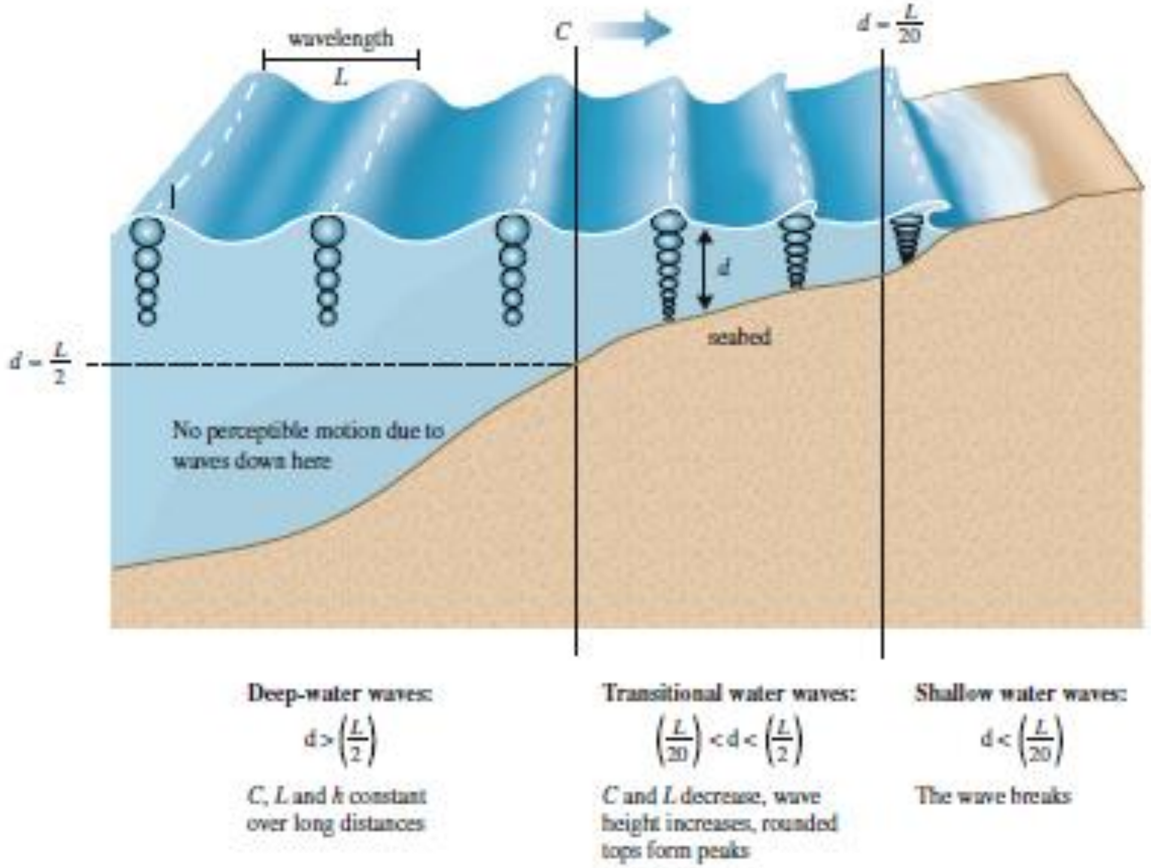
Wave Mechanics

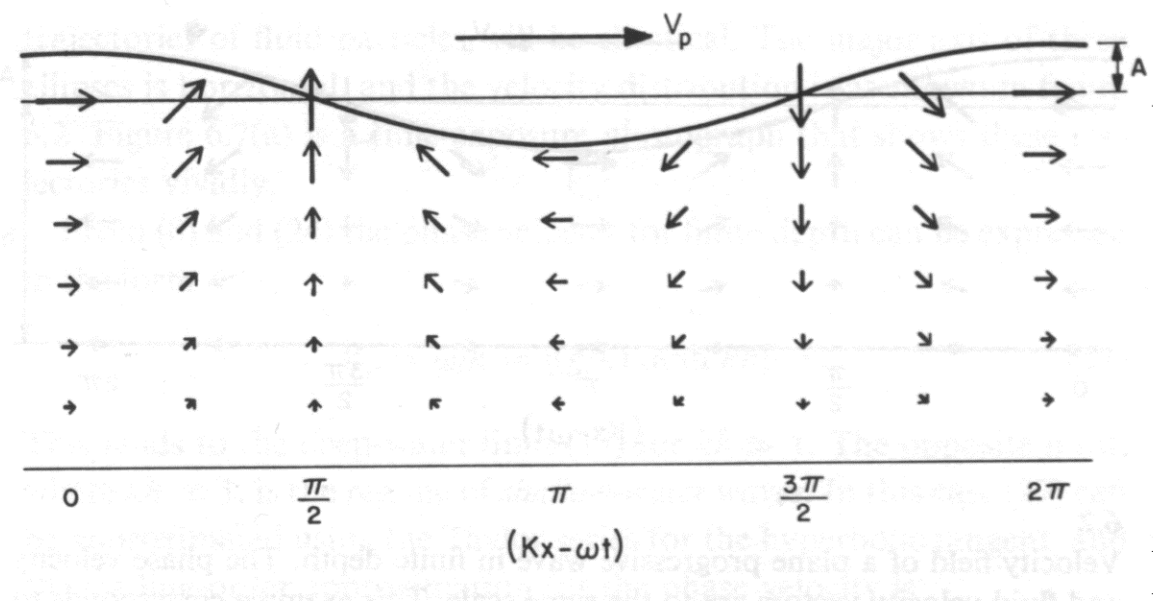
- Surface waves are associated with a periodic water flow:



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

Wave Mechanics

- For **deep waters** ($h>\lambda/2$), orbits are essentially circular and their radius **decay exponentially** with depth;
- The flow velocity field exhibits the following behavior:



Source: Newman, J.N., Marine Hydrodynamics (1977) [6]

Wave Mechanics

- …and velocities in any point of the flow can be calculated as:

$$\vec{v}(x,z,t) = u(x,z,t)\vec{i} + w(x,z,t)\vec{k}$$

- with:

$$u(x,z,t) = \omega A e^{kz}\cos(kx - \omega t)$$

$$w(x,z,t) = \omega A e^{kz}\sin(kx - \omega t)$$

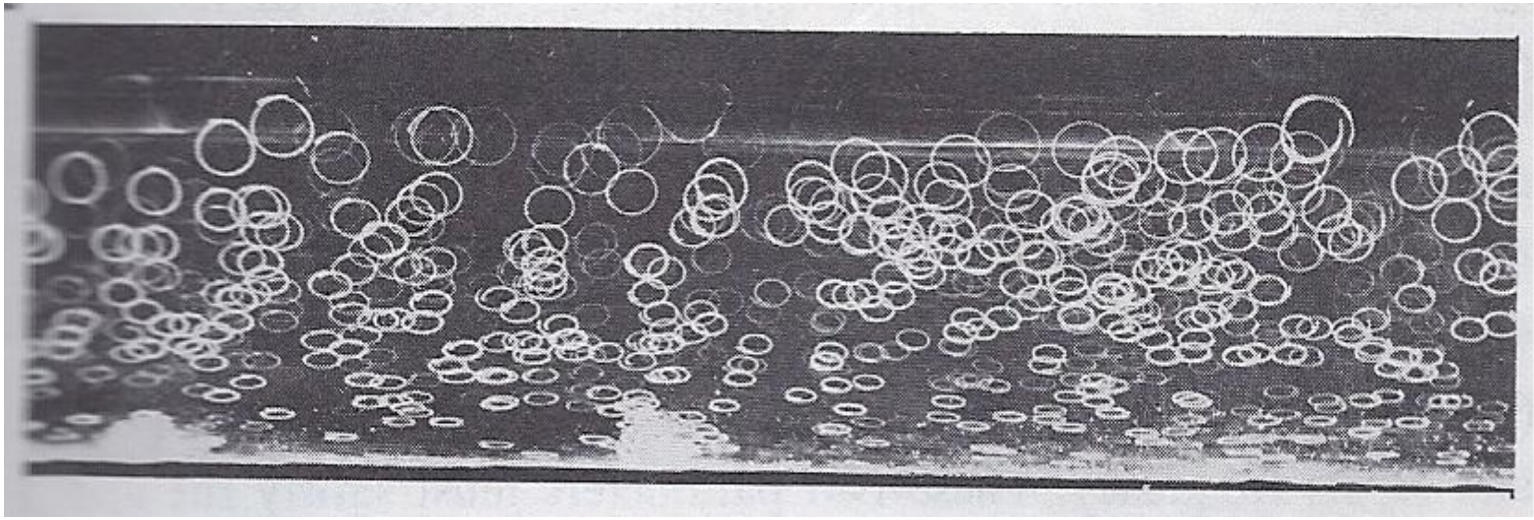
- Thus:

$$|\vec{v}(x,z,t)| = \omega A e^{kz}$$

Flow energy is concentrated close to the surface

Wave Mechanics

- For **finite water depths** ($h<\lambda/2$), orbits are essentially elliptic and decay hyperbolically with depth:



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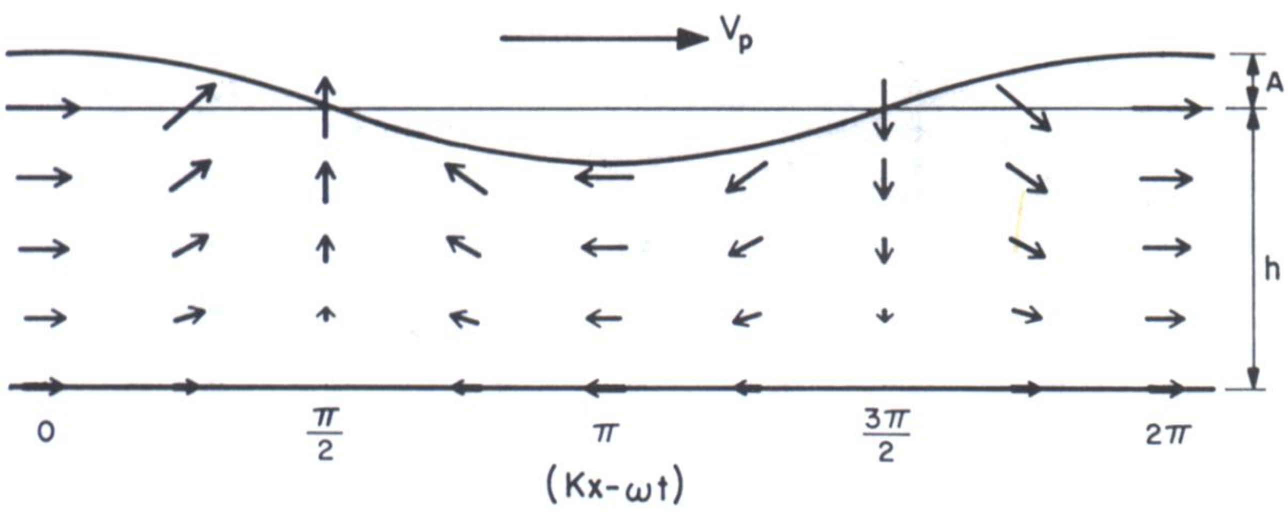

