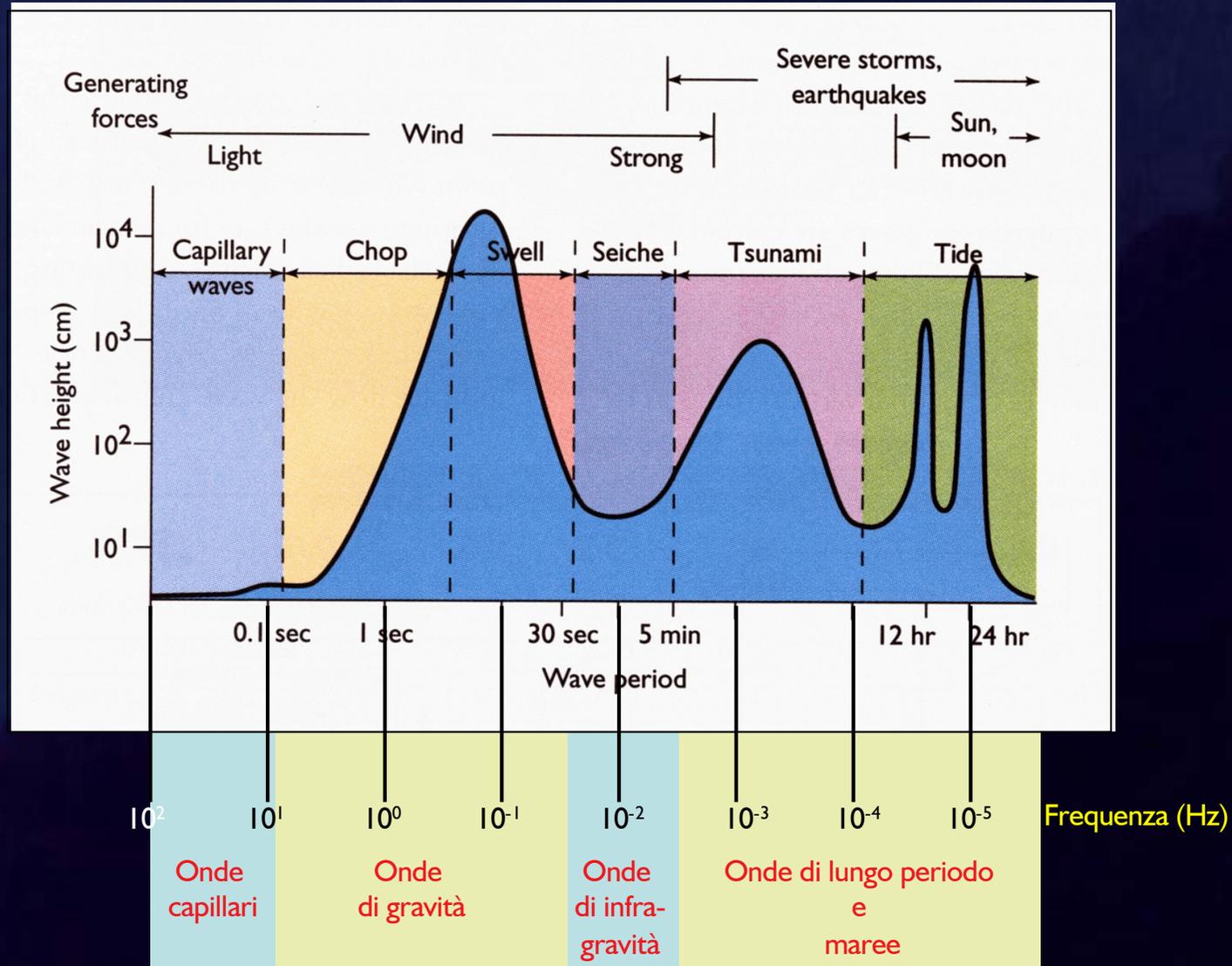


A large, curling ocean wave with white foam, under a clear blue sky. The wave is the central focus, showing its characteristic barrel shape. The water is a deep blue, and the sky is a clear, bright blue. The text 'MOTO ONDOSO' is overlaid in the center of the image.

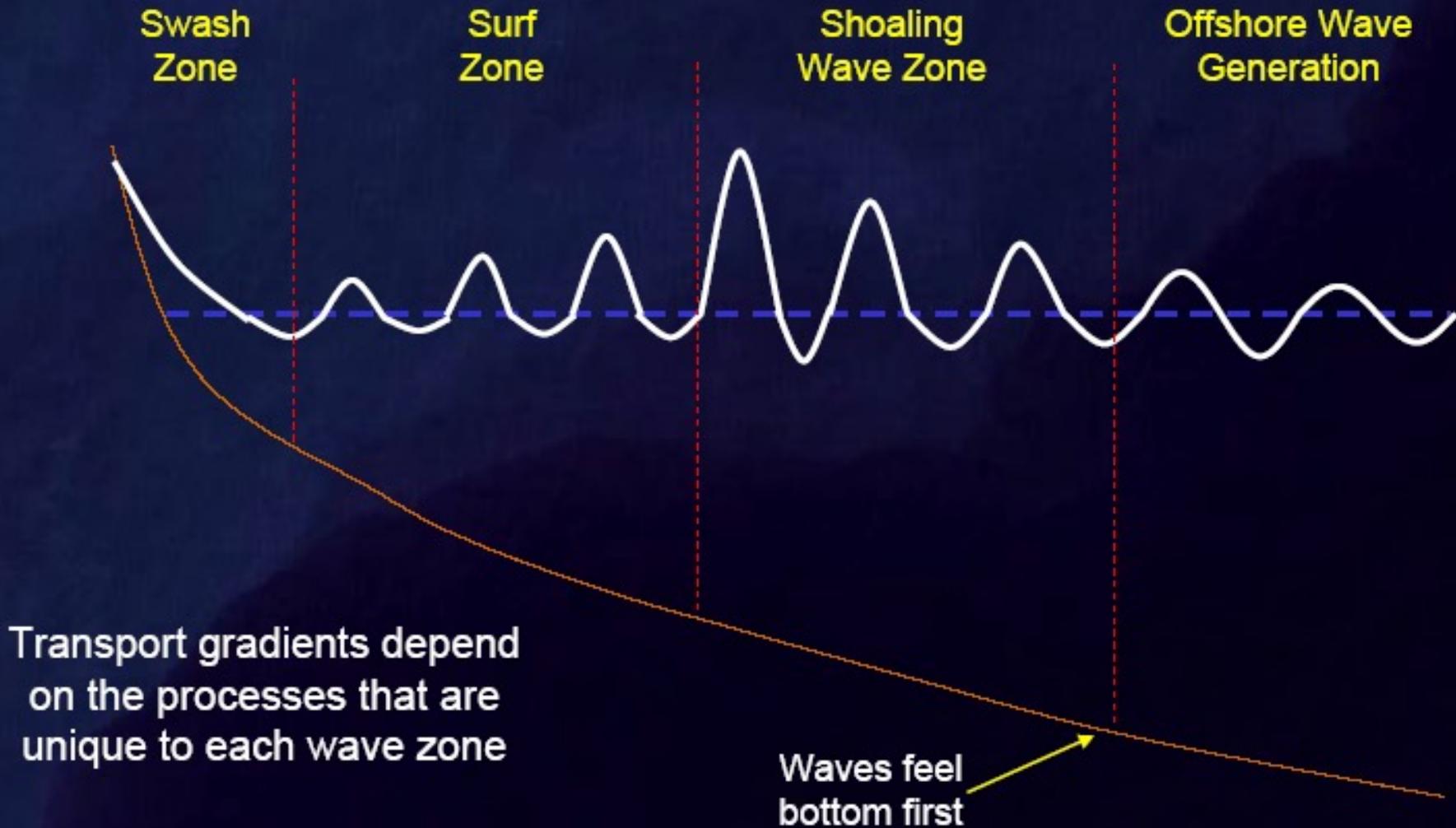
MOTO ONDOSO

Distribuzione dell' energia d' onda

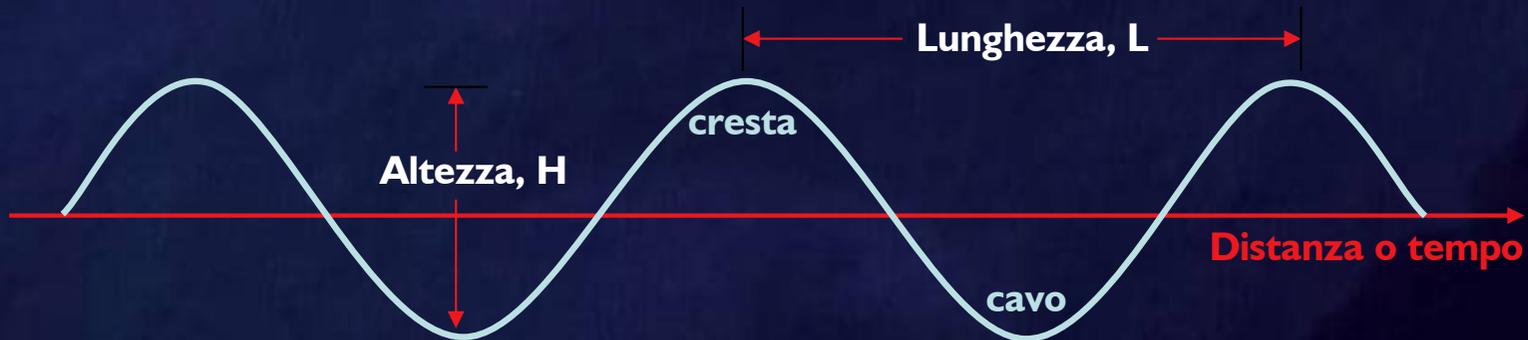
In oceano in funzione del periodo (o frequenza) d' onda



Wave Zones



Parametri d' onda



- **Ampiezza** (a) = Semi-altezza ($H/2$)
- **Periodo** (T) = Tempo impiegato da una cresta d'onda per percorrere la lunghezza d'onda L (unità: tempo)
- **Frequenza** (f) = Numero di creste per unità di tempo che passano in una posizione fissa (unità: $1/T$ o T^{-1})
- **Velocità** (C) = Distanza percorsa da una cresta per unità di tempo (unità: spazio/tempo = L/T)

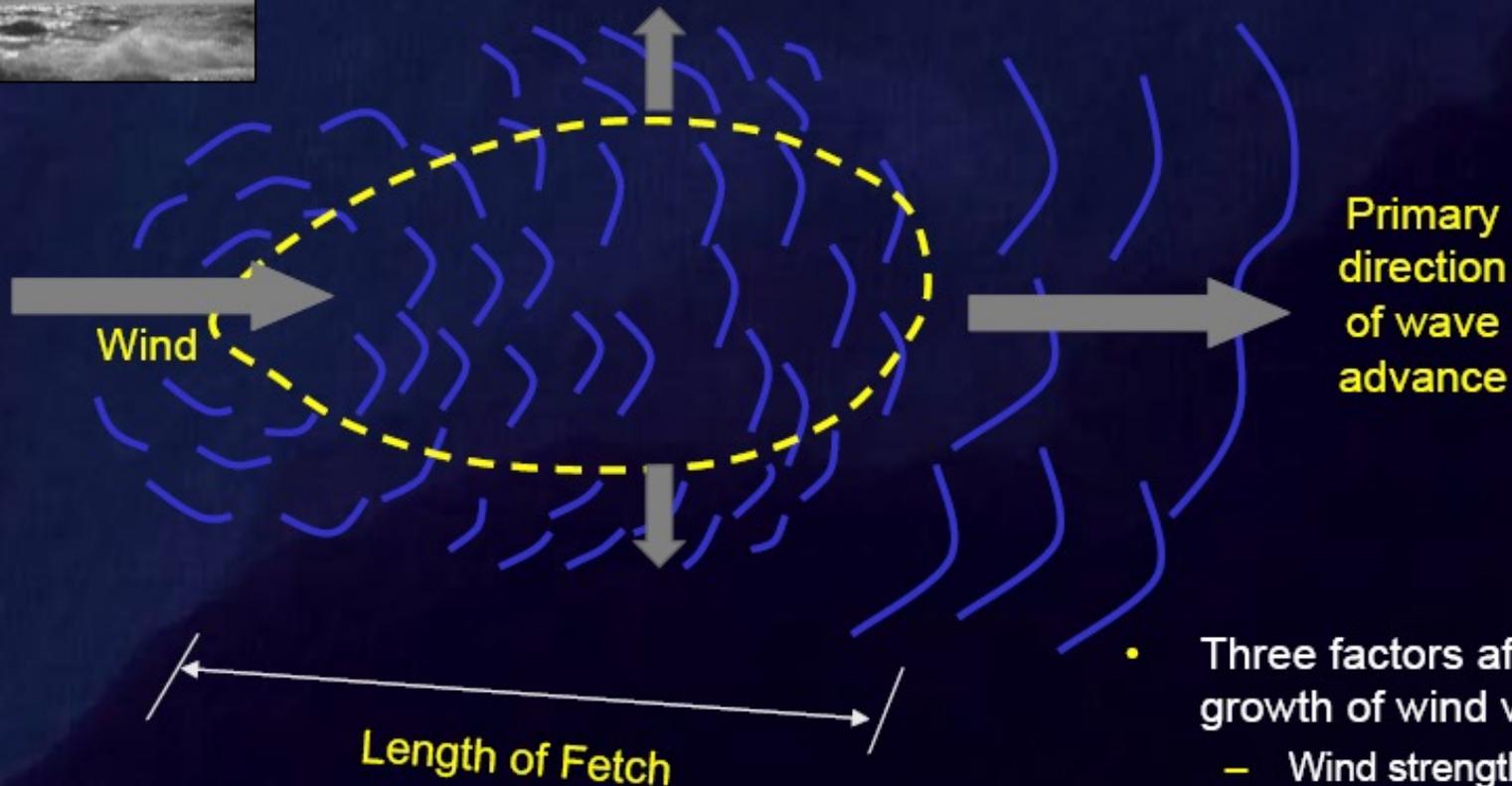
Wave Growth



Ripples to chop
to wind waves

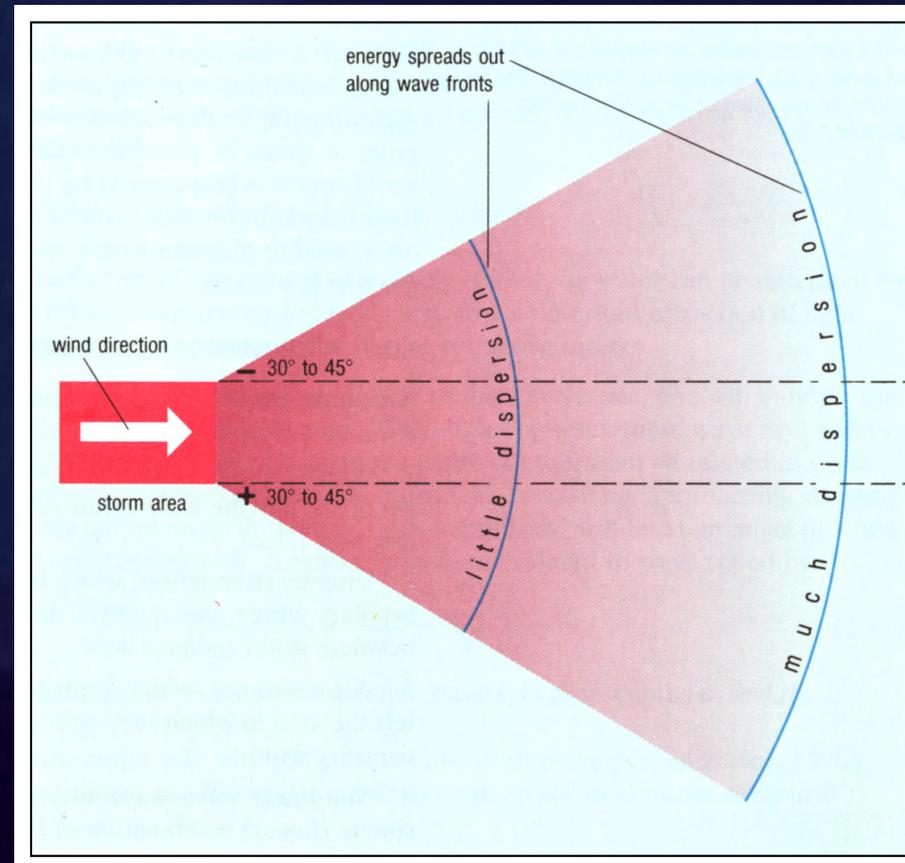
Fully Developed
Sea

Changing to
Swell: Dispersion



- Three factors affect the growth of wind waves:
 - Wind strength
 - Wind duration
 - Fetch length

Lateral Spreading of Wave Energy from a Storm Source



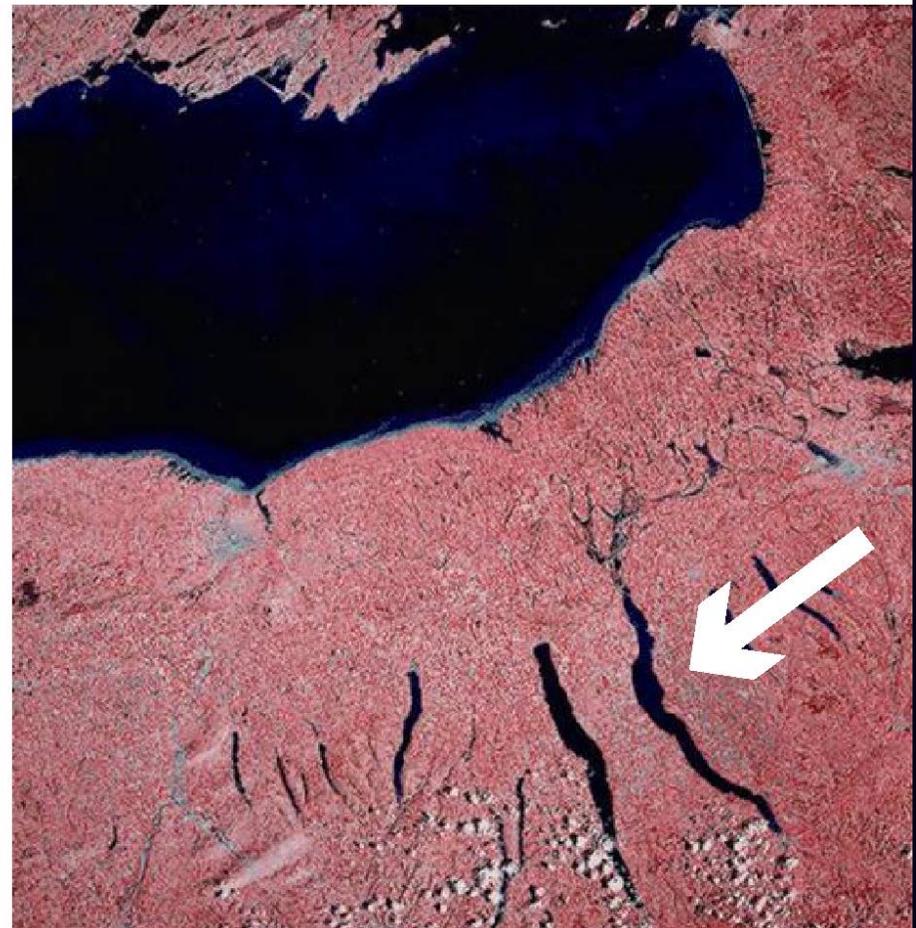
(95% of Energy Contained Within $\pm 45^\circ$ of Storm Direction)

