EWC 471: Basic Coastal Engineering

Lecture 11 and 12

Topic: Wave Deformation/ Wave Transformation

From last class: Wave transformation

Processes that can affect a wave as it propagates from deep into shallow water include:

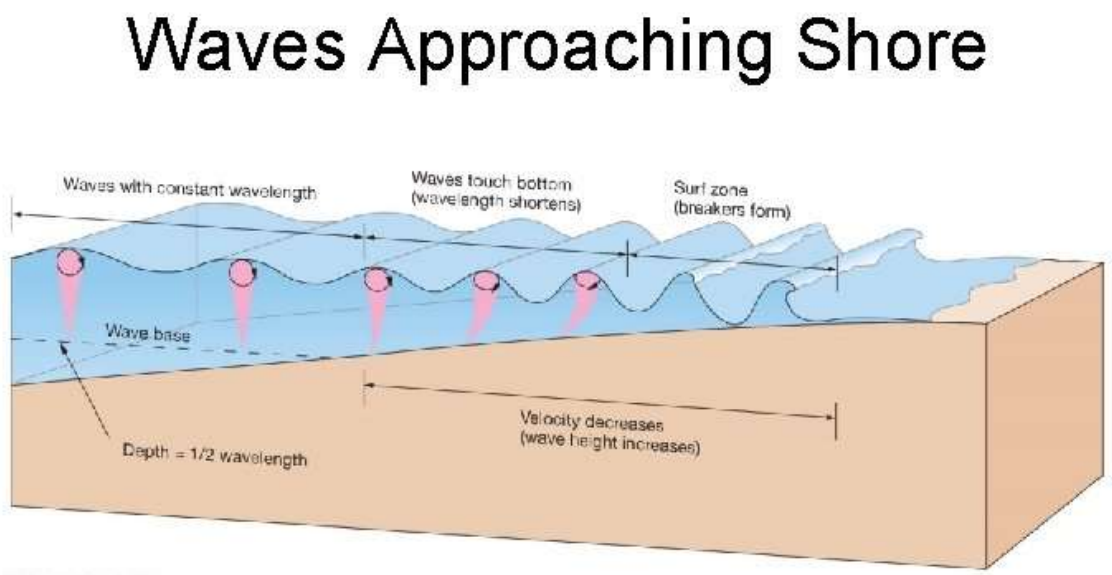
1. Shoaling ✓
2. Refraction ✓
3. Diffraction ✓
4. Bottom friction
5. Depth-induced wave-breaking
6. Wave set-up, set-down
7. Wave swash
8. Wave run-up
9. White-capping
10. Wave overtopping

Additionally, the following phenomena may occur, but not due to shallow water effect:

11. Dissipation due to friction.
12. Dissipation due to percolation.
13. Additional growth due to the wind.
14. Wave-current interaction.
15. Wave-wave interactions

Bottom friction

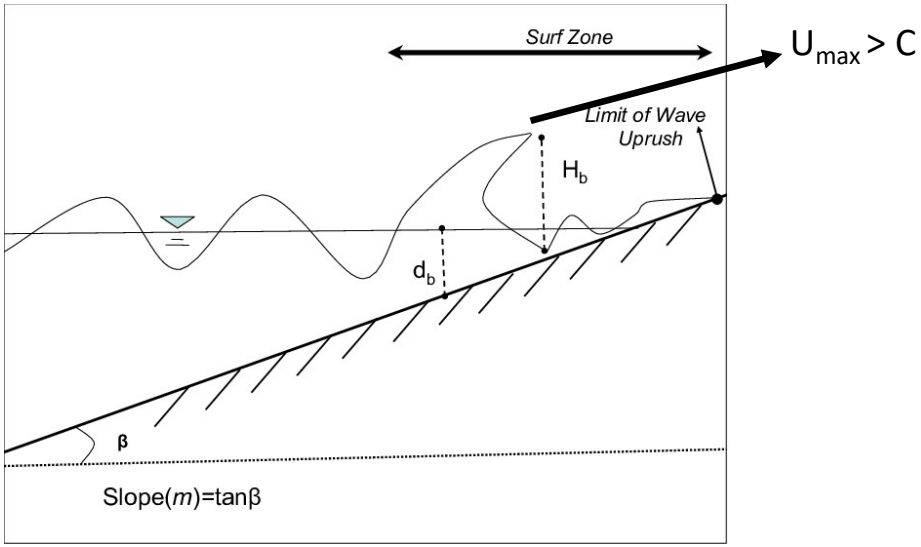
Bottom friction causes energy dissipation and thereby wave height reduction as the water depth becomes more and more shallow. Friction is of special importance over large areas with shallow water.



Depth-induced wave-breaking

Depth-induced wave-breaking of individual waves starts when the wave height becomes greater than a certain fraction of the water depth. As a rule of thumb, the wave height of an individual wave at breaking is often said to be around 80% of the water depth, but this is a very approximate figure. Breaking waves are generally divided into four main types, depending on the steepness of the waves and the slope of the shoreface:

- Spilling
- Plunging
- Collapsing
- Surging



Wave Breaking

Wave breaking is one of the most important phenomena to coastal engineers since it greatly influences both the behavior of sediments on beaches and the magnitudes of the forces experienced by coastal structures. At the same time, breaking is possibly the most difficult wave phenomenon to describe mathematically.

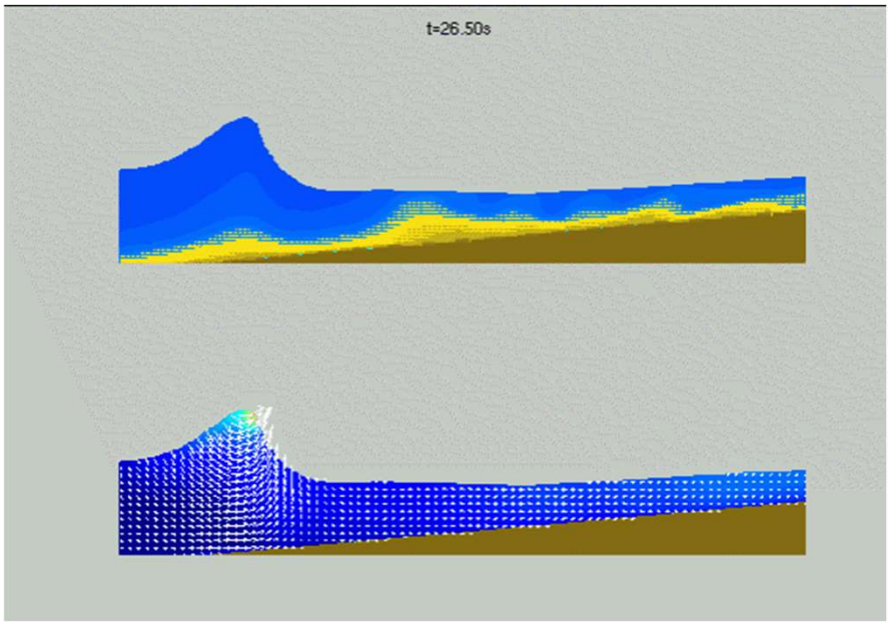




Wave Breaking

Why do waves break?

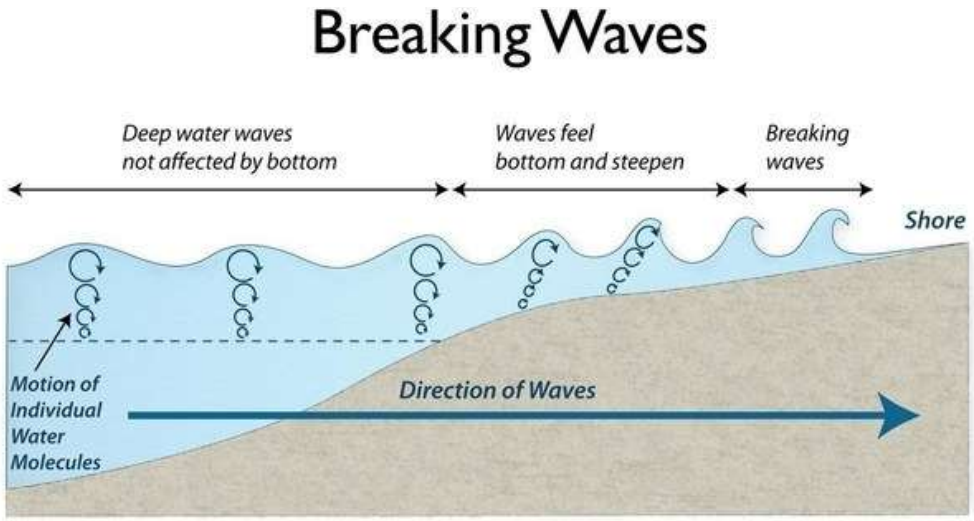
As a wave enters shallower water, its wavelength shortens and its height and steepness increase due to interaction with the bottom. The lower part of the wave slows through frictional drag along the bottom, while the top of the wave continues to propagate at a higher rate of speed. The top of the wave eventually outruns the slower moving base and it begins to spill over, breaking down the front of the wave.



Wave Breaking

Breaking of water surface waves may occur anywhere that the amplitude is sufficient, including in mid-ocean.

However, it is particularly common on beaches because wave heights are amplified in the region of shallower water (because the group velocity is lower there).



Incipient wave breaking: As a wave approaches a beach, its length L decreases and its height H may increase, causing wave steepness H/L to increase. Waves break as they reach a limiting steepness, which is a function of relative depth d/L and the beach slope $tan\beta$.