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Wave Mechanics

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$$\vec{v}(x,z,t) = u(x,z,t)\vec{i} + w(x,z,t)\vec{k}$$

- with:

$$u(x,z,t) = \omega A \frac{cosh\,\mathrm{k(z+h)}}{\sinh(kh)} \cos(kx - \omega t)$$

$$w(x,z,t) = \omega A \frac{sinh\,\mathrm{k(z+h)}}{\sinh(kh)} \sin(kx - \omega t)$$

Wave energy and its propagation

- **Wave energy** is composed of:
  - **Potential energy**, associated to wave elevation
  - **Kinetic energy**, associated with fluid flow
- For a regular progressive wave:

$$Energy = \frac{1}{2}\rho g A^2$$

Mean wave energy per surface area of the sea
(J/m^2)

Wave energy and its propagation

- However, in general, **this energy is not transmitted with the wave celerity (c), but rather with a smaller velocity named group velocity (c_g)**

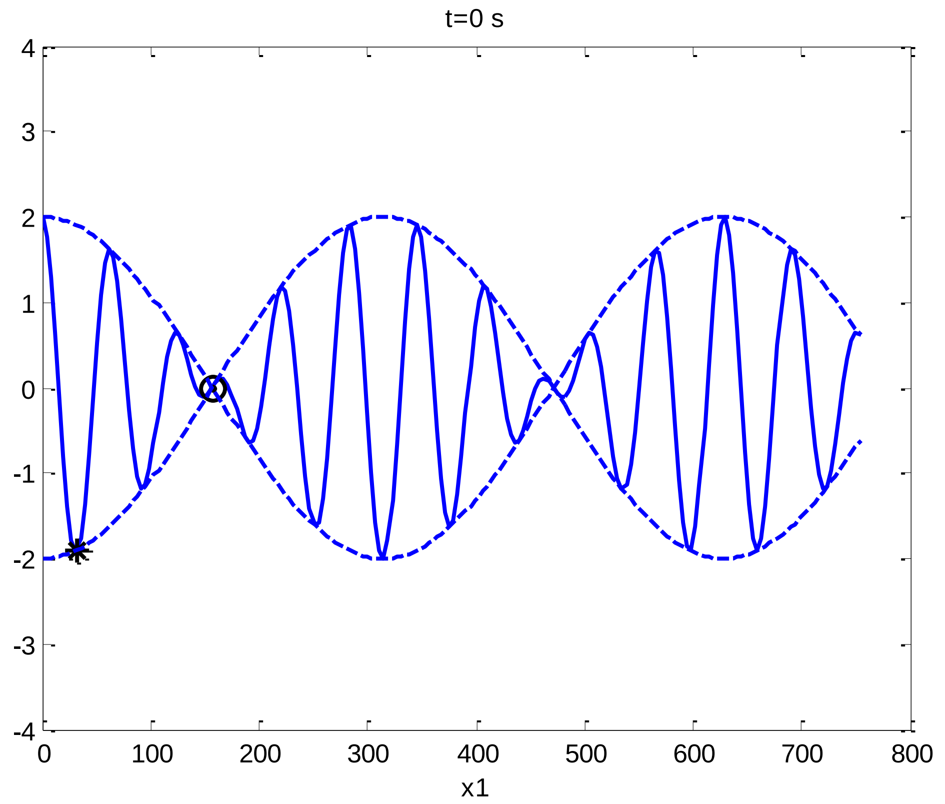
- For understanding this, let's consider two waves of same amplitude $A/2$ and almost the same frequencies {($\omega - \delta\omega$) and ($\omega + \delta\omega$)}, which propagate in the same direction. It is easy to show that, in this case, the wave equation is given by

$$\zeta(x,t) = A\cos(\delta kx - \delta\omega t)\cos(kx - \omega t)$$

Wave **modulation**:
Large wavelength: $2\pi/\delta k$
High period: $2\pi/\delta\omega$

Wave energy and its propagation

- The wave moves with celerity c, but it is confined in a “wave group”…

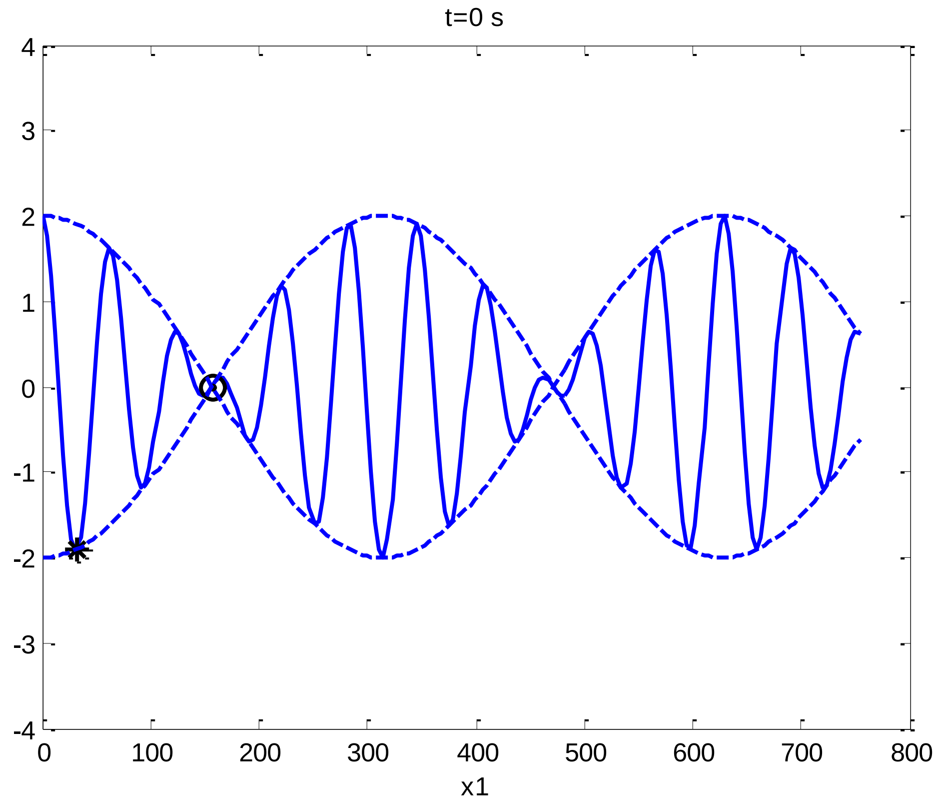


- …which moves with *group velocity*:

$$c_g = \frac{d\omega}{dk}$$

Wave energy and its propagation

- As an example: the next figures show the evolution in time of a wave point (with c) and of a group point (with c_g)



wave celerity (*) and group velocity (o)

Wave energy and its propagation

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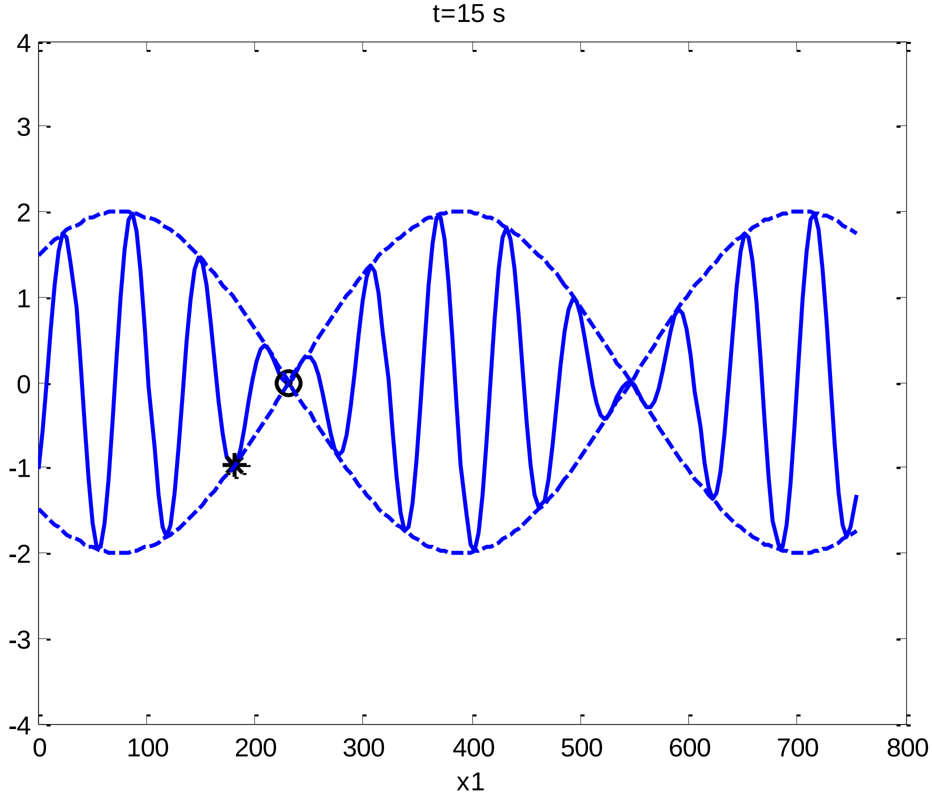

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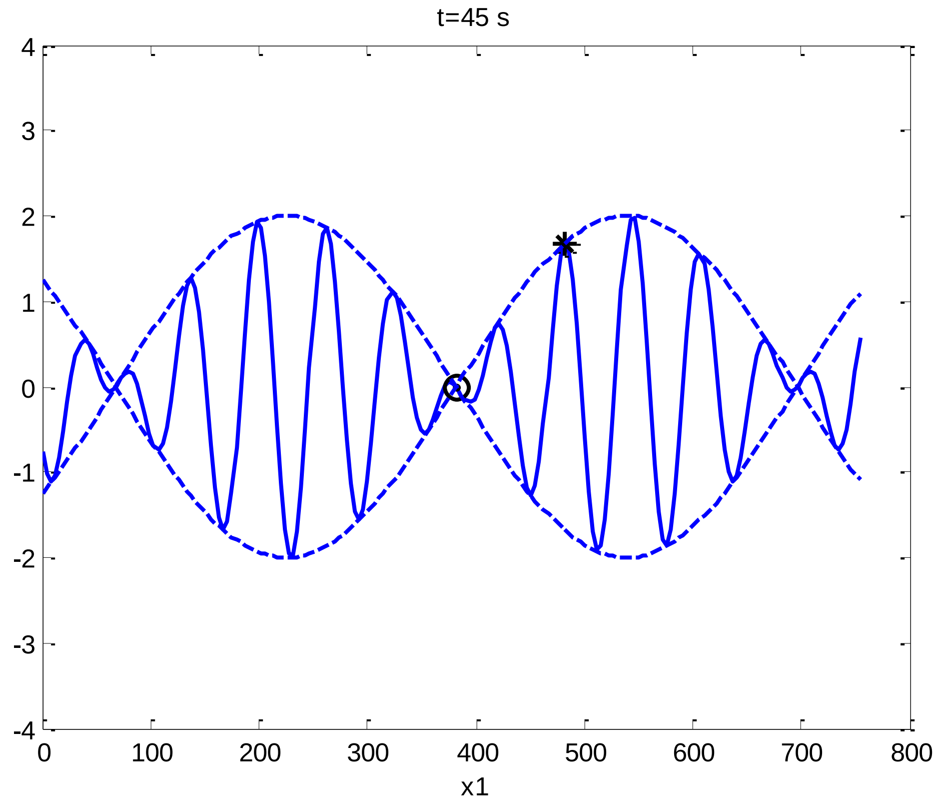