The Importance of Fetch

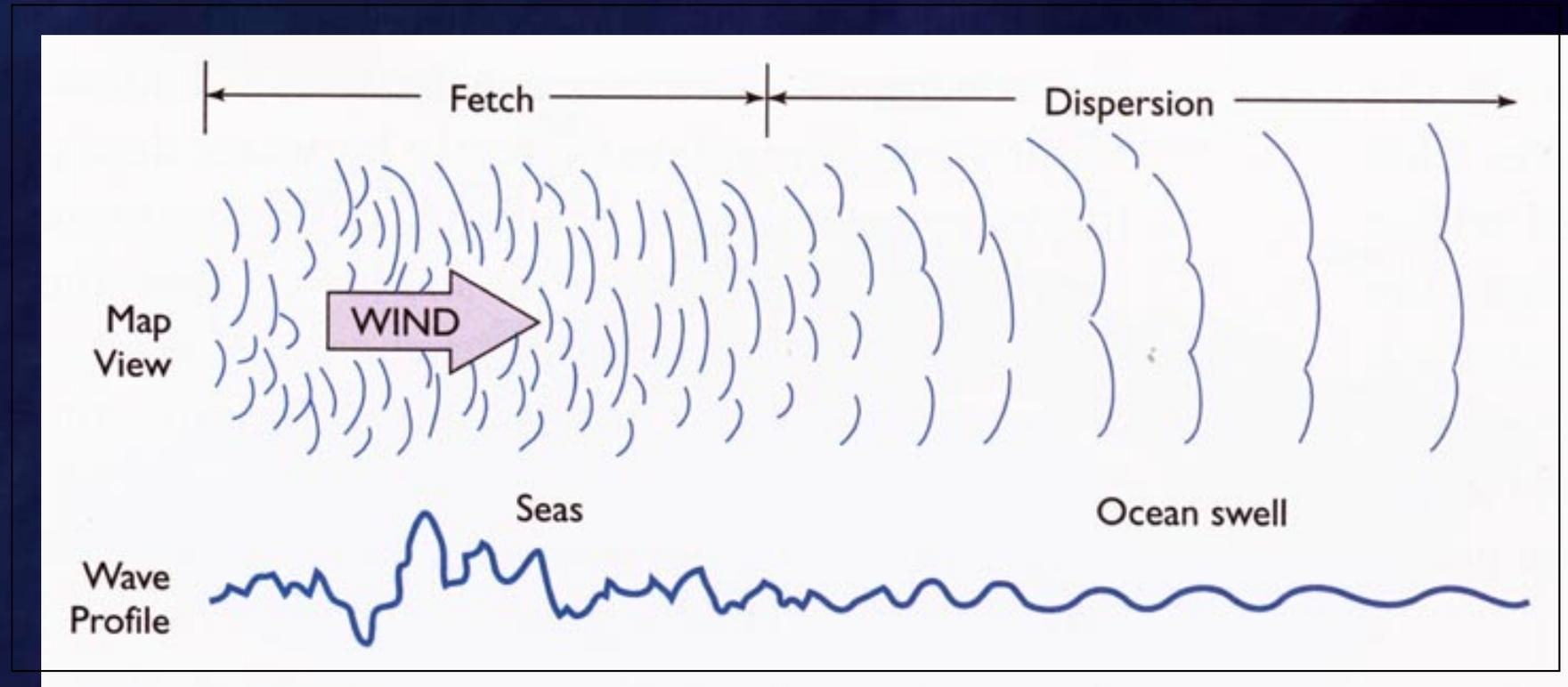
**Northly Wind:
Long Fetch along Finger Lakes**



**Easterly Wind:
Short Fetch along Fingerl Lakes**



Wave Dispersion: Self Sorting of *Deep-Water* Waves Leaving a Storm Region based on Wavelength. It Occurs Because Longer Wavelength Waves Travel Faster than Shorter Wavelength Waves (*for Deep Water*).



Transformation at Sea

- **Directional spreading**
- **Dispersion**
 - Waves of different length travel at different speeds
- **Friction with continental shelf**
 - Energy of the largest waves dissipated through friction with bed
- **Viscous dissipation**
 - Energy within the waves is dissipated through viscosity
- **Wave interference**
 - additive and constructive interference creates wave groups

Question: why are waves along the Gulf Coast smaller than along the Atlantic Coast?

Dispersion

- Waves of different length travel at different speeds
- In deep water the wavelength (**L**) and wave celerity (**C**) are proportional to the wave period (**T**):

$$L = \frac{gT^2}{2\pi}$$

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

These equations
are only valid for
deep water



Photography AcclamImages.com Photography

When should I go surfing: before or after a storm passes the coast?

Before: the large swell (surfing) waves hit the coastline first

Teoria dell'onda lineare (Airy)

Equazione di dispersione
(relazione tra L e T)

$$\omega^2 = g k \tanh(kd)$$

dove:

$$k = \frac{2\pi}{L} =$$

numero d'onda

$$\omega = \frac{2\pi}{T} =$$

frequenza angolare

Trasformando:

$$\frac{(2\pi)^2}{T^2} = \frac{g \cdot 2\pi}{L} \tanh\left(\frac{2\pi d}{L}\right)$$

Teoria dell'onda lineare (Airy)

$$\frac{(2\pi)^2}{T^2} = \frac{g \cdot 2\pi}{L} \tanh\left(\frac{2\pi d}{L}\right)$$

Da questa possiamo derivare le relazioni tra k, L e c

$$L = \frac{g \cdot T^2}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)$$



$$\frac{L}{T} = c = \frac{g \cdot T}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)$$

$$\frac{L^2}{T^2} = c^2 = \frac{g \cdot L}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)$$

Velocità di propagazione

$$c = \frac{\text{Lunghezza, (L)}}{\text{Periodo, (T)}}$$

Matematicamente si esprime mediante:

$$c^2 = \frac{g \cdot L}{2\pi} \cdot \tanh \frac{2\pi d}{L}$$

g = acc. gravità, 9.81 ms^{-2}

d = profondità

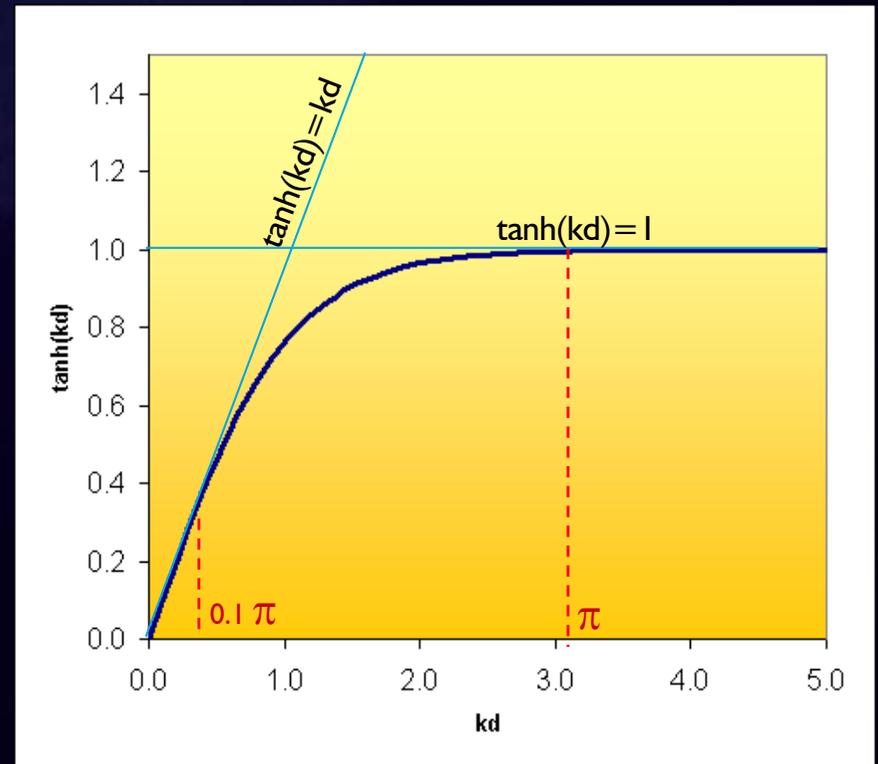
$\tanh(x)$ = tangente iperbolica =

$$\frac{e^x - e^{-x}}{e^x + e^{-x}}$$

Proprietà delle funzioni iperboliche:

Se x è piccolo $\rightarrow \tanh(x) \sim x$

Se $x > \pi$ $\rightarrow \tanh(x) \sim 1$



Velocità di propagazione

$$c^2 = \frac{g \cdot L}{2\pi} \cdot \tanh \frac{2\pi d}{L}$$

Se x è piccolo $\rightarrow \tanh(x) \sim x$

Se $x > \pi$ $\rightarrow \tanh(x) \sim 1$

Velocità d'onda in acque profonde

Se: $d > \frac{L}{2} \Rightarrow c^2 = \frac{g \cdot L}{2\pi} \cdot \tanh\left(> \frac{2\pi L}{2L}\right) \Rightarrow c^2 = \frac{g \cdot L}{2\pi} \cdot \tanh(> \pi)$

$$c^2 = \frac{g \cdot L}{2\pi}$$

La velocità dipende solo dalla lunghezza d'onda

Velocità d'onda in acque basse

Se: $d < \frac{L}{20} \Rightarrow c^2 = \frac{g \cdot L}{2\pi} \cdot \tanh\left(\frac{2\pi d}{L}\right) \Rightarrow c^2 = \frac{g \cdot L}{2\pi} \cdot \frac{2\pi d}{L} = gd$

$$c^2 = g \cdot d$$

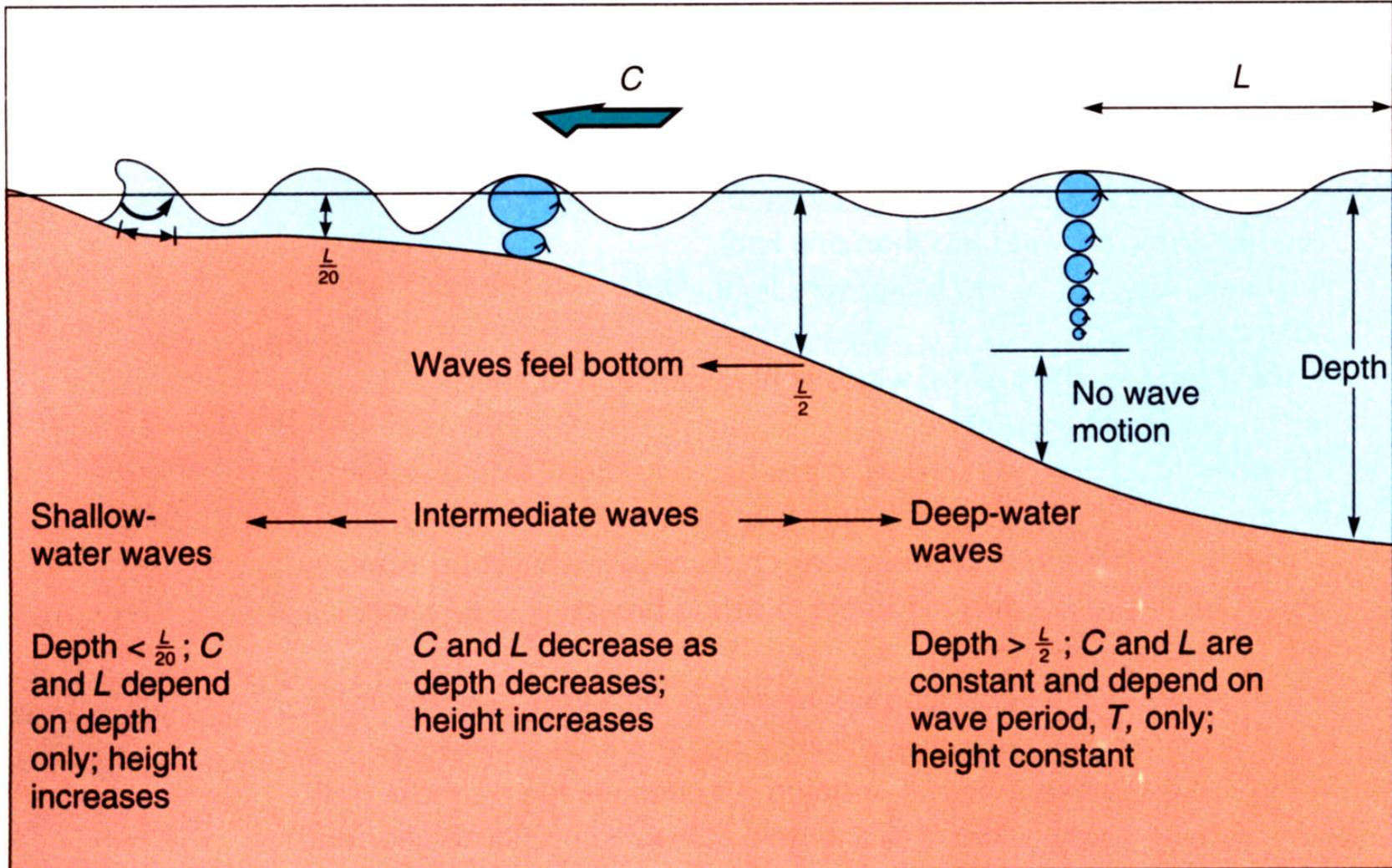
La velocità dipende solo dalla profondità

Onda di Airy

determinazione della lunghezza
d'onda dal Periodo

$$c^2 = \frac{L^2}{T^2} = \frac{g \cdot L}{2\pi} \Rightarrow L = \frac{g \cdot T^2}{2\pi} \Rightarrow L_0 = 1.56 \cdot T_0^2$$

Le regioni d'onda: acque profonde ed acque basse



TSUNAMI

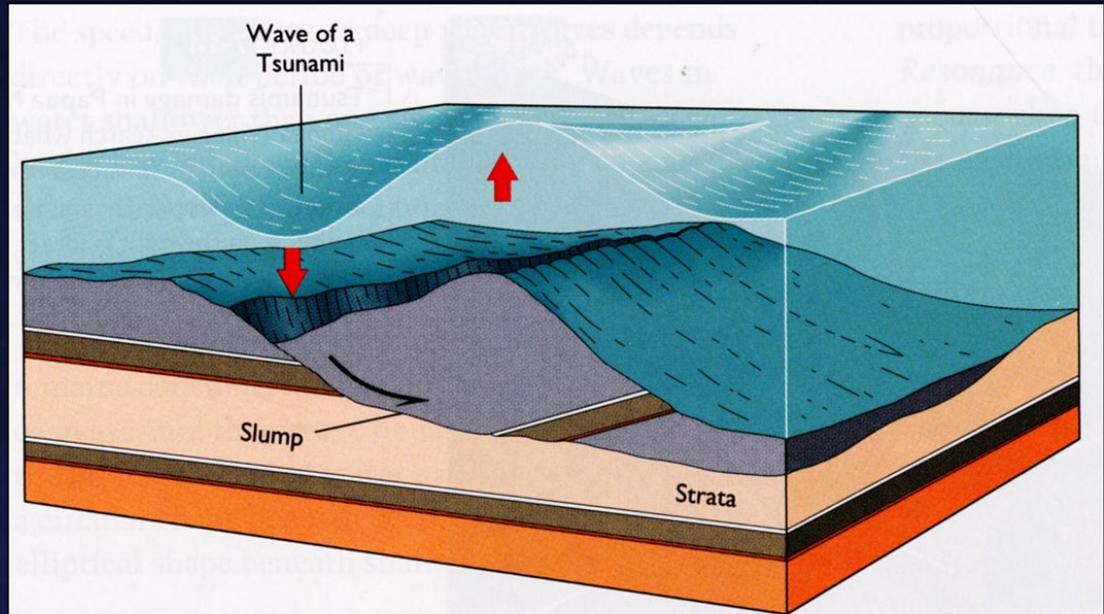
$$C = (g d)^{1/2}$$

Esempio:

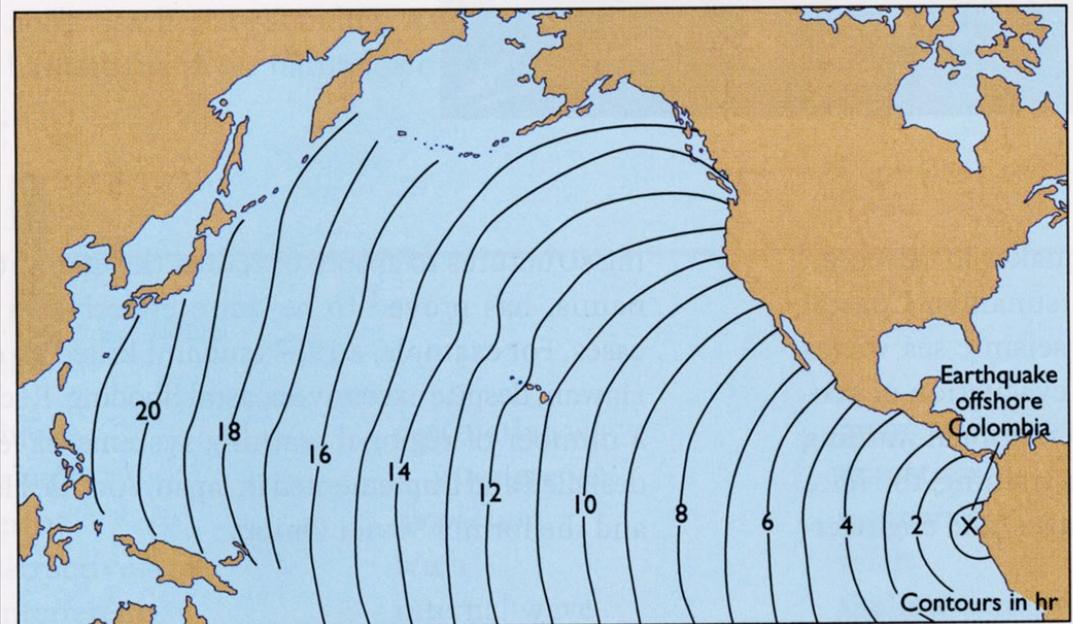
$$C = (9.81 \cdot 4000 \text{ m})^{1/2}$$

$$C = 198 \text{ m/s} = 713 \text{ km/h}$$

Percorrenza giornaliera:
Circa 17.000 km

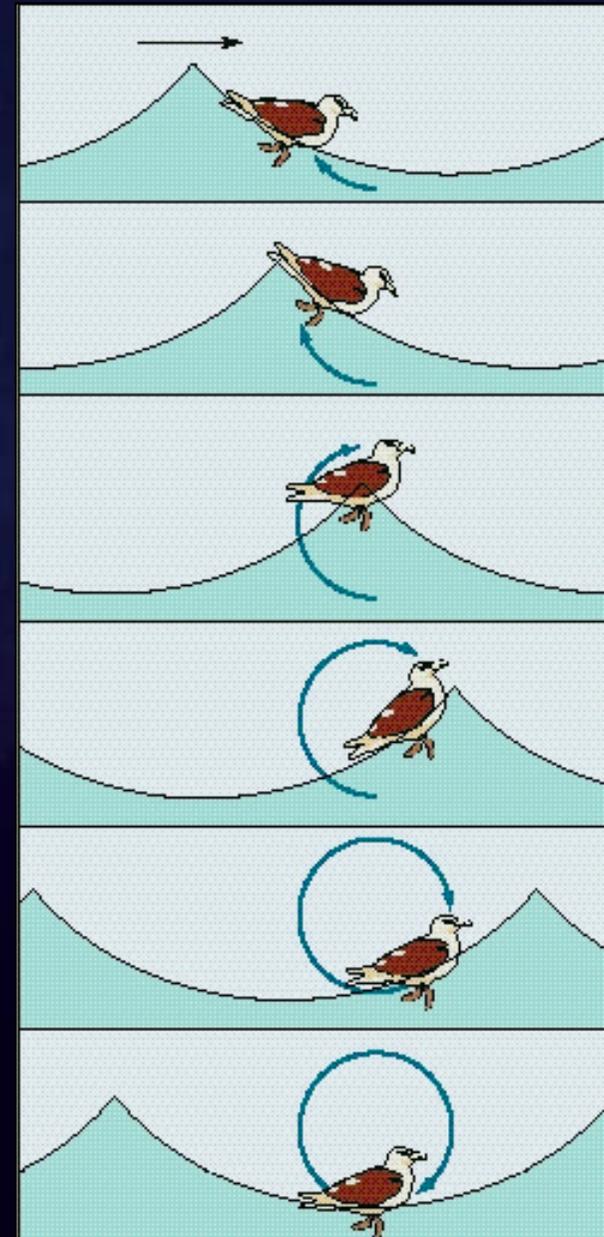
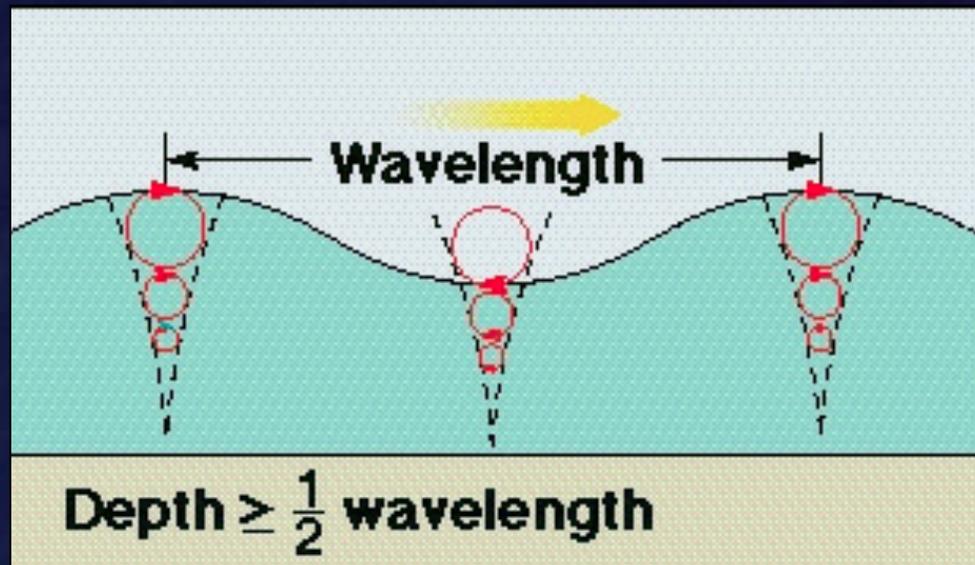


(a) GENERATION OF A TSUNAMI



(b) REFRACTION PATTERN OF 1979 TSUNAMI

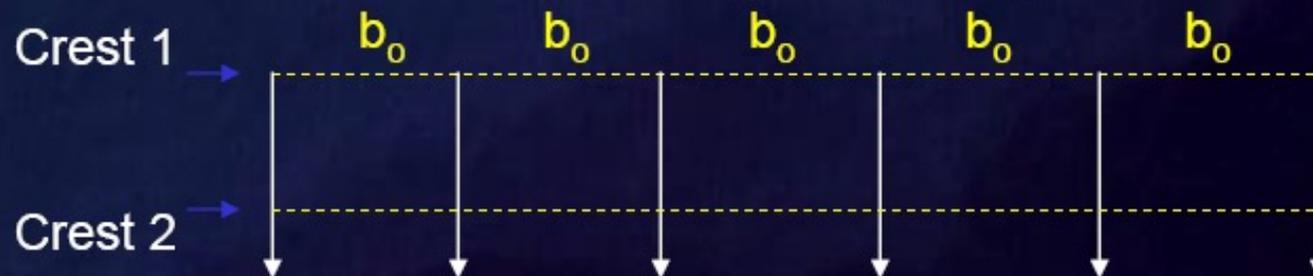
Le onde ideali propagano energia e non massa



Energy Flux

- Assuming no diffraction in deep water, then:

Energy Flux = f (Energy Density, Phase velocity, Orthogonal spacing)



DEEP WATER:

$$P_o = \frac{1}{2} E_o C_o b_o$$

Orthogonal Spacing along wave crest

WAVE RAYS

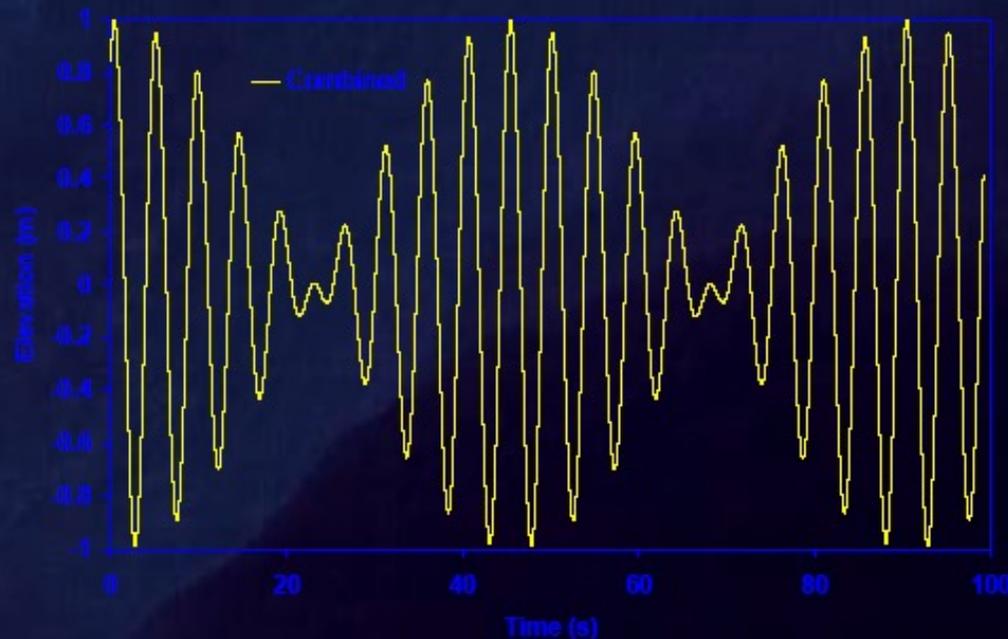
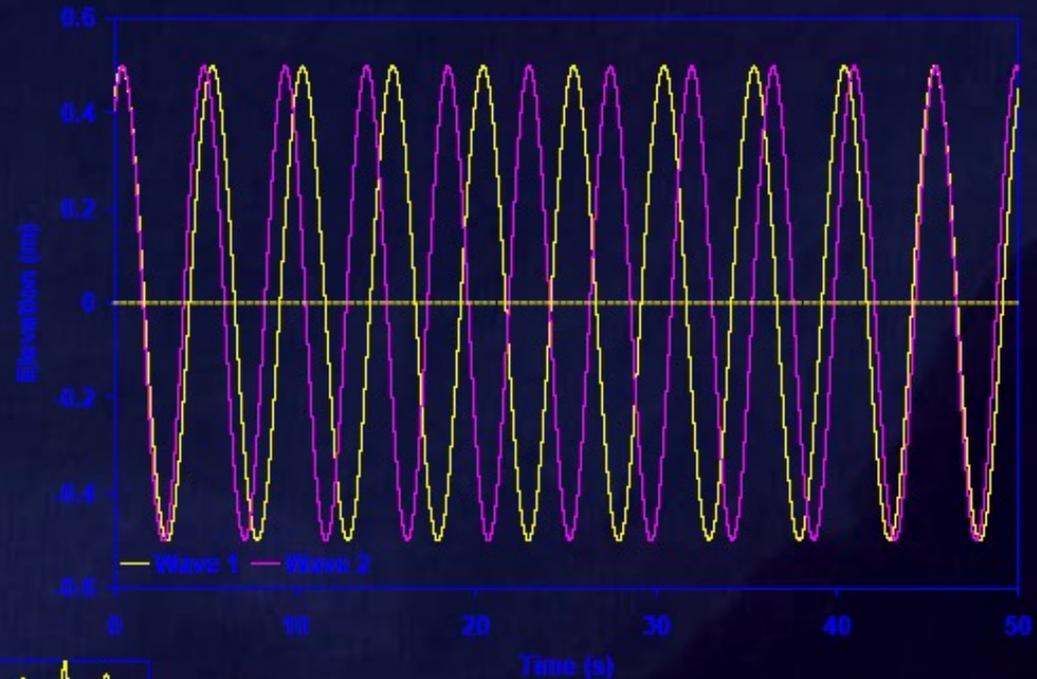
INTER. DEPTH:

$$P_h = E_h C_h b_h n$$

Why is n here?

Wave Interference

- Two waves with different periods will move at different speeds



- Wave 1: 5 s
- Wave 2: 4.5 s
- Creates a **WAVE GROUP** with a period >20 s

Shoreface Transformation

- **Shoaling**
 - Change in wave form in shallow water
- **Refraction**
 - changes in speed of propagation along crest causes a *bending* of crests
- **Breaking**
 - Wave collapses
- **Reflection**
 - Waves (particularly long waves) are reflected from any sloping surface (including gently sloping shoreface, but especially steeper beach face)
- **Friction at bed and percolation into bed**

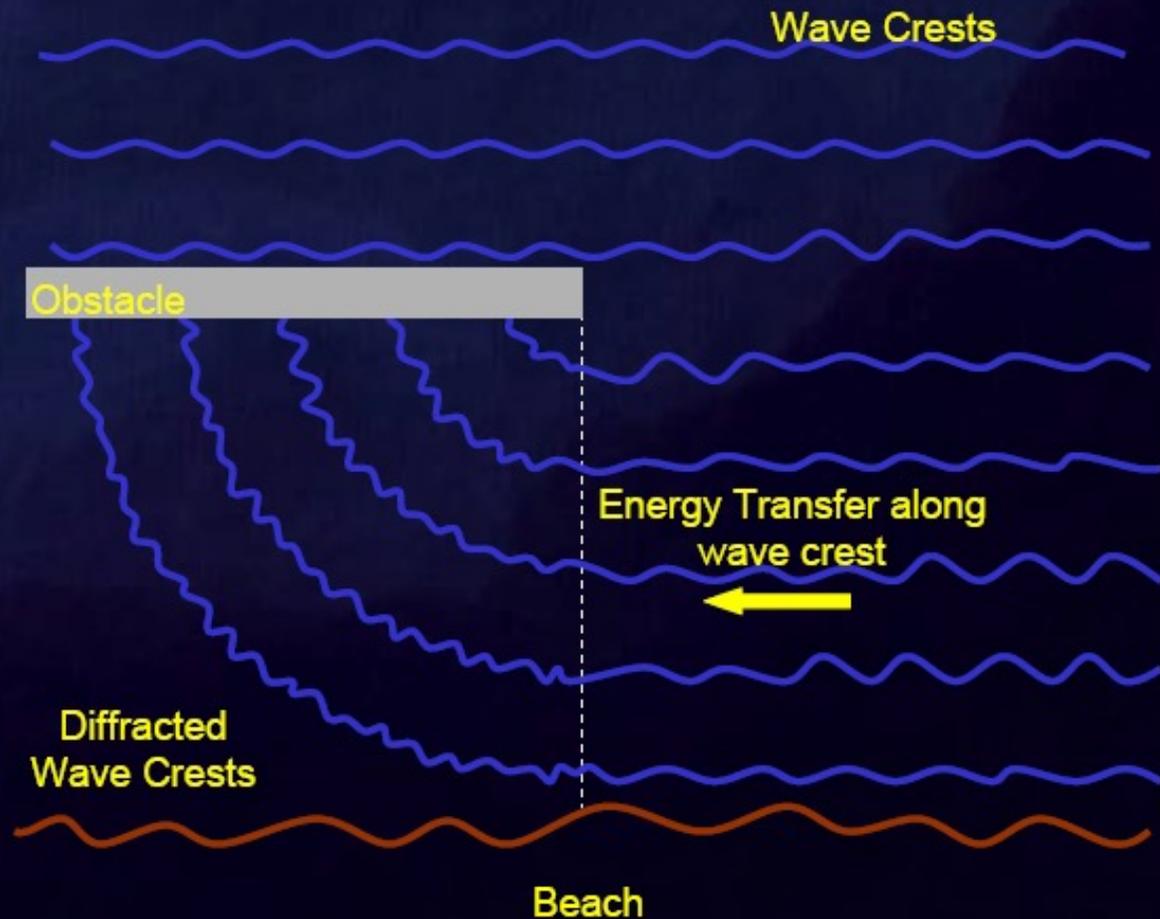
Reflect a feedback with the pre-existing morphology of the shoreface

How the waves change the beach may be more a reflection of the beach morphology than the magnitude of the storm

- Variation in crest and trough elevations perpendicular to the direction of propagation results in **energy transfers along the crest/trough** and thus **change in wave height**
- Energy can be transferred into sheltered areas