Breaker Types

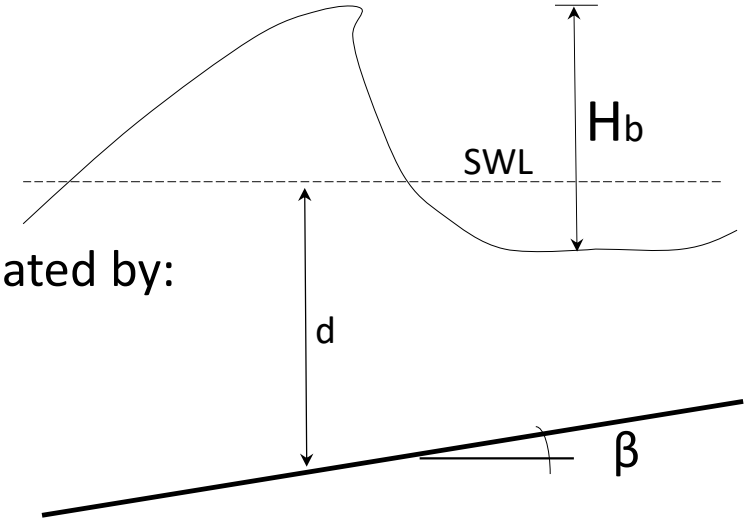
- Breaker type: it refers to the form of the wave at breaking.
- The manner in which a wave breaks depends on the wave's (water) depth with respect to the bathymetry. Understanding this dependency helps to identify locations where hazardous breakers and significant beach erosion could be expected for a given wave period and tidal phase.
- There are four basic types of breaking waves:
  1. Spilling
  2. Plunging
  3. Collapsing , and
  4. Surging
- Since breaker types are dependent on the depth of the water, **tidal variations** must be taken into consideration when anticipating breaker type.

Breaker Types

Breaker type may be correlated to the surf similarity parameter ξ_o *or* ξ_b, defined as:

$$\xi_0 = \tan\beta \left(\frac{H_0}{L_0}\right)^{-\frac{1}{2}} \text{ or } \xi_b = \tan\beta \left(\frac{H_b}{L_0}\right)^{-\frac{1}{2}}$$

the subscript *o* denotes the deep water condition.



- On a uniformly sloping beach, breaker type is estimated by:
  - Spilling $\xi_o < 0.5$; $\xi_b < 0.4$
  - Plunging $0.5 < \xi_o < 2.3$; $0.4 < \xi_b < 1.5$
  - Collapsing $2.3 < \xi_o < 3.2$; $1.5 < \xi_b < 2$
  - Surging $\xi_o > 3.2$; $\xi_b > 2$

Note that, in reality, there are no precise boundaries separating the values of ξo associated with the different types of wave action (in much the same way in which there are no precise boundaries between the colors in a rainbow). Furthermore, the values are somewhat modified for slopes which are rough and permeable.

Breaker Types

Four types of wave breaking (Galvin 1968):

1. Spilling breakers: Spilling breakers occur in areas with gradual, gently sloped bathymetry. They are characterized by their gentle slope and the way the breaking water spills directly down along the forward slope of the wave producing a foamy water surface. The depth at which a spilling wave will begin to break is approximately **1.67H**, where **H** is the wave height at breaking.



Breaker Types

2. Plunging breakers: They occur when the wave encounters an abrupt transition from deep to shallow water. The base of the wave decelerates rapidly, while the top of the wave continues moving at a higher speed. With this large speed differential, the top of the wave pitches out in front, forming a curl or tube and resulting in a high splash.

Plunging breakers can be more dangerous for beachgoers because the breaking action is much more sudden and concentrated. This type of breaker can also cause much more beach erosion than other types because it breaks with such concentrated force in shallow water, scouring sand away.





Breaker Types

3. Collapsing breakers: For this breaker type the crest remains unbroken while the lower part of the shoreward face steepens and then falls, producing an irregular turbulent water surface.

Collapsing breakers occur with very small, short-period waves, which shoal and collapse right onto the beach. These breakers are operationally insignificant because they are so small and pose negligible hazard.



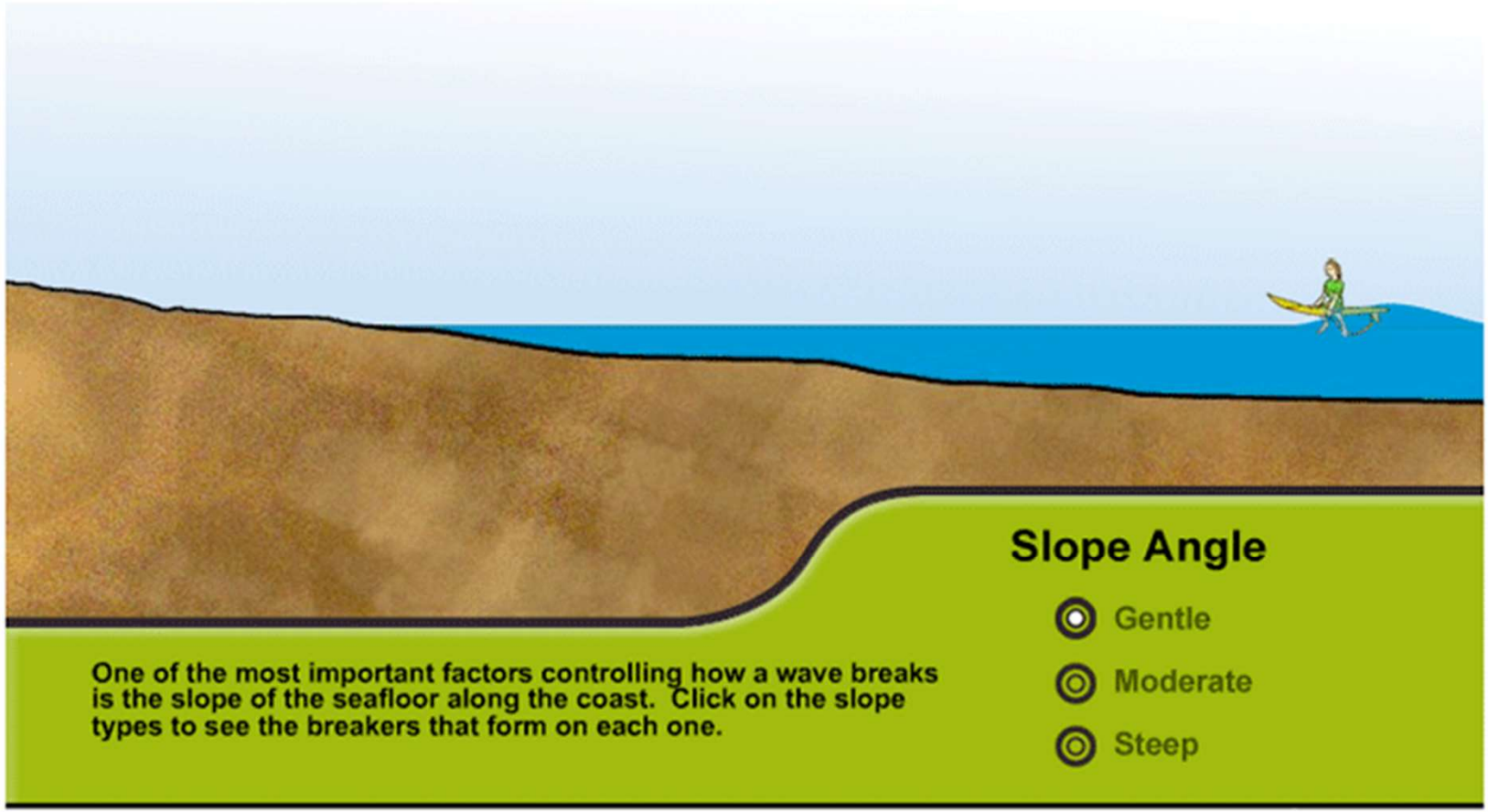
Breaker Types

4. Surging breakers: Here also the crest remains unbroken and the front face of the wave advances up the beach with minor breaking.

Surging breakers occur along stretches of coastline where there is no shoaling zone due to extremely rapid drop-offs. If this is the case, the deep water waves never break before reaching land. Instead, the water just pushes or surges up onto the beach. Since surging breakers do not break off shore, they do not lose energy and therefore may run up the beach with force and distance.

