Chapter Outline

Wave Refraction, Diffraction, Reflection

- Three-Dimensional Wave Transformation
- Wave Refraction
- Refraction by Currents
- Wave Diffraction
- Wave Reflection
- Vessel-Generated Waves

Prof. Marta Cianferra e-mail: marta.cianferra@dia.units.it

Three-Dimensional Wave Transformation

Ocean waves rarely propagate in uniform depth or open ocean conditions. When waves approach the coast, spatial variations in bathymetry, currents, and coastal structures modify wave properties.

Key wave parameters affected:

- Wave direction
- Wavelength
- Phase speed
- Wave height
- Energy distribution

Main transformation processes:

- **Refraction** – direction change due to depth or currents
- **Diffraction** – lateral spreading of wave energy around obstacles
- **Reflection** – energy returning from boundaries
- **Shoaling** – wave height change due to depth variation

Wave transformation **redistributes energy** spatially but does not destroy it unless dissipation occurs.

Three-Dimensional Wave Transformation

Wave **refraction** occurs in transitional and shallow water depths because wave celerity decreases with decreasing water depths **to cause the portion of the wave crest that is in shallower water to propagate forward at a slower speed than the portion that is in deeper water**. The result is a bending of the wave crests so that **they approach the orientation of the bottom contours**.

Diffraction will occur when the height of a wave is greater at one point along a wave crest than at an adjacent point. This **causes a flow of energy along the crest in the direction of decreasing height and a consequent adjustment of wave height along the crest** as the wave propagates forward. This is particularly important, for example, **when a wave crest is truncated as it passes the end of a structure** that extends out into the water. Diffraction will then cause a flow of wave energy into the shadow region in the lee of the structure.

The effects of wave **shoaling, refraction, and diffraction** all **depend on the period of the wave being considered**. Also, the effects of wave refraction and diffraction **depend on the incident direction of the wave**. Thus, for a spectrum of wind-generated waves having a range of component periods and directions, the different components of the spectrum will be advected differently as they propagate from deep water to the point of interest.

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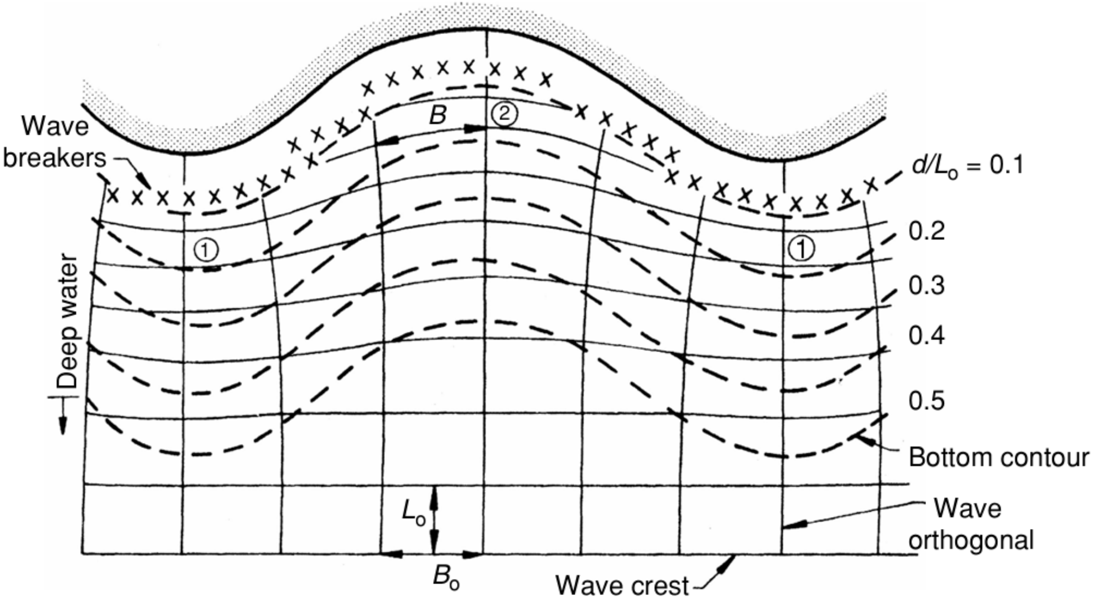
Wave Refraction

Wave refraction occurs when **wave speed varies spatially**, causing the wave crest to bend.



