These lecture materials are for the Marine Coastal and Delta Sustainability for Southeast Asia (MARE) (Project No. 610327-EPP-1-2019-1-DE-EPPKA2-CBHE-JP).

This project has been funded with support from the European Commission. This publication reflects the views only of the authors, and the Commission cannot be made responsible for any use which may be made from the information contained herein.

Co-funded by the Erasmus+ Programme of the European Union

TOPIC 2

WAVES

TOPIC 2: WAVES

- Part 1: Introduction to Ocean Waves
- Part 2: Linear Wave Theory
- **Part 3: Nearshore Wave Transformation**
- Part 4: Wave Statistics

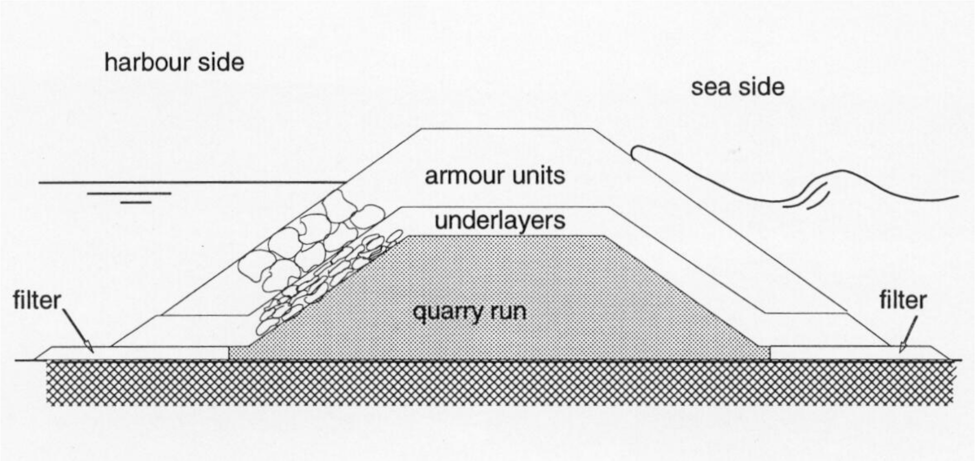
WAVE DIFFRACTION

LEARNING OUTCOMES

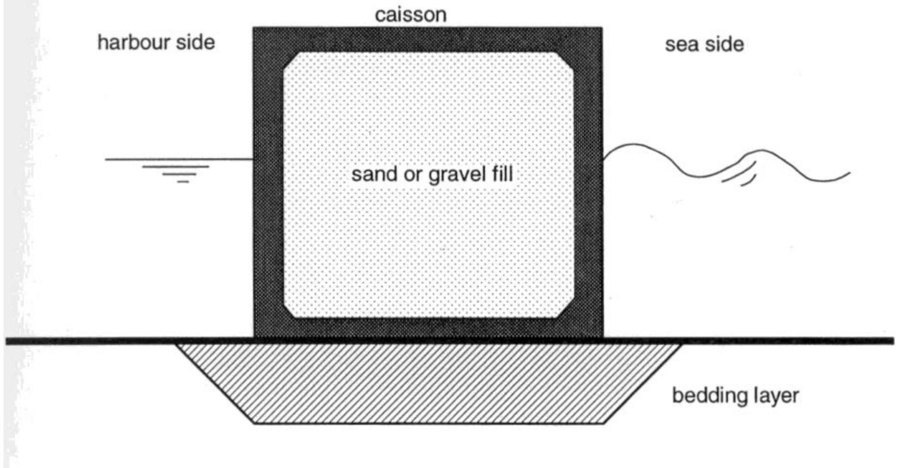
Upon completion of this topic, students should be able:

- To assess the wave diffraction processes.
- To estimate the diffracted wave height at the lee of a breakwater.

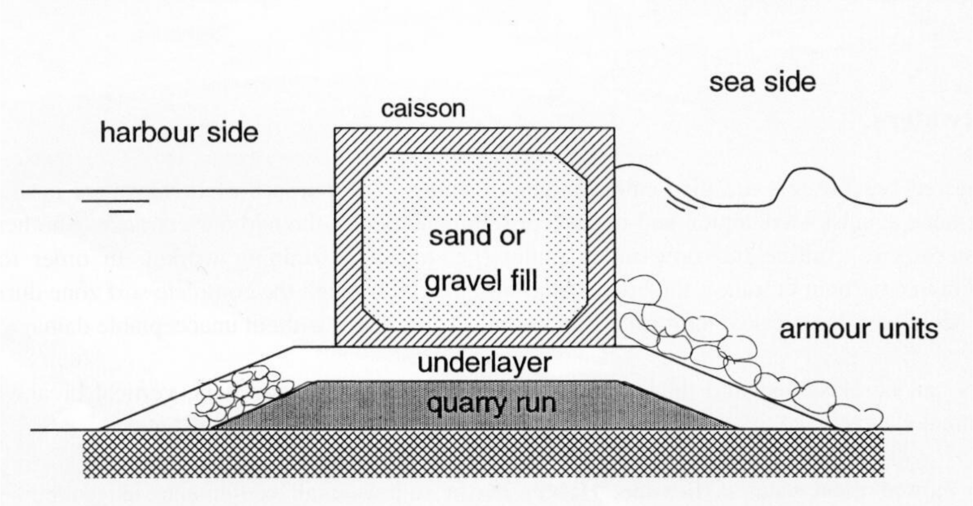
BREAKWATERS



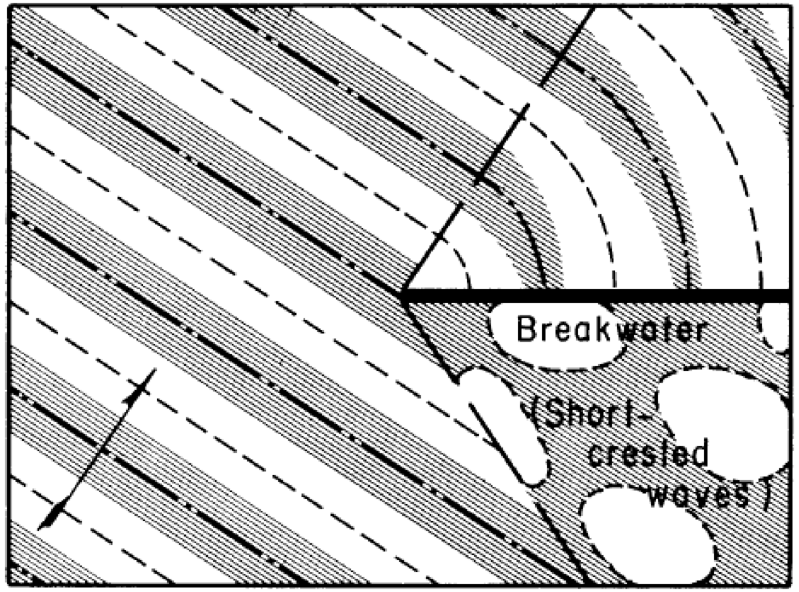
Rubble mound breakwater



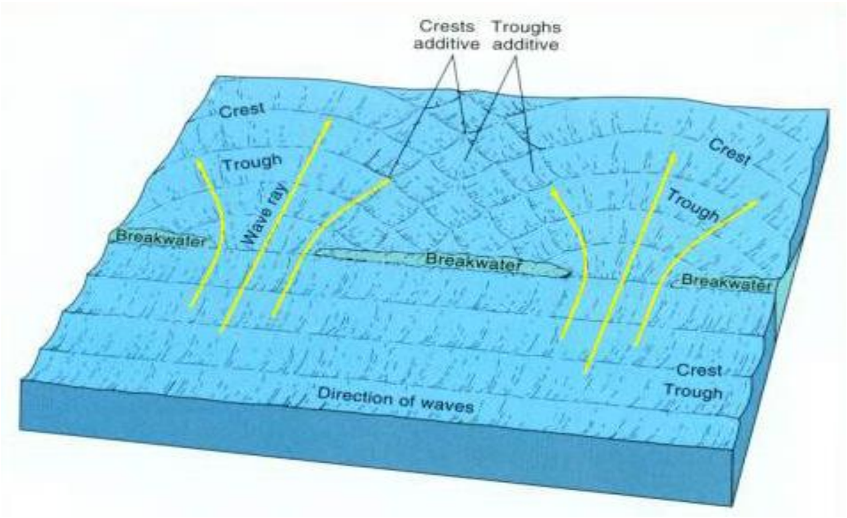
Vertical caisson breakwater



Composite breakwater



WAVE DIFFRACTION



- Wave diffraction is a process where wave energy is laterally transferred along a wave crest as the wave bend around an obstruction (e.g. offshore breakwater and island).
- Diffraction has a particularly significant effect on wave conditions inside a harbor.
- When waves propagate past the tip of a breakwater, diffraction causes the wave crests to spread into the shadow zone in the lee of the breakwater.
- The wave crest orientations and wave heights in the shadow zone are significantly altered.