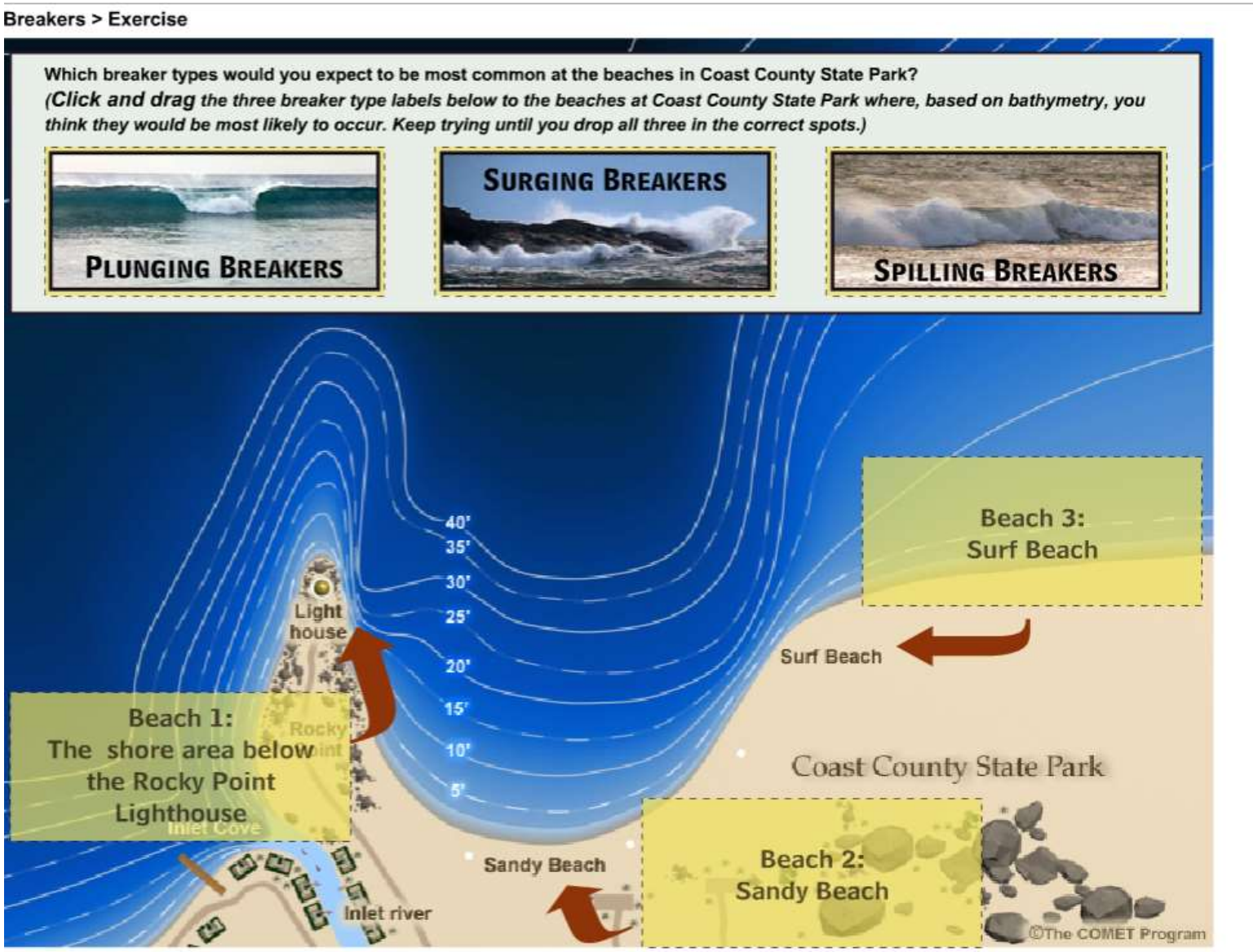


Breaker Types



Breaker Types Exercise:

- Spilling
- Plunging
- Collapsing
- Surging



Breaker Criteria

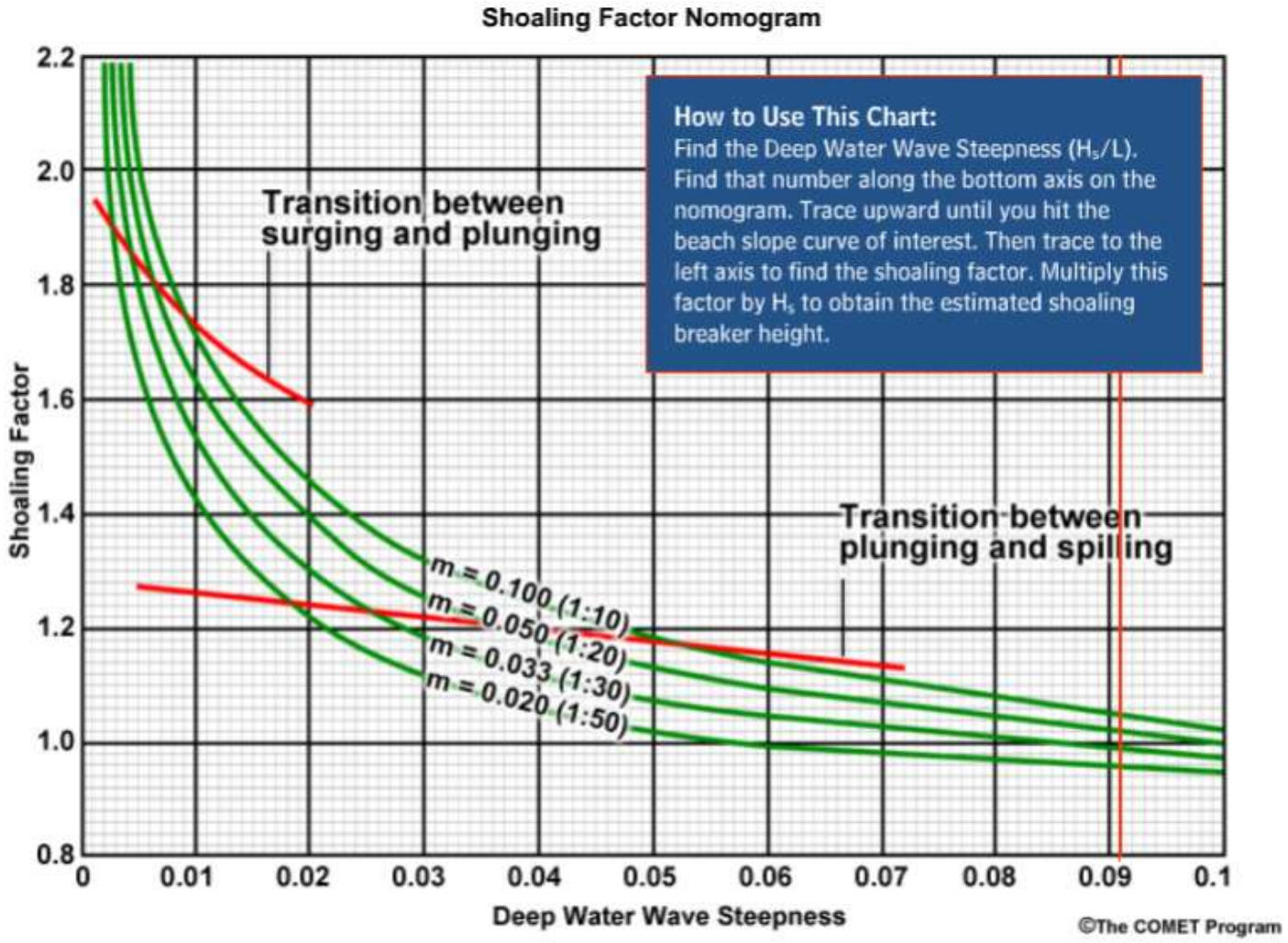
- Many studies have been performed to develop relationships to predict the wave height at incipient breaking H_b. The term *breaker index* is used to describe non-dimensional breaker height.
- Two common indices are :

  the *breaker depth* index $\gamma_b = \frac{H_b}{d_b}$

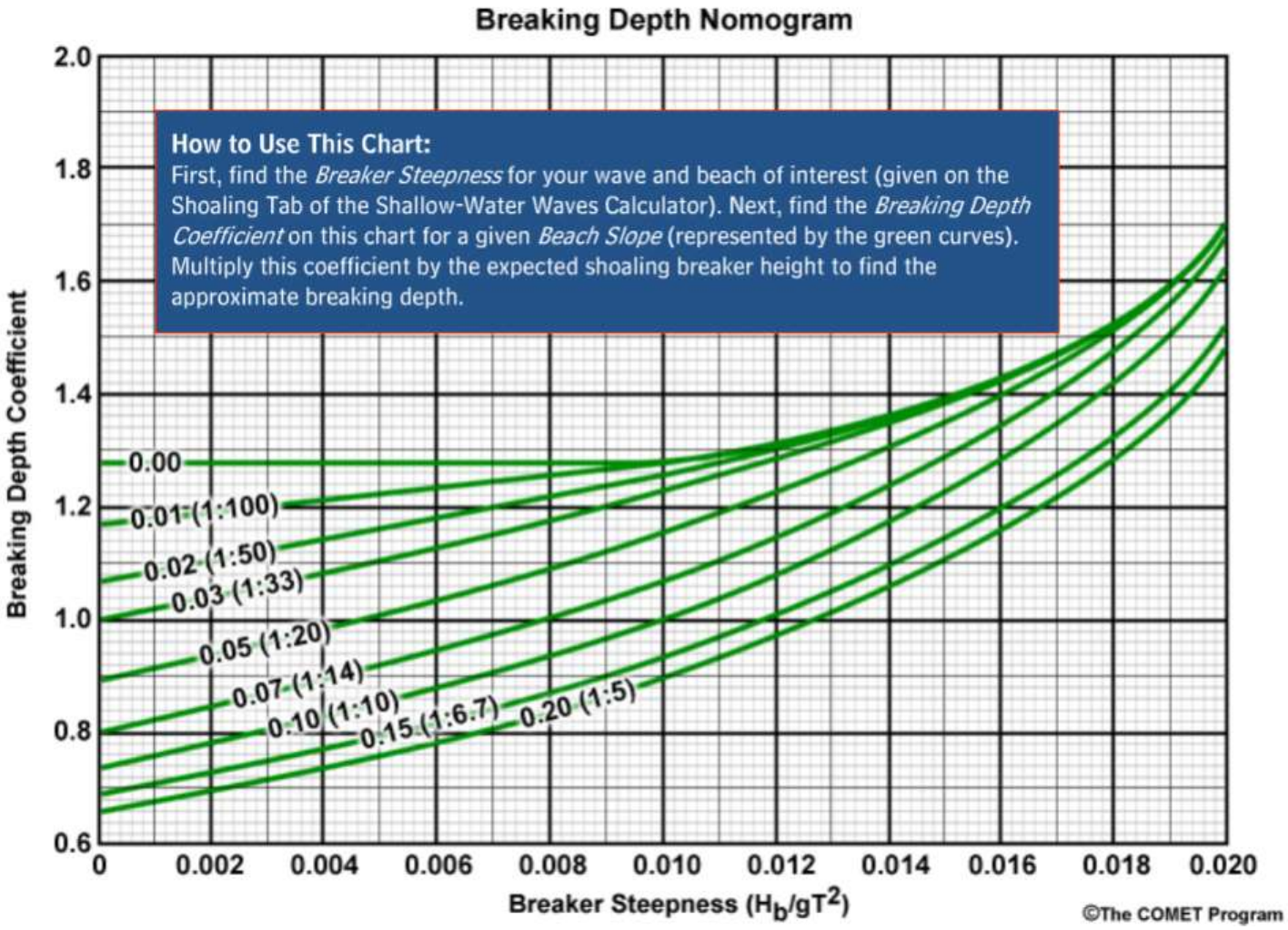
  the *breaker height* index $\Omega_b = \frac{H_b}{H_0}$

- H_b refers to wave height at breaking, d_b refers to water depth at breaking, H_0 is deep water wave height.