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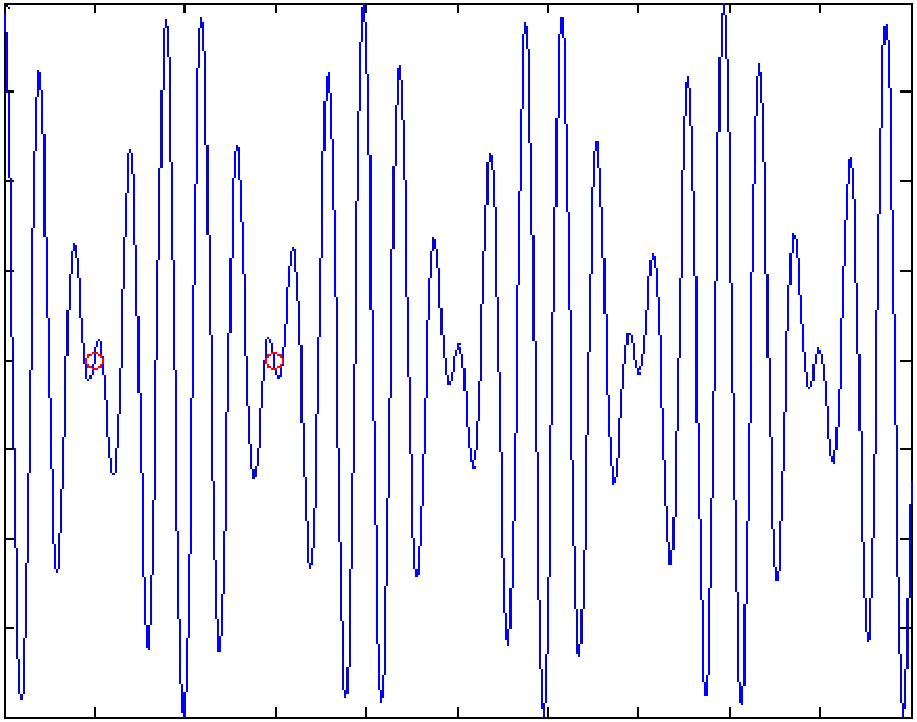


wave celerity (*) and group velocity (o)

Wave energy and its propagation

- Thus, the **mean wave energy propagates with the group velocity** which, *in its turn, depends on the water depth*:

$$c_g = \frac{c}{2}$$ (deep water)

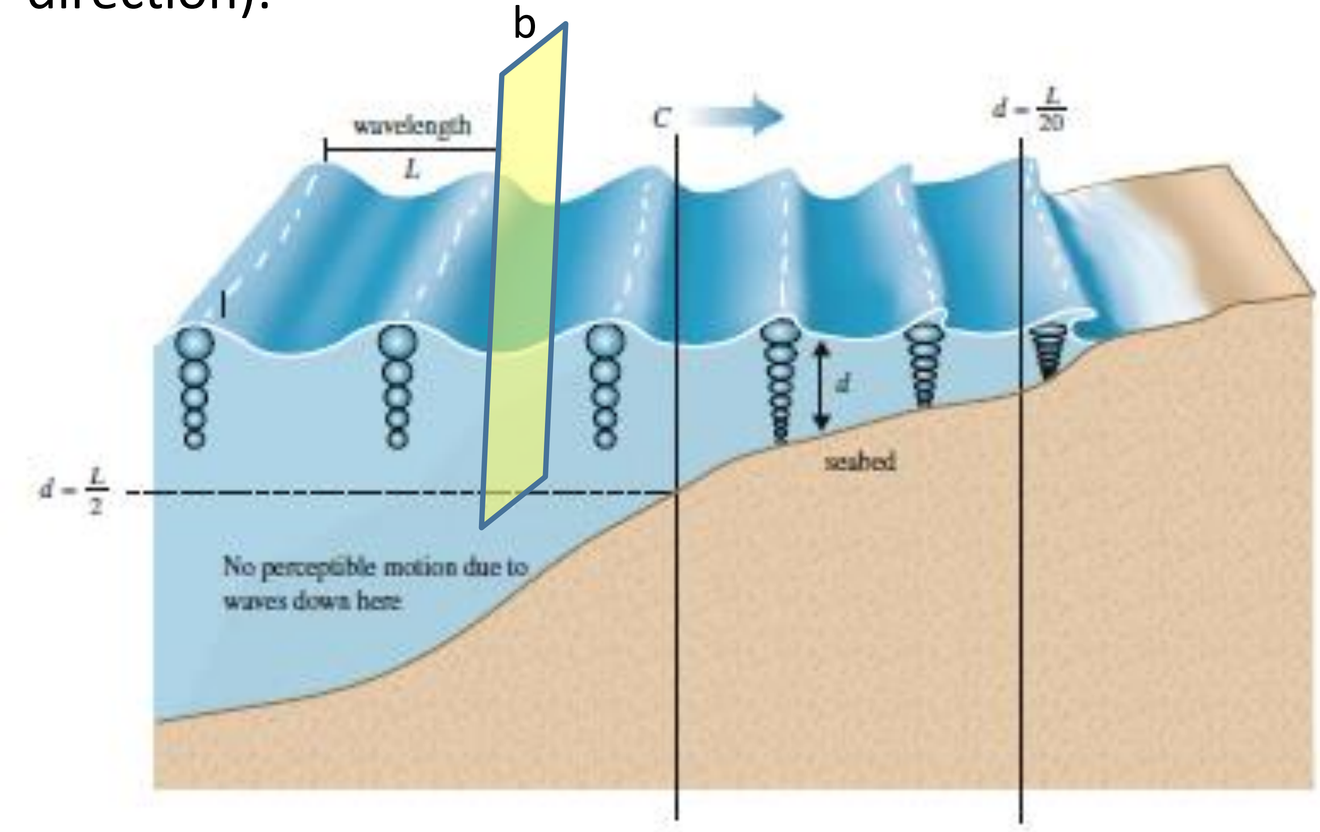
$$c_g = \frac{d\omega}{dk} \Rightarrow c_g = \frac{c}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)$$

$$c_g = c$$ (shallow water)

$\lambda/h<1/20$

Wave energy and its propagation

- Therefore, if we want to know the **wave mean energy flux (power) through a section of width b** (perpendicular to the wave direction):



Wave energy and its propagation

- This **mean power** will be:

$$power = \frac{1}{2}\rho g A^2 c_g b \quad \text{(W)}$$

This is the maximum available power that can be extracted from a width *b* parallel to the wave crests in the sea

Wave energy and its propagation

- **Example:**
- Let's consider a wave in deep water, with amplitude A=1m and period T=10s. Then:

$\rho=1025\ kg/m^3$

$g=9,81\ m/s^2$

$c_g= 1/2c=1/2(gT/2\pi)=7,81m/s$

$power/m = \frac{1}{2}\rho g A^2 c_g$ = 39,25 (kW/m)

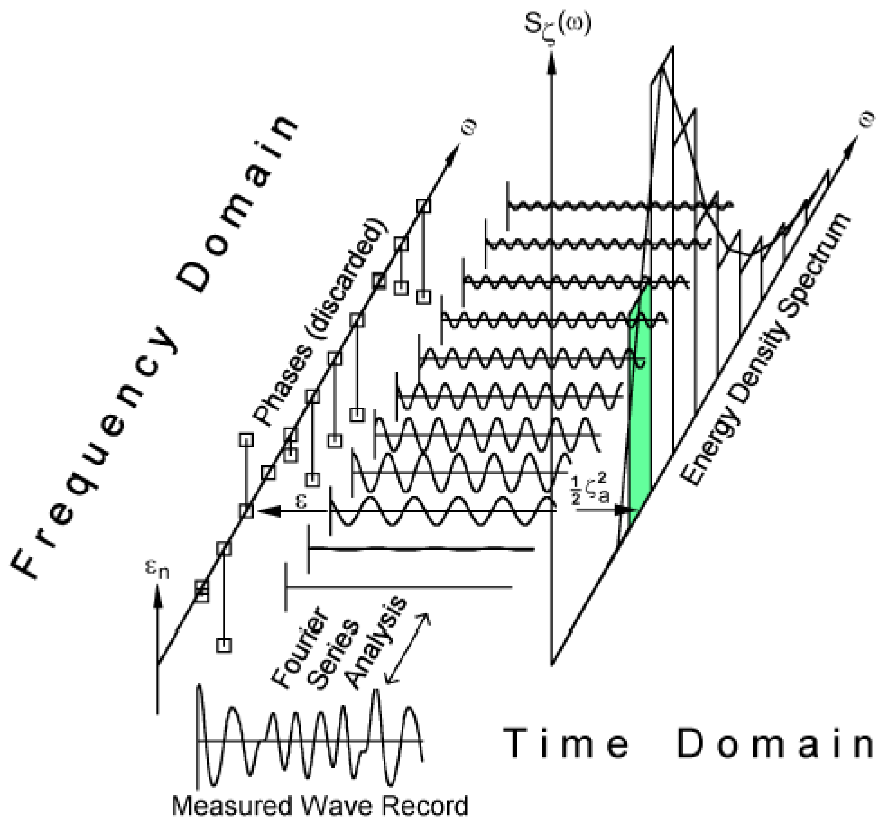
Wave energy and its propagation

- Have in mind that WECs are designed considering:
  - **An optimum wave frequency (or wavelength), and**
  - **An optimum wave direction**

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

Wave energy and its propagation

- **However,** in a **real sea**, there is always a *spread of wave energy in the different wave frequencies* (represented by a **wave energy spectrum**):



Source: Journée & Massie (2001) [5]

Wave energy and its propagation

- **Main statistical quantities:**
  - Spectral moments: $m_k = \int_0^\infty \omega^k S_\zeta(\omega).d\omega$
  - Standar deviation: $\sigma = RMS = \sqrt{m_0} = \left[\int_0^\infty S_\zeta(\omega).d\omega \right]^{1/2}$
  - Significant wave amplitude/height $A_{1/3} = 2\sqrt{m_0}$ $H_{1/3} = 4\sqrt{m_0}$
  - (Mean) Central period: $T_1 = 2\pi \frac{m_0}{m_1}$
  - Zero up-crossing period: $T_2 = 2\pi \sqrt{\frac{m_0}{m_2}}$