→ Have a look here Wave Refraction

Prof. Marta Cianferra e-mail: marta.cianferra@dia.units.it

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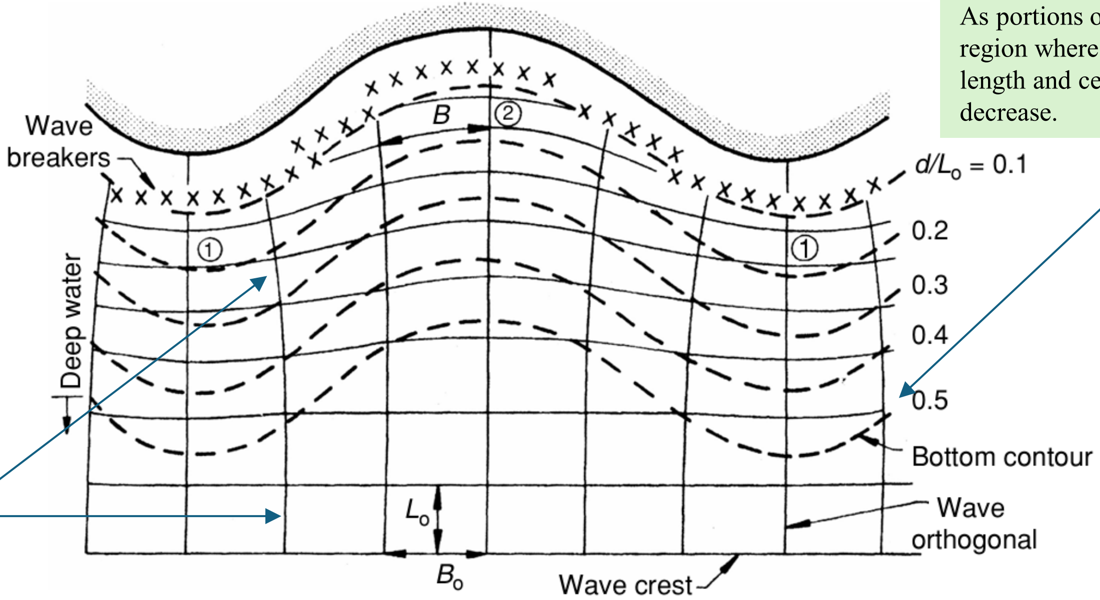

As portions of the wave crest enter the region where $d/L_0 < 0.5$ the wave length and celerity commence to decrease.

If one constructs **equally spaced orthogonal lines along the deep water wave crests** and extends these lines toward the shore, being sure that they **remain normal to the wave crests**, one can see the pattern of energy distribution at any point along a wave crest. **Where orthogonals converge there is an increase in the energy per unit crest length**, and vice versa.