WAVE DIFFRACTION IN A HARBOUR

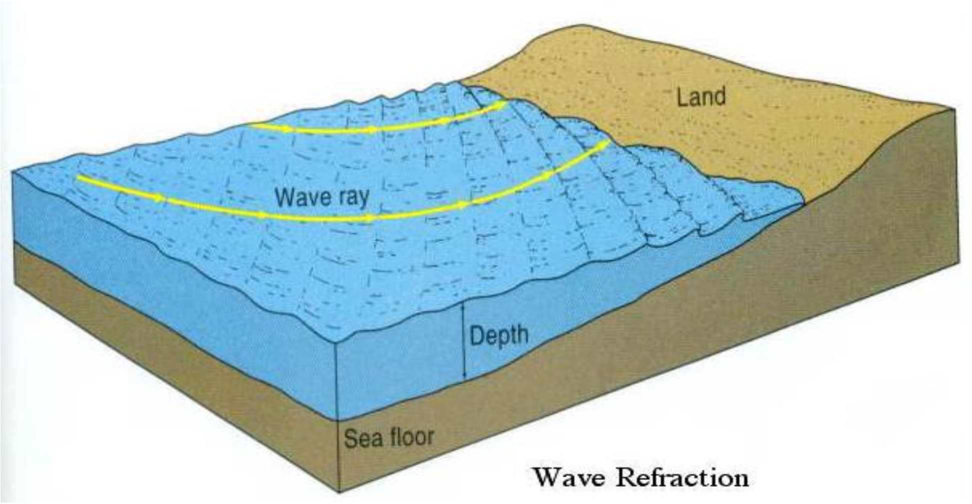
- Wave height distribution in a harbor or sheltered bay is determined to some degree by the diffraction characteristics of both the natural and manmade structures. Therefore, a knowledge of the diffraction process is essential in planning such facilities.
- These waves may shoal and refract after they pass through the harbor entrance; but the dominant process affecting interior wave conditions is usually wave diffraction.
- The proper design of and location of harbor entrances to reduce problems like silting and harbor resonance also require a knowledge of the effects of wave diffraction.

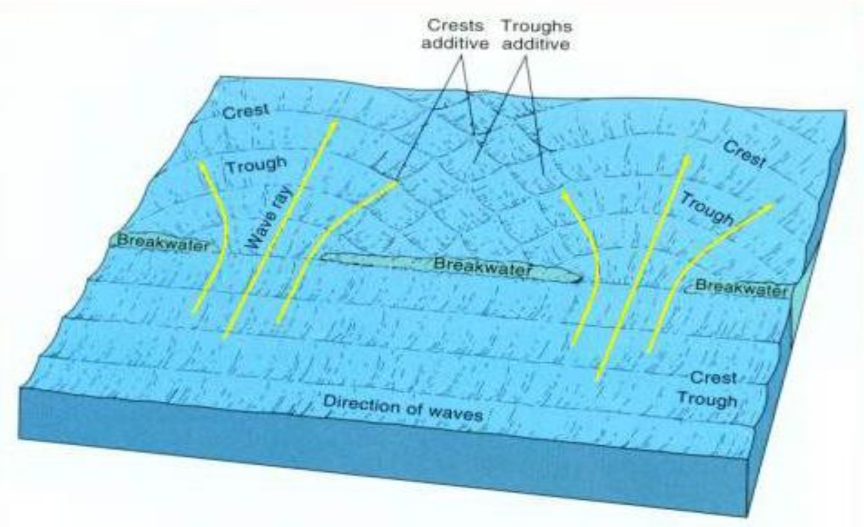
IMPLICATIONS

Complete siltation of a harbour entrance, Calabria, Italy

A T-shaped breakwater armoured with concrete units, a tombolo has formed behind it, Calabria, Italy

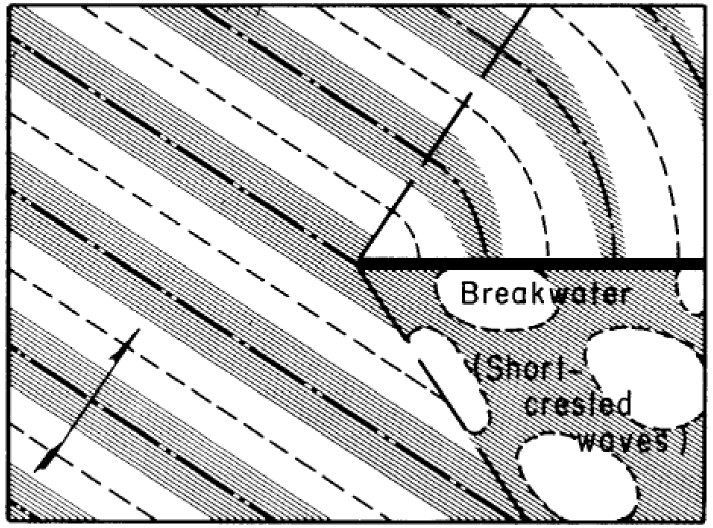
DIFFRACTION VS. REFRACTION





- Diffraction and refraction are closely related processes as they take place simultaneously shoaling water.
- Refraction is concerned with gently changing depth, causing waves to shoal and the wave crests to bend.
- Diffraction is concerned with constant depth and solves for sudden changes in wave condition caused by obstructions.

ASSUMPTIONS OF DIFFRACTION THEORIES



1. Water is an ideal fluid, i.e. invicid and incompressible.
2. Waves are of small amplitude and can be described by linear wave theory.
3. Flow is irrotational.
4. Depth shoreward of the breakwater is constant.

- Note: If assumption (4) is not valid then the processes of both refraction and diffraction come into play.

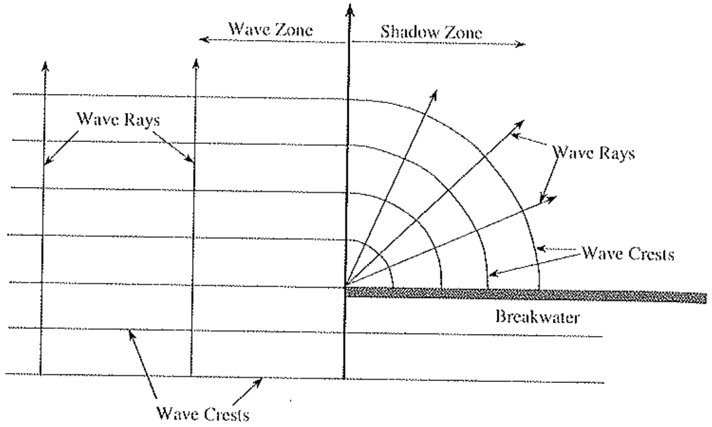
DIFFRACTION AT A HARBOUR ENTRANCE

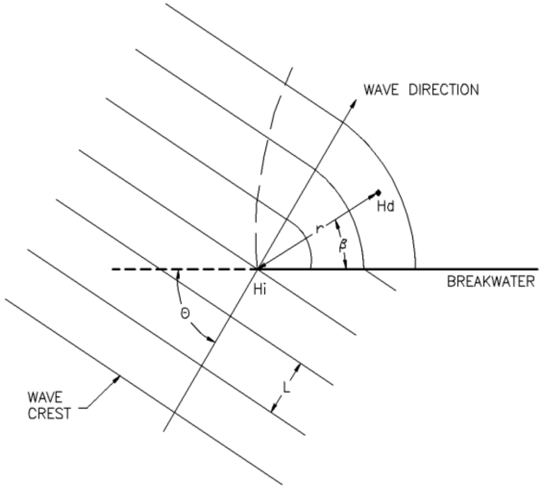
- A major concern in the planning and design of coastal harbors is the analysis of wave conditions (i.e. height and direction) that occur inside the harbor for selected incident design waves.
- These waves may shoal and refract after they pass through the harbor entrance; but the dominant process affecting interior wave conditions is usually wave diffraction.
- Two generic types of conditions are most commonly encountered:

  (1) Wave passing a single long breakwater

  (2) Wave passing a gap width

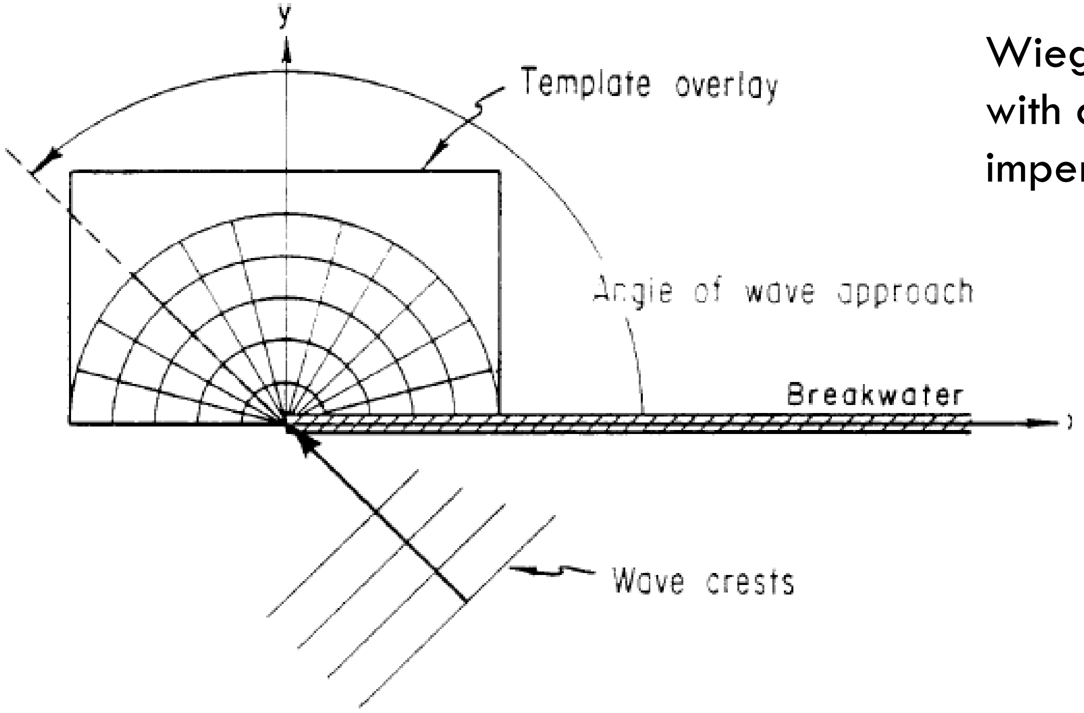
WAVE PASSING A SINGLE STRUCTURE



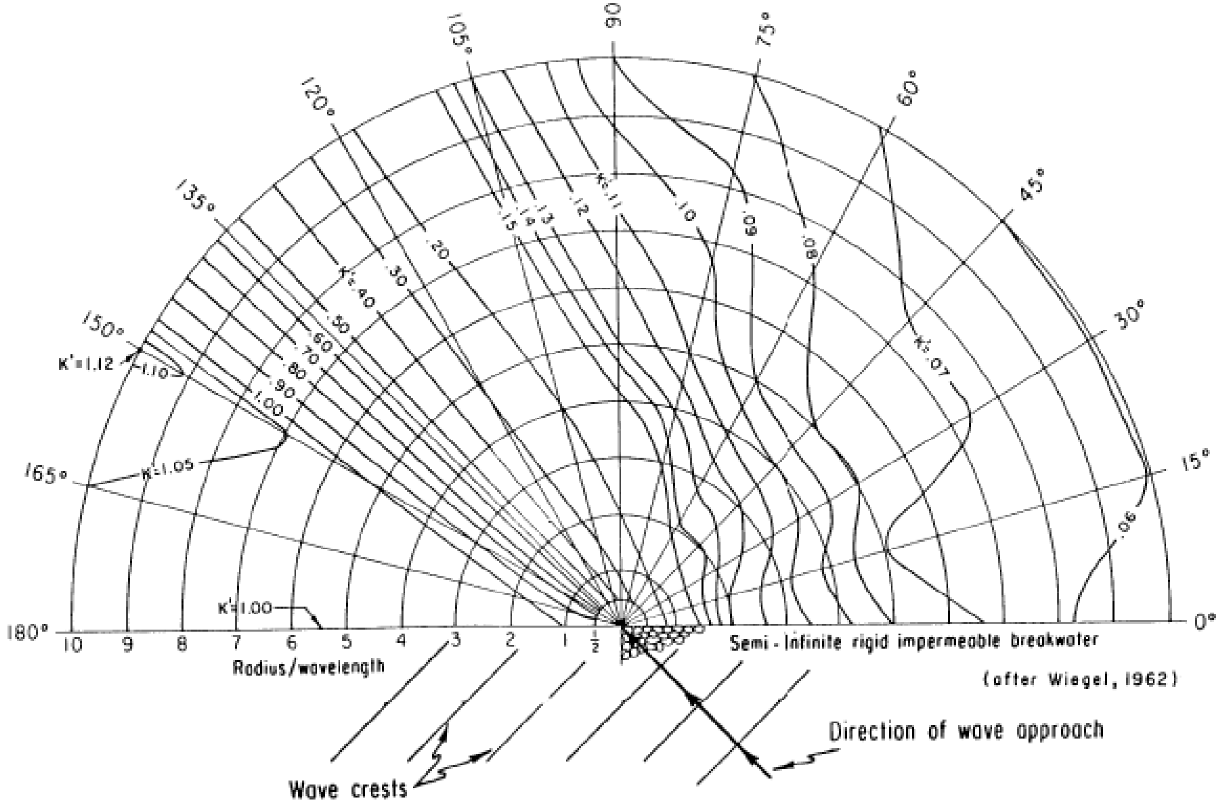


- A long-crested monochromatic wave approaching a breakwater in a region where the water depth is constant (i.e. no wave refraction or shoaling).
- A portion of the wave will hit the breakwater where it will be partially dissipated and partially reflected.
- The portion of the wave that passes the breakwater tip will diffract into the breakwater lee.
- The diffracted wave crests will essentially form circular arcs.

WAVE DIFFRACTION DIAGRAM



Wiegal (1962) presented diffraction diagrams for $\theta = 0° - 180°$ with an interval of 15°, for a uniform depth adjacent to an impermeable breakwater.

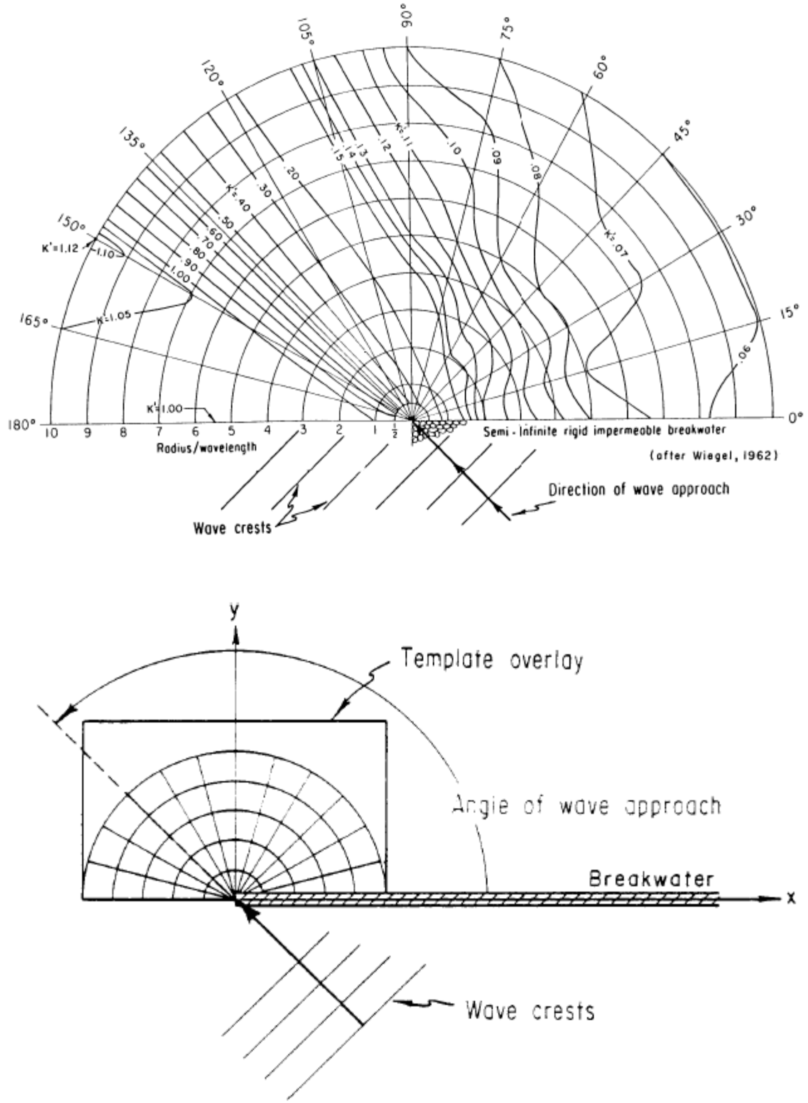


The diffraction diagrams show wave height reduction given in terms of a diffraction coefficient K_d, which is