Breaking wave height and breaker depth



Breaking wave height and breaker depth



Wave Breaking Exercise:

1. (a) A wave measured to be 4.5 m in height in deep water with a period of 8 s propagates from deep to shallow water over a slope of *m* = 0.05. Estimate at what depth the wave will break and the breaking wave height. What sort of breaker will it be? (Spilling, plunging or surging).

(b) Repeat (a) for a wave of 10 s period. What do the results indicate about the relationship between wave period and wave breaking?

Solution: (a)

Deep water wave length, $L_0 = 1.56\ T^2 = 1.56*(8)^2 = 99.84$ m

Deep water wave steepness: $H_0/L_0 = 4.5/99.84 = 0.045$

From Nomogram 1, for slope = 0.05, Shoaling factor = 1.16

So, estimated shoaling breaker height, $H_b = 4.5*1.16 = 5.22$m

Wave Breaking Exercise:

Solution: (a) continued

Breaker steepness = $H_b/gT^2 = 5.22/(9.81*8^2) = 0.0083$

From Nomogram 2, for slope =0.05, breaking depth coefficient = 1.09

So, approximate breaking depth = 1.09*5.22 = 5.7m BREAKER TYPE: Spilling (SS Parameter = 0.23)

Solution: (b)

Deep water wave length, $L_0 = 1.56\ T^2 = 1.56*(10)^2 = 156$ m

Deep water wave steepness: $H_0/L_0 = 4.5/156 = 0.0288$

From Nomogram 1, for slope = 0.05, Shoaling factor = 1.26

So, estimated shoaling breaker height, $H_b = 4.5*1.26 = 5.67$m

Breaker steepness = $H_b/gT^2 = 5.67/(9.81*10^2) = 0.00578$

From Nomogram 2, for slope =0.05, breaking depth coefficient = 1.03

So, approximate breaking depth = 1.03*5.67 = 5.84m BREAKER TYPE: Spilling (SS Parameter = 0.29)

$$\xi_0 = \tan\beta \left(\frac{H_0}{L_0}\right)^{-\frac{1}{2}}$$

- Spilling $\xi_o < 0.5$;
- Plunging $0.5 < \xi_o < 2.3$;
- Collapsing $2.3 < \xi_o < 3.2$;
- Surging $\xi_o > 3.2$;

T=	8s	10s
Breaking height	5.22m	5.67m
Breaking depth	5.7m	5.84m

Wave Breaking Exercise:

2. A wave approaches a beach which has a bottom slope of 1:20. The deep water wave height is 3.0 m. As it approaches the beach to the point of breaking, the refraction coefficient is *Kr* = 1.05. The wave period is 10 s. Calculate the breaking wave height and the depth at which breaking occurs.

Solution:

Deep water wave length, $L_0 = 1.56\ T^2 = 1.56*(10)^2 = 156$ m

Deep water wave steepness: $H_0/L_0 = 3/156 = 0.019$

From Nomogram 1, for slope = 0.05, Shoaling factor = 1.4, given that refraction coefficient Kr = 1.05

So, Refracted shoaling breaker height, $H_b = H_0 * Kr * Ks = 3*1.05*1.4 = 4.41$m

Breaker steepness = $H_b/gT^2 = 4.41/(9.81*10^2) = 0.0045$

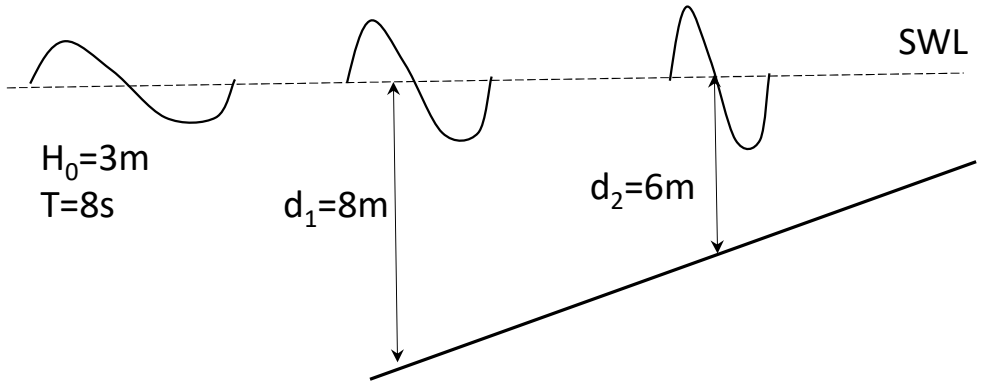
From Nomogram 2, for slope =0.05, breaking depth coefficient = 1.0

So, approximate breaking depth = 1.0*4.41 = 4.41 m

Exercise:

3. (a) In deep water a wave has a height of 3 m and a period of 8 s. The wave moves into a water depth of 8 m. Calculate the wave height and period at the new depth. The wave does NOT refract.

(b) The same wave moves from 8 m depth to 6 m depth. Calculate the new wave height (assuming you don't know the deep water wave height).



Exercise:

Solution: First check breaking water depth:

Deep water wave length, $L_0 = 1.56\ T^2 = 1.56*(8)^2 = 99.84$ m

Deep water wave steepness: $H_0/L_0 = 3/99.84 = 0.03$

From Nomogram 1, assuming average slope = 0.05, Shoaling factor = 1.26

So, estimated shoaling breaker height, $H_b = 3*1.26 = 3.78$m

Breaker steepness = $H_b/gT^2 = 3.78/(9.81*8^2) = 0.006$

From Nomogram 2, for slope =0.05, breaking depth coefficient = 1.04

So, approximate breaking depth = 1.04*3.78 = 3.93m

So, the waves will remain unbroken at depths 8m and 6m.

(a) At 8m depth, $d_1/L_0 = 8/99.84 = 0.08$ (transitional)

From figure, $d_1/L_1 = 0.13$, $L_1 = 8/0.13 = 61.5$ m

From energy principles, $\frac{\rho g H_0^2 L_0}{8} = \frac{\rho g H_1^2 L_1}{8}$

$$\frac{3^2 * 99.84}{8} = \frac{H_1^2 * 61.5}{8}$$

$H_1 = 3.82$m

(b)

At 6m depth, $d_2/L_0 = 6/99.84 = 0.06$ (transitional)