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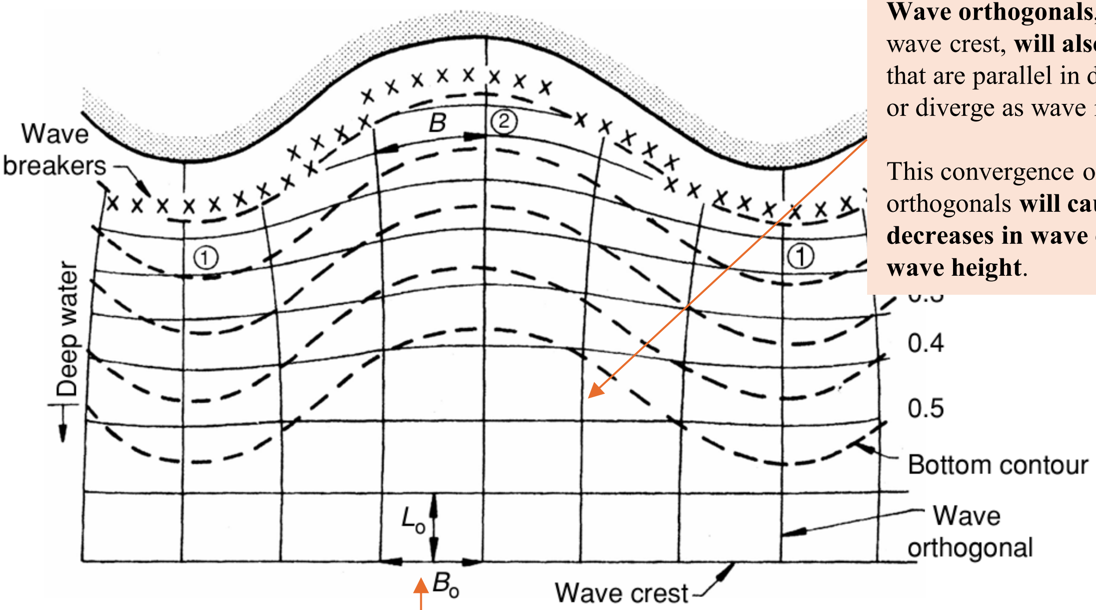


Wave orthogonals, to remain normal to the wave crest, **will also bend** so that orthogonals that are parallel in deep water may converge or diverge as wave refraction occurs.

This convergence or divergence of wave orthogonals **will cause local increases or decreases in wave energy and consequently wave height**.

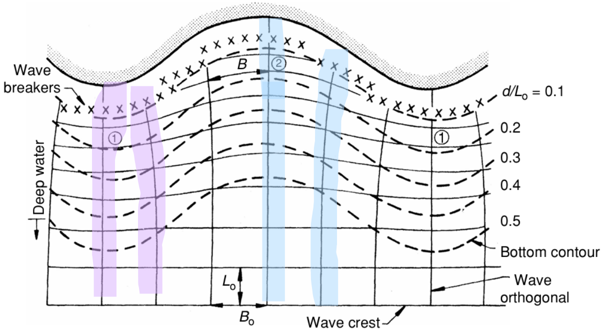
A wave train with a deep water wave length L_0 **is approaching the shore** with a crest orientation in deep water that is parallel to the average shoreline position.

Prof. Marta Cianferra e-mail: marta.cianferra@dia.units.it

Wave Refraction

The convergence and divergence of the wave orthogonals along with the effects of wave shoaling cause the wave height variation from deep water defined by

$$\frac{H}{H_o} = \underbrace{\sqrt{\frac{L_o}{2nL}}}_{K_s}\underbrace{\sqrt{\frac{B_o}{B}}}_{K_r} = \frac{H}{H'_o}\sqrt{\frac{B_o}{B}}$$



The orthogonal spacing ratio ($B_0\,/B = K_r^2$) for a nearshore point of interest must be determined from a refraction analysis.

Note: since wave celerity depends on the wave period, waves with different periods will refract differently as they approach the shore. Longer period waves begin to feel bottom and refract in deeper water and consequently may undergo greater refraction as they approach the shore. The resulting wave refraction pattern will also be different for each different deep water approach direction. For a typical wave analysis at a coastal site refraction patterns must be investigated for a representative range of wave periods and deep water directions to determine the most critical wave height/direction combinations at the site.

Prof. Marta Cianferra e-mail: marta.cianferra@dia.units.it

Wave Refraction

Refraction analyses were initially done by the manual construction of refraction diagrams. Now they are mostly done by numerical/computer analysis, except for situations that only involve a limited number of wave conditions.

The first method used for the construction of refraction diagrams is known as the wavecrest method (Johnson and co-authors, 1948).

1) A wave crest having the proper orientation is constructed in deep water.
2) Then, points along the wave crest are advanced normal to the crest by an integral number of wave lengths and the new crest position is drawn.