$$K_d = H_d/H_i$$

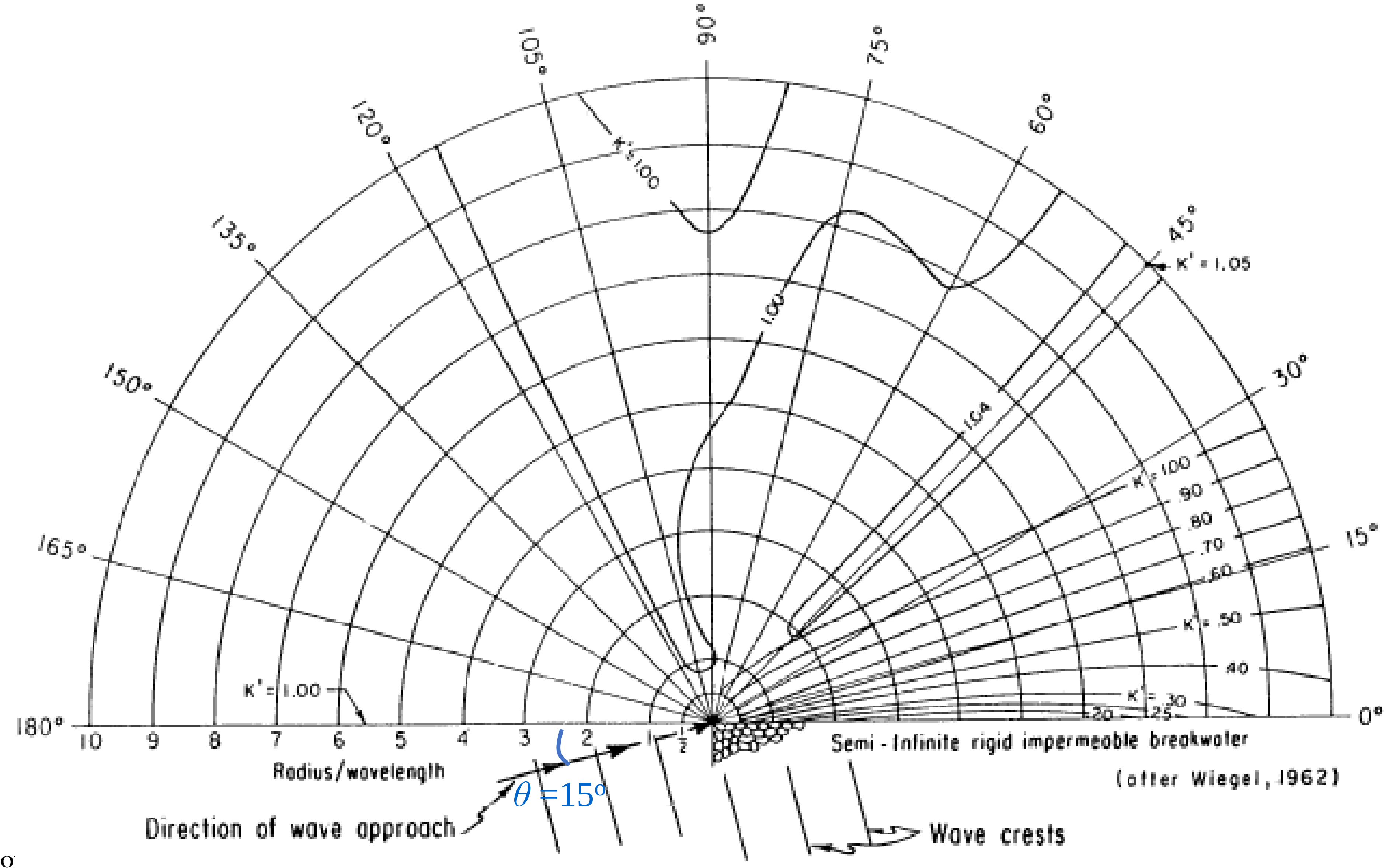
H_d = diffracted wave height; $H_{i:}$ = incident wave height

WAVE DIFFRACTION DIAGRAM

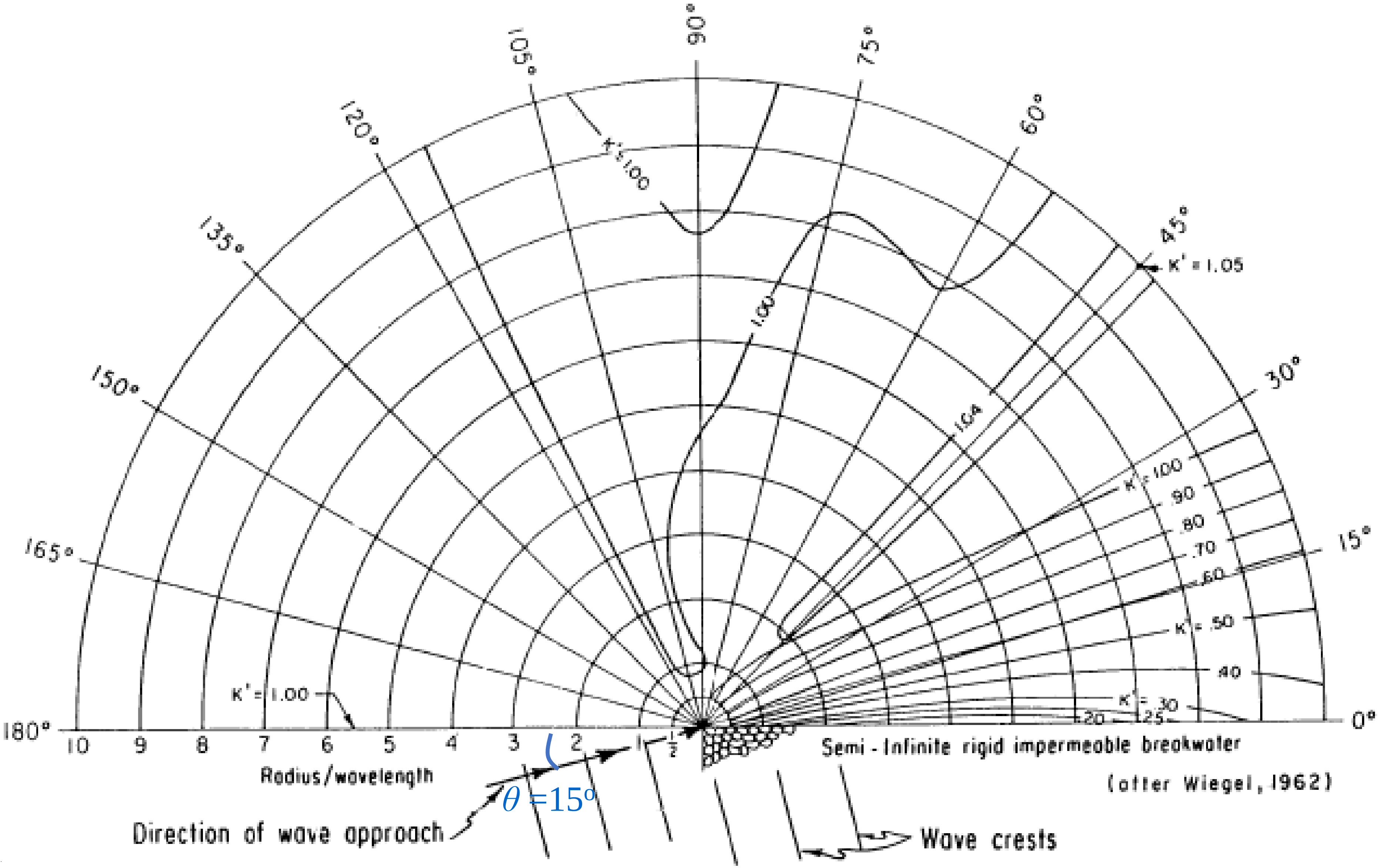


- The diffraction diagrams K' contours are drawn with respect to the ratio of radius to local wavelength, R/L in water depth d_s.
- In application, a diffraction diagram must be scaled up or down so that the particular wavelength corresponds to the scale of the hydrographic chart being used.
- The use of an overlay template to correspond to the hydrographic chart.