From figure, $d_2/L_2 = 0.1$, $L_2 = 6/0.1 = 60$ m

From energy principles,

$$\frac{\rho g H_1^2 L_1}{8} = \frac{\rho g H_2^2 L_2}{8}$$

$$\frac{3.81^2 * 61.5}{8} = \frac{H_2^2 * 60}{8}$$

$H_2 = 3.87$m

Exercise 3

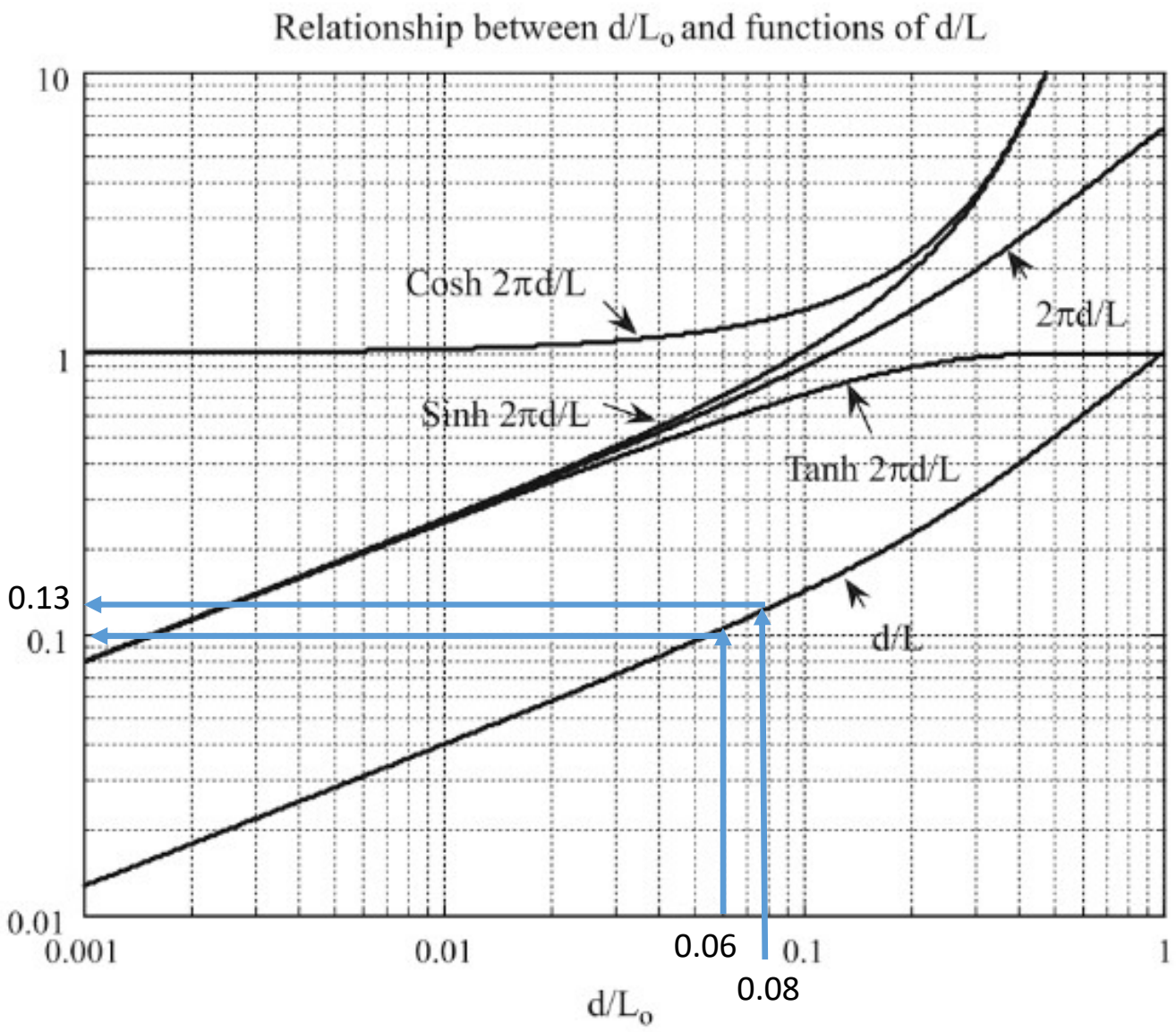
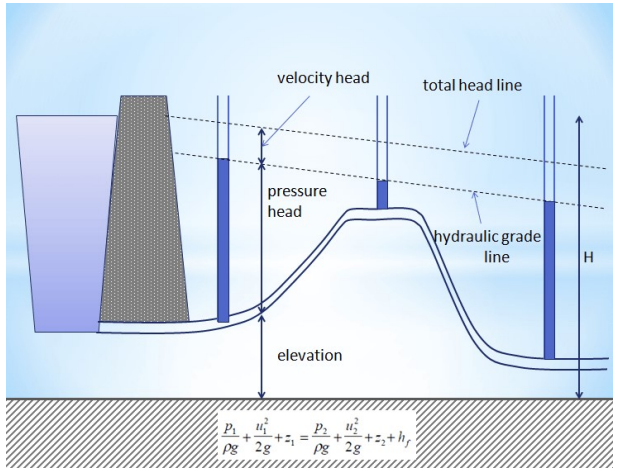
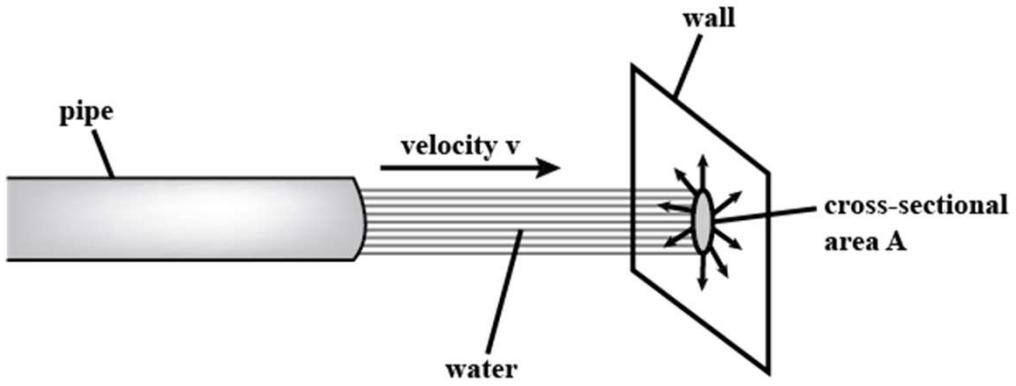


Figure A

Radiation Stress // Wave setup and set-down

In fluid flow problems, some analyses are best carried out by energy considerations (e.g., head loss along a length of pipe) and some by momentum considerations (e.g., force exerted by a water jet hitting a wall).





Similarly, for waves it is better to consider the flux of momentum for some problem analyses. For wave analyses, the flux of momentum is commonly referred to as the wave ‘‘radiation stress’’.

Radiation Stress // Wave setup and set-down

Radiation stress can be defined as ‘‘the excess flow of momentum due to the presence of waves which is exerted on the mean flow.”

The radiation stress describes the additional forcing due to the presence of the waves, which changes the mean depth-integrated horizontal momentum in the fluid layer. (Longuet-Higgins and Stewart, 1964)

Problems commonly addressed by the application of radiation stress include the lowering (setdown) and raising (setup) of the mean water level that is induced by waves as they propagate into the nearshore zone, the interaction of waves and currents, and the alongshore current in the surf zone induced by waves obliquely approaching the shore.

Radiation Stress // Wave setup and set-down

For unidirectional wave propagation – say in the x-coordinate direction – the component of the radiation stress tensor of dynamical importance is Sxx. It is defined as:

$$S_{xx} = \int_{-d}^{\eta} \overline{(p + \rho u^2) dz} - \int_{-d}^{o} \rho g dz$$ (the static pressure must be subtracted to obtain the radiation stress for only the wave)

where p(x,z,t) is the fluid pressure, u(x,z,t) is the horizontal x-component of the oscillatory part of the flow velocity vector, z is the vertical coordinate, t is time, z = −h(x) is the bed elevation of the fluid layer, and z = η(x,t) is the surface elevation. Further ρ is the fluid density and g is the acceleration by gravity, while an overbar denotes phase averaging. The last term on the right-hand side, ½ρg(h+η)^2, is the integral of the hydrostatic pressure over the still-water depth. Subscript xx denotes the x-directed momentum flux across a plane defined by x = constant.

Radiation Stress // Wave setup and set-down

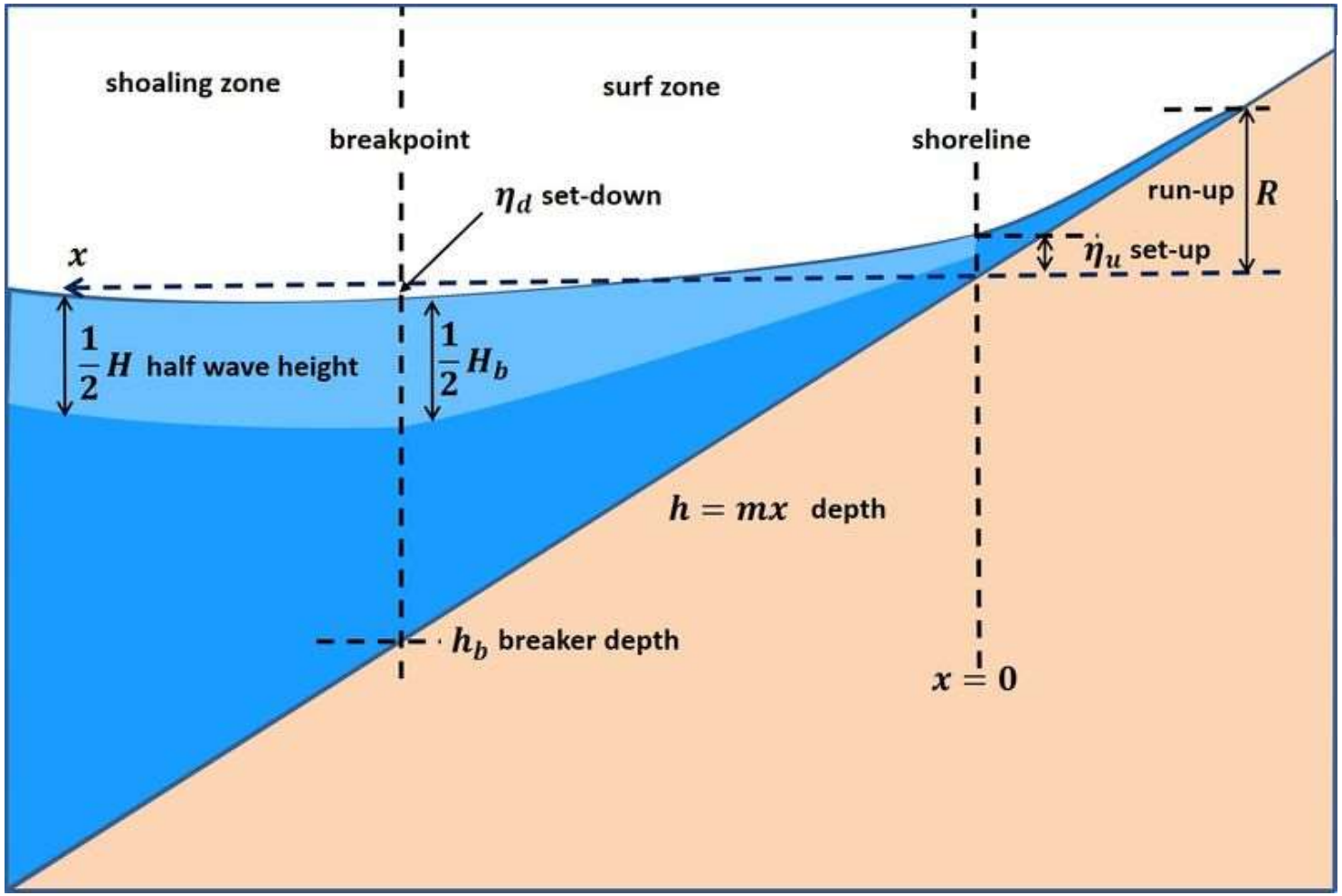
Inserting the pressure and the particle velocity leads to: (Longuet-Higgins and Stewart, 1964)

$$S_{xx} = \frac{\rho g H^2}{8}\left(\frac{1}{2} + \frac{2kd}{\sinh 2kd}\right) = \bar{E}\left(2n - \frac{1}{2}\right)$$

n=0.5 at deep ~ n=1.0 at shallow. So, S_{xx}=E/2 at deep ~ S_{xx}=3E/2 at shallow

So, like wave energy, the radiation stress changes as a wave propagates through water of changing depth.