Wave energy and its propagation

- **For example, the JONSWAP energy spectrum:**
  - *Joint North Sea Wave Project* (1968-1969)
  - *North Sea – 100 nm from Sylt Island*
  - *Fetch limited seas*
  - ITTC (1984) recommended:

$$S_\zeta(\omega) = \frac{320.H_{1/3}^{\ 2}}{T_p^{\ 4}}\,\omega^{-5}\exp\left\{\frac{-1950}{T_p^{\ 4}}\,\omega^{-4}\right\}\gamma^{A}$$

$$\gamma = 3.3$$

Peakedness factor

$$A = \exp\left\{-\left(\frac{\omega/\omega_p - 1}{\sigma\sqrt{2}}\right)^2\right\}$$

$$\sigma = 0.07; \quad \omega < \omega_p$$

$$\sigma = 0.09; \quad \omega > \omega_p$$

Nowadays γ is a 3rd parameter: universality

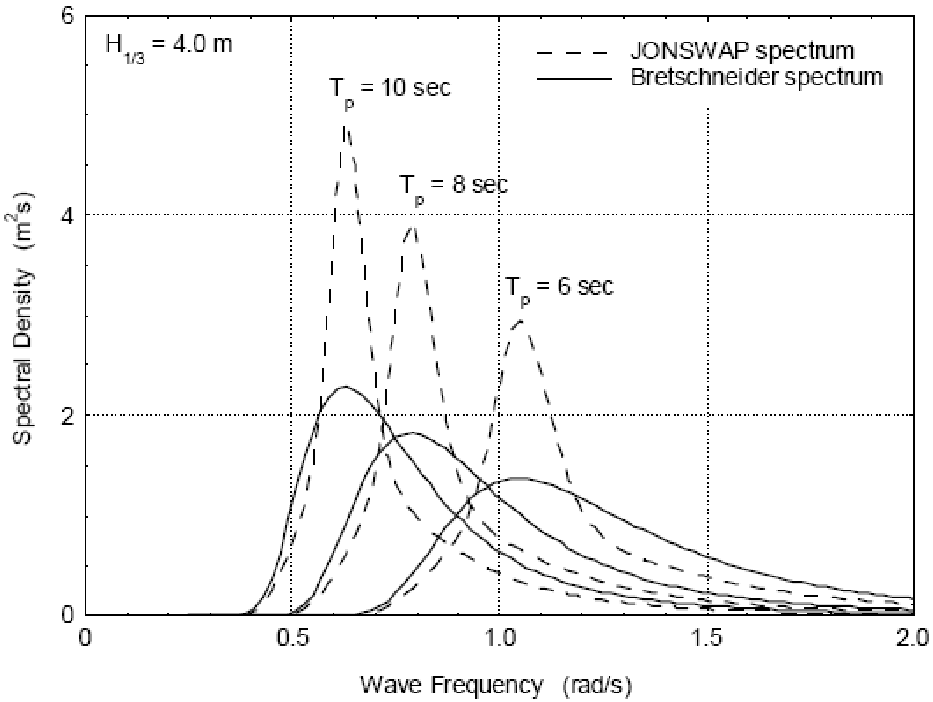
$$T_p = 1.199T_1 = 1.287T_2$$

Wave energy and its propagation

- **For example, the JONSWAP energy spectrum:**
  - *Comparison with Brestscheider spectrum (for fully developed seas)*

IF: γ^A=1.522

JONSWAP=Bretsch.



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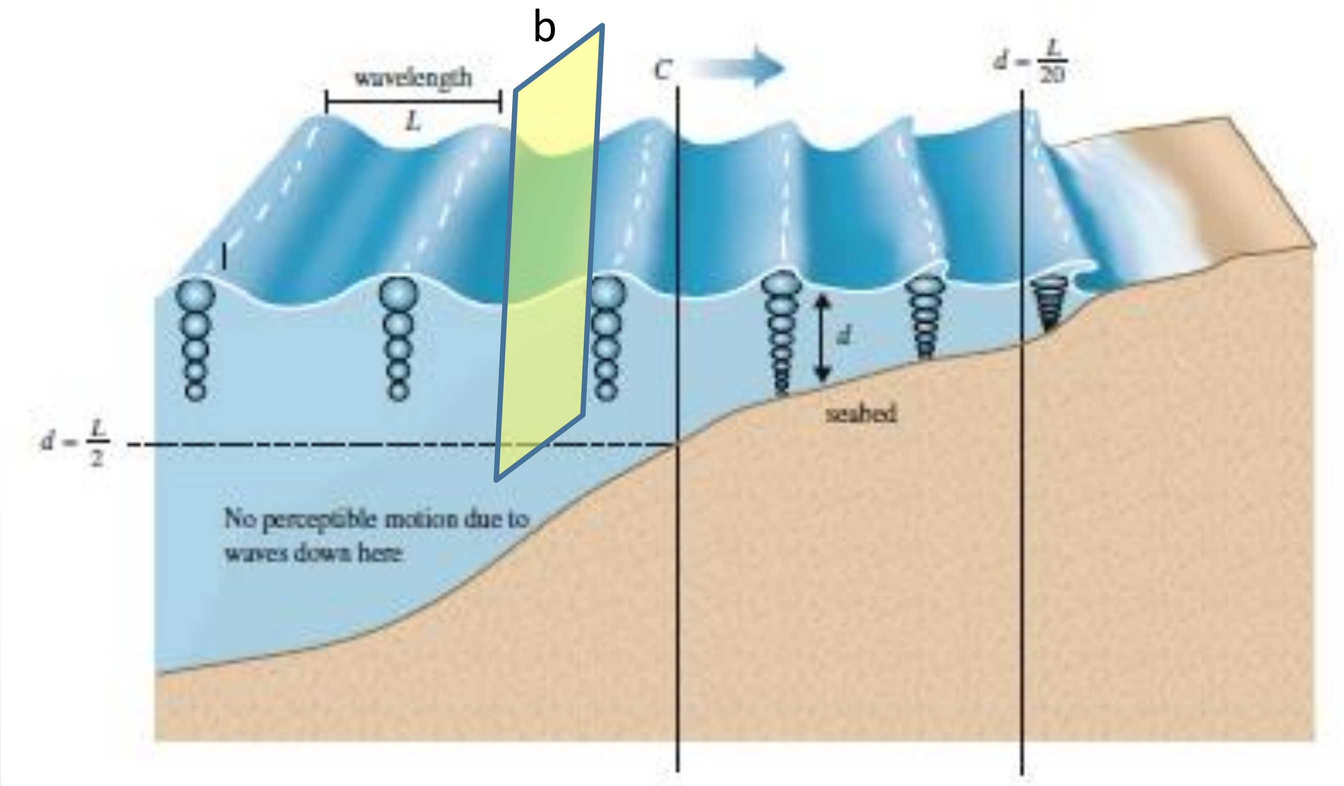
Wave energy and its propagation

We saw that:

$$power = \frac{1}{2}\rho g A^2 c_g b \quad \text{(W)}$$



Wave power in irregular waves (real sea)

For a regular wave:

$$\bar{W}/_b = \frac{1}{2}\rho g A^2 c_g \quad \text{(W/m)}$$

with:

$$c_g(\omega) = \frac{c}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)$$

Thus, for a given sea state (wave spectrum):

$$\overline{W_s}/_b = \int_0^\infty \frac{1}{2}\rho g A^2(\omega) c_g(\omega) d\omega \quad \text{(W/m)}$$

$$\overline{W_s}/_b = \rho g \int_0^\infty S(\omega) c_g(\omega) d\omega \quad \text{(W/m)}$$

Wave power in irregular waves (real sea)

For practical purposes, a simpler statistical measure is usefull:

$$\overline{W_s}/_b = \frac{1}{2}\rho g A_{1/3}^2 \, c_g(\omega_p) \quad \text{(W/m)}$$

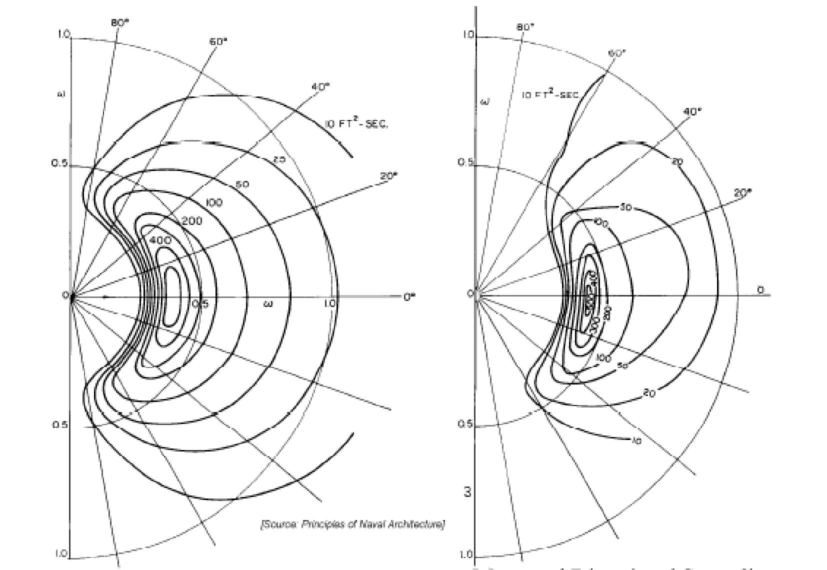
or:

$$\overline{W_s}/_b = \frac{1}{8}\rho g H_{1/3}^2 \, c_g(\omega_p) \quad \text{(W/m)}$$

...from which statistical wave data (metocean data) for a given location can be easily applied for a prediction of its wave power potential

Wave energy and its propagation

- **Spread of wave energy in direction:**
  - *In a real sea, there will always be some spreading of energy (power) in diferent wave directions;*
  - *Directional wave spectrum:* $S(\omega,\theta) = S(\omega)G(\theta)$
    - *Example: cosine-squared model:*



Cosine-Squared Spreading   Measured Directional Spreading

$$S_\zeta(\omega,\theta) = \left\{\frac{2}{\pi}\cos^2(\theta - \bar{\theta})\right\} S_\zeta(\omega)$$

$$-\frac{\pi}{2} \le (\theta - \bar{\theta}) \le \frac{\pi}{2}$$

Wave energy and its propagation

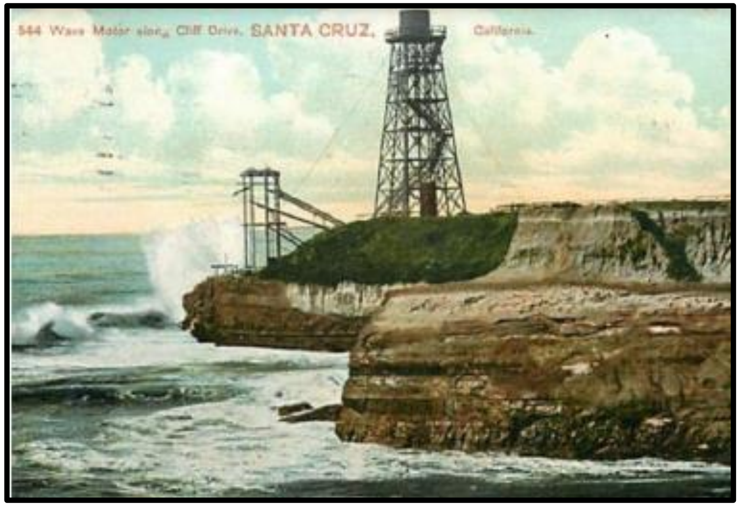
- **In open sea, wave direction is usually** **highly variable** (local wind direction and swell coming from distant regions)...
- **Near the shore** (shallow waters), waves undergo *refraction* and tend to align with the shore line...