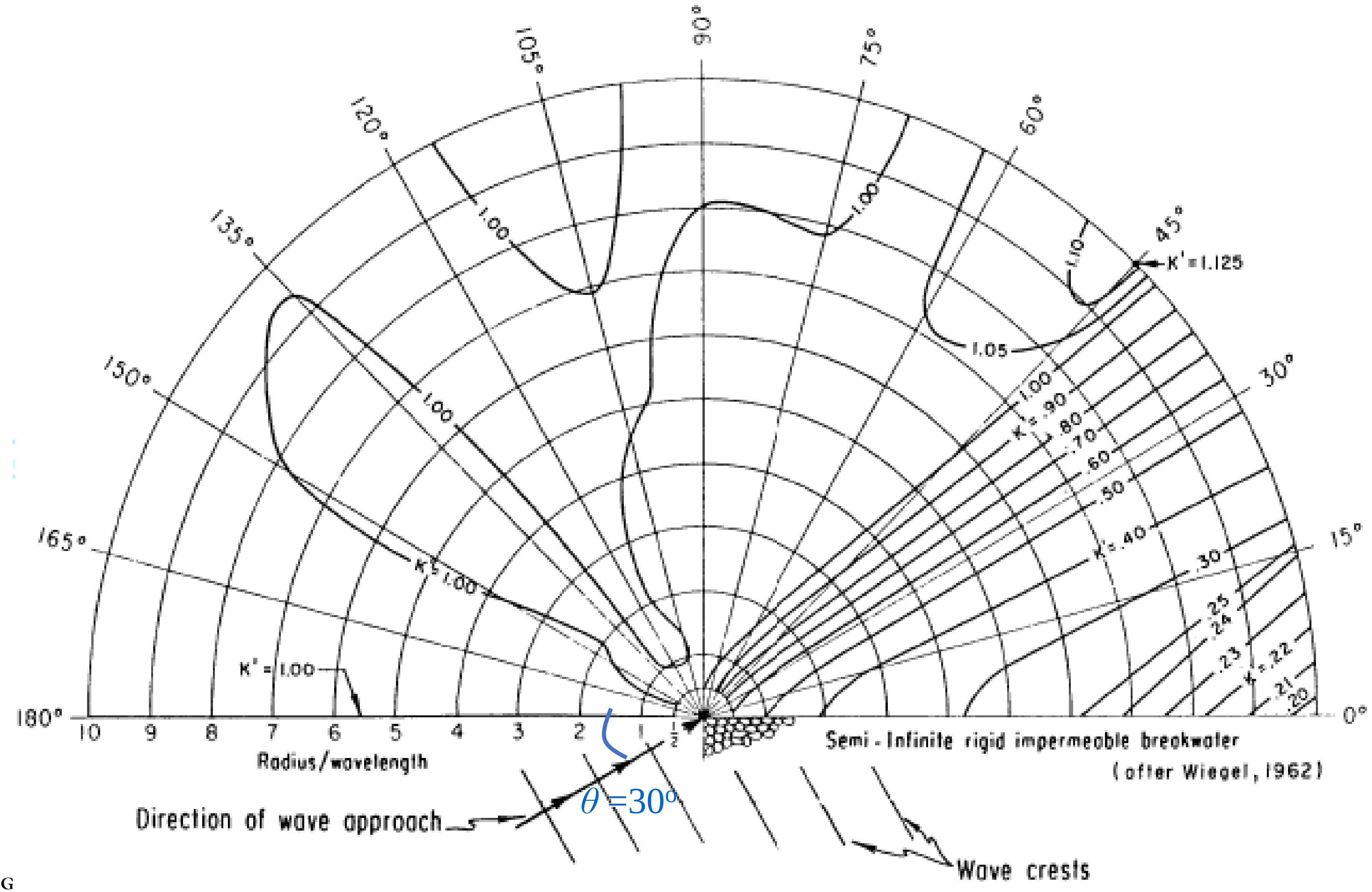
Wave Diffraction Diagram – Wave Angle θ =15°