Wave setup and set-down



$$S_{xx} = \frac{\rho g H^2}{8}\left(\frac{1}{2} + \frac{2kd}{\sinh 2kd}\right)$$

Wave set-down η_d occurs in the shoaling zone where the wave amplitude increases; wave wet-up η_u occurs in the surf zone where the wave amplitude decreases.

Wave setup and set-down

When a train of waves propagates toward the shore, at some point, depending on the wave characteristics and nearshore bottom slope, the waves will break. Landward of the point of wave breaking a surf zone will form where the waves dissipate their energy as they decay across the surf zone.

As the waves approach the breaking point there will be a small progressive **set down** of the mean water level below the still water level. This set down is caused by an increase in the radiation stress owing to the decreasing water depth as the waves propagate toward the shore. The set down is maximum just seaward of the breaking point.

Set down just prior to breaking: $\eta_d = - H^2/16d$

Wave setup and set-down

In the surf zone, there is a decrease in radiation stress as wave energy is dissipated. This effect is stronger than the radiation stress increase owing to continued decrease in the water depth. The result is a progressive increase or **setup** of the mean water level above the still water level in the direction of the shore. This surf zone setup typically is significantly larger than the set down that occurs seaward of the breaking point.

In the surf zone, the rate of energy dissipation by wave breaking will depend on the type of breaker that occurs. This rate of energy dissipation is complex and typically nonuniform. The following equation gives the slope of the mean water level as a function of the bottom slope in the surf zone from which wave set up can be calculated:

$$\frac{dd'}{dx} = \left(1 + \frac{8}{3\gamma^2}\right)^{-1} \frac{dd}{dx}$$

Bottom slope

factor

$\gamma = 0.9$

Wave setup and set-down

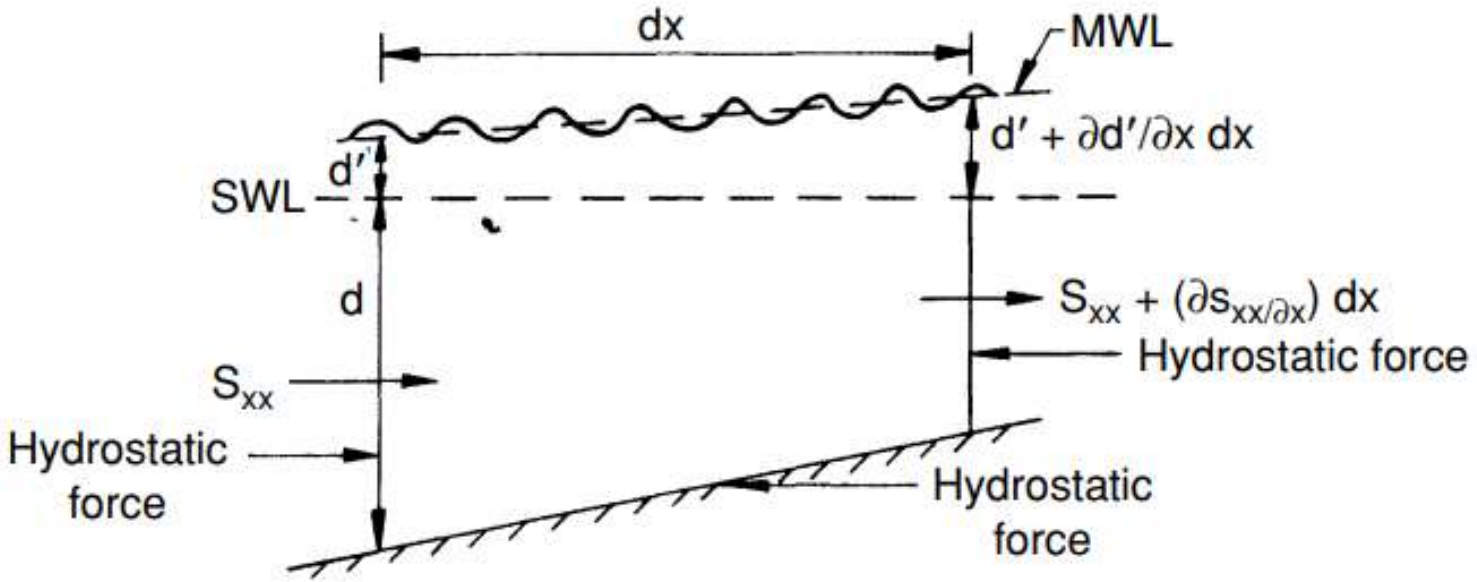
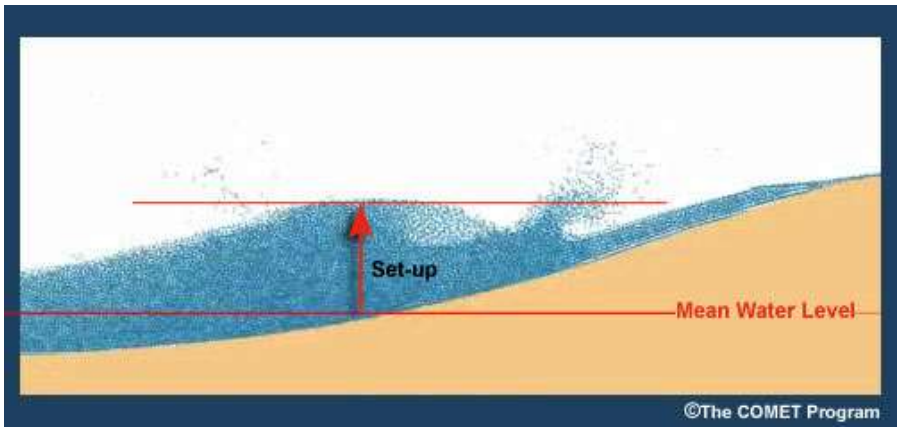


Figure 2.7. Force balance for wave-induced setup analysis.

Wave set-up

- Wave setup is the water rise at the coast due to breaking waves on the beach. The return flow of white water from waves that have already broken is much slower than the speed of incoming waves before breaking. The result is a piling up of water in the surf zone as wave action continually forces water up onto the beach. Wave set-up differs from run-up in that set-up is the continual piling of up water, while run-up is the transient encroachment of individual waves.
- The height of this piling up is directly proportional to the breaking wave height. It can range from a few inches or less for very small waves to 10 feet or more for large breaking waves such as those produced by nor'easters, hurricanes, and other strong storms.
- Wave set-up is breaker-height dependent, and hence, breaker-depth dependent as well. Set-up magnitudes generally range between 10 and 15 percent of shoaling breaker heights :
- **S = 10 to 15% of Shoaling Breaker Heights**



Wave set-up

- **Significance:** Wave set-up contributes significantly to coastal water rise and can cause coastal flooding in high surf. Also, since wave set-up is breaker-depth dependent, it is an independent factor from storm surge, which is wind-driven. When combined, the effects of wave set-up and storm surge can have devastating impacts.
- For example, the storm surge for Hurricane Opal in 1995 was estimated to be about eight feet, but the actual water rise at the coast was measured to be between 21 and 25 feet. The 14+ foot difference between storm surge and actual water rise was caused by wave set-up. Therefore, it is essential to include wave set-up in any forecast for coastal impacts from large storms.
- **Example Exercise:** What set-up would be expected for 20-second, 4.5 m swell? Ignore refraction effects for this example. Assume 1:20 beach slope. Choose the best answer:

  a) 0.6-1.2 m
  b) 1.8-2.7 m
  c) 3-4 m

Wave setup and set-down

Consider a wave that has a height of 2 m in water 2.2 m deep (below the mean water level) as it is about to break. The nearshore bottom slope through the surf zone is 0.02. Find the setdown at the breaker point and the setup (above the still water line) at the still water line contour of the shore. Assume shallow water wave conditions throughout.

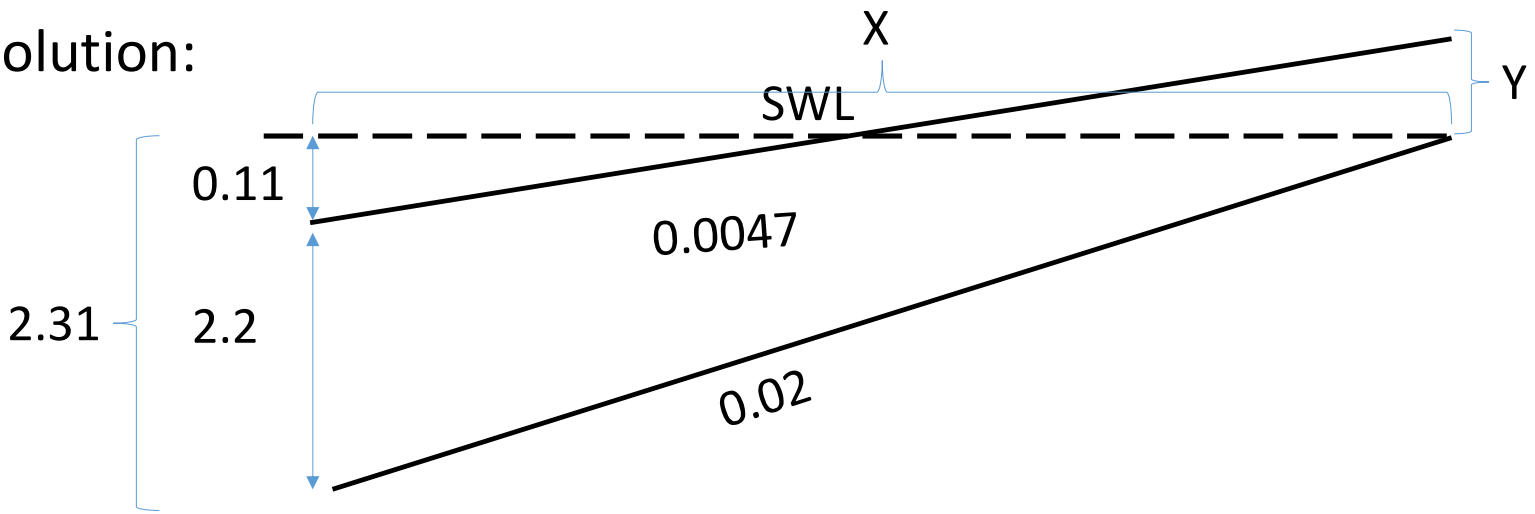
Solution: Set down at the breaker line: $\eta_d = - H^2/16d = - (2)^2/(16*2.2)$ = - 0.11m