... in this case, at least, the **wave direction is more stable** and known in advance;

Also, the **directional energy spreading is reduced** as the waters get shallower.

WECs: some history

- The idea goes way back in time:
  - **In 1799 – Girard pere et fils**, in France, proposed the use of a raft to convert wave energy into mechanical energy (first patent) !!
  - Other experiments took place during the 1800s:



The Santa Cruz wave-motor experiment

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

  - **Modern advances** came through mainly **after the oil crisis in the 1970s;**
  - **By the early 1980s** there were already **more than 1000 patents [7]!**

WECs: some history

- During the 1970s and 1980s, some of the main developments happened in Europe (Scotland, Norway) and Japan.

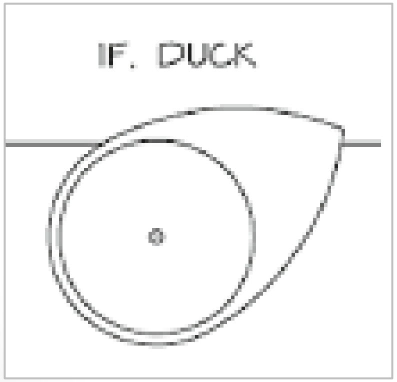
- Special note must be given to the work of Prof. Stephen Salter, and the development of the Salter’ Duck…

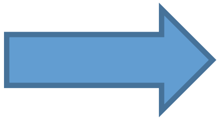
A rotating floating device that would extract the *wave energy from the wave flow*

- ...and the history of this development is quite illustrative of the principles, challenges and drawbacks of many modern WEC devices.

WECs: some history

- There are many reasons why rotating devices would be preferable over translating ones (see, e.g., [8]):
  - Less energy dissipation
  - Don’t require stops
  - Easier to seal
  - Less maintenance
- With the help of small-scale models in a wave flume (2D), they devised an optimum hydrodynamic shape (the duck):

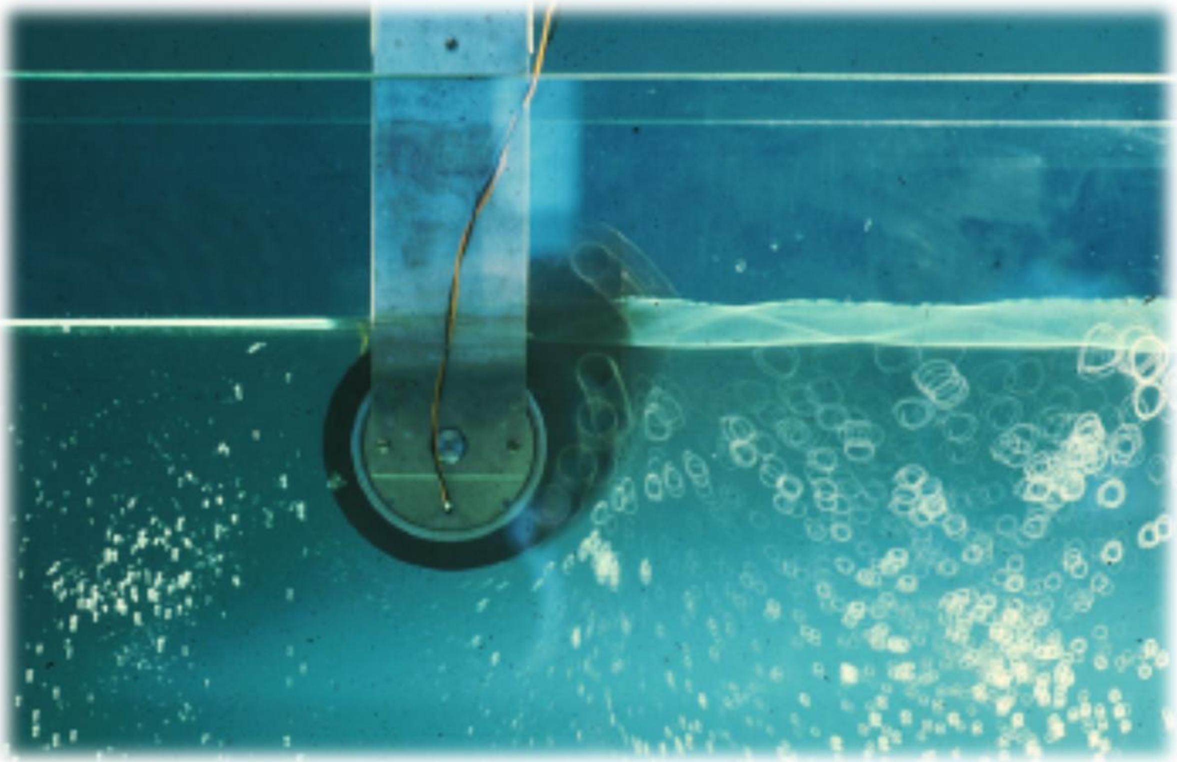




90% efficiency in absorbing wave power!!

WECs: some history

- The "trick" of the shape was to follow the exponential decay of wave action with depth…



Source: Salter, S. (2016) [8]

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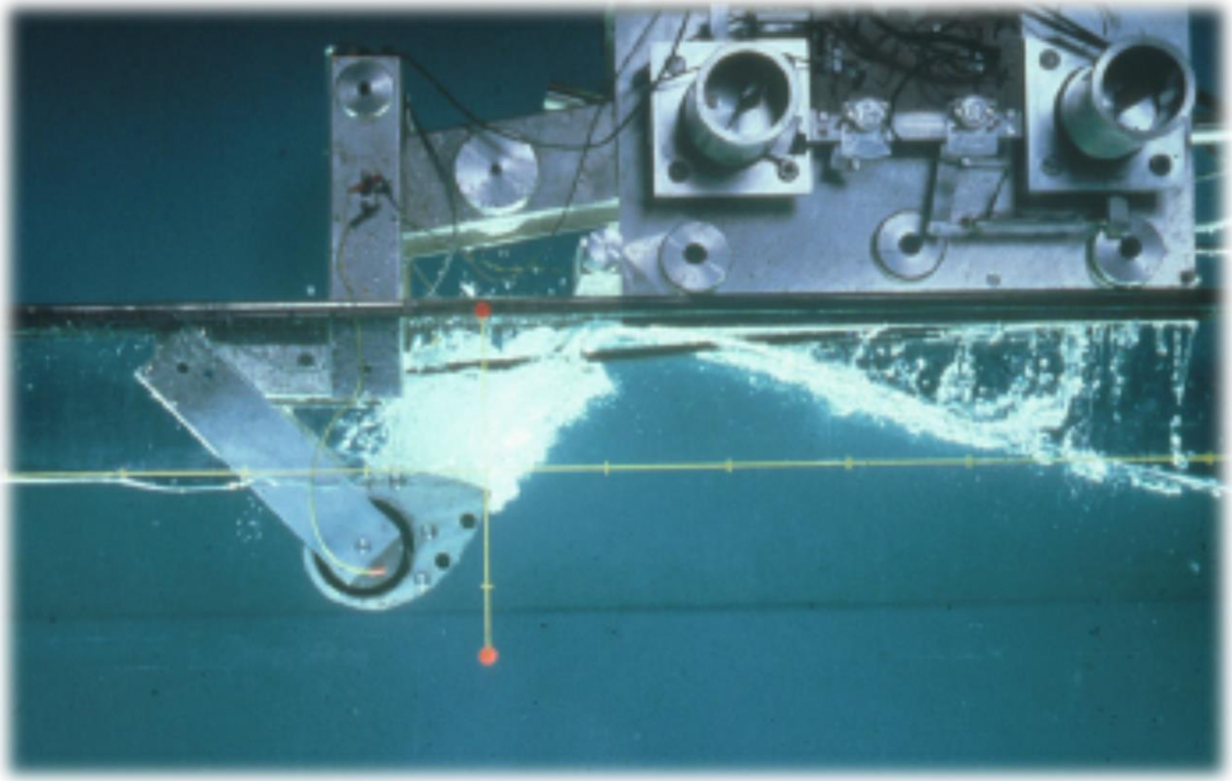


Source: Salter, S. (2016) [8]

WECs: some history

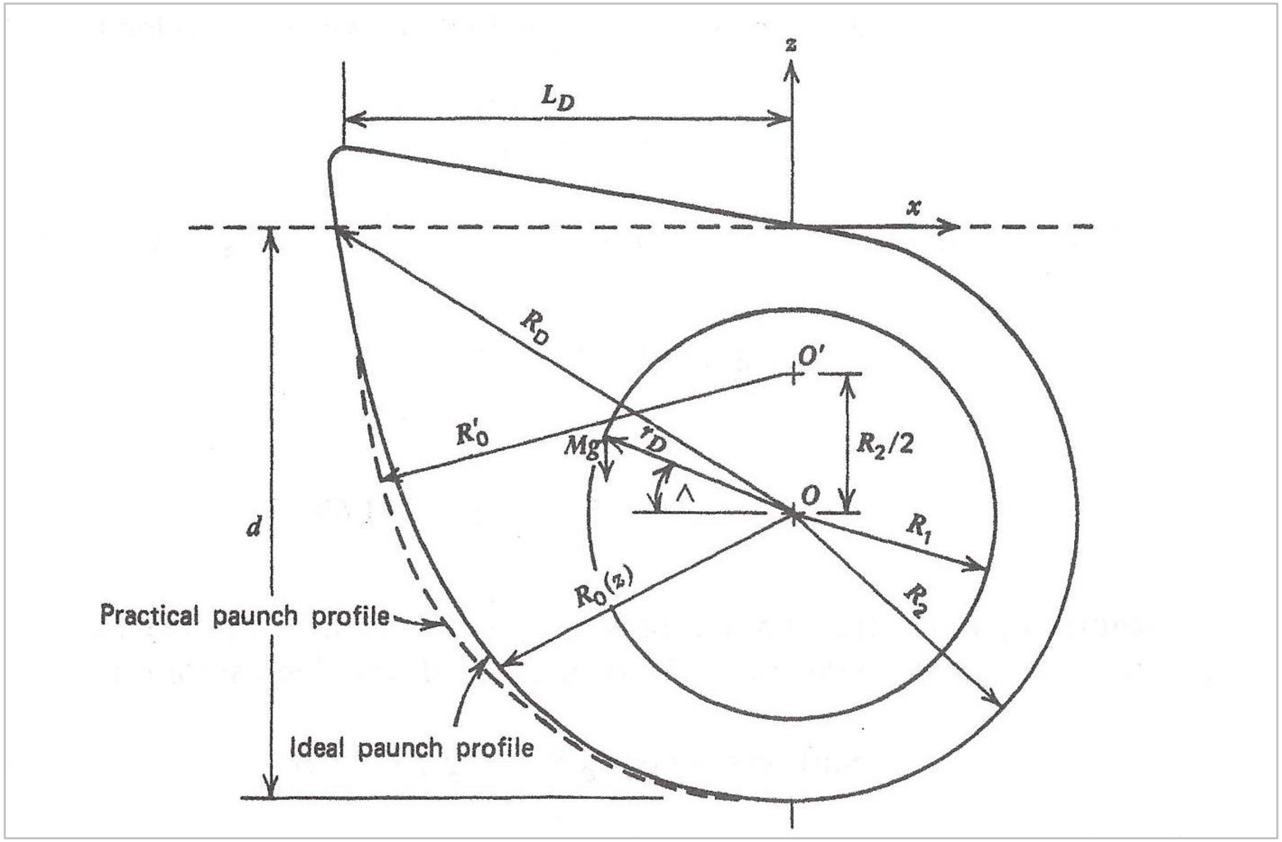
- In order to maximize motions, another common feature of the WECs is to *tune natural period of motion (in the duck's case, pitch) to the incoming wave period*...

$$T_{n,pitch} = 2\pi \sqrt{\frac{inertia}{stiffness}} = T_{wave}$$

WECs explore RESONANCE!