→ Given the deep water wave length and the local average water depth over which the wave will advance, the advancing wave length can be calculated from

$$\frac{C}{C_o} = \frac{L}{L_o} = \tanh\frac{2\pi d}{L}$$

For engineering analysis it is most important to produce an accurate depiction of the wave orthogonal pattern

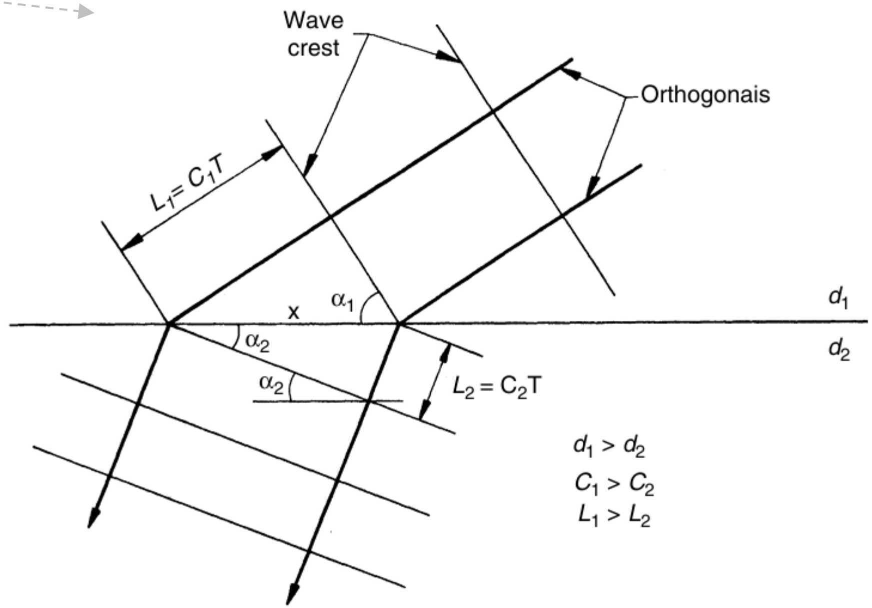
Wave Refraction

A second graphical method for constructing refraction diagrams, known as the orthogonal method, is based on Snell's Law which may be derived by considering the figure

- Consider a train of waves propagating over a step where the water depth instantaneously decreases from d_1 to d_2
- This causes the wave celerity and length to decrease from C_1 and L_1 to C_2 and L_2, respectively.
- For an orthogonal spacing x and a time interval T, $\sin\alpha_1 = C_1T\ /\ x$ and $\sin\alpha_2 = C_2T\ /\ x$. Dividing yields

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{C_1}{C_2} = \frac{L_1}{L_2}$$

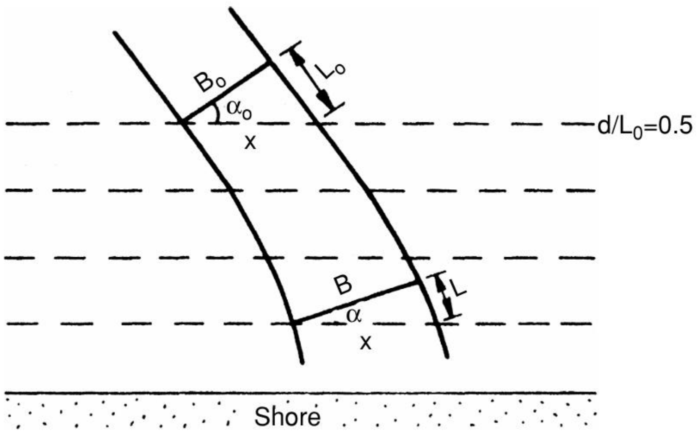
Snell's law



Wave Refraction

Applying Snell equation to wave refraction over a gradually varying bottom slope, α_1 and α_2 become the angles between the wave crest and bottom contour line at successive points along an orthogonal as a wave propagates forward, and L_1 and L_2 become the wave lengths at the points where α_1 and α_2 are measured.