Wave Diffraction Diagram – Wave Angle θ =15°

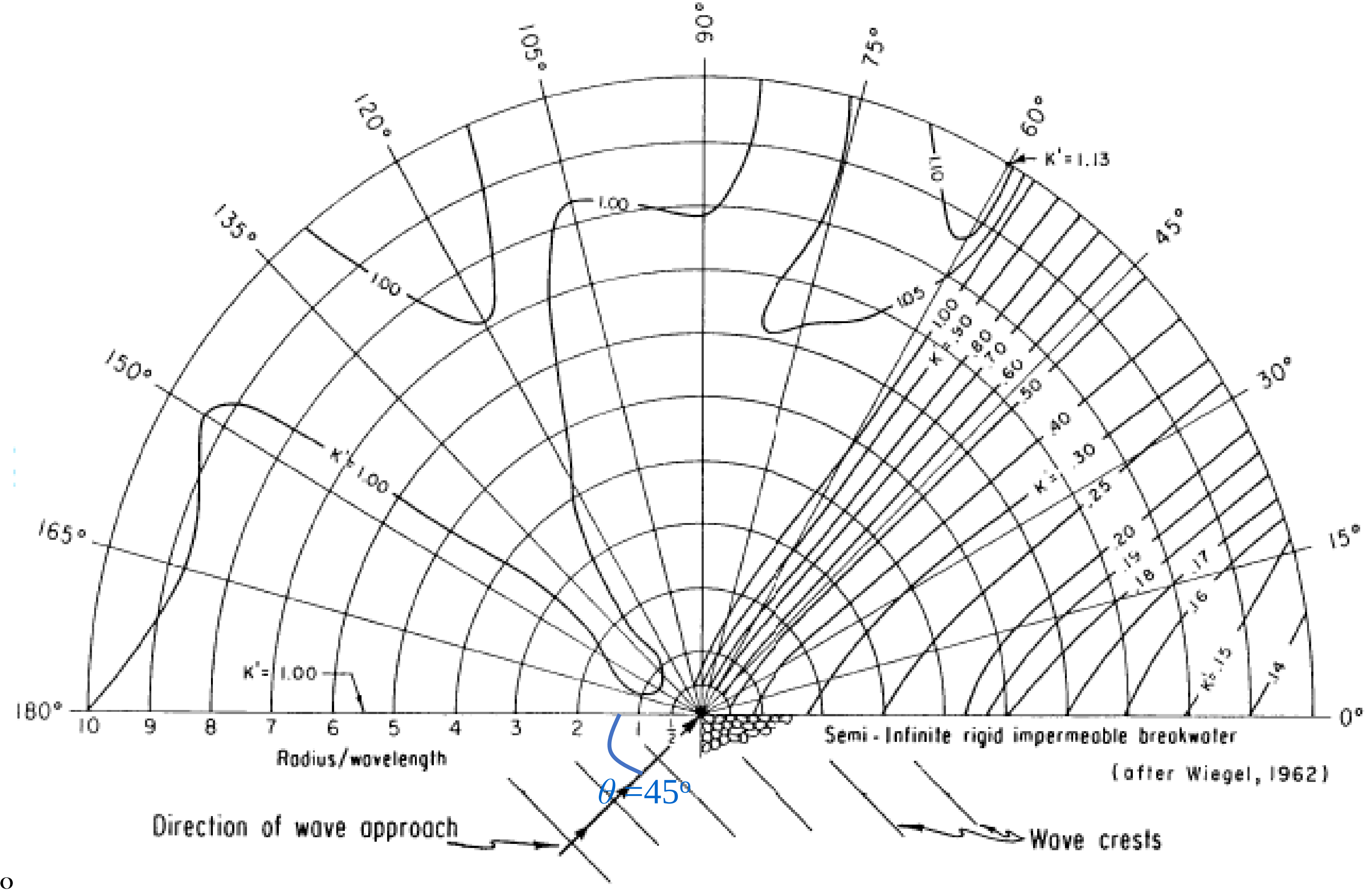


Wave Diffraction Diagram – Wave Angle θ =30°



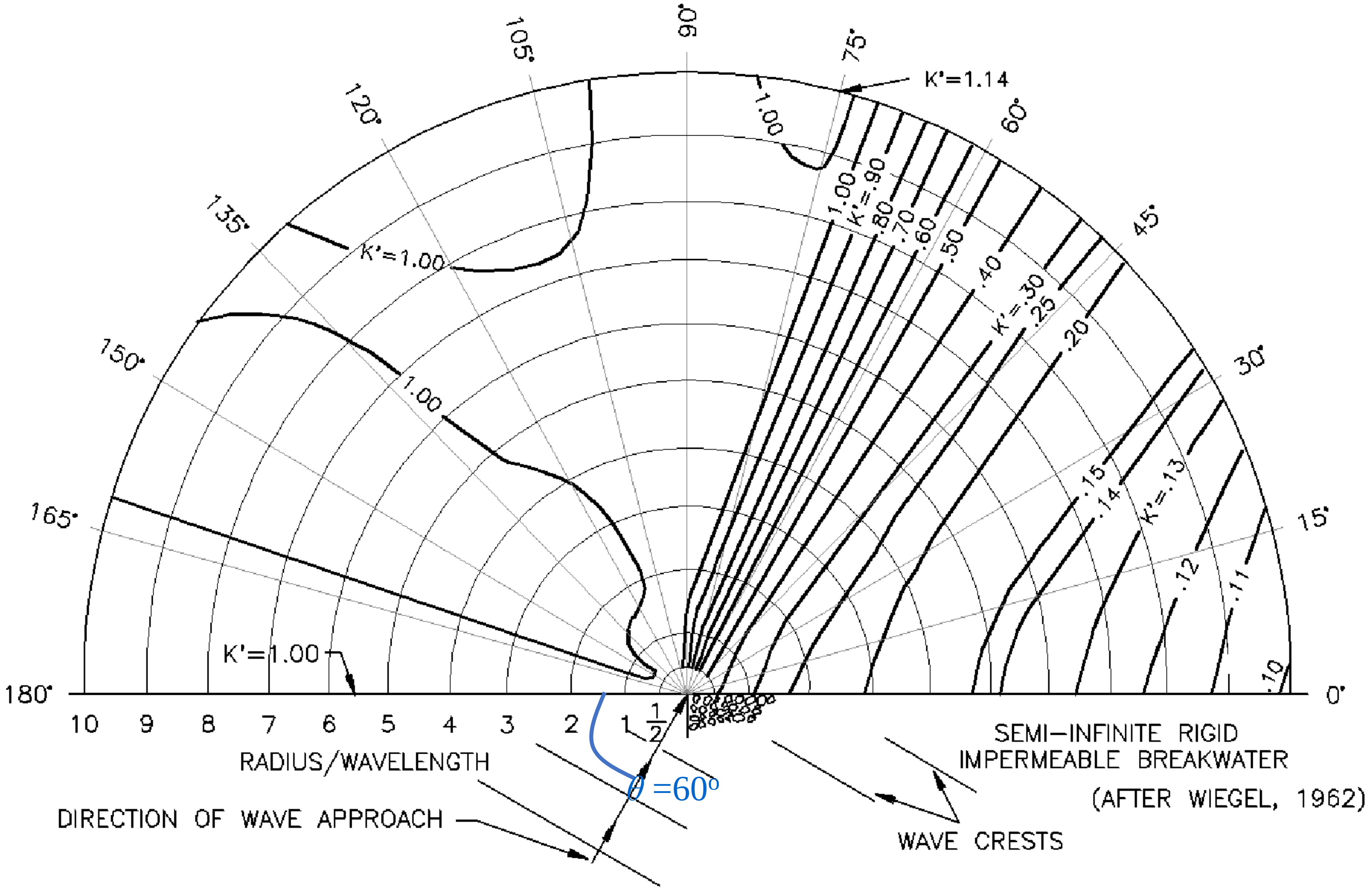
(after Wiegel, 1962)

Wave Diffraction Diagram – Wave Angle θ =45°

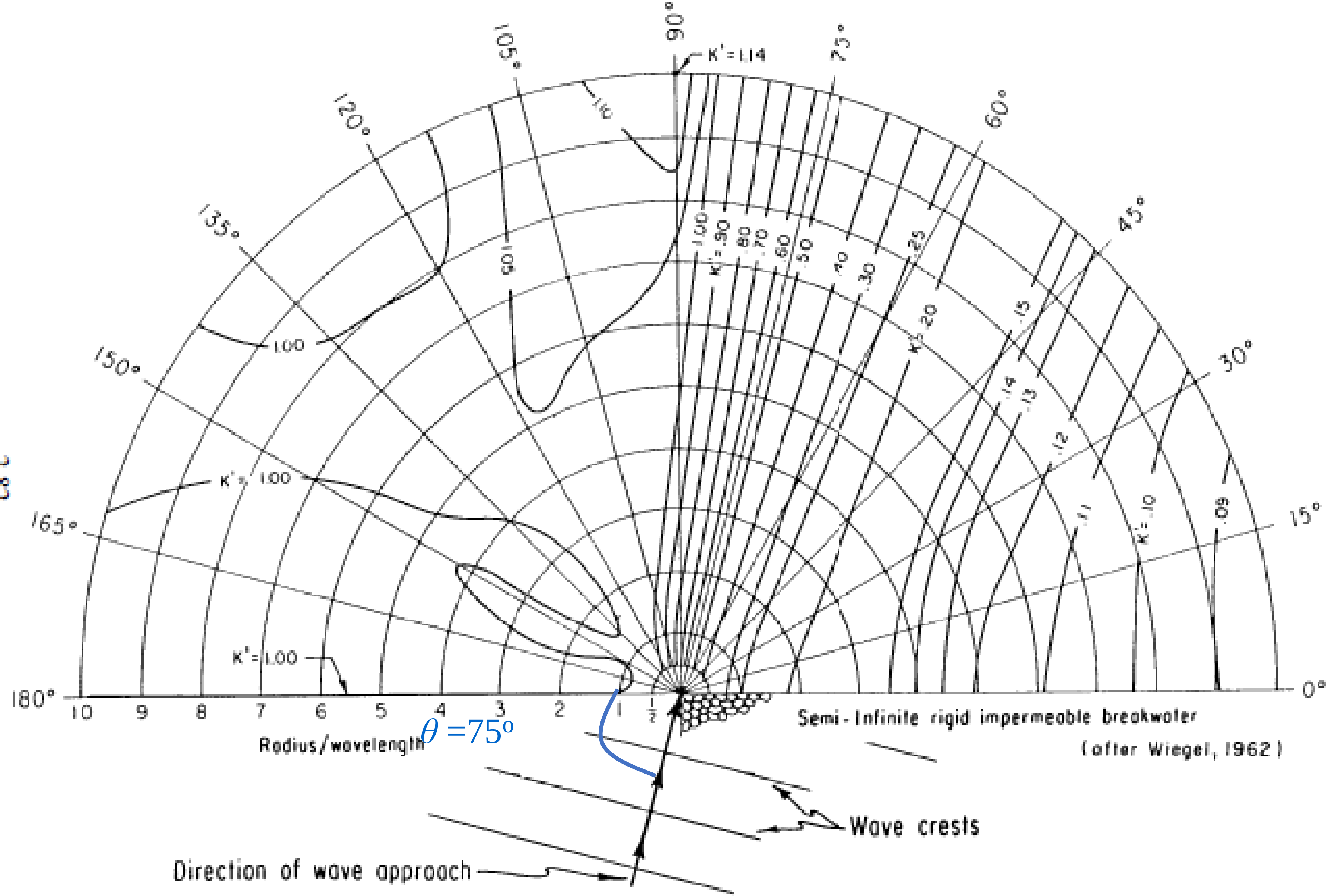


(after Wiegel, 1962)