Possible Obstacles:
Breakwater
Island
Submerged Obstacle

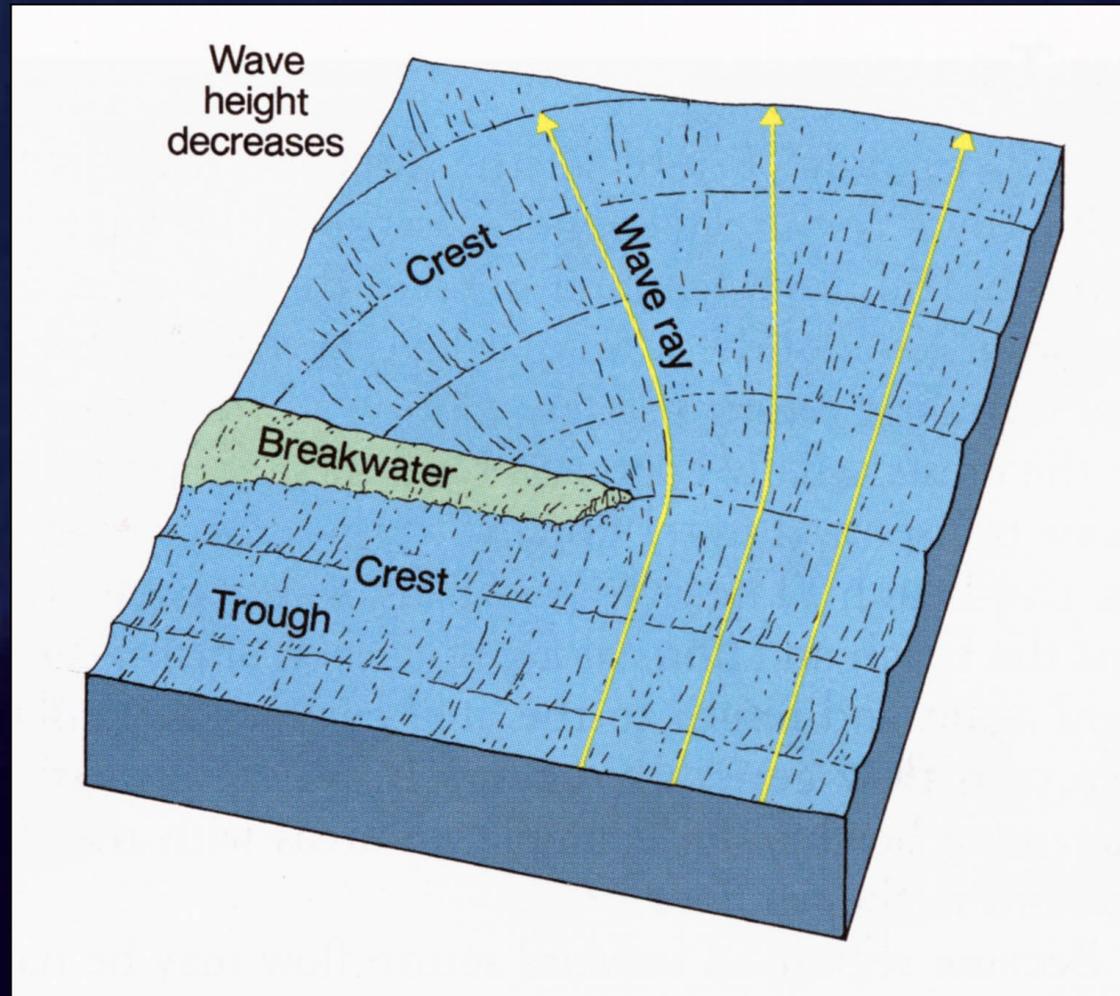
Diffraction



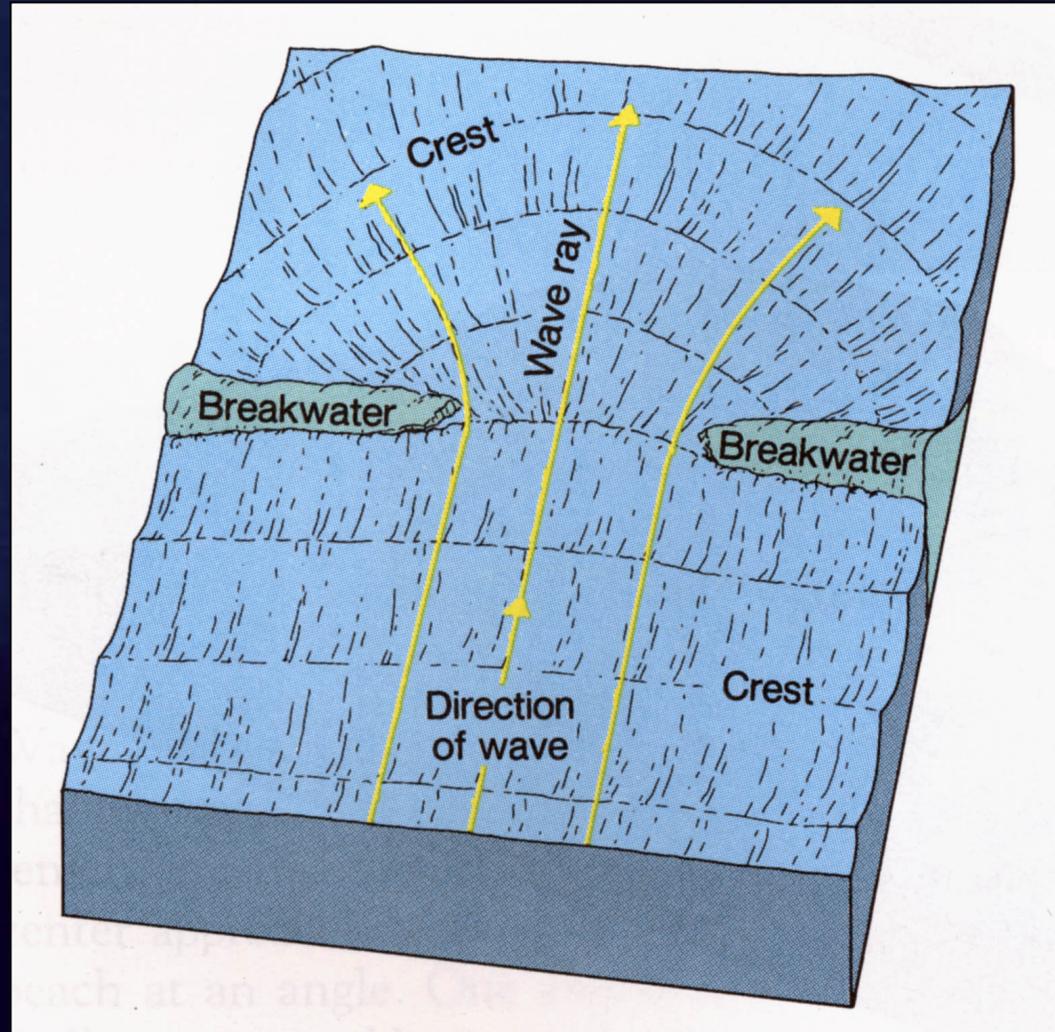
What is the consequence of wave diffraction for coastal processes?

DIFFRAZIONE

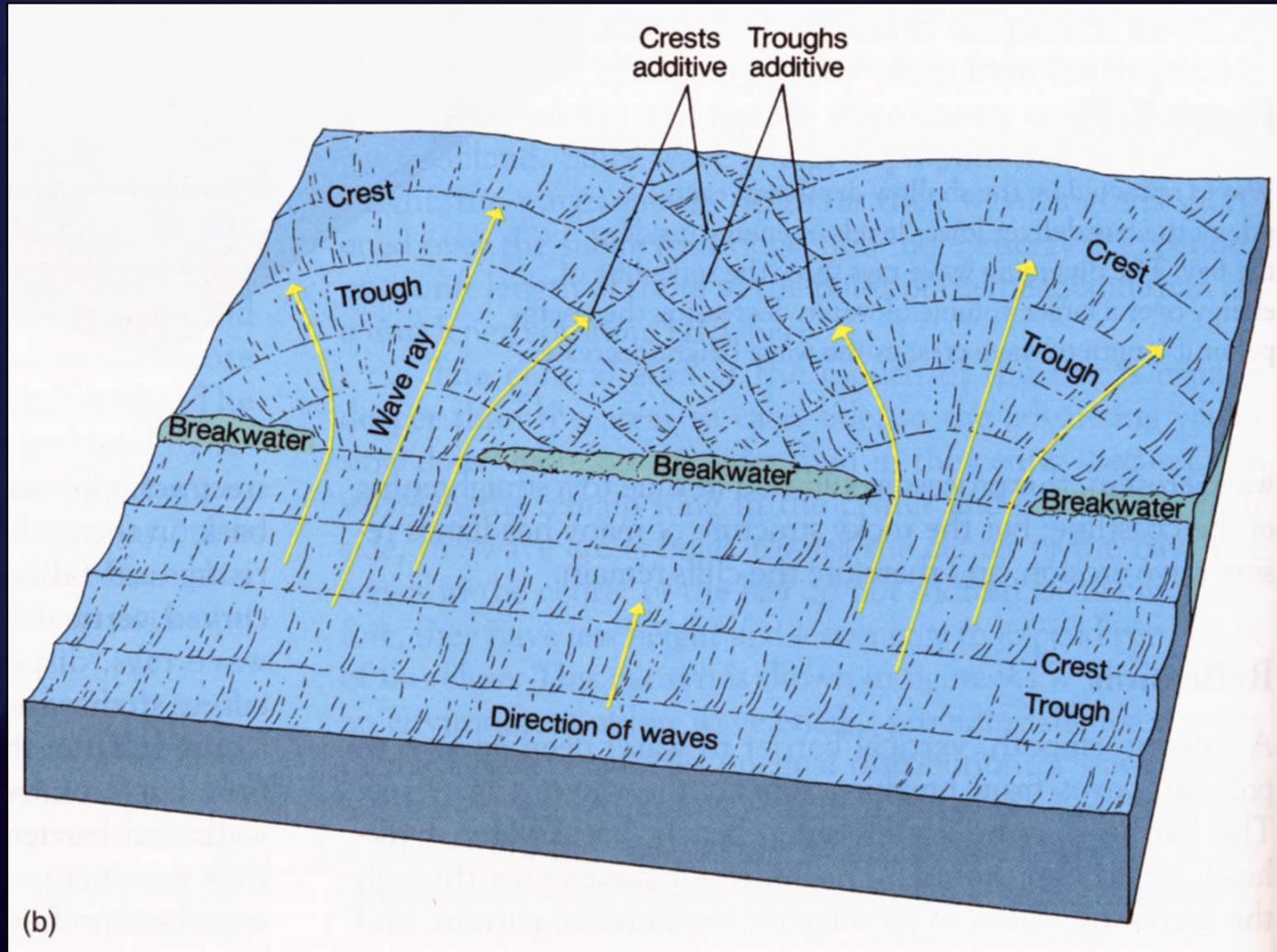
(sorgente puntiforme)



DIFFRAZIONE (sorgente lineare)

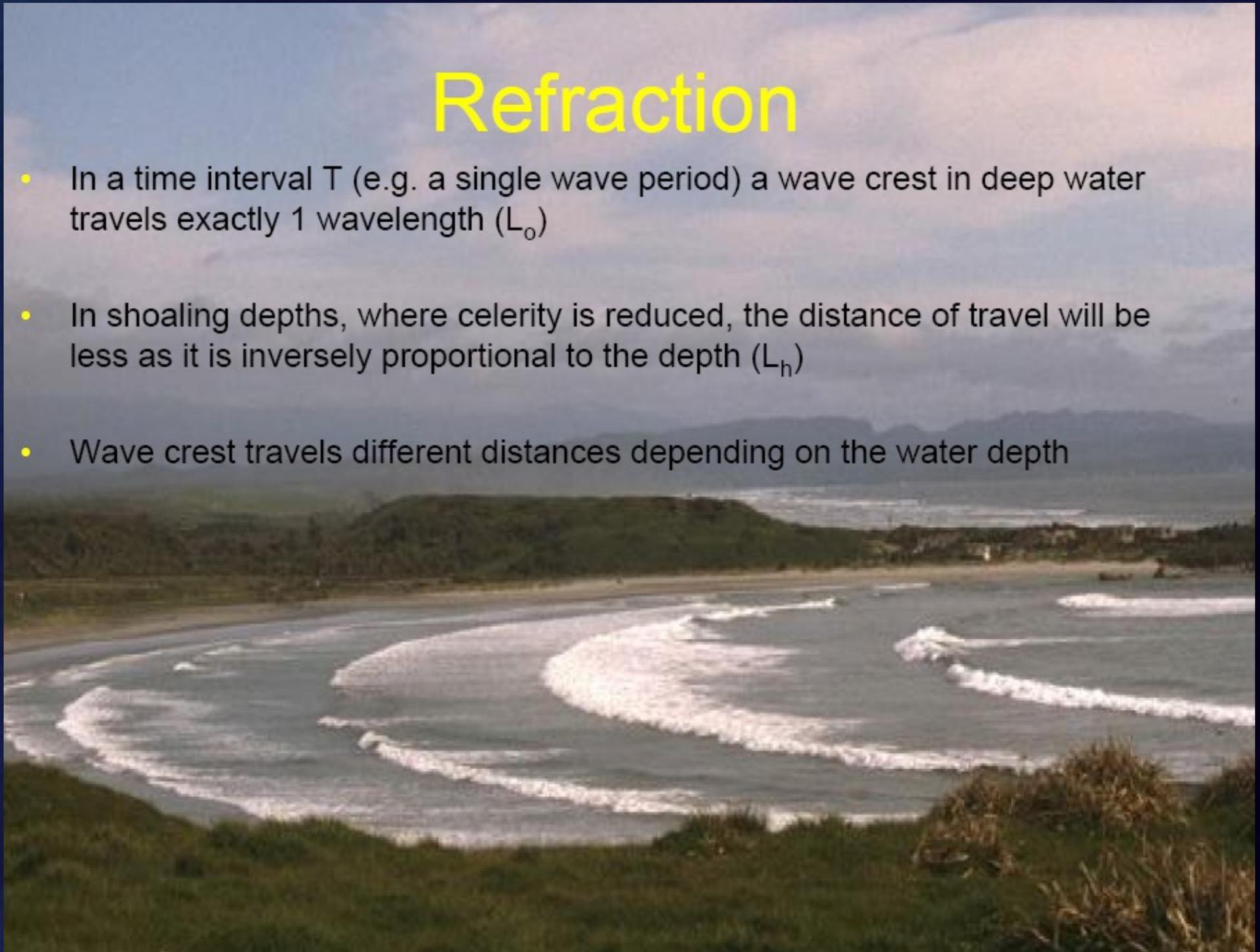


DIFFAZIONE (sorgente lineare multipla)



Refraction

- In a time interval T (e.g. a single wave period) a wave crest in deep water travels exactly 1 wavelength (L_o)
- In shoaling depths, where celerity is reduced, the distance of travel will be less as it is inversely proportional to the depth (L_h)
- Wave crest travels different distances depending on the water depth

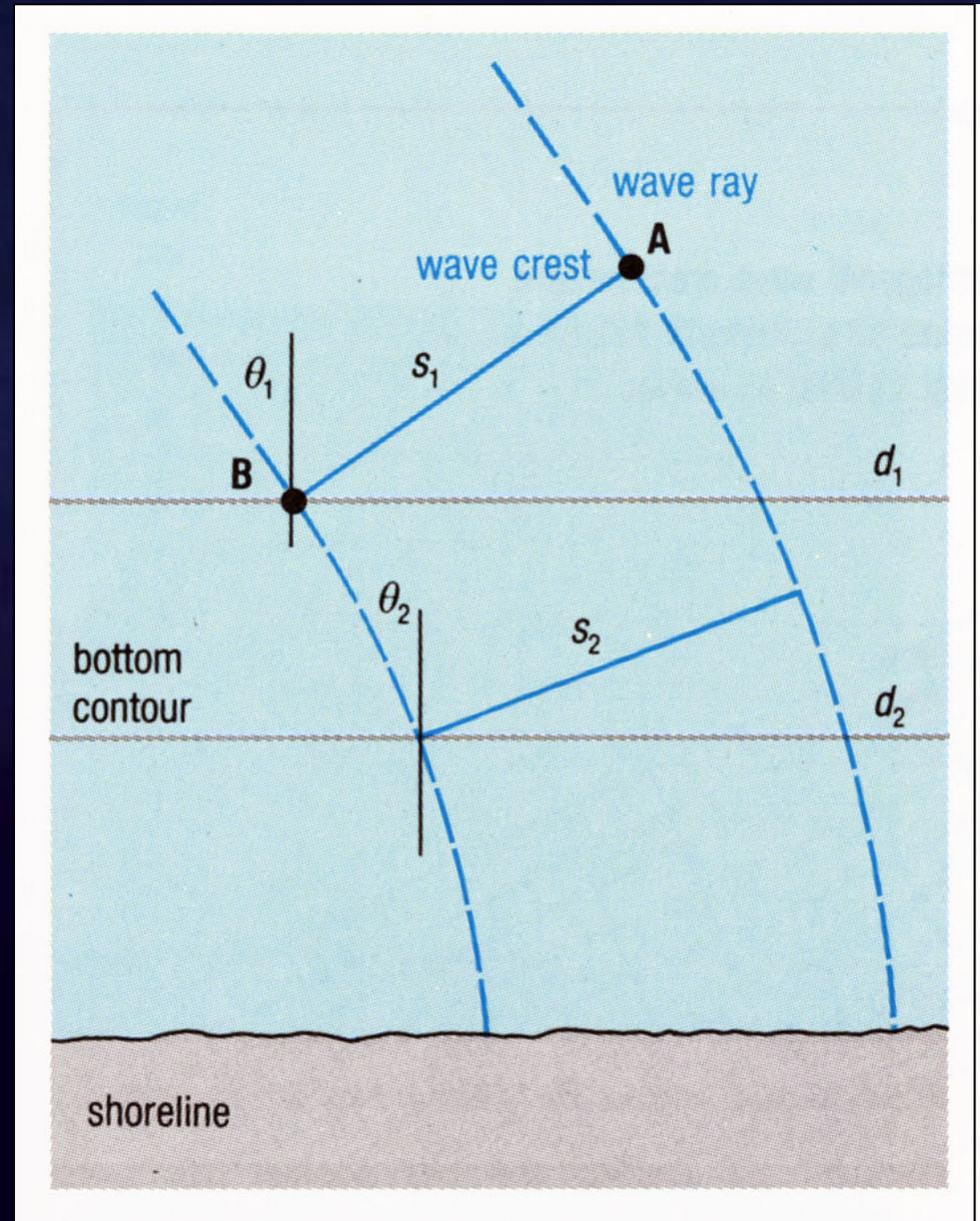


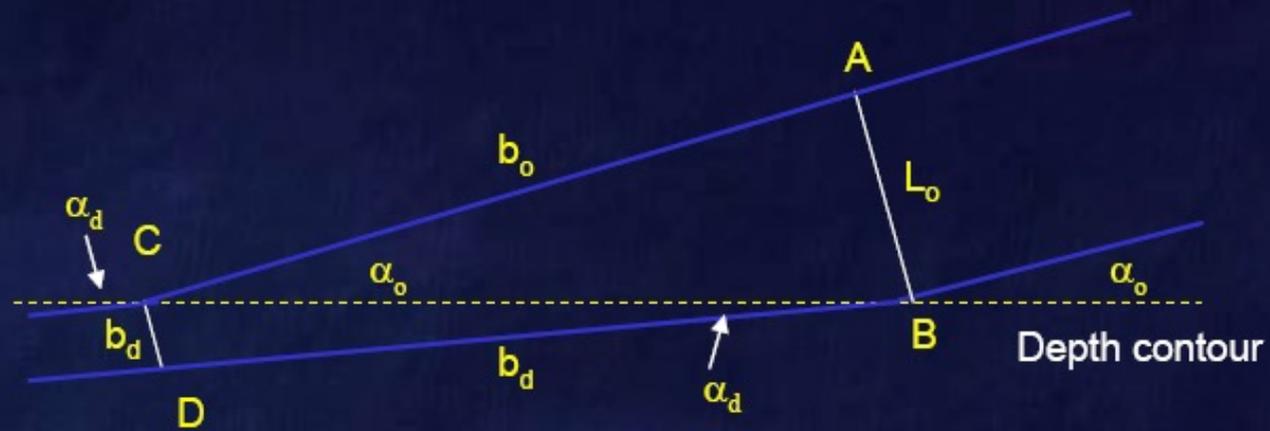
Rifrazione delle onde:

La curvatura dei fronti d'onda in acque basse è dovuta ai cambiamenti di profondità.

La parte verso terra del fronte d'onda (in **B**) entra in acque più basse e rallenta, mentre il resto del fronte (in **A**) continua a muoversi più velocemente.

Il risultato è una rotazione dei fronti d'onda che tendono a raggiungere una configurazione parallela all'andamento batimetrico.





- From trigonometric relationship for the two similar triangles **ABC** and **BCD**

$$\sin \alpha_h = \frac{L_h}{CB}$$

$$\sin \alpha_o = \frac{L_o}{CB}$$

$$\frac{\sin \alpha_h}{\sin \alpha_o} = \frac{L_h}{L_o} = \frac{C_h}{C_o}$$

Legge di Snell

$$\sin \alpha_h = \frac{C_h}{C_o} \sin \alpha_o$$

Consequence of Wave Refraction

Focusing and Defocusing of Wave Energy on Headlands and Bays, Respectively

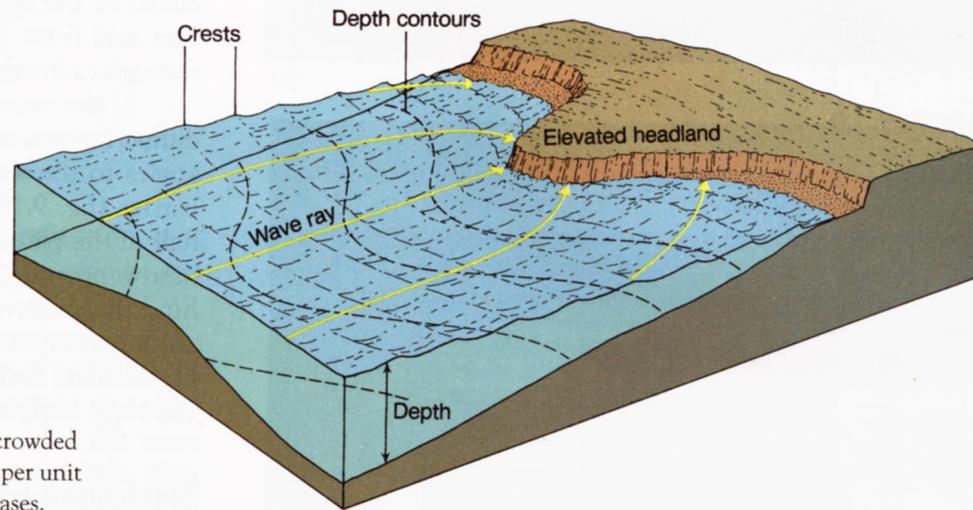


Figure 9.14

The energy of waves refracted over a shallow submerged ridge is focused on the headland. The converging wave rays show the wave energy being crowded into a small volume of water, increasing the energy per unit length of wave crest as the height of the wave increases.