When waves propagate shoreward over bottom contours that are essentially straight and parallel as shown in the figure below



When waves propagate shoreward over bottom contours that are essentially straight and parallel (as shown in the left figure)

$$\frac{\sin \alpha_o}{L_o} = \frac{\sin \alpha}{L} = \frac{1}{x}$$

If we choose B_0 and B so that the orthogonal lengths equal L_0 and L as shown. Then

$$\frac{B_o}{\cos \alpha_o} = x = \frac{B}{\cos \alpha}$$

$$K_r = \sqrt{\frac{B_o}{B}} = \sqrt{\frac{\cos \alpha_o}{\cos \alpha}}$$

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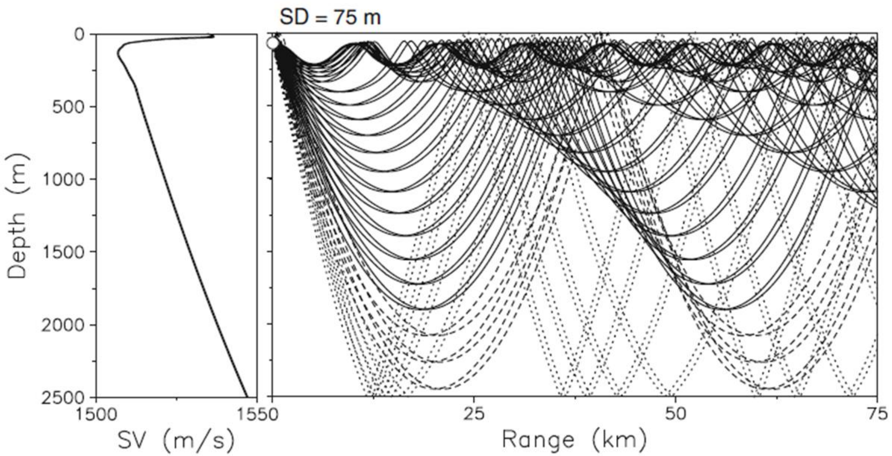
Wave Refraction

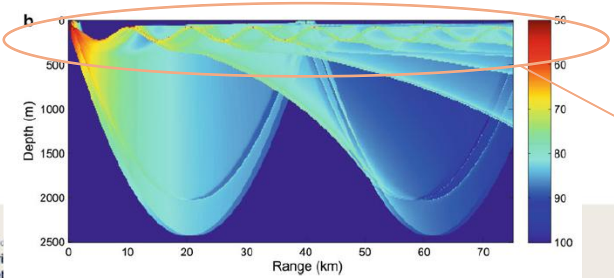
Analogy with Underwater Radiated Noise: lines in the figure represent normals to wavefront, the latter originated from a monopole source (75 m deep). The difference in the speed of sound makes the wavefront to blend.



$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$$

Snell's law

- Reflection effects due to the boundaries (sea bottom, free-surface, coastal areas, measurement tanks..)
- Refraction effects due to density variation



SOFAR Channel: it acts as a waveguide for sound, and low-frequency sound waves within the channel can travel thousands of miles before dissipating.

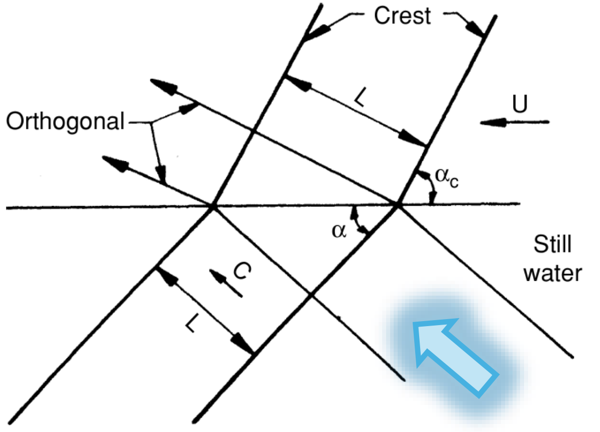
Refraction by Currents

When a wave train propagates in a region where there is a current of varying velocity, the wave celerity relative to the fixed sea floor will change, causing the wave to refract.