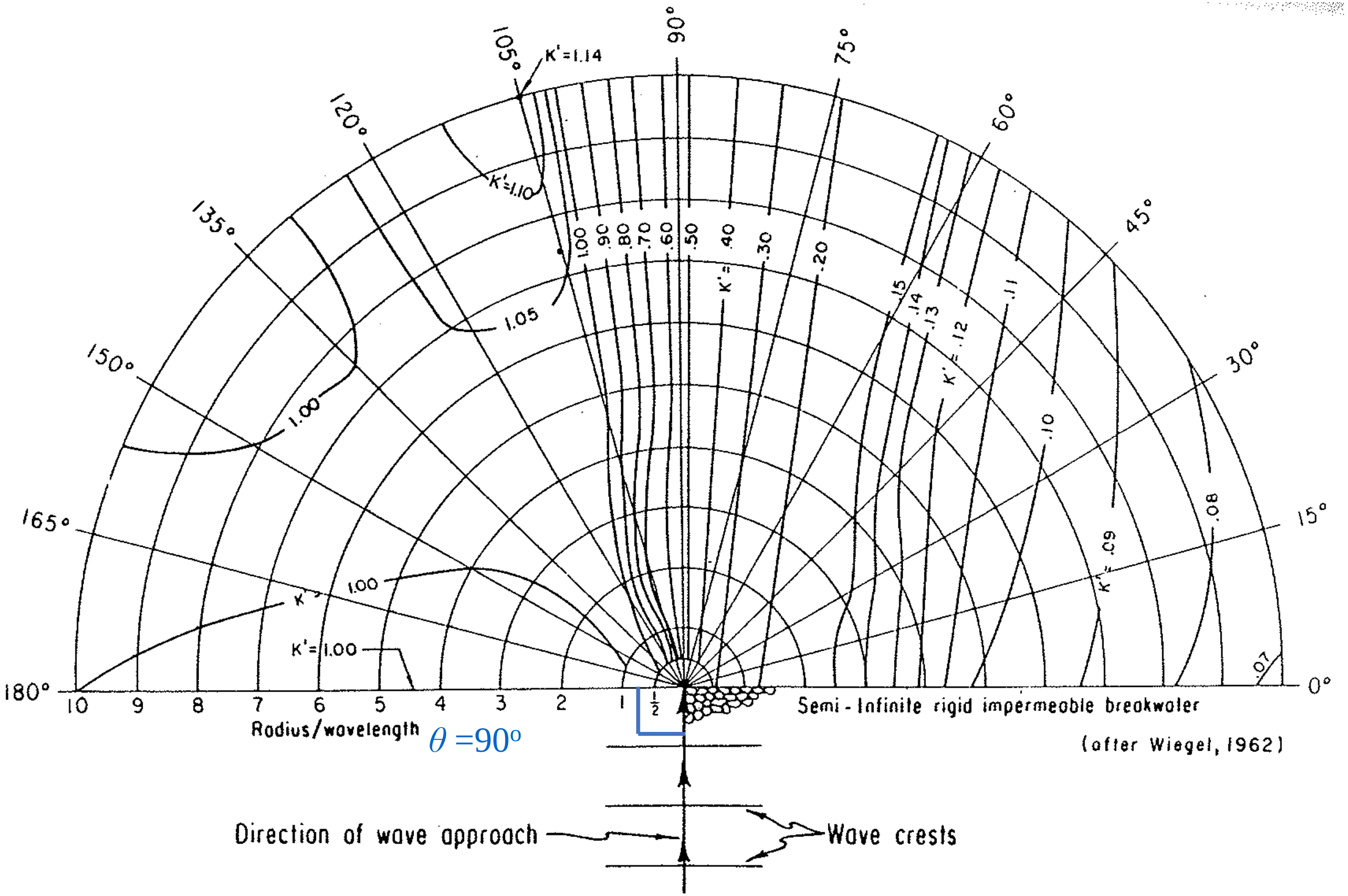
Wave Diffraction Diagram – Wave Angle θ =60°



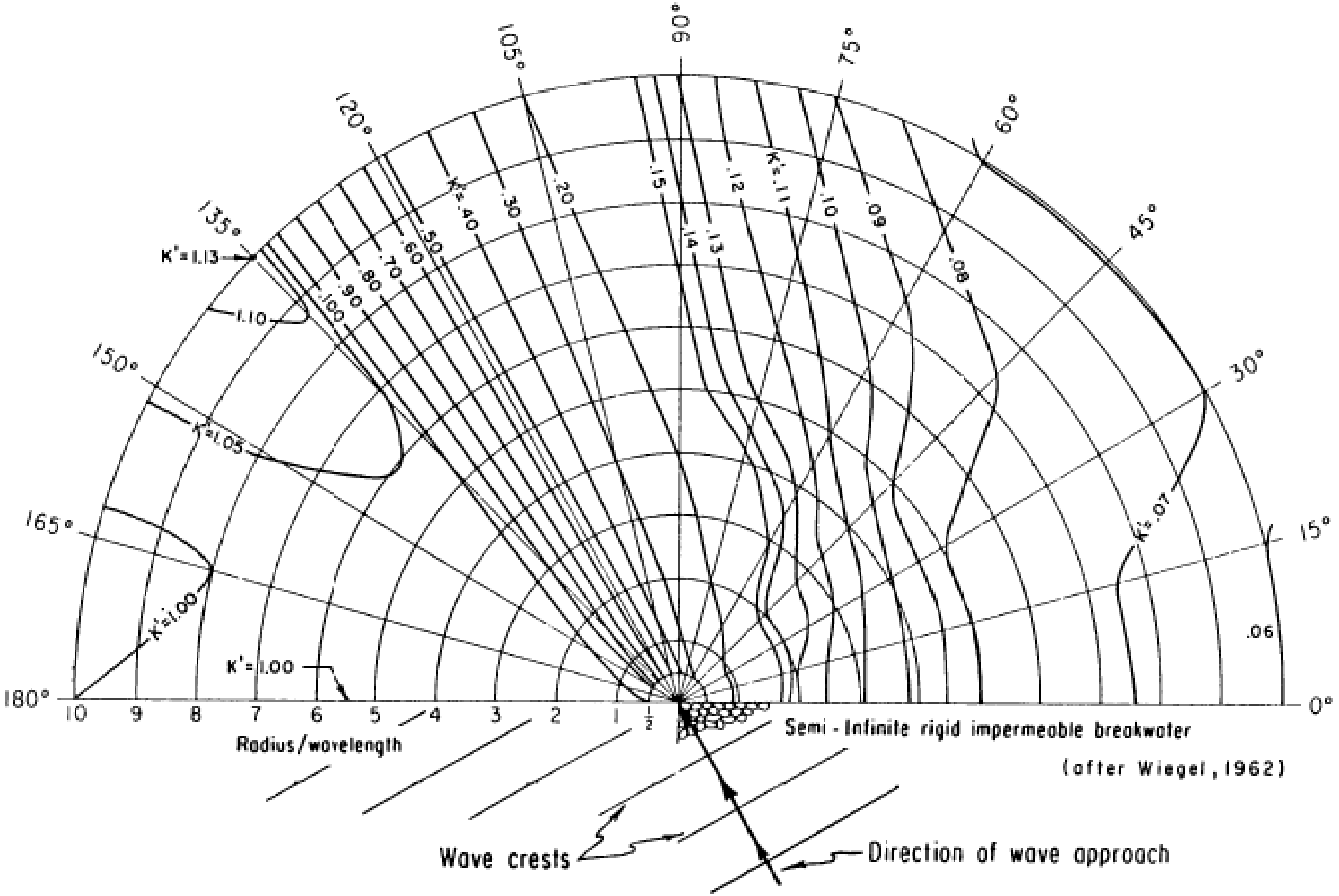
Wave Diffraction Diagram – Wave Angle θ =75°