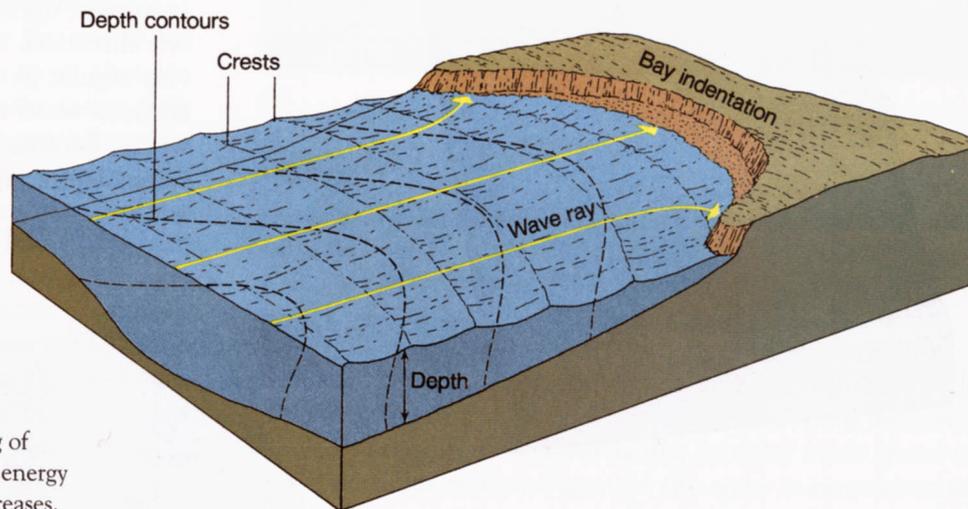
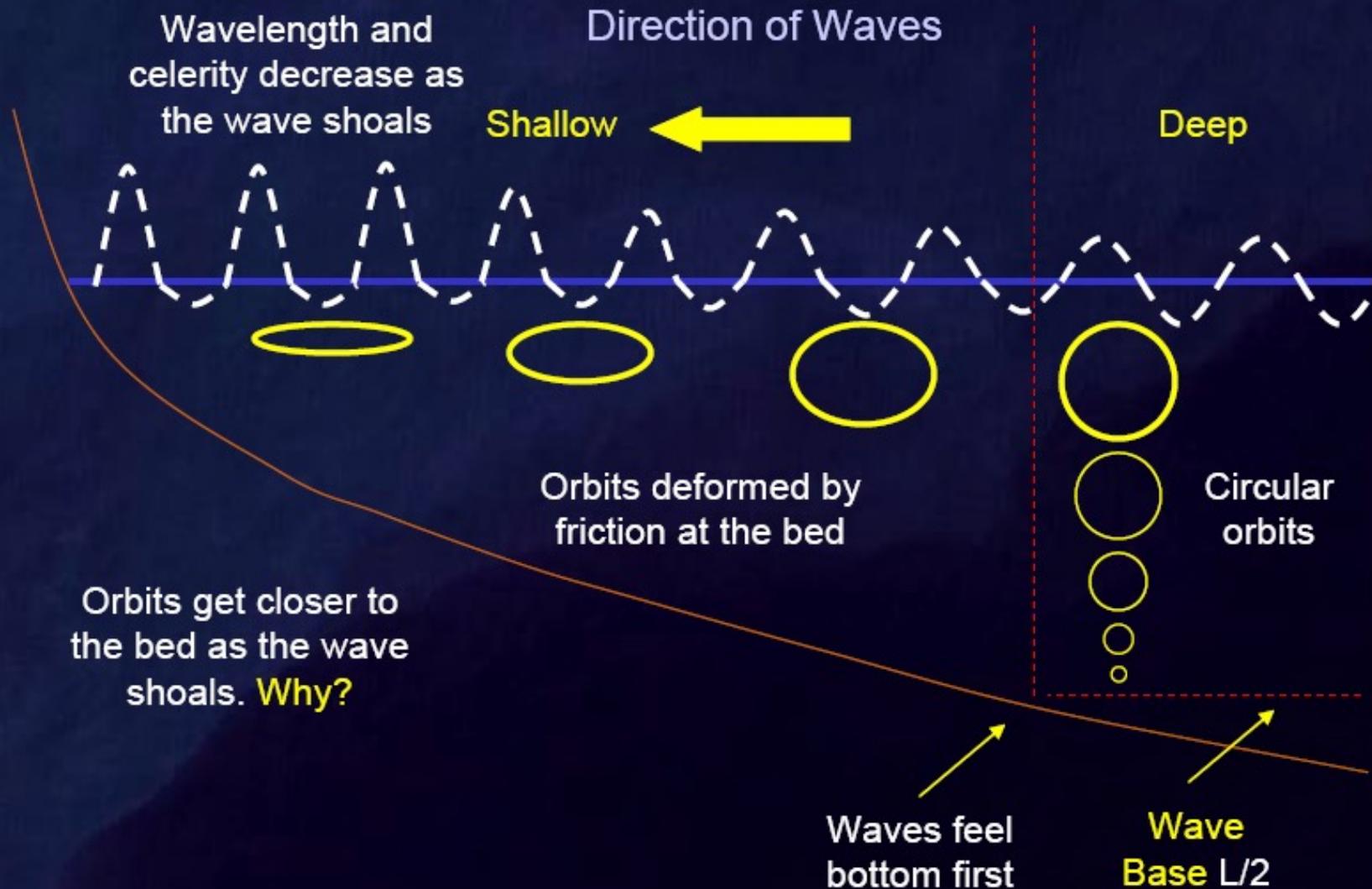


Figure 9.15

Waves refracted by the shallow depths on each side of the bay deliver lower levels of energy inside the bay. The diverging wave rays show the spreading of energy over a larger volume of water, decreasing the energy per unit length of wave crest as the wave height decreases.

Shoaling Changes

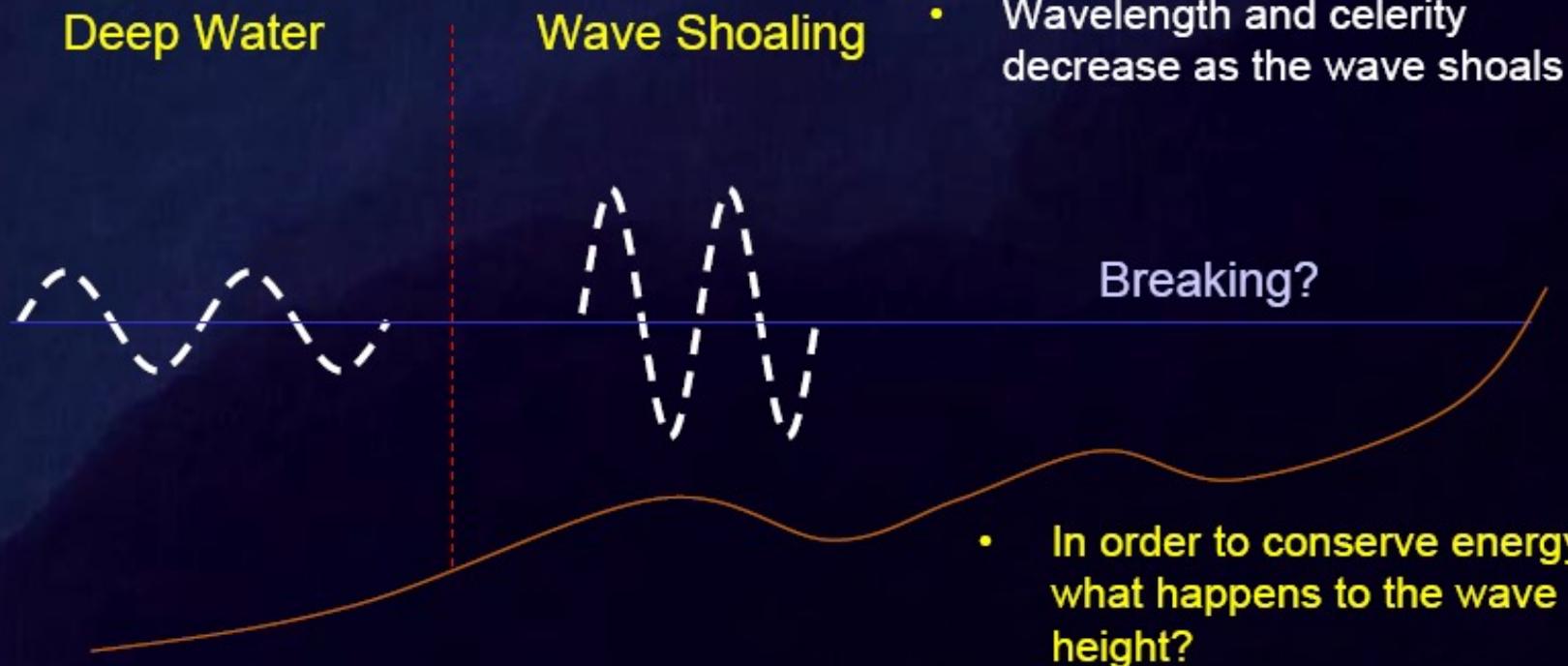


Shoaling

- In **shallow water** the wavelength (L) and wave celerity (C) are proportional to the water depth (h)
- Wave period does not change

$$L = T \sqrt{gh}$$

$$C = \sqrt{gh}$$



The shape of a wave

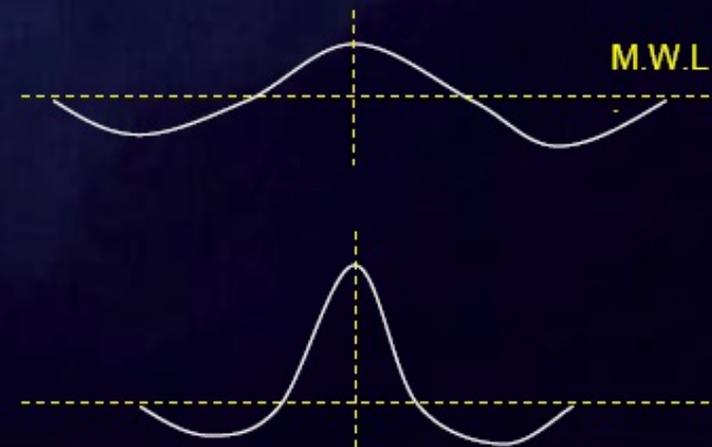
- The waves shown to this point have been sinusoidal
 - This is **only** valid for **deep water waves**
- There are two general classes of models:

DEEP WATER

Linear

SHALLOW WATER

Non-linear

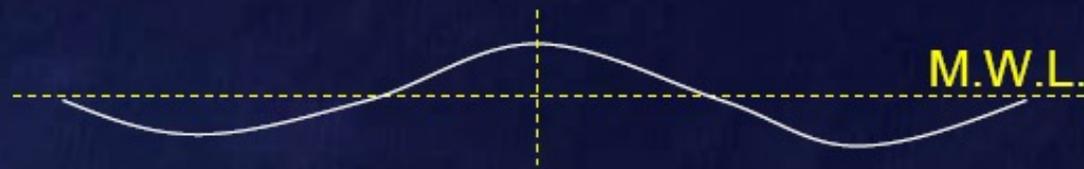


- All models vary in their level of approximation to real wave forms

- **Linear**

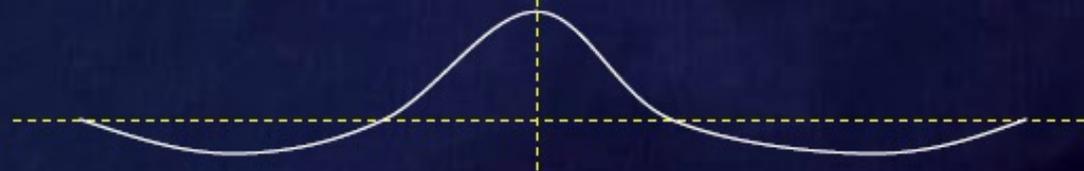
- **AIRY**: deep water $H L^{-1} \rightarrow 0$

Symmetric in the horizontal and the vertical



- **Non-Linear**

- **STOKES**: deep water $H L^{-1}$ large

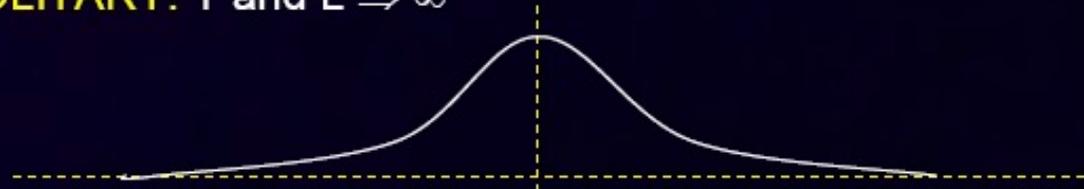


- **CNOIDAL**: shallow water

Asymmetric in the Vertical but symmetric in the horizontal



- **SOLITARY**: T and $L \rightarrow \infty$



Wavelength

Direction of Waves



Wave Height

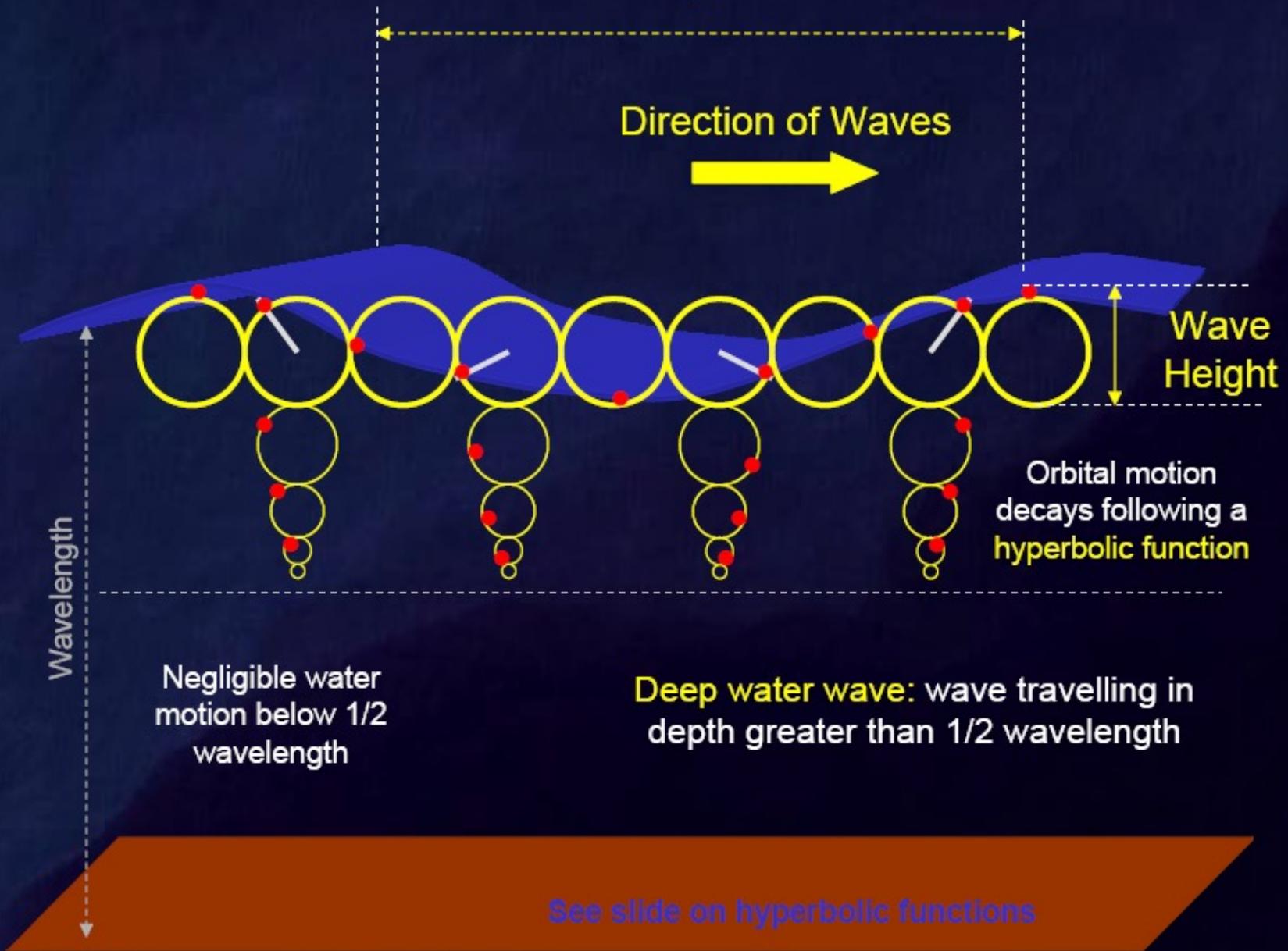
Orbital motion
decays following a
hyperbolic function