Johnson (1947) presented an analysis of this phenomenon assuming deep water waves. A similar analysis can be carried out for intermediate and shallow water waves. The results would be similar but with much more complex equations.

The orthogonal direction relative to the current interface changes from a to α_c and the wave crest and orthogonal pattern change as

$$\sin \alpha_c = \frac{\sin \alpha}{\left(1 - \frac{U}{C} \sin \alpha\right)^2}$$



This phenomenon is common, for example, when deep water waves from the Atlantic Ocean cross the Gulf Stream near the U.S. coastline or when waves propagating toward the coast interact with the tide-induced ebb current at a coastal entrance

From the conservation of energy flux between two orthogonals Johnson found the following relationship for wave height change:

$$\left(\frac{H_c}{L_c}\right)^2 = \left(\frac{H}{L}\right)^2 \frac{\cos \alpha}{\cos \alpha_c} \left[\frac{\left(1 - \frac{U}{C} \sin \alpha\right)^6}{1 + \frac{U}{C} \sin \alpha}\right]$$

When waves enter a navigation channel where the current is ebbing, the current will cause the waves to decrease in length and increase in height, possibly to the point of breaking. This can have serious negative consequences on navigation, particularly for small vessels.

Wave Diffraction

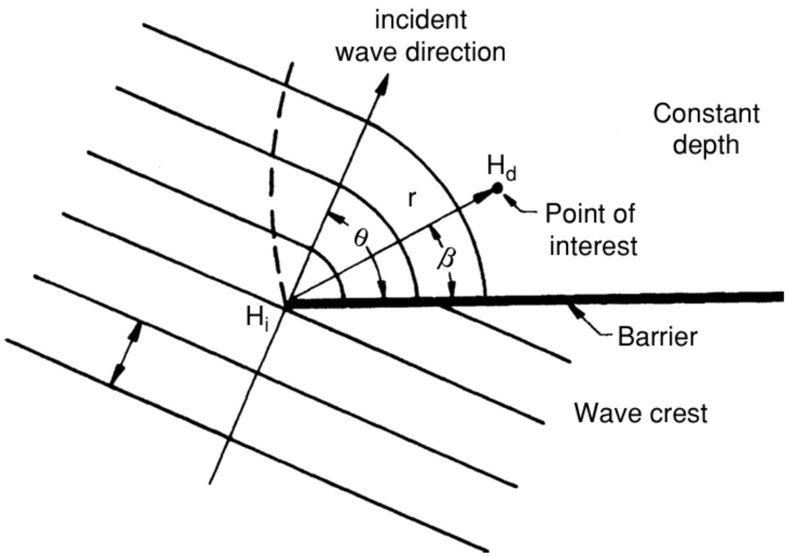
Consider a train of waves approaching a barrier as shown below. The portion of the wave that hits the barrier will be reflected and dissipated, with the possible transmission of some wave energy through or over the barrier depending on the cross-section geometry and composition of the barrier.

The **shadow region out to the dashed line** will have a wave height that is less than the incident wave height at the end of the barrier. Note that the water depth in the figure is assumed constant.

If H_i is the incident wave height at the end of the barrier and H_d is the diffracted wave height at a point of interest in the lee of the barrier, we can define a diffraction coeffcient $K_d = H_d/H_i$.

The value of K_d depends on the location behind the barrier defined by r and β, and the incident wave direction defined by θ, or in dimensionless form $K_d = f(u, b, r/L)$ where L is the wavelength in the lee of the barrier.

Since the wave length is a function of the wave period and water depth, the resulting diffraction coeffcient for each component of the wave spectrum would depend onthe incident direction and period of that component.