Slope of mean water level in the surf zone: $\frac{dd'}{dx} = \left(1 + \frac{8}{3\gamma^2}\right)^{-1} \frac{dd}{dx}$

$$\frac{dd'}{dx} = \left(1 + \frac{8}{3(0.9)^2}\right)^{-1} (0.02) = 0.0047$$

Wave setup and set-down

Solution:



X= 2.31/ 0.02=115.7m

(Y+0.11)=115.7*0.0047; Y = 0.425 m; ie Set up = 0.425m

Wave swash

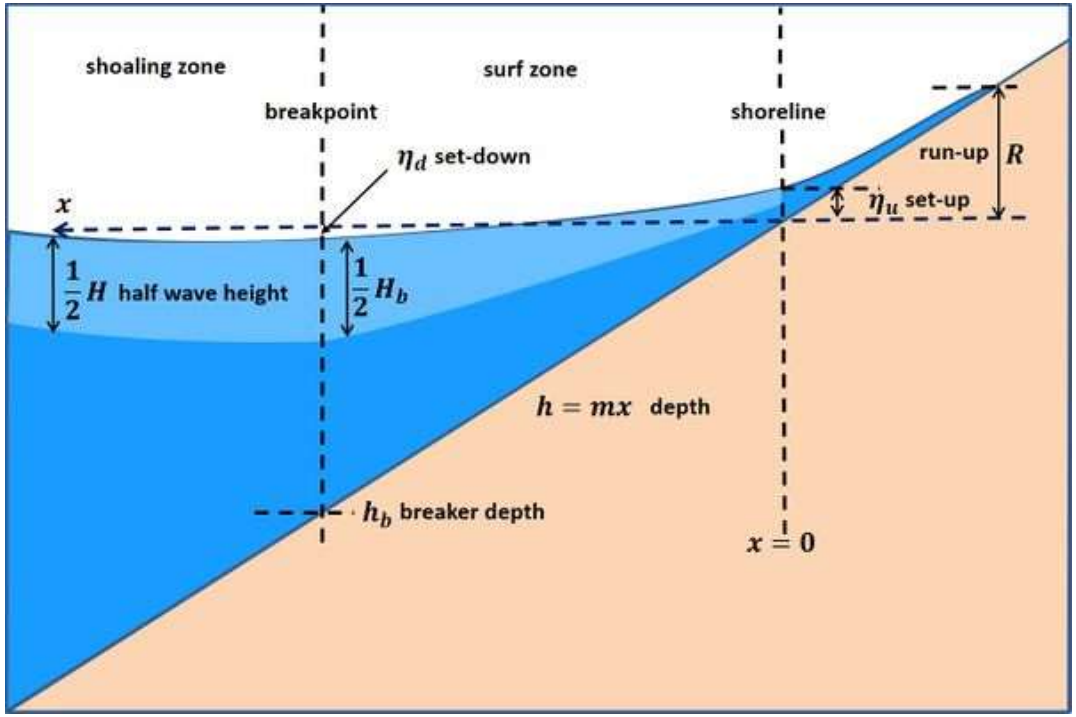
Wave swash or Wave uprush is the propagation of the waves onto the beach slope. The swash consists of an onshore phase with decelerating upwards flow (uprush or swash) and an offshore phase with accelerating downwards flow (down rush or backwash)



Animation: https://www.istockphoto.com/video/aerial-view-of-clear-turquoise-sea-and-waves-gm1194337503-340040318?irgwc=1&cid=IS&utm_medium=affiliate&utm_source=Oxford%20Media%20Solutions&clickid=2epQbaUFYxyIWHm3t7TLPT4mUkGUElUdq1%3Ayxg0&utm_term=&utm_campaign=cat_sponsored_all&utm_content=1020582&irpid=51471

Wave run-up

Wave run-up is the sum of the wave set-up and the wave swash. The wave run-up is this the maximum level the waves reach on the beach relative to the still water level.



Wave run-up

- On any beach at a given time, crashing waves will run up the slope generally about the same distance. Periodically, however, a wave will crash and run up the beach much higher than the average waves. This is called breaker run-up and results from the fact that waves represent a spectrum of heights and periods.
- Approximately: vertical water rise for the highest 2% of waves is estimated to be one half the predicted breaking wave height plus 50 cm:
- **$R_{(2\%)} = 0.5(H_B) + 0.5$ m**



Wave run-up

- We calculate 2% because approximately 2 out of every 100 waves during a particular high surf event will be large enough to pose a significant threat to beach goers or cause beach erosion. But, how far this water rise will travel up a given beach depends on beach composition, water saturation levels, and slope of the foreshore, or shore area that lies between the high and low water marks. Run-up is reduced during the period of rising tide because the dry sand over which incoming waves travel absorbs more water, reducing the overall water volume and energy of incoming waves.
- Breaker run-up is a very difficult factor to account for in an operational setting because there is so much natural variability in foreshore slope, both horizontally and between sections of beach exposed during high and low tides. However, in some situations, where specific forecasts are required for a beach that has very even slope, breaker run-up calculations may be operationally useful, especially when you consider that significant wave run-up can sometimes knock beachgoers off their feet, pull them into the surf, and drown them.

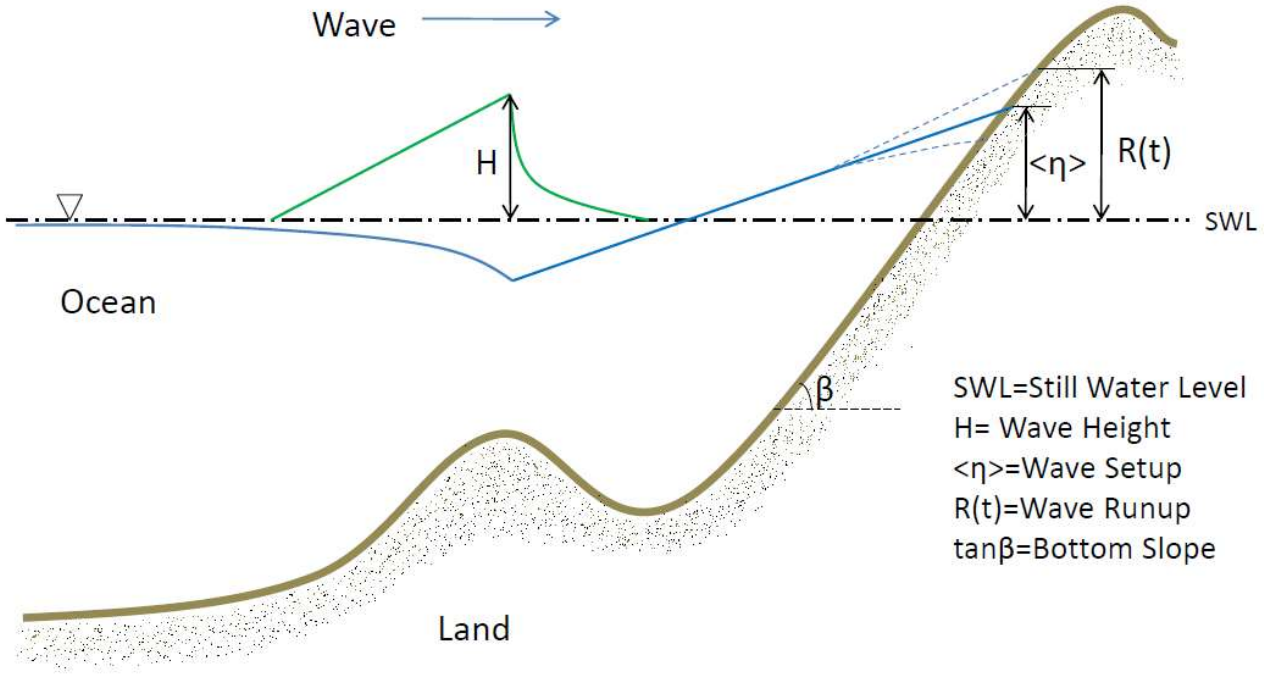
Wave run-up and wave set-up

Wave runup is the maximum vertical extent of wave uprush on a beach or structure above the still water level (SWL).

Wave setup is the increase in mean water level due to the presence of breaking waves.