WECs: some history

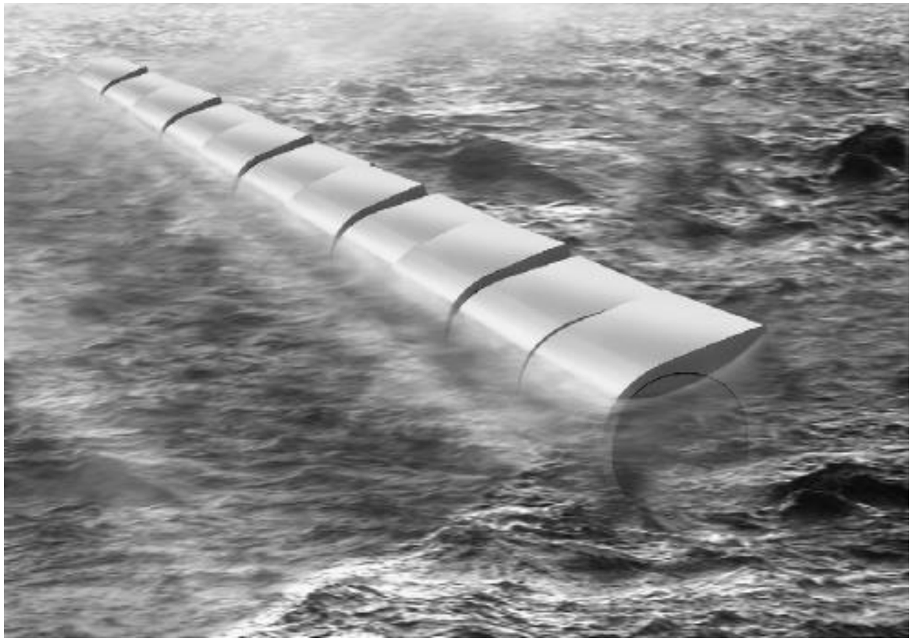
- The geometry of the duck was designed in order to maximize the absorption of the wave flow:



Source: McCormick, ME. Ocean Wave Energy Conversion [7]

WECs: some history

- Floating devices (cylindrical spines) were devised for holding an array of ducks and augment the wave power extraction in sea



Source: Falnes, J. (2007) [9]

- The duck's relative motions would drive a hydraulic power take-off mechanism.

WECs: some history

- However:

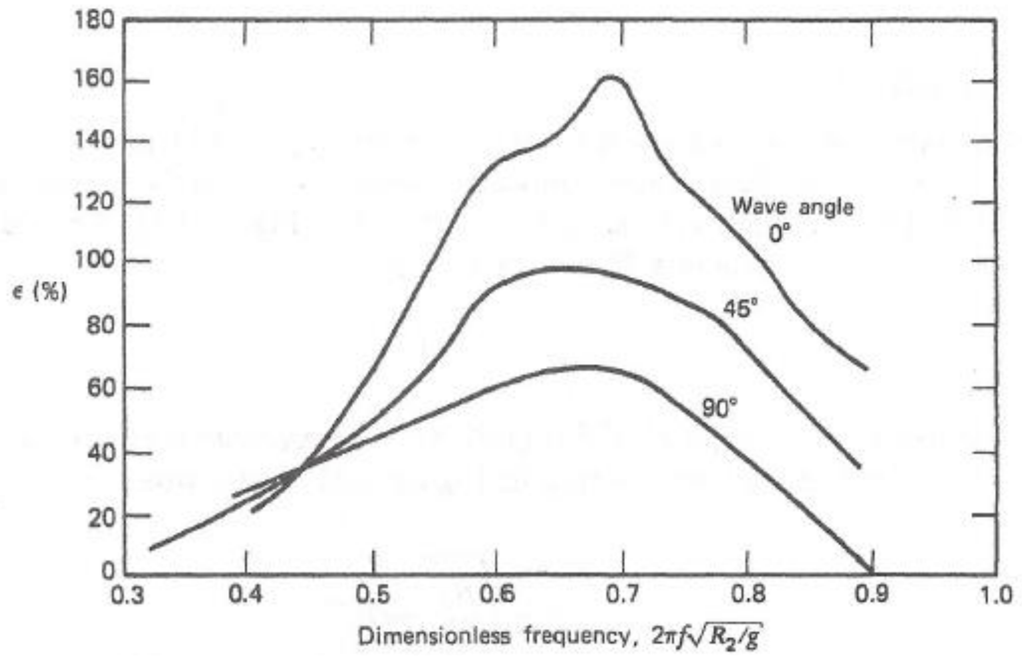
> "The change from testing in regular waves to more realistic irregular ones with a Gaussian distribution of wave amplitudes is an unpleasant experience for wave inventors." [8]

  - Many drawbacks made the **efficiency of the real device drop** (see [7]), mainly:
    - Wave frequency spread
    - Variability in wave direction
    - The dynamic effects induced by **mooring** devices...

  - which ultimately threatened *economical* viability of the devices.

WECs: some history

- Effect of wave frequency and direction on the energy absorption efficiency:

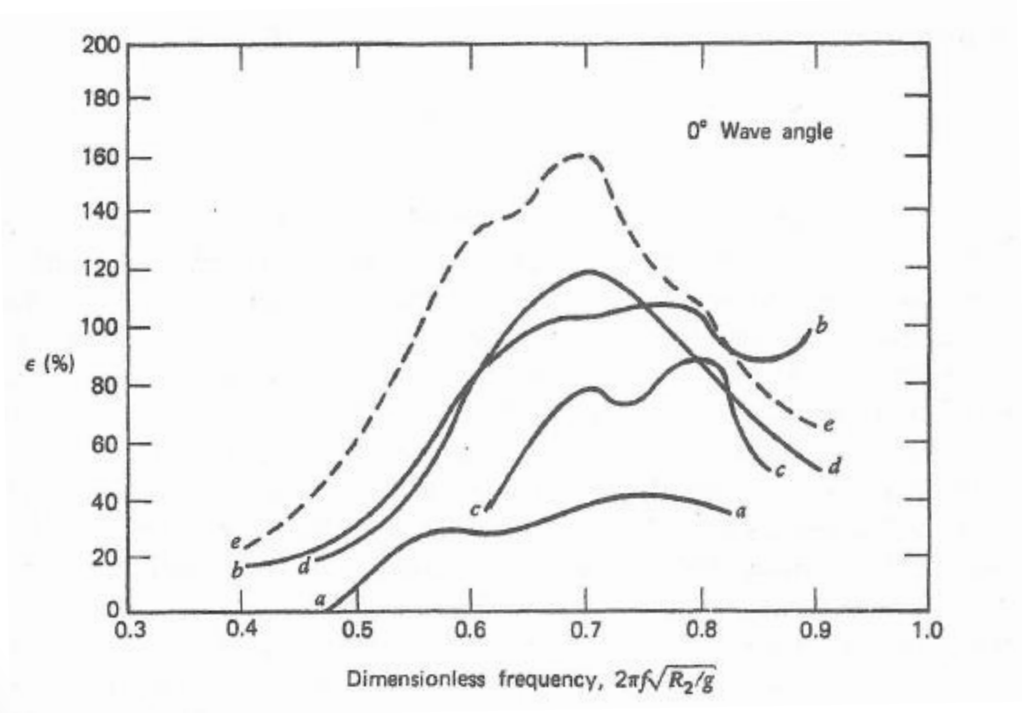


Note: Efficiencies larger than 100% measured in the tests result from interaction between incident and radiated waves

Source: McCormick, ME. Ocean Wave Energy Conversion [7]

WECs: some history

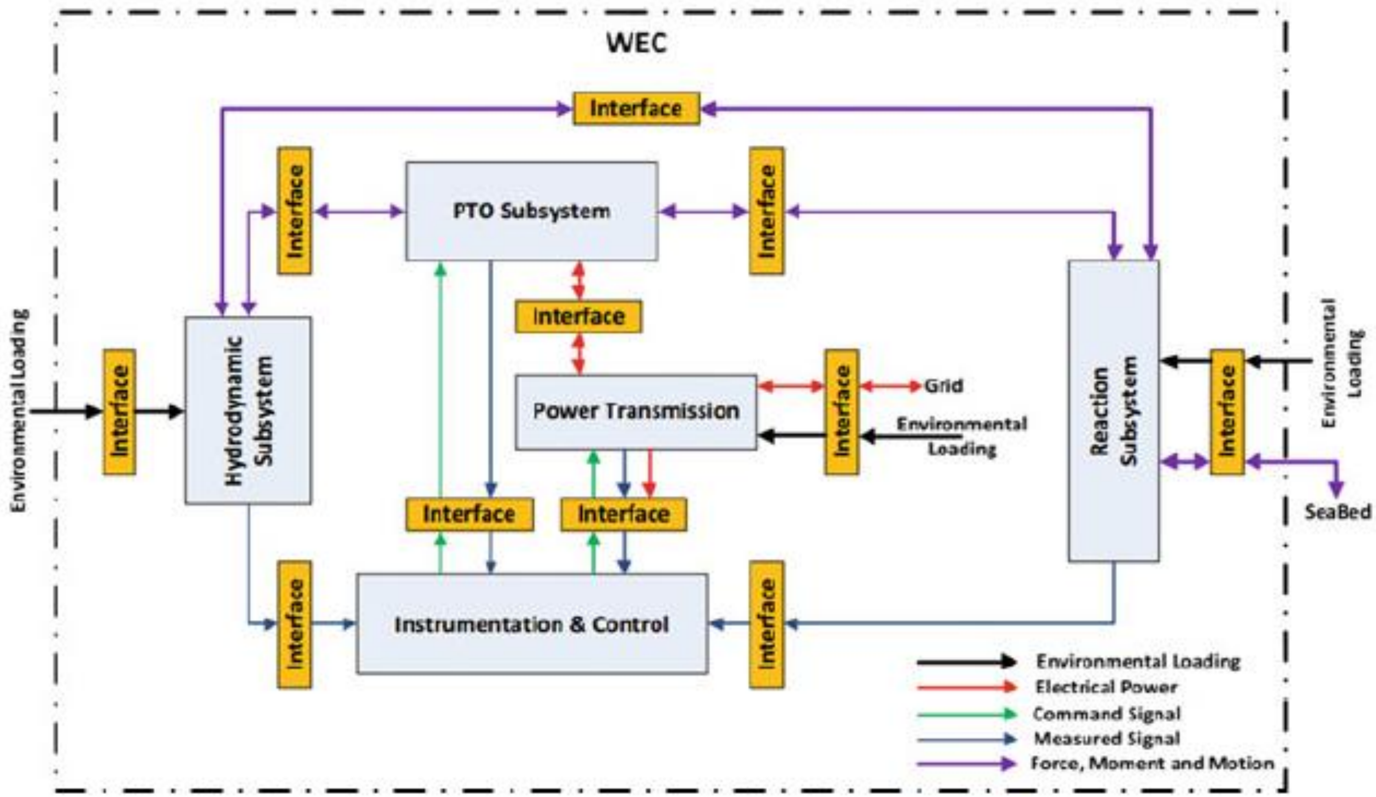
- Effect of mooring dynamics on the energy absorption efficiency:



a – slack moorings
b – chain taut moorings
c – single taut moorings
d – four chain taut
e – rigid frame