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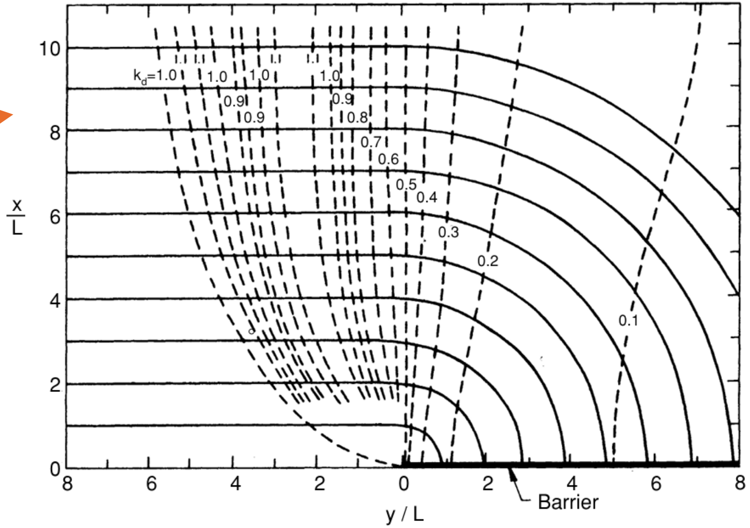
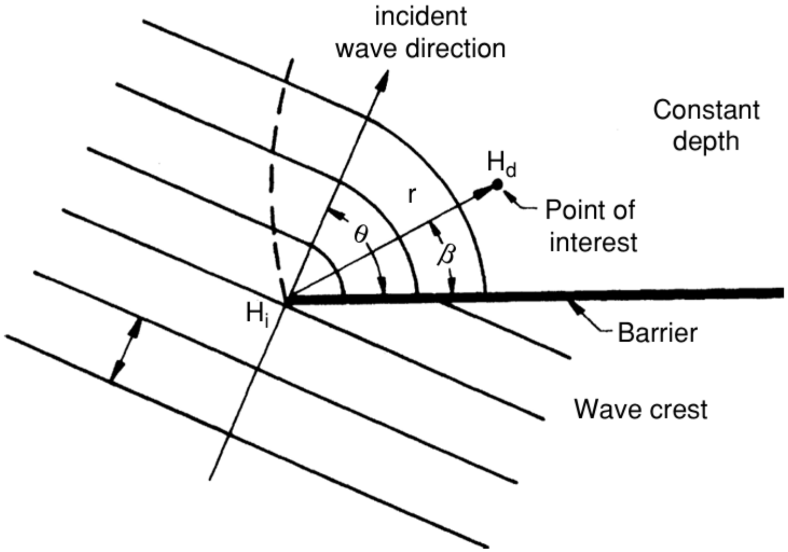
Wave Diffraction

A summary of the diffraction solution for a semi-infinite barrier is presented by Wiegel (1964) and by Putnam and Arthur (1948), who also conducted some wave tank experiments to verify results.

Here is an example of these diagrams for the incident wave approach angle $\theta = 90°$





Wave crest pattern and related $K_d = H_d/H_i$ values for normal wave incidence

Prof. Marta Cianferra e-mail: marta.cianferra@dia.units.it

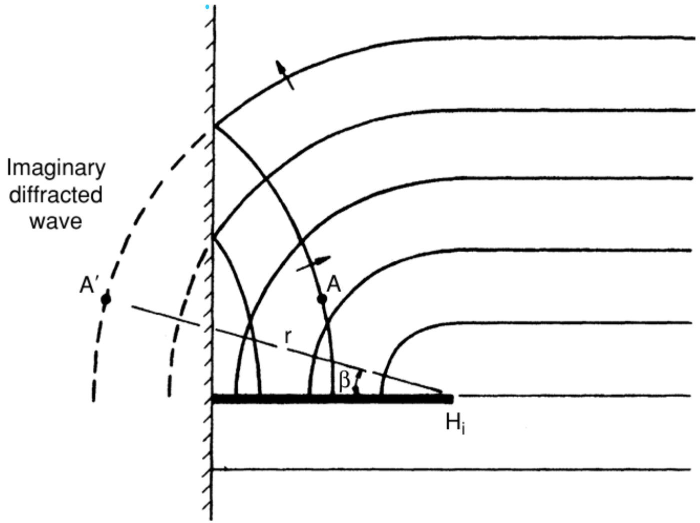
Wave Reflection

To construct the reflected wave crest pattern:

1) first construct imaginary mirror image bottom contours in the lee of the reflecting barrier
2) then extend the incident wave crest into this imaginary domain (refracting and diffracting it as necessary).
3) then construct a mirror image of this wave crest that was constructed in the imaginary domain.