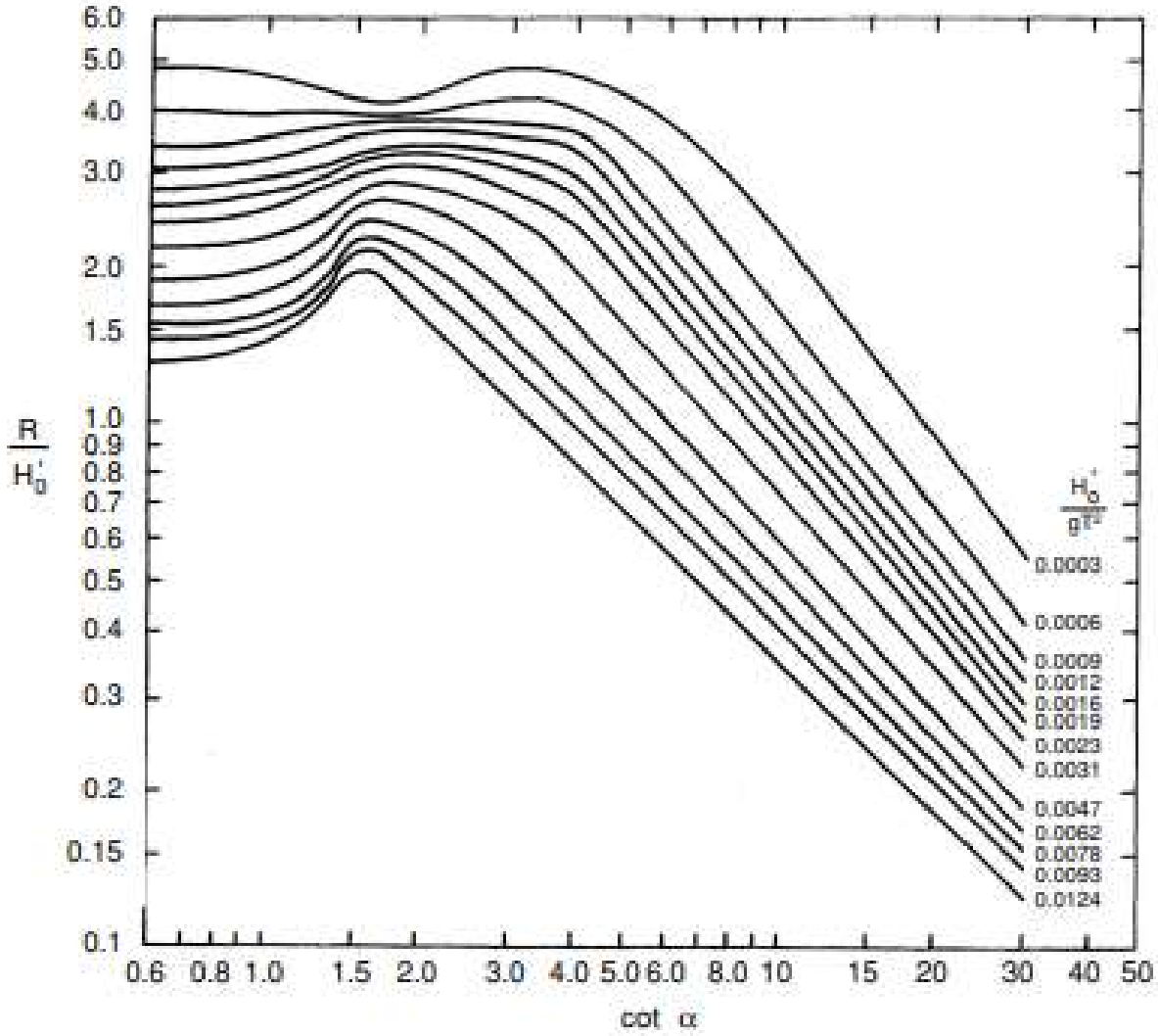
So, Wave setup is a component in wave runup.

The SWL is defined as the water level in the absence of waves but with all other processes present.



Wave run-up

Dimensionless runup on smooth impermeable slopes versus bottom slope and incident deep water wave steepness; $1 < ds/H_0 < 3$. (Modified from U.S. Army Coastal Engineering Research Center, 1984.)



Wave run-up

Table 2.1. Runup Factors for Various Slope Conditions

Slope facing	r
Concrete slabs	0.9
Placed basalt blocks	0.85–0.9
Grass	0.85–0.9
One layer of riprap on an impermeable base	0.8
Placed stones	0.75–0.8
Round stones	0.6–0.65
Dumped stones	0.5–0.6
Two or more layers of riprap	0.5
Tetrapods, etc.	0.5

From Battjes, 1970.

Wave run-up

Consider a deep-water wave with height of 2 m and period of 10 s propagating toward the shore without refracting. The wave breaks and runs up on a 1:10 grass covered slope having a toe depth of 4 m. Breaking wave height is 3.2 m, Determine the wave runup elevation on the grass-covered slope.

Solution: From figure, since $ds/H_0=4/2 = 2$, cot a =1/m = 1/0.1=10

$H_0/gT^2= 0.002$ cot a = 10

From figure $R/H_0 = 0.85$; uncorrected smooth slope run up R= 0.85*2 = 1.7 m

From table, correction factor is 0.875, Run up R= 1.7*0.875 = 1.5m on a grass covered slope.

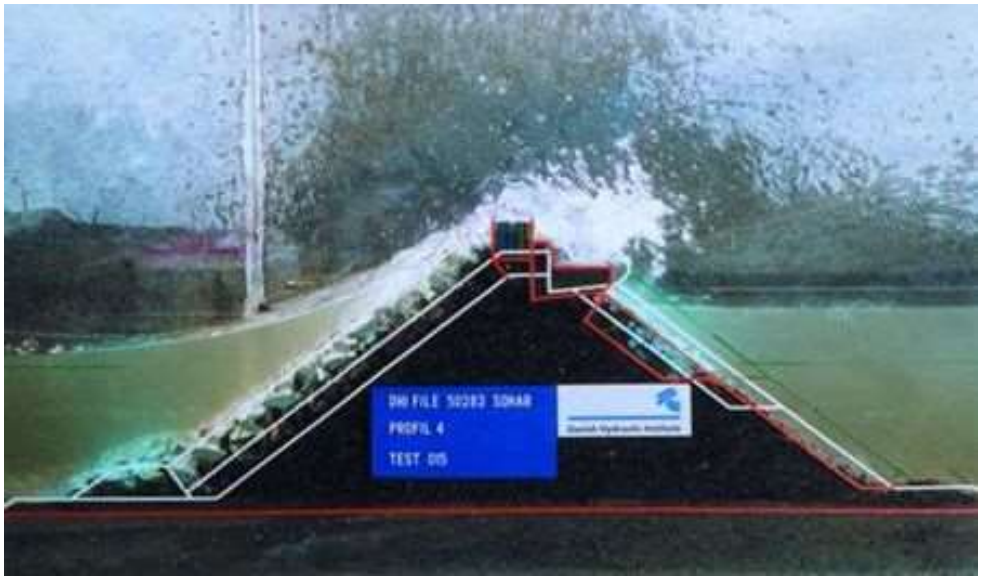
White-capping

White-capping or top-breaking is steepness-induced wave-breaking, which occurs in deeper water when the wave height becomes too large compared to the wavelength. (see Fig.)



Wave overtopping

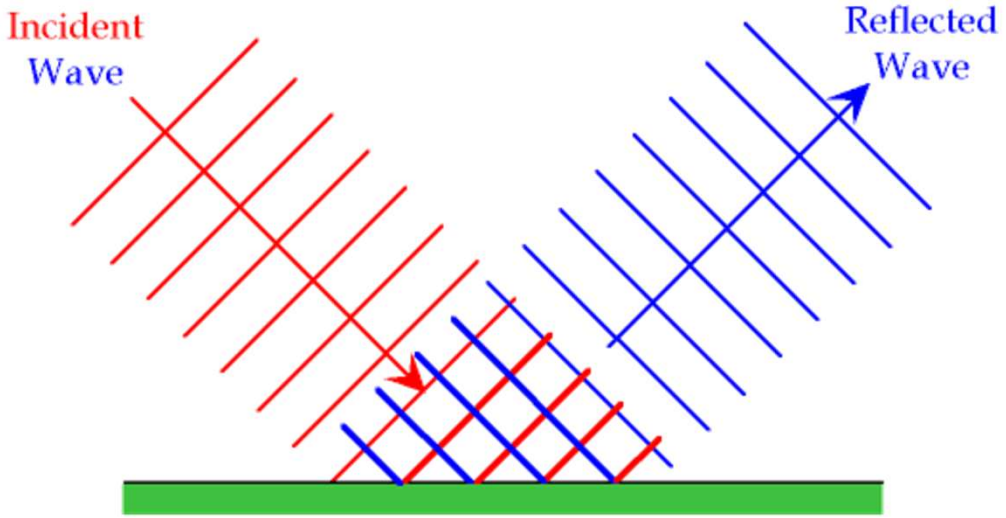
Wave-overtopping takes place when waves meet a submerged reef or structure, but also when waves meet an emerged reef or structure lower than the approximate wave height. During over-topping, two processes important to the coastal processes take place: wave transmission and the passing of water over the structure. (see Fig.)



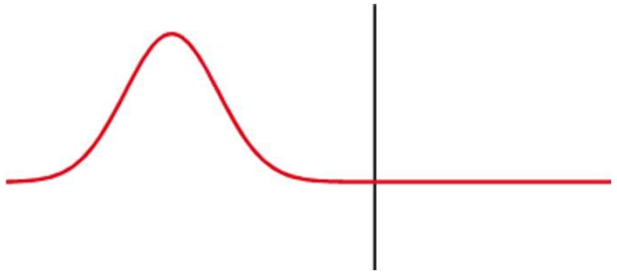


Wave reflection

Waves that propagate into a solid object such as a breakwater, a seawall, a cliff, or a sloping beach may reflect. In the case of a vertical, hard structure, the fraction of wave energy reflected can be large. For permeable structures or gentle slopes, the reflection will be much less. For nearshore wave propagation problems, reflections are usually ignored because the reflected wave may often be less than 10 percent of the incident wave. Reflected waves may sometimes cause standing waves after superposition upon incident waves.



Solid structure



Permeable structure

Wave diffraction, refraction, shoaling and reflection





Thank You