Source: McCormick, ME. Ocean Wave Energy Conversion [7]

WECs: basic features and main types



WEC system design breakdown

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

WECs: basic features and main types

- Some rule-of-thumb figures for comparing the main categories of WECs can be given.
- Regarding the wave power absorption efficiency, an **indicative capture ratio** is provided below (according to [4]):

WEC type	Capture width ratio (%)
Floating overtopping device	17
Oscillating water column	29
Point absorber	16
Pitching flap (bottom fixed)	37

WECs: basic features and main types

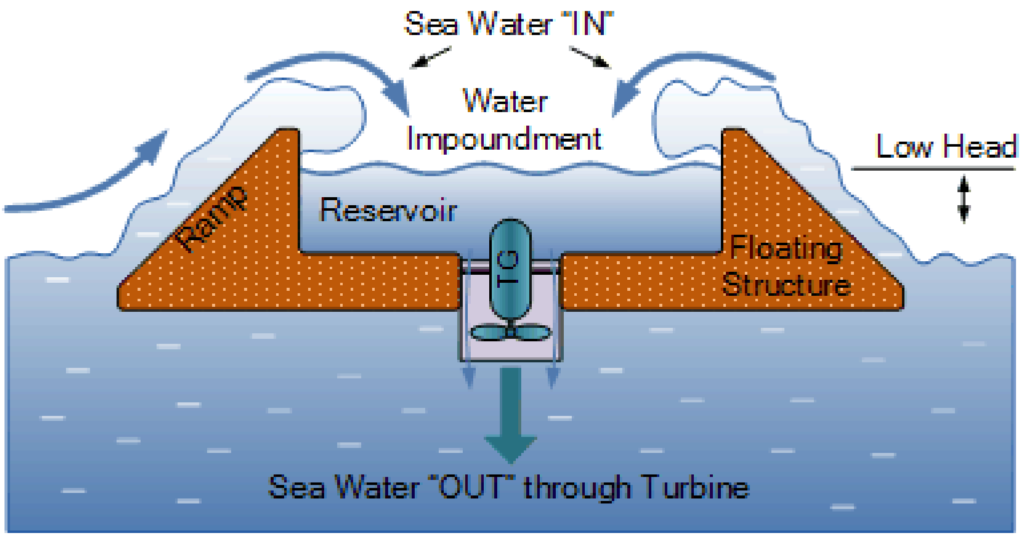
- There are numerous concepts of WECs (*remember there are thousands of patents by now!!*).

- The pitching flaps resemble the nodding duck, so next we will review the main features and examples of:
  - **Overtopping devices**
  - **Point absorbers**
  - **Oscillating Water Columns (OWCs)**

- For a more extensive review, students may refer to the suggested references, mainly [4], [7] and [9]

WECs: basic features and main types

- **OVERTOPPING DEVICES**
- **Principle**: wave runs-up a structure, embarks and then flows out running a hydro-power turbine.
- For this sort of WEC, much more complicated hydrodynamics must be used to predict the run-up and amount of water taken in.



Source: *blackfishengineering.com*

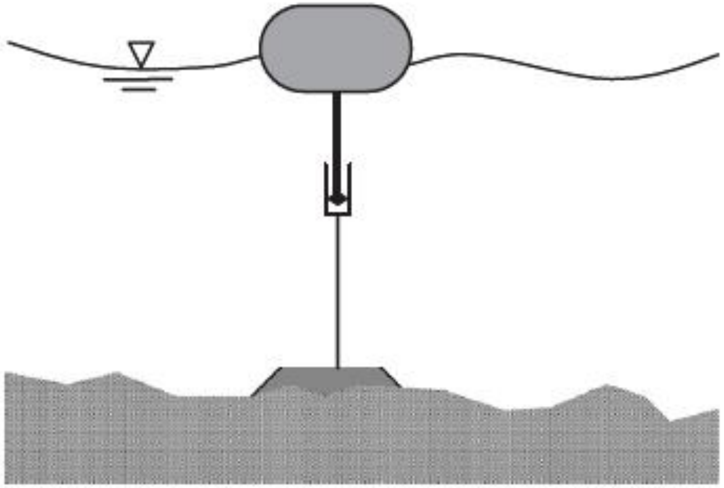
WECs: basic features and main types

- **OVERTOPPING DEVICES**
- **Example**: The *Wave Dragon* – 1:4.5 scaled grid-connected prototype tested in Denmark

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

WECs: basic features and main types

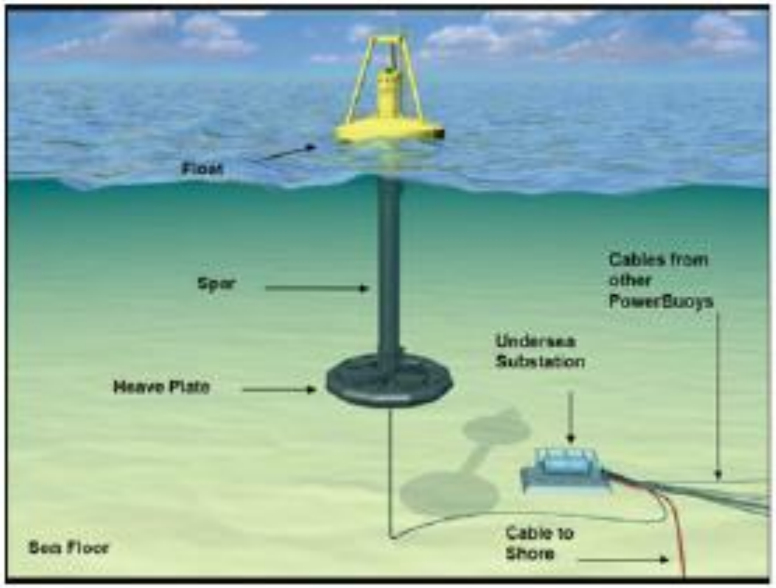
- **POINT ABSORBERS**
- **Principle**: A floating device explores the potential wave energy to excite motions (preferably resonant) and run a PTO system (e.g., a hydraulic pump)



Source: Falnes, J. (2007) [9]

WECs: basic features and main types

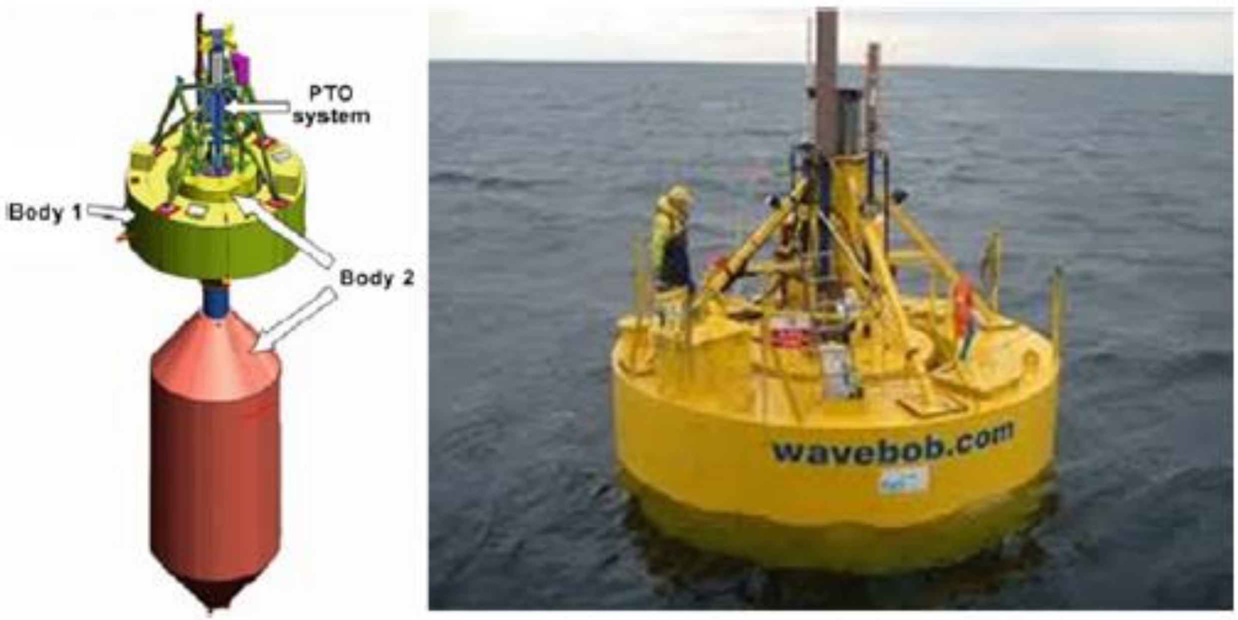
- **POINT ABSORBERS**
- **Example**: OPT's Powerbuoy PT40 (40kW)



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

WECs: basic features and main types

- **POINT ABSORBERS**
- **Example**: The *Wavebob*



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

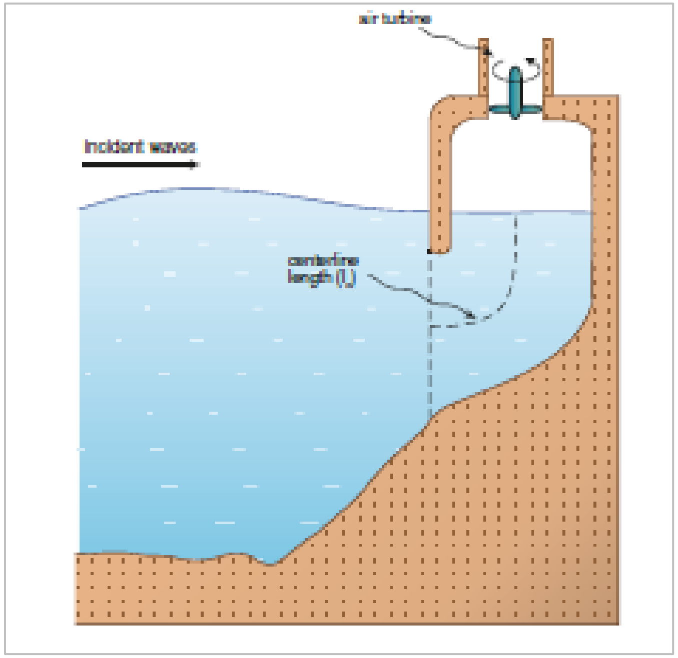
WECs: basic features and main types

- **POINT ABSORBERS**
- **Example**: Wave energy converter prototype installed at Pecém port, northern Brazil

WECs: basic features and main types

- **OSCILLATING WATER COLUMN (OWC)**
- **Principle**: wave resonance in a cavity/moonpool moves an air column; a double-action turbine (e.g. Wells type) converts kinetic energy of the high velocity air flow into electrical energy.