This will be the pattern of the reflected wave crest. The wave height at any point along the reflected wave crest will be the wave height at the equivalent point in the imaginary domain times the reflection coefficient of the barrier:

$$C_r = H_r \,/\, H_i$$



For example: vertical wall $C_r = 0.92$; dissipative rubble-mound breakwater $C_r = 0.15$.
An analysis of the reflection patterns and related reflected wave heights may indicate potential ‘‘trouble spots’’ in a harbor. Inspection of the pattern of reflected waves will indicate possible desired changes in the harbor boundaries (e.g., lowering the reflection coeffcient of a segment of the harbor boundary by changing it from a vertical bulkhead to a sloping stone revetment).

Vessel-generated waves

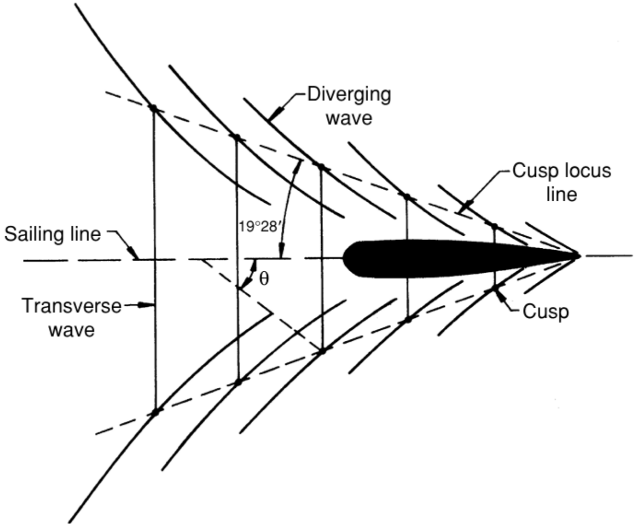
In restricted areas, owing to the relatively short expanse of water over which the wind can generate waves, the waves generated by a moving vessel often are the dominant waves for design.

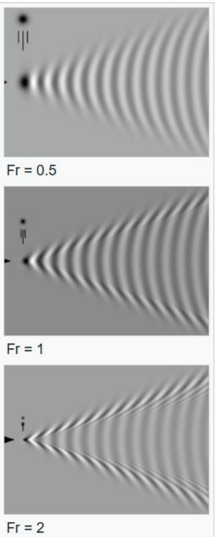
As a vessel moves across the water surface, the flow of water back across the vessel hull causes a varying pressure distribution over the hull surface. The magnitudes of these dynamic pressures depend on the vessel speed, the water depth (if sufficiently shallow), the vessel hull geometry and draft, and the channel
cross-section shape if the channel is relatively narrow.

→ The amplitude of the waves will depend on the magnitude of the pressure variation (i.e. on the vessel speed, hull geometry and draft, and the water depth).

→ The period (length) and direction of propagation of the waves depends only on the vessel speed and water depth.

*In deep water, the Kelvin wake angle is constant (~19.47°) and independent of the vessel's shape and speed, while in shallow water the wake angle depends on the depth-based Froude number and can vary significantly. → have a look on this [Why Do Boats Make This Shape?]





Kelvin wake simulation for Gaussian distortion (shown besides the wake) at various Froude numbers

If the vessel speed is increased, the wave lengths would accordingly increase, but the overall pattern (including the 19°28' angle) would retain the same form*.

Since the wave pattern remains steady relative to the vessel, the celerity C of all of the waves in the pattern must be related to the vessel speed $C = V \cos\theta$ - where θ is the angle between the sailing line and the direction of wave propagation

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