Wave Diffraction Diagram – Wave Angle θ = 90°

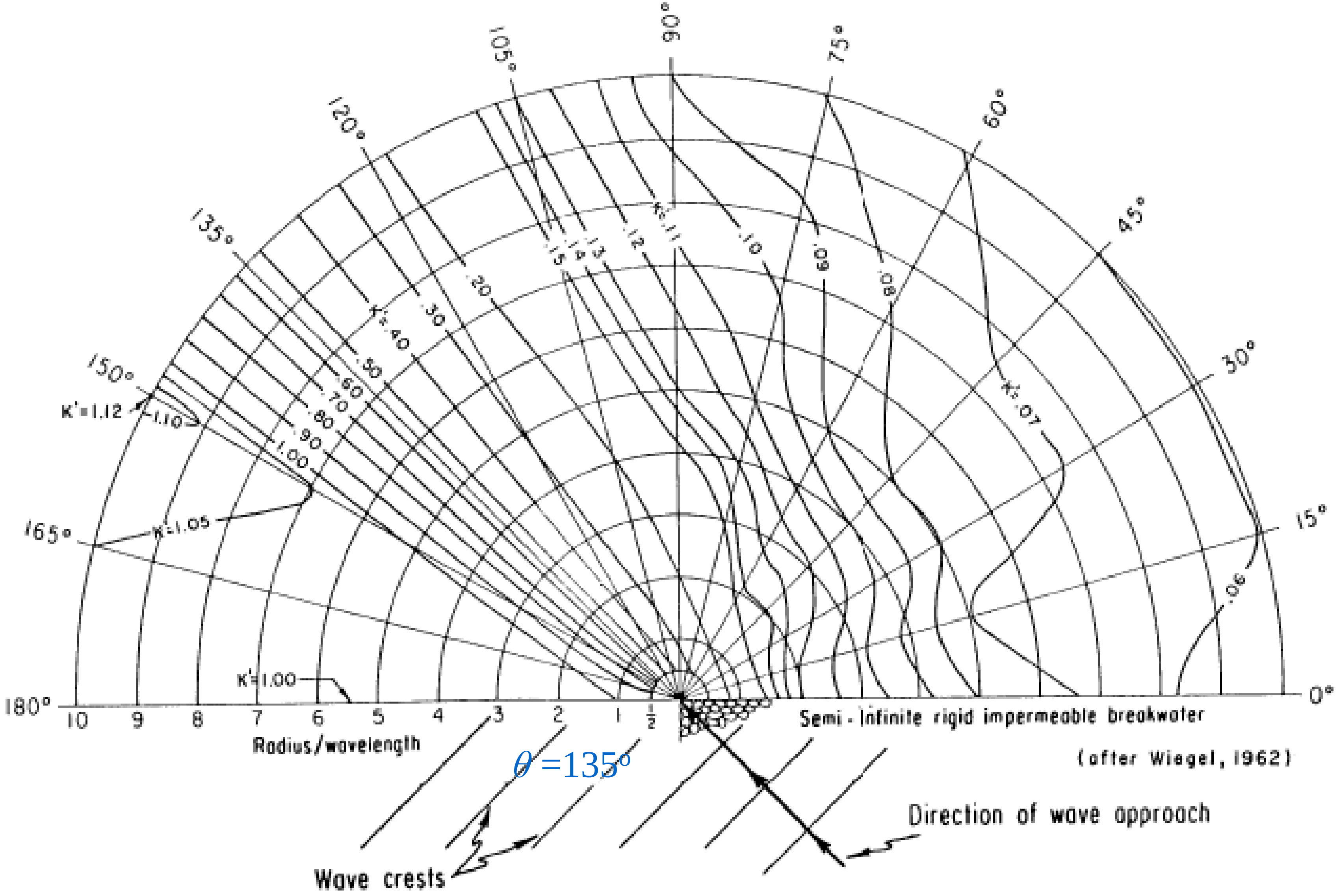


Wave Diffraction Diagram – Wave Angle θ = 120°

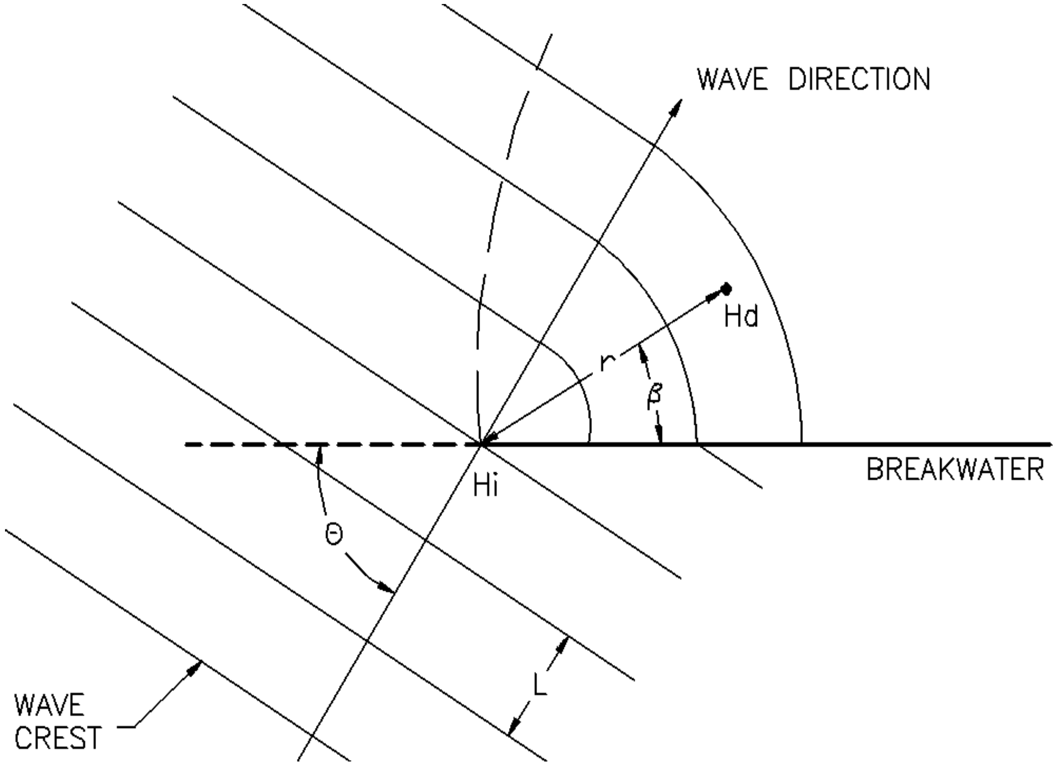


(after Wiegel, 1962)

Wave Diffraction Diagram – Wave Angle θ =135°



WAVE PASSING A SINGLE STRUCTURE



$$H_d = K_d \times H_i$$

H_d = Diffracted wave height

H_i = Incident wave height

K_d = Diffraction coefficent = $f\ (\theta,\ \beta,\ r/L)$

r = Radial distance from the breakwater tip to the point of interest

β = Angle between the breakwater and the radial, r

θ = Incident wave direction from the breakwater

L = Local wavelength

WAVE DIFFRACTION COEFFICIENT

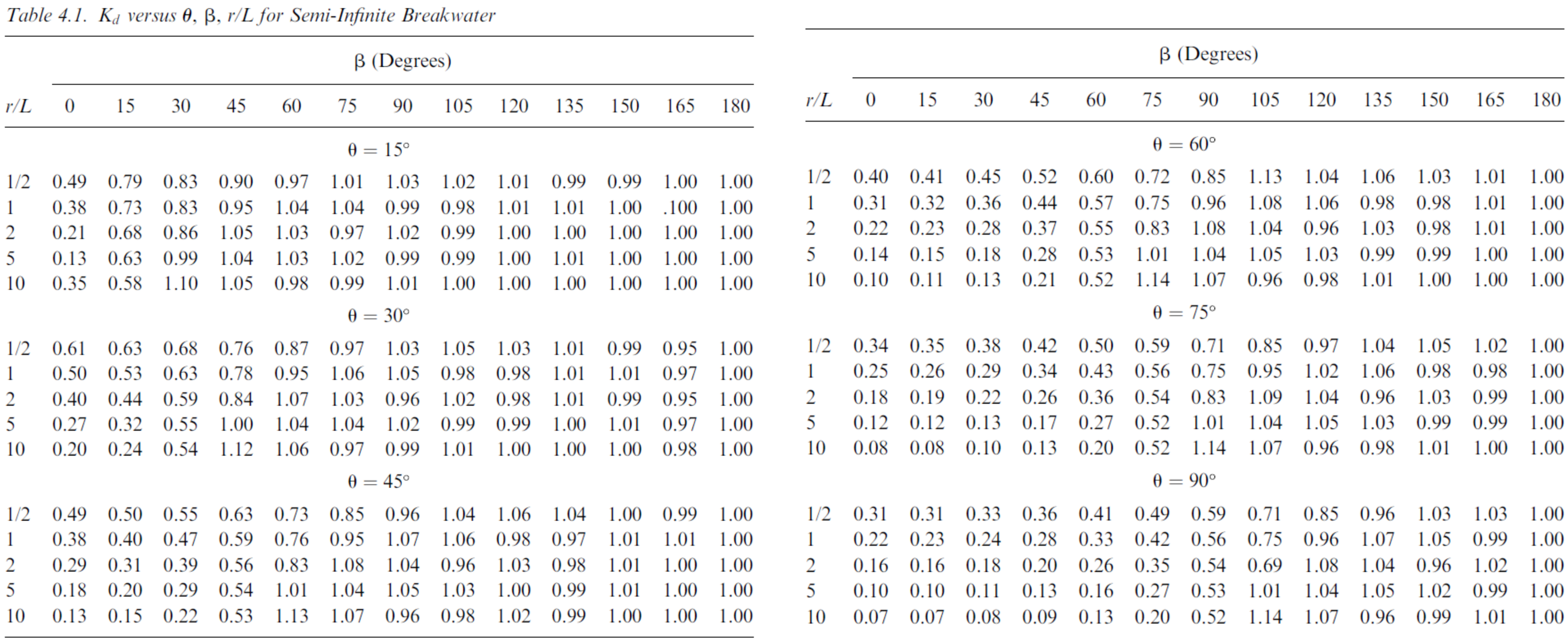