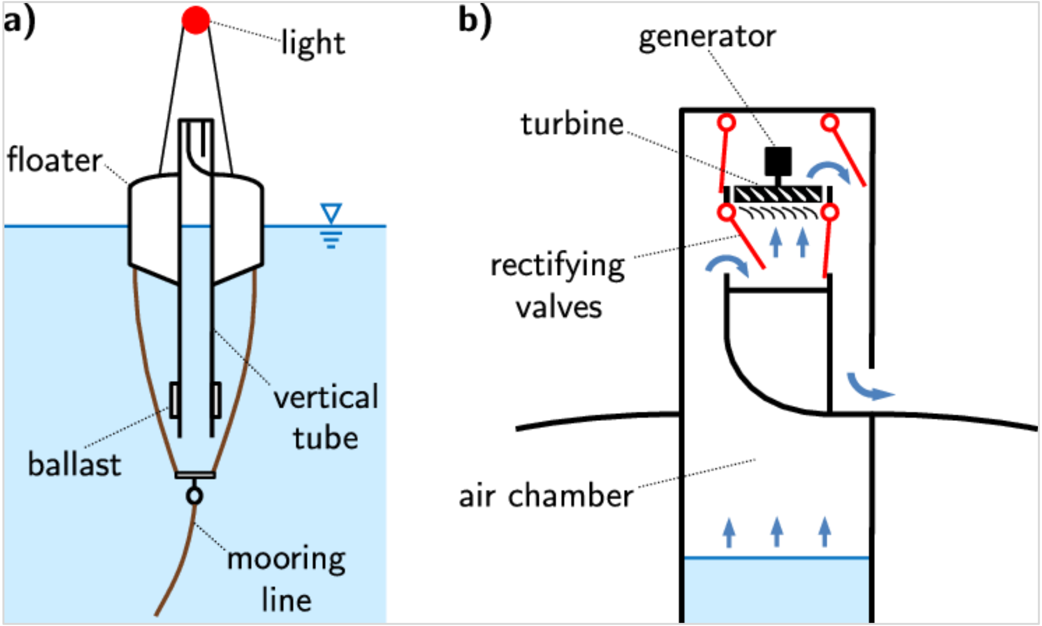
Resonance of the water column motion is also explored for increasing power



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

WECs: basic features and main types

- **OSCILLATING WATER COLUMN (OWC)**
- **History**: Thanks to the work of Yoshido Masuda in the 1960's, a small-scale power OWC was used in many commercial buoys (first example of commercial application)



Source: *Henriques J.C.C. et al.* [10]

WECs: basic features and main types

- **OSCILLATING WATER COLUMN (OWC)**
- **History**: He was also involved in JAMSTEC's *Kaimei* experiments (1st round 1978-1979, 2nd round 1985-1986), in which many OWC chambers were mounted on an 80m long ship-shaped barge, moored northwest of the town of Yura (40m depth).

Source: *Falcão, A.F.O and Henriques J.C.C. (2016).* [11]

WECs: basic features and main types

- **OSCILLATING WATER COLUMN (OWC)**
- **Recent Example**: OceanLynx, Australia

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

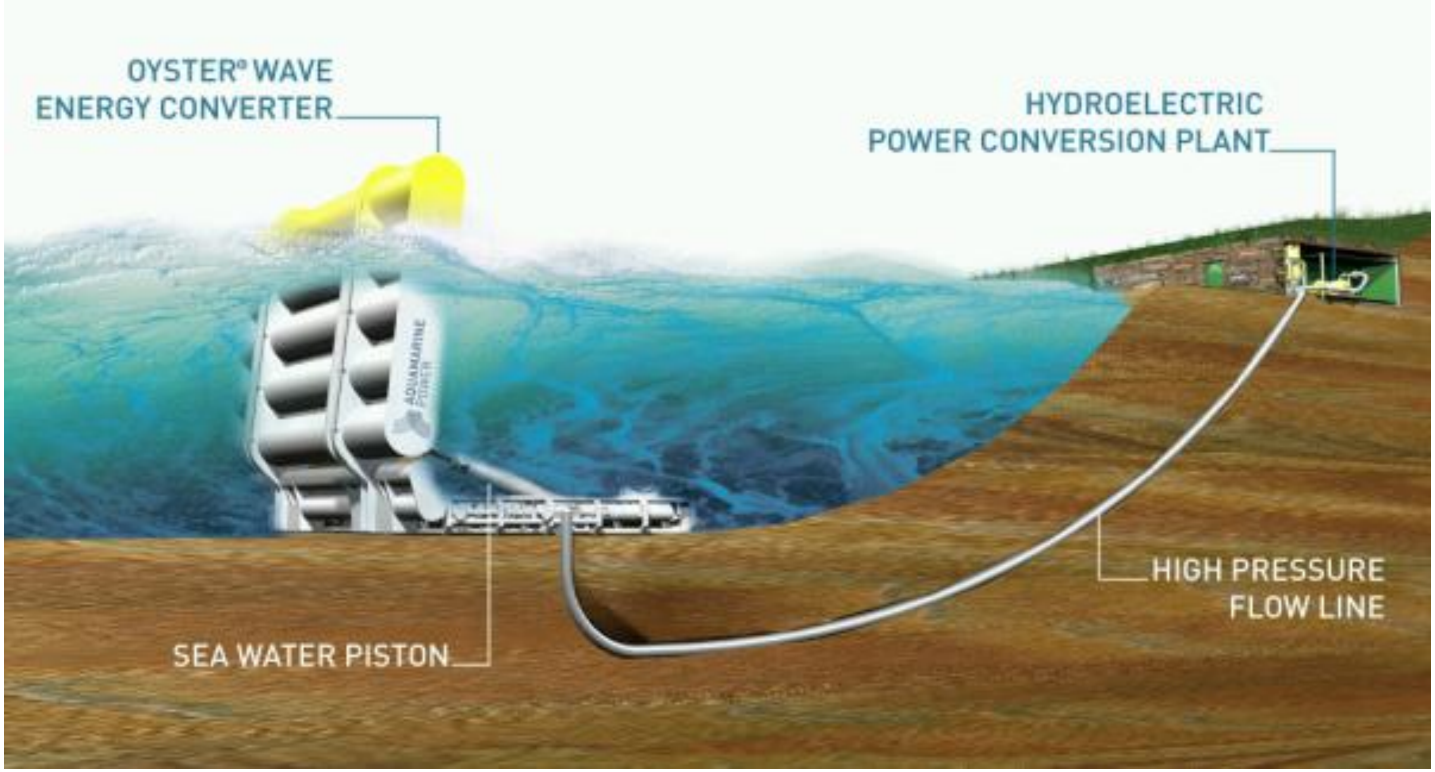
WECs: basic features and main types

- **OSCILLATING WATER COLUMN (OWC)**
- **Recent Example**: Oceantec's MARMOK-A-5, SPAIN (5m diameter, 42 meter draft floating OWC being tested at BIMEP testing site in Biscay bay)

Source: *tecnalia.com*

WECs: basic features and main types

- **PITCHING FLAPS**
- There are many recent examples on this kind of device



Ex: Oyster ®

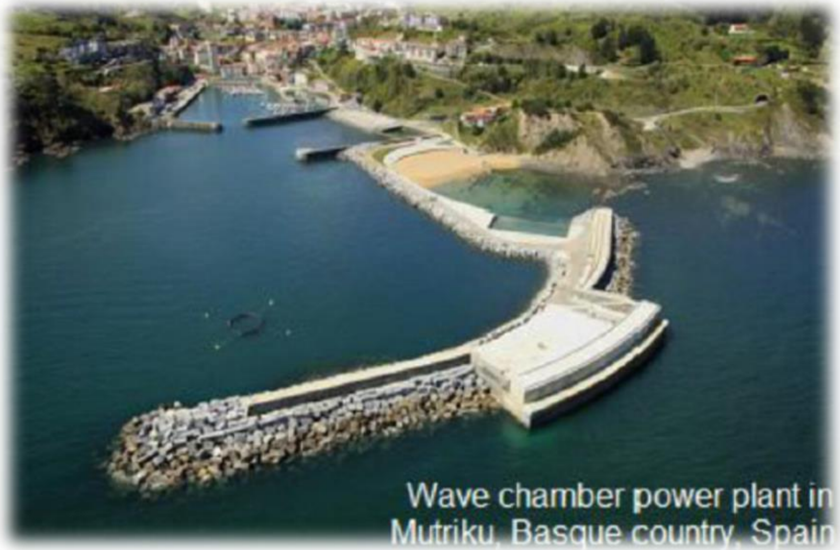
WECs: basic features and main types

- **OTHER TYPES OF WECs**
- Include a large range of devices, such as:

Ex: Pelamis ®

Recent trends and perspectives

- According to a recent analysis by Stephen Salter [8]: "*The challenge eventually must be to reduce costs of wave energy by a factor of about two*."
- Fixed coastal structures have a better cost prospective, but are more prone to face problems with environmental aspects. A promising policy seems to be joining this devices to existing breakwaters, as for example:



Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

Recent trends and perspectives

- New PTO technologies are in continuous development, with the main goal of reducing wave energy costs. More advanced examples include the application of piezoelectric materials, among other techniques.

- Floating devices still struggle with costs, which in this case also include **offshore maintenance, moorings and power cable to the shore**. Apparently, there is a trend in favor of floating OWCs.

Recent trends and perspectives

- A promising strategy for floating devices seems to be their application in **hybrid offshore power plants** (floating wind turbines + WECs), which attenuates the relative costs for the WEC.

Floating Power Plant: multiple Point Absorbers in Vindeby's offshore wind farm (Denmark)

Source: *Pecher, A. & Kofoed, J.P. (editors), Handbook of Ocean Wave Energy* [4]

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