Negligible water
motion below $1/2$
wavelength

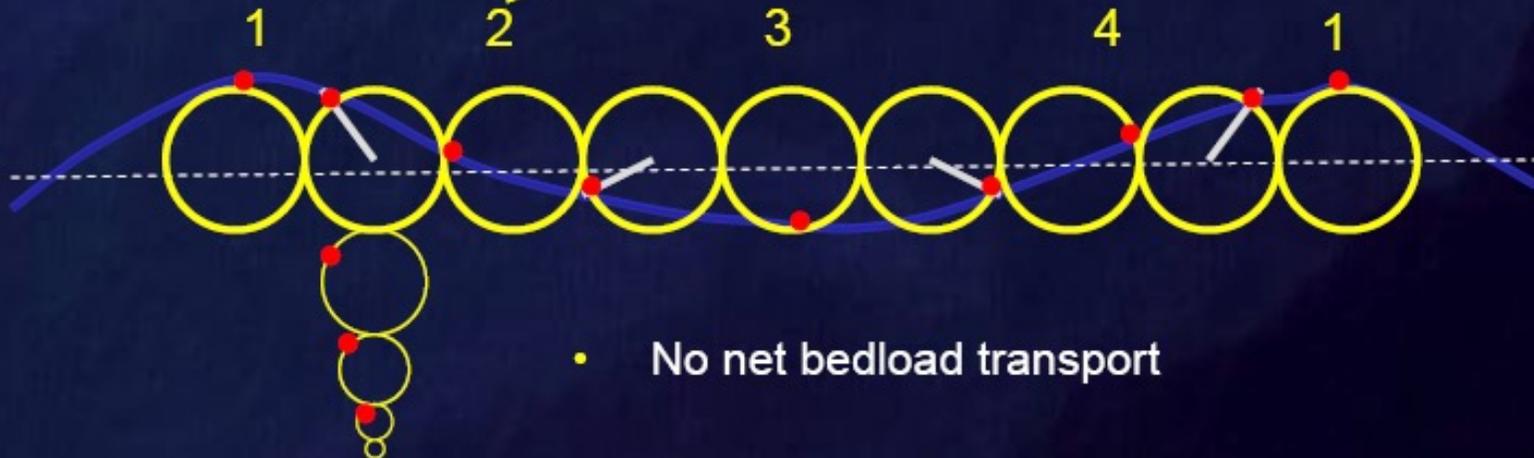
Deep water wave: wave travelling in
depth greater than $1/2$ wavelength

See slide on hyperbolic functions

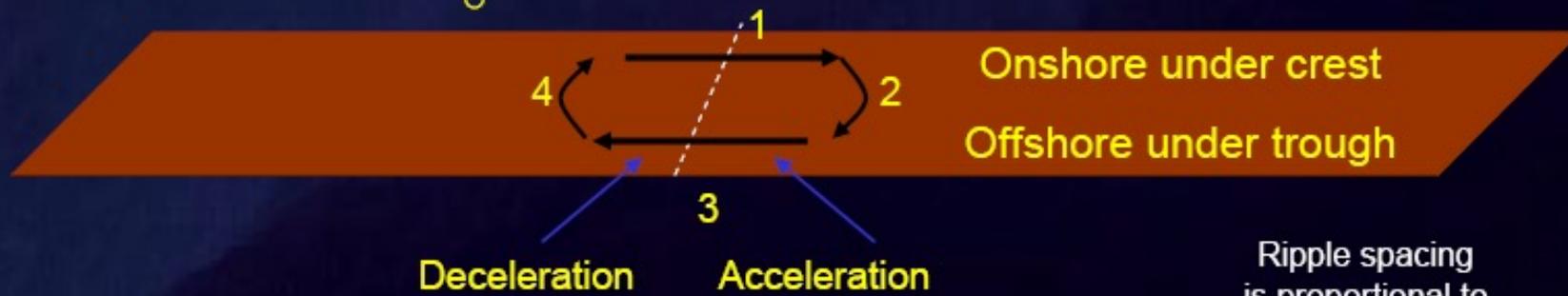
Wavelength



Direction of Waves



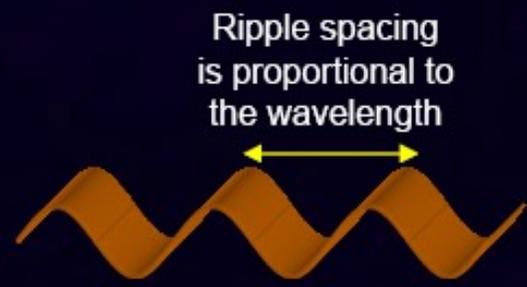
- No net bedload transport



Onshore under crest
Offshore under trough

Deceleration Acceleration

- Forms symmetrical orbital ripples



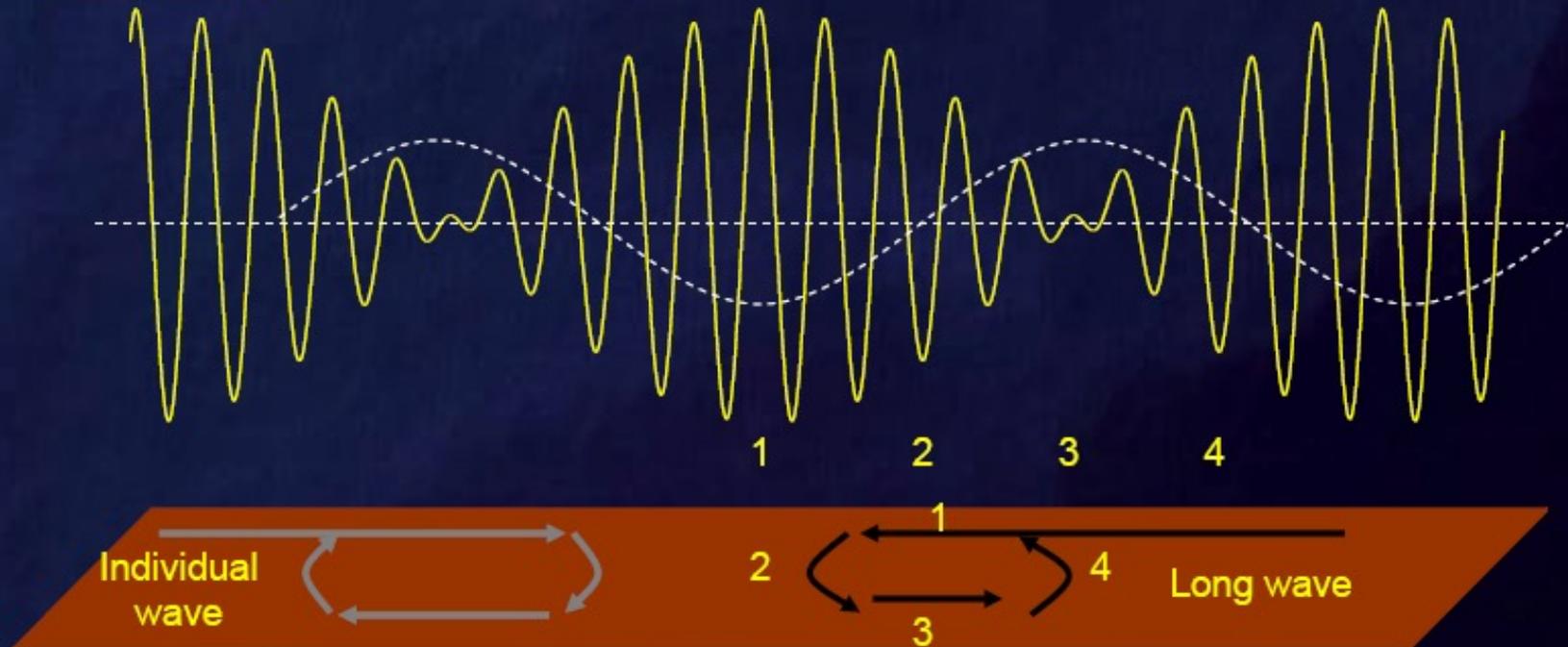
Ripple spacing
is proportional to
the wavelength

Direction of
Waves



Sand at the Bed

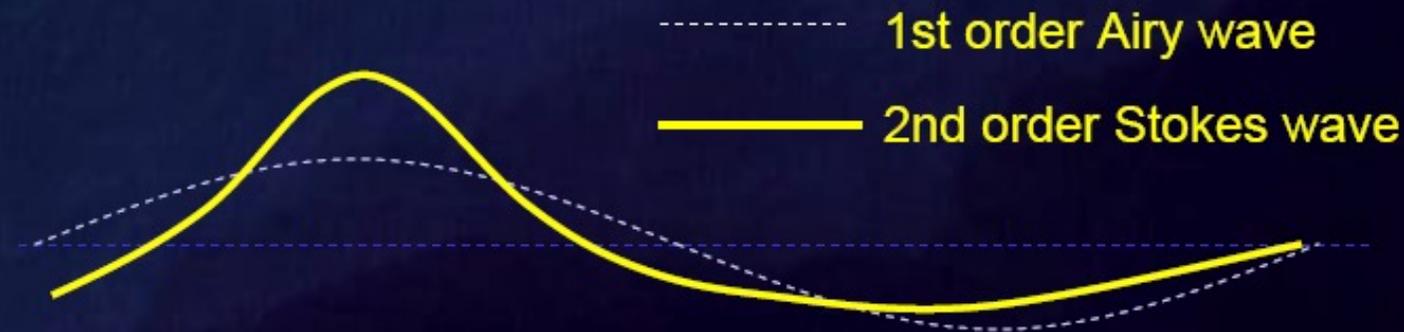
Wave Group- Shoaling Zone



- Individual gravity waves move sediment landward (Stokes Drift)
 - Sediment suspended under long wave trough moves offshore
 - Bigger waves under the long wave trough- more sediment suspended-> offshore transport

Stokes Wave

- Non-linear approach results in several predictions which more closely fit the behavior of real waves:
 - allows for the possibility of *increases in crest amplitude and decreases in trough amplitude* which is observed as waves shoal



- Still symmetrical relative to planes through the crest and trough
- Difference (between crest and trough) increases with H/L

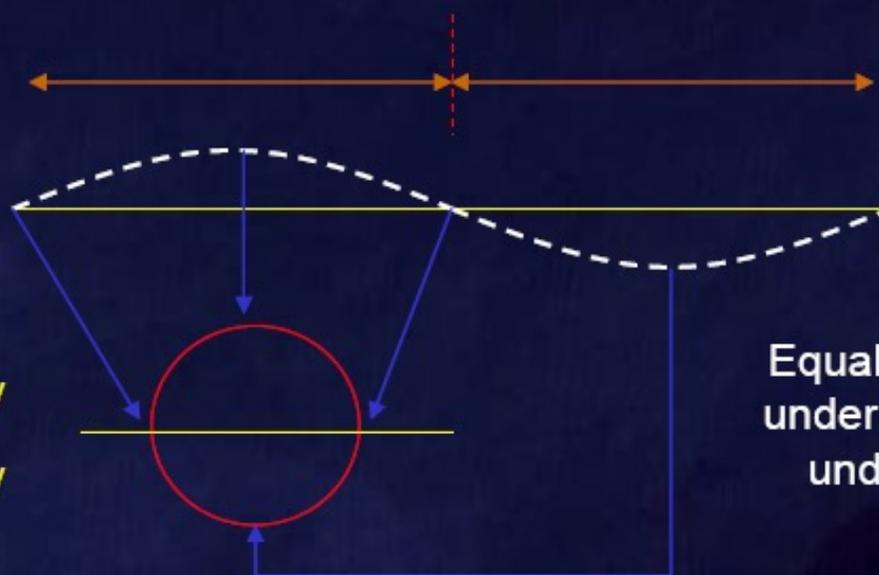
An important prediction of Stokes' Theory is that:

Water particle orbits are **NOT CLOSED**

AIRY WAVE

Onshore velocity

Offshore velocity

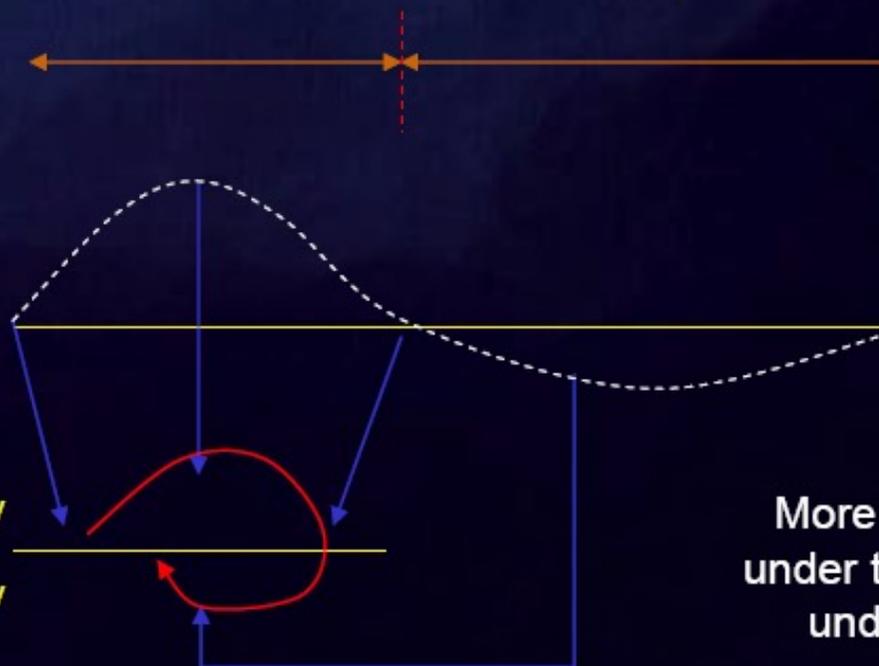


Equal time is spent under the trough as under the crest

STOKES WAVE

Onshore velocity

Offshore velocity



More time is spent under the trough than under the crest

Sand at the Bed

Direction of
Waves



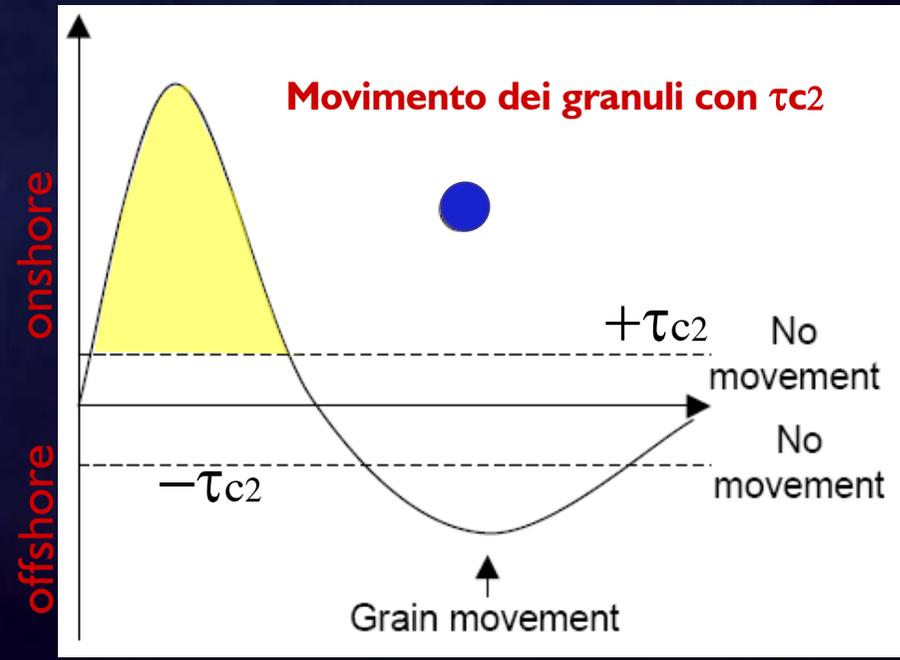
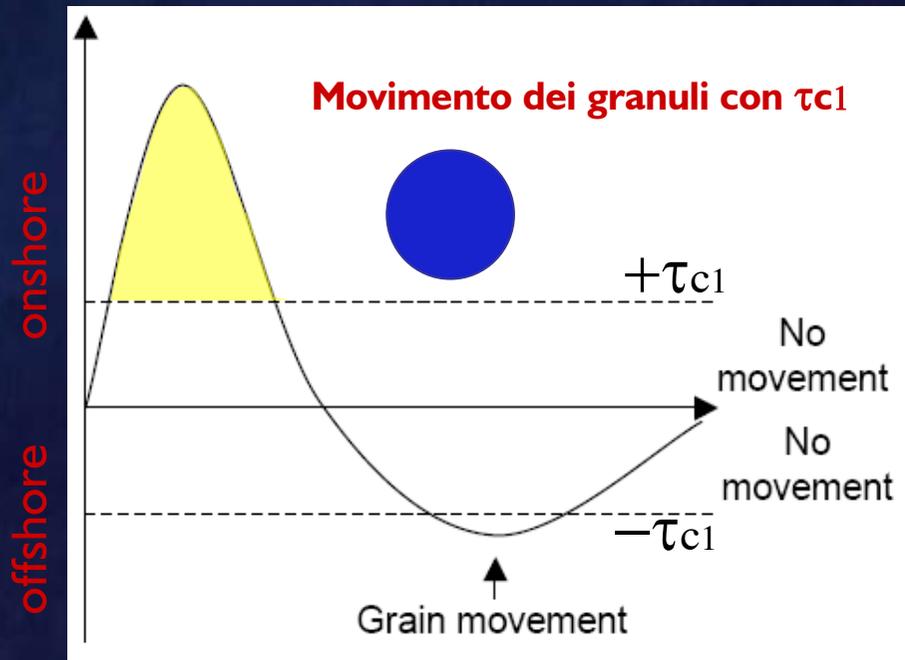
Stokes Wave



- Net onshore bedload transport



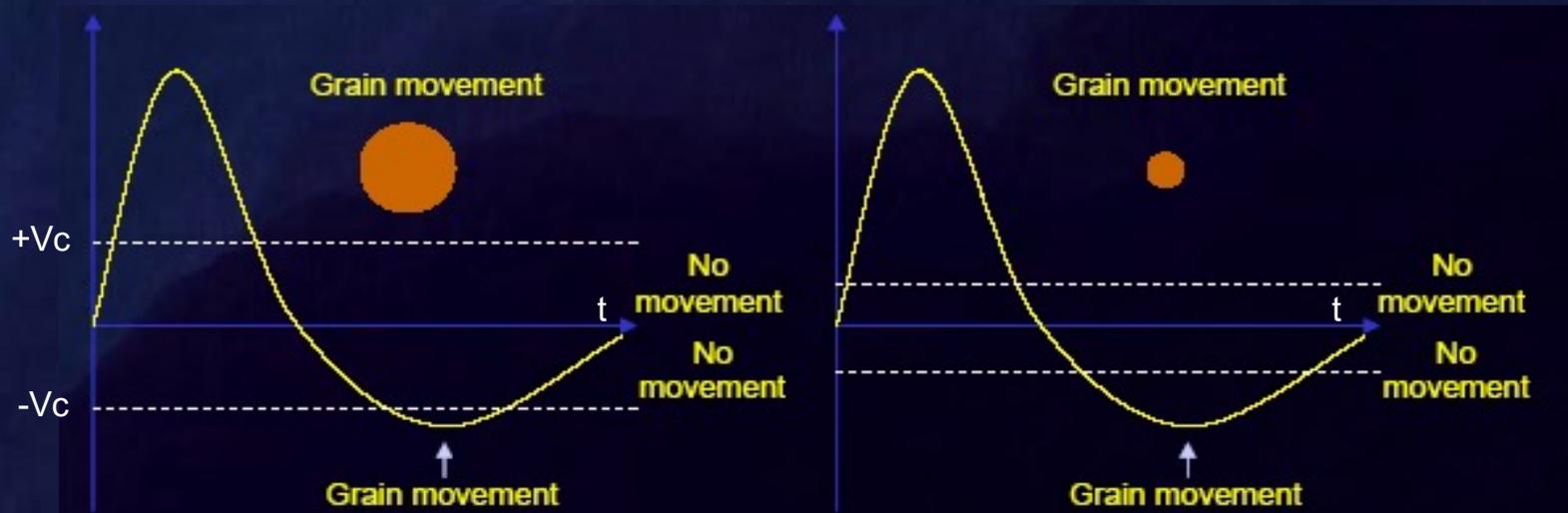
- Transport varies nonlinearly with the instantaneous oscillatory velocity
 - More sediment is transported by the larger onshore-directed velocities under the sharply peaked crests of skewed waves than by the longer-duration, but smaller offshore directed velocities under their broad, flat troughs



Il trasporto al fondo e la selezione dei materiali

Il risultato è un movimento verso riva più efficace nel trasportare il materiale grossolano:

- il materiale a granulometria maggiore non riesce ad essere preso in carico dalla corrente offshore
- il materiale fine si muoverà sia sotto la cresta che sotto il cavo d'onda, con deriva netta verso il largo



CASO A: Granulometria grossolana

- La velocità critica di erosione è superata sotto il passaggio della cresta e molto poco sotto il cavo
- componente netta di deriva: ONSHORE

CASO B: Granulometria fine

- La velocità critica di erosione è superata sia sotto il passaggio della cresta che sotto il cavo
- maggior durata della velocità al cavo
- componente netta di deriva: OFFSHORE

Breaking

- The wave motion at some stage becomes **UNSTABLE**

WAVE FORM relative to the **OSCILLATORY MOTION**

- At some point the **ORBITAL VELOCITY = PHASE VELOCITY** and the wave becomes unstable and **BREAKS**
- Wave breaks give rise to:
 - Large increase in **TURBULENCE**
 - **AIR ENTRAINMENT**
 - Complex **FLUID DYNAMICS**
- Secondary **CURRENTS**
- **INFRAGRAVITY (EDGE) WAVES**



Can oppose onshore transport by orbital skewness

- Stokes solution also predict an **UPPER LIMIT** to **WAVE HEIGHT** for a given depth of water and wave period

A WAVE BREAKING CRITERION

WATER PARTICLE VELOCITY AT CREST

=

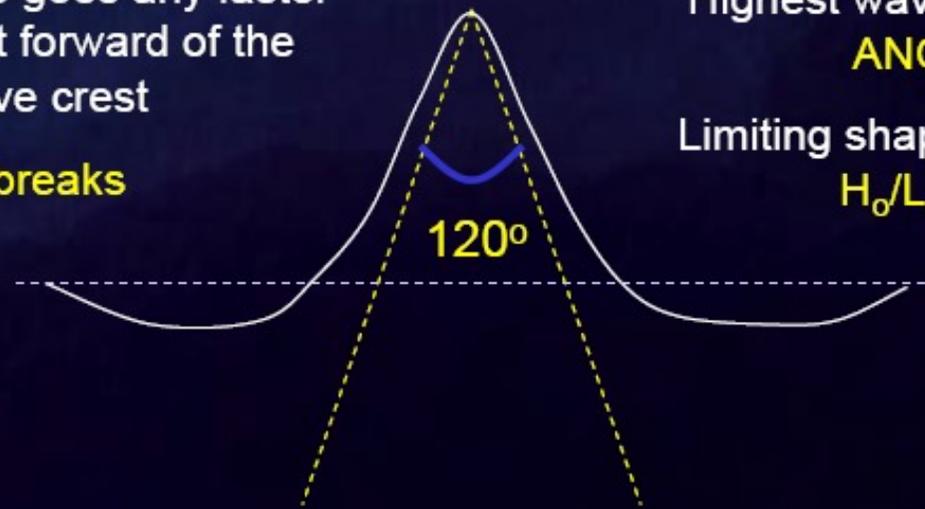
WAVE CELERITY

If the particle goes any faster
it will shoot forward of the
wave crest

it breaks

Highest wave was distinctly
ANGULAR

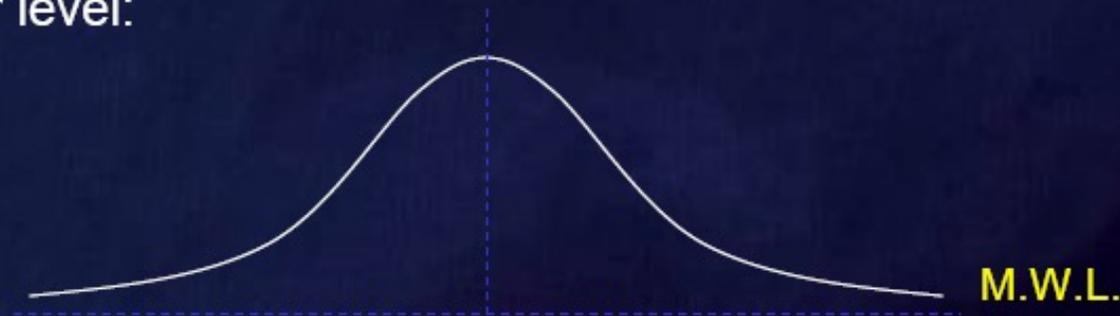
Limiting shape occurs when:
 $H_o/L_o=0.142$



INTERNAL ANGLE AT WAVE CREST=120°

Solitary Wave

- Russell (1938) noted the existence of a wave form lying entirely above the mean water level:



- Consists of a **SINGLE CREST**
- Troughs are very long and flat
 - basic oscillatory nature is lost
- Gives a **CRITICAL CONDITION** for **WAVE BREAKING**:

$$\frac{H_b}{h} = 0.78$$

Breaker Forms

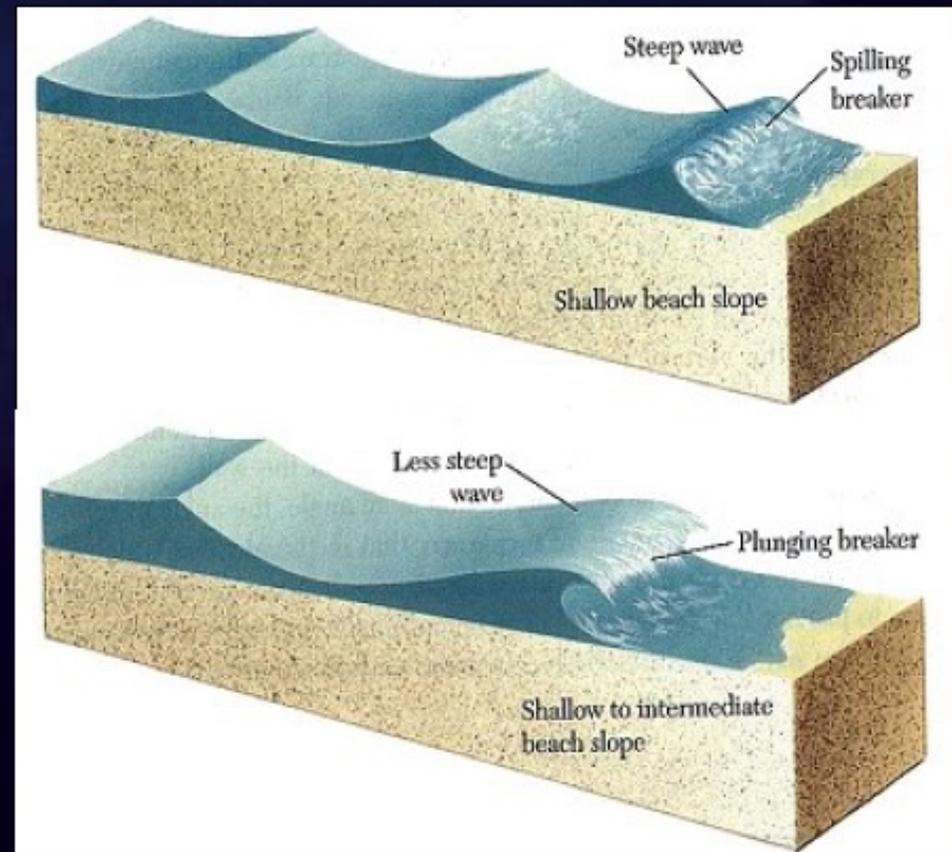
- Galvin (1968) defined 4 wave types:

- Spilling**

- Remains oscillatory
- Little mass transport
- No reverse flow on face

- Plunging**

- Creates a roller vortex
- Reversed slopes



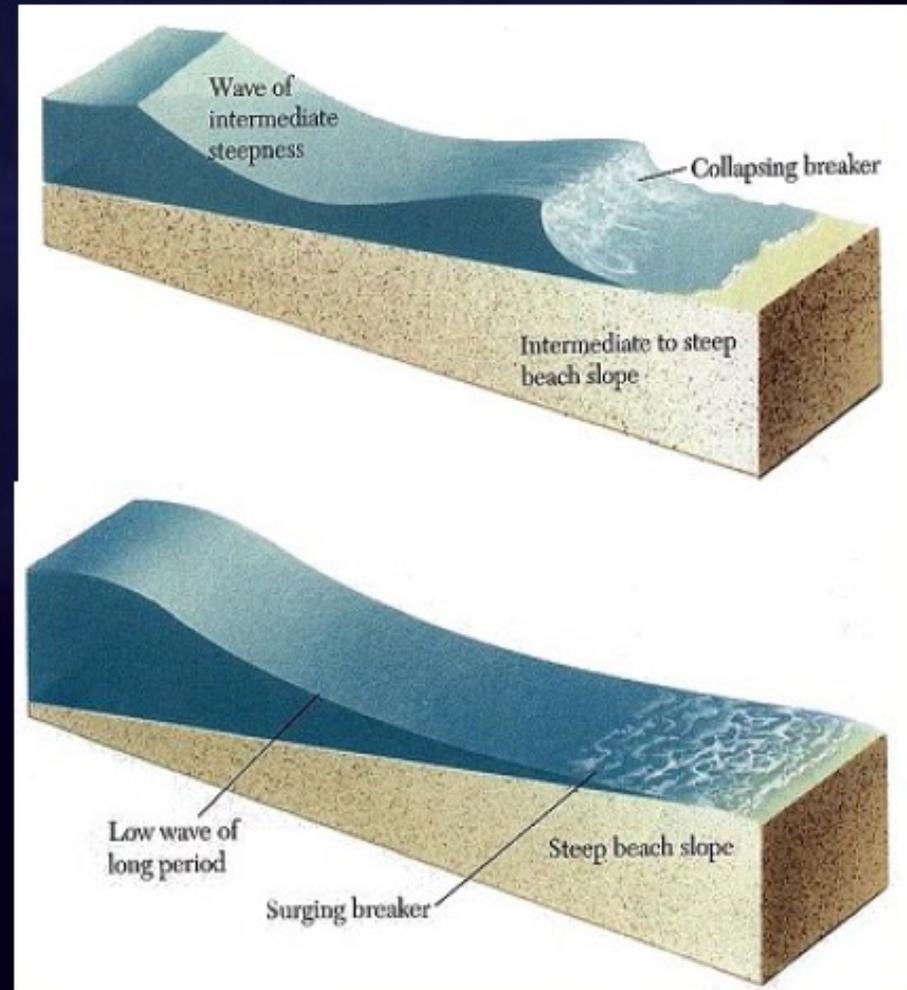
Breaker Forms

- **Collapsing**

- Tend to be associated with reflection
- Cusps and synchronous edge waves
- transition between plunging and surging

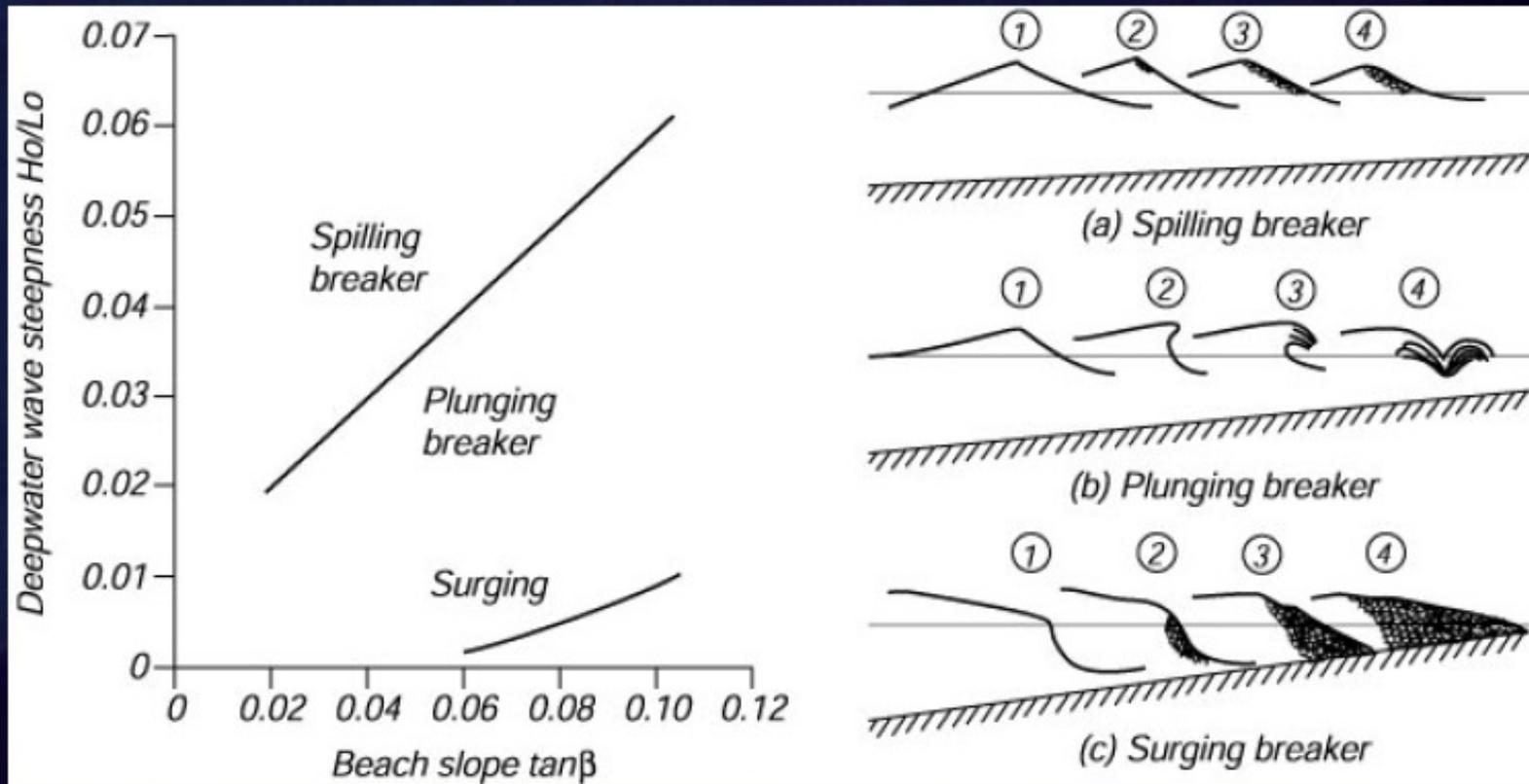
- **Surging**

- Landward and seaward motion controlled by oscillatory
- Tends to be low frequency
- Short distance of energy dissipation



- **BREAKER FORM** varies and depends on:
 - Wave height
 - Wave period (wavelength)
 - Beach slope

Breaker Type



Similarity

- More recent research on beaches has emphasized:

MODE & DEGREE of ENERGY DISSIPATION

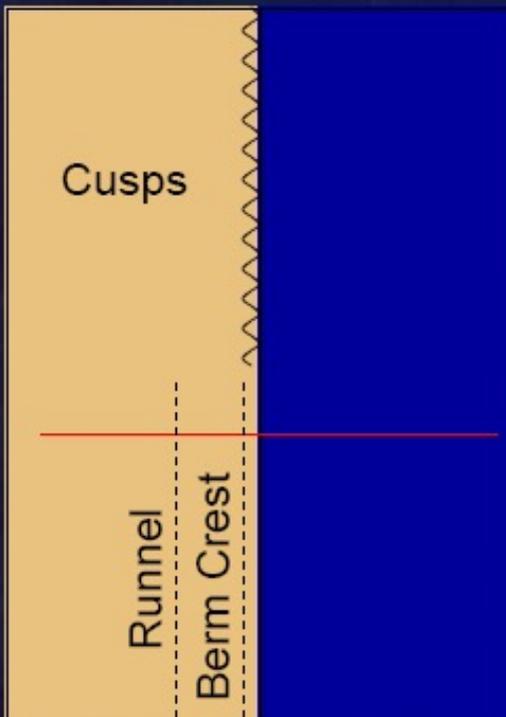
- There has been an effort to compare beaches in this regard
 - Concept of **SIMILARITY**
- **BATTJES SURF SIMILARITY PARAMETER**
 - Derived from the analysis of important **DIMENSIONS** in the system
 - **DIMENSIONLESS NUMBER** describing the fundamental properties of the hydrodynamic system:

$$\xi_b = \frac{\tan \beta}{\sqrt{\frac{H_b}{L_o}}}$$

tanβ= slope

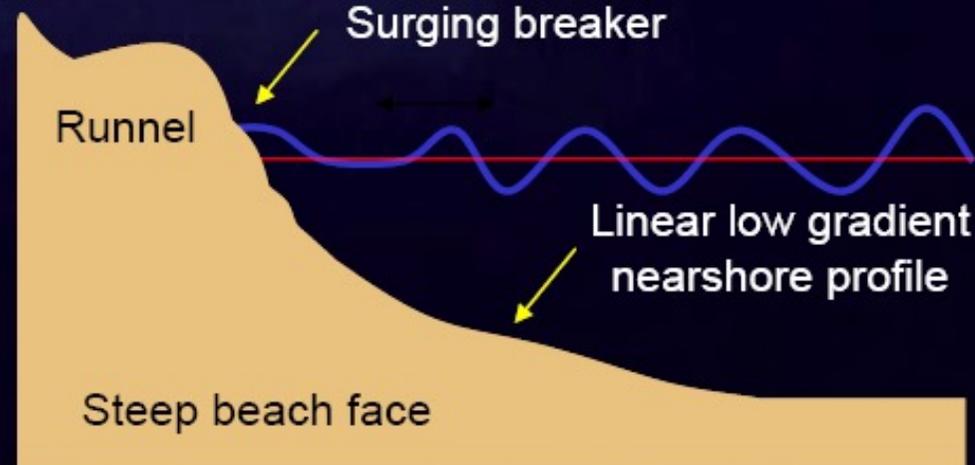
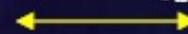


REFLECTIVE → $\xi_b > 2.0$
Surging/Collapsing Breakers



Reflective Domain

Small ξ_b



Surging breaker

Runnel

Linear low gradient
nearshore profile

Steep beach face

INTERMEDIATE $\rightarrow 0.4 < \xi_b < 2.0$

Plunging Breakers

Type III

Cusps may be present

Trough

Type II

Outer breaker zone

Type I

Welded bars

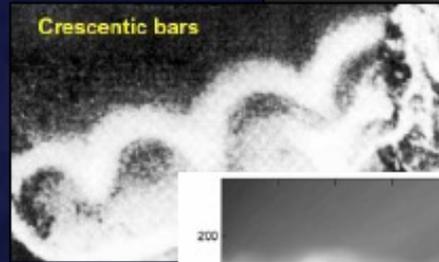
Rip Cells

Reflective Dissipative
Plunging breaker Spilling breaker

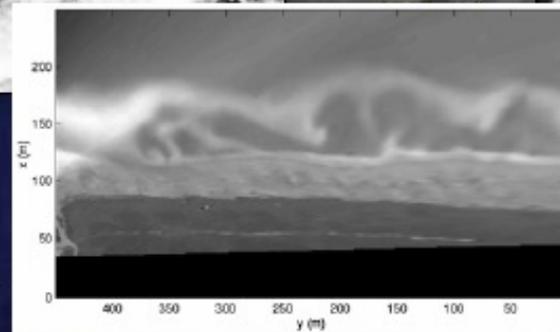
Flat-concave beach face

Trough

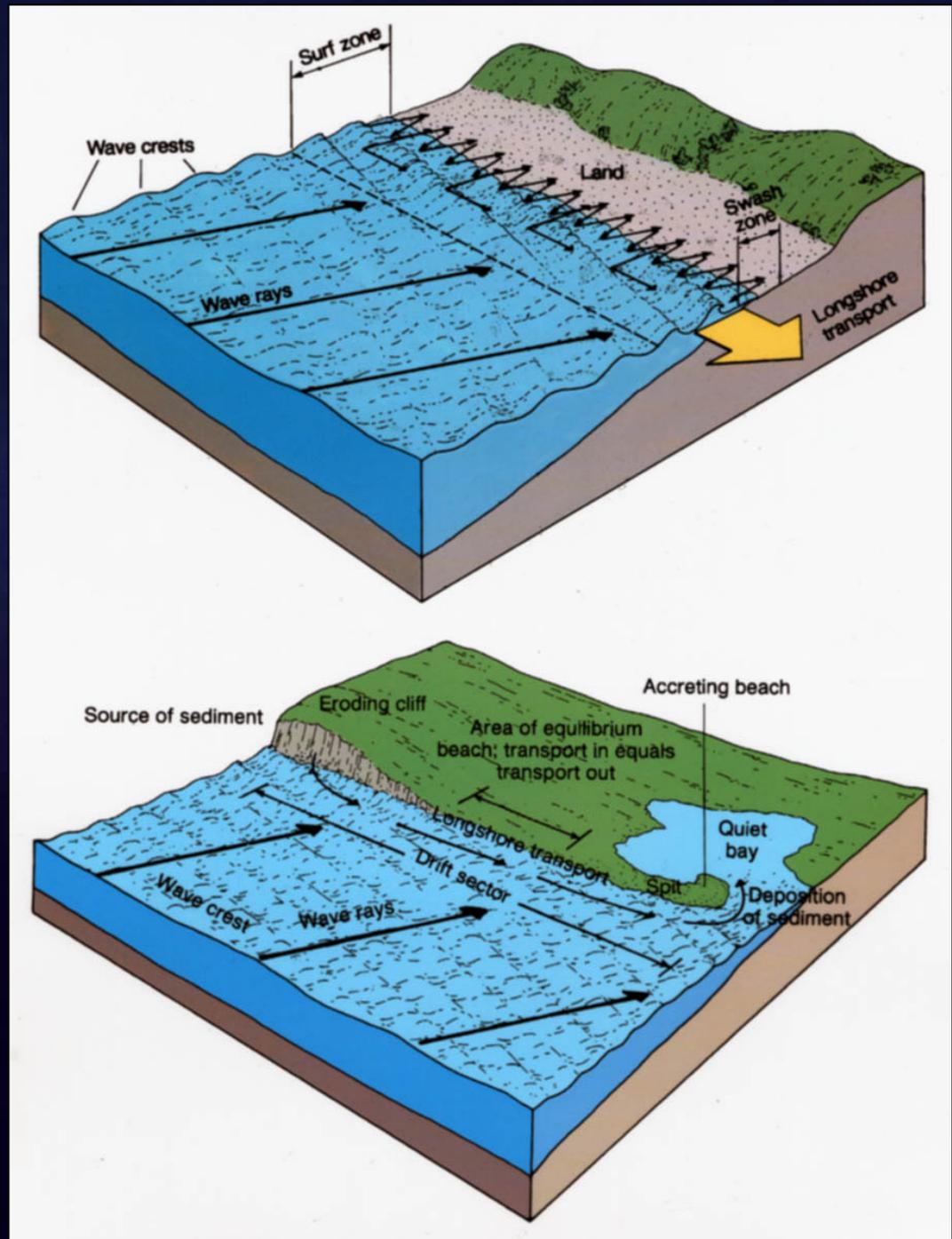
Nearshore bar

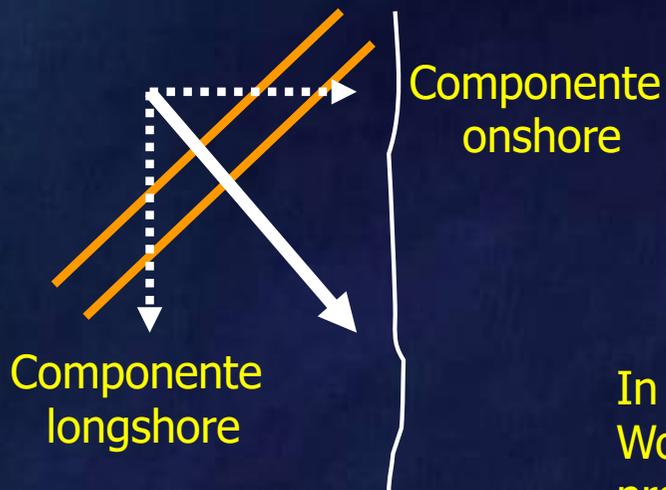


Palm Beach Australia



Il trasporto lungo riva





Flusso di energia $P_L = E C n$

$$E = \frac{1}{8} \rho \cdot g \cdot H^2$$

In termini unitari (per unità di larghezza di cresta d'onda $AB = W_o = 1\text{m}$), la componente longshore del flusso di energia si propaga per una larghezza pari ad AC , entro un tratto unitario di linea di riva pari a BD .

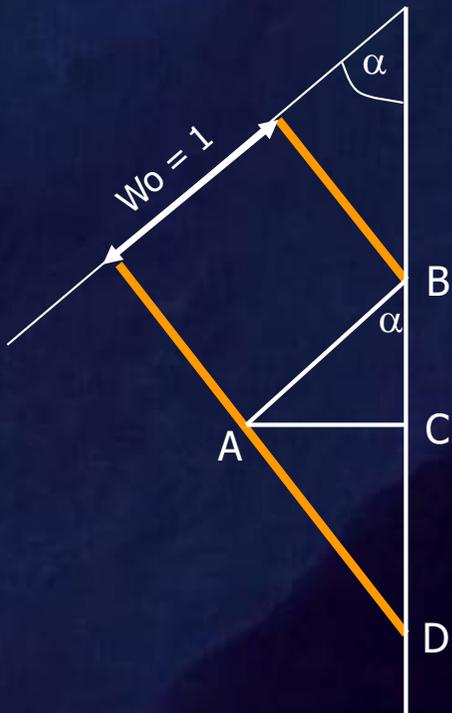
Poiché $AC = AB \sin \alpha = 1 \sin \alpha$ e $BD = 1/\cos \alpha$

$$P_L = \frac{(ECn)_b \sin \alpha_b}{\frac{1}{\cos \alpha_b}}$$

ovvero:

$$P_L = (ECn)_b \sin \alpha_b \cos \alpha_b$$

Componente longshore del flusso di energia



IL TRASPORTO LONGSHORE

Il trasporto lungo riva può essere espresso sia in forma volumetrica Q_L che in forma di peso immerso I_L tramite la seguente relazione:

$$I_L = (\rho_s - \rho) \cdot g a' Q_L$$

Dove a' rappresenta il fattore di porosità per convertire volume in peso; per le sabbie possiamo assumere tale valore pari a circa 0.6 (=porosità del 40%).

Il vantaggio dell'utilizzo di I_L è che tiene conto della densità dei granuli e che dimensionalmente viene espresso nella stessa forma di P_L (Newton/s o Watt/m).

La proporzionalità tra I_L e P_L è stata dimostrata sperimentalmente e di conseguenza:

$$I_L = k P_L = k (ECn)_b \sin \alpha_b \cos \alpha_b$$

Poiché il fattore di proporzionalità k si deriva sperimentalmente, il valore cambia molto a seconda dei casi (da 0.4 a più di 1). In generale assume il valore di 0.77 (Komar & Inman, 1970) ma in pratica può essere considerato il valore di 0.7.

Il coefficiente k

Autore	Note	k
Swart	Dipende dalla granulometria	$K = A \log_{10} (0.00146/D_{50})$ A sperimentale
C.E.R.C. (Komar)	Statistica generale	0.77
Kamphuis & Readshow	Dipende dal numero di Iribarren, ζ $\zeta_b = \frac{\tan \beta}{\left(\frac{H_b}{L_0}\right)^{1/2}}$	0.28 per $\zeta_b < 0.4$ (spiagge dissipative)
		0.7 ζ_b per $0.4 \leq \zeta_b \leq 1.0$ (spiagge interm.-dissip.)
		1.0 per $\zeta_b > 1.0$ (spiagge interm.-riflettent)

Per $k = 0.7$:

$$I_L = 0.7 \cdot P_L = 0.7(ECn)_b \sin \alpha_b \cos \alpha_b$$

$$I_L = 0.7 \left(\frac{1}{8} \rho \cdot g H^2 Cn \right)_b \sin \alpha_b \cos \alpha_b$$

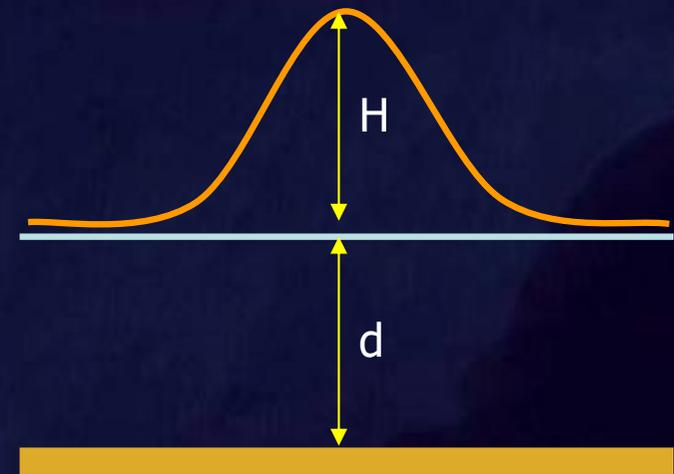
In acque basse può essere assunto $n = 1$ e usare la teoria dell'onda solitaria per computare $C = (g d)^{1/2}$, semplicemente aumentando il battente d'acqua del valore corrispondente all'altezza dell'onda

Semplificando il criterio di frangenza con $\gamma = d/H = 1$ invece che 0.78

$$I_L = 0.7 \left(\frac{1}{8} \rho \cdot g H_b^2 \right) \cdot (2g \cdot H_b)^{1/2} \sin \alpha_b \cos \alpha_b$$

$$I_L = 0.12 \rho \cdot g^{3/2} H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

Onda solitaria



$$C = \sqrt{g \cdot (d + H)}$$

In frangenza (semplificazione):
 $d/H = 1 \rightarrow d = H$

$$C = \sqrt{g \cdot (2H_b)}$$

$$I_L = 0.12 \rho \cdot g^{3/2} H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

Poiché:

$$I_L = (\rho_s - \rho) \cdot g a' Q_L$$

Assumendo una densità $\rho_s = 2650 \text{ kg/m}^3$ (quarzo) e una densità dell'acqua $\rho = 1020 \text{ kg/m}^3$ si ottengono le seguenti relazioni:

$$Q_L = 6.2 \cdot P_L$$

$$Q_L = 1.1 \cdot \rho \cdot g^{3/2} H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

$$Q_L = 34474 \cdot H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

$$Q_L = 17237 \cdot H_b^{5/2} \sin 2\alpha_b$$

Esprese in m^3/giorno

$g = 9.81 \text{ m/s}^2$

$\rho = \text{kg/m}^3$

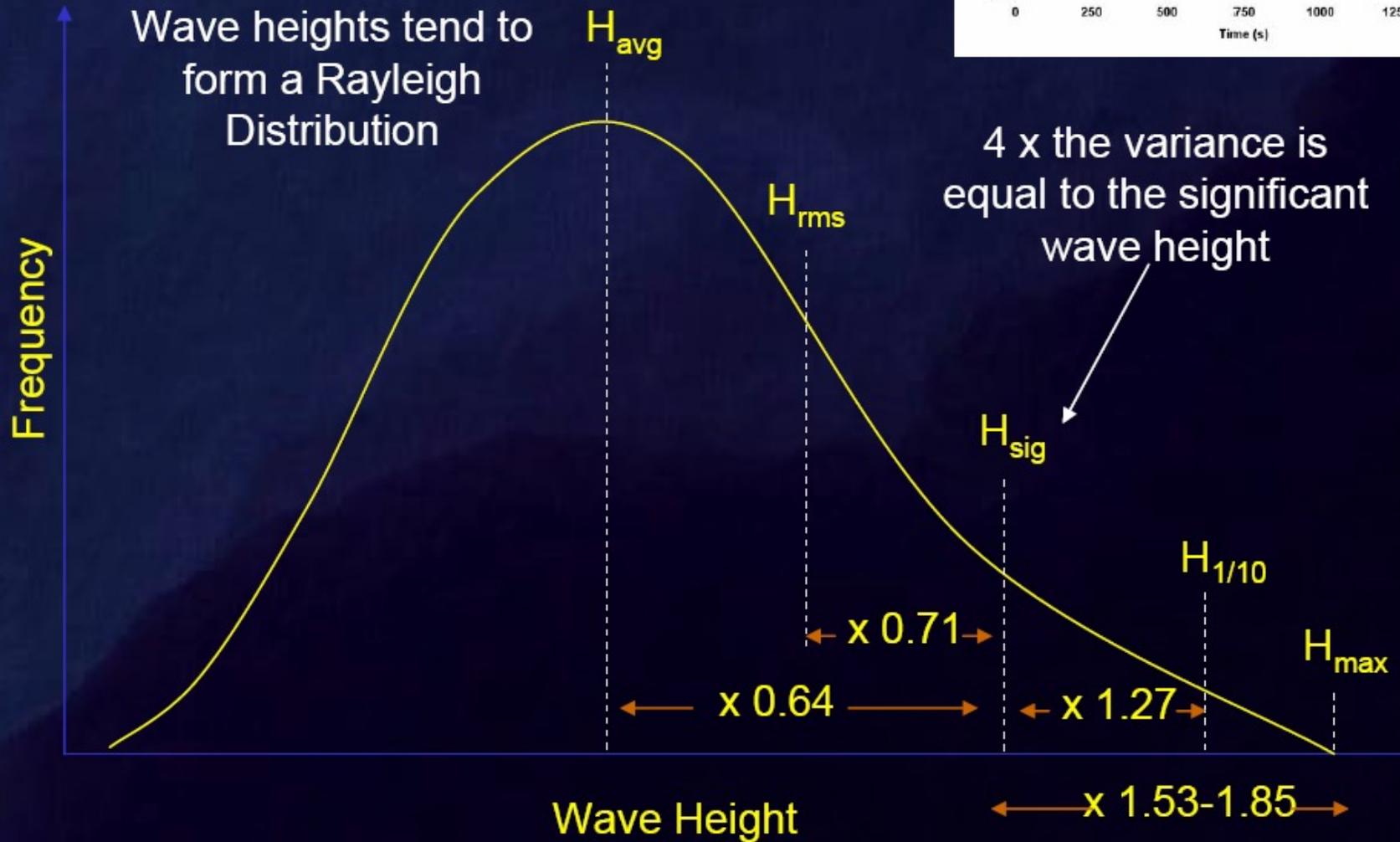
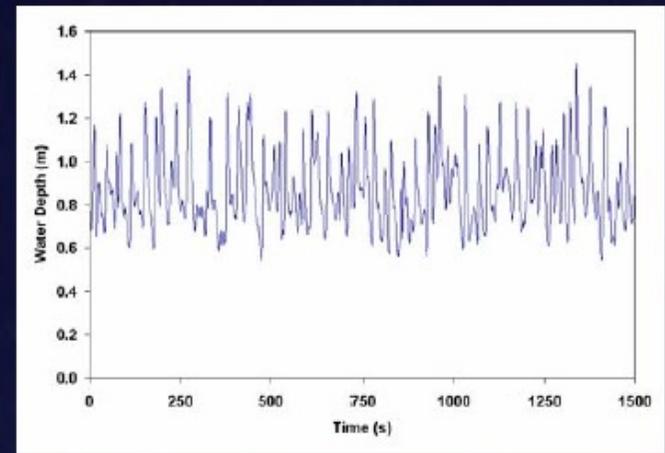
$P_L = \text{watt/m}$

E poiché \rightarrow

$$\sin \alpha_b \cos \alpha_b = \frac{1}{2} \sin 2\alpha$$

Le relazioni espresse finora considerano H in frangenza come valore dato dalla radice dell'altezza quadratica media, che è più corretta per definire E

Altezze d'onda



Se vogliamo usare l'altezza dell'onda significativa in frangenza:

$$H_s = 1.41 H_{rms}$$

**Conseguentemente l'energia varierà di un fattore $(1.41)^2 \sim 2.0$
Mentre la velocità C varierà di un fattore $(1.41)^{0.5} \sim 1.2$**

$$I_L = 0.30 \cdot P_L = 0.053 \rho \cdot g^{3/2} H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

$$Q_L = 0.46 \cdot \rho \cdot g^{3/2} H_b^{5/2} \sin \alpha_b \cos \alpha_b$$

$$Q_L = 0.23 \cdot \rho \cdot g^{3/2} H_b^{5/2} \sin 2\alpha_b$$

sempre in m³/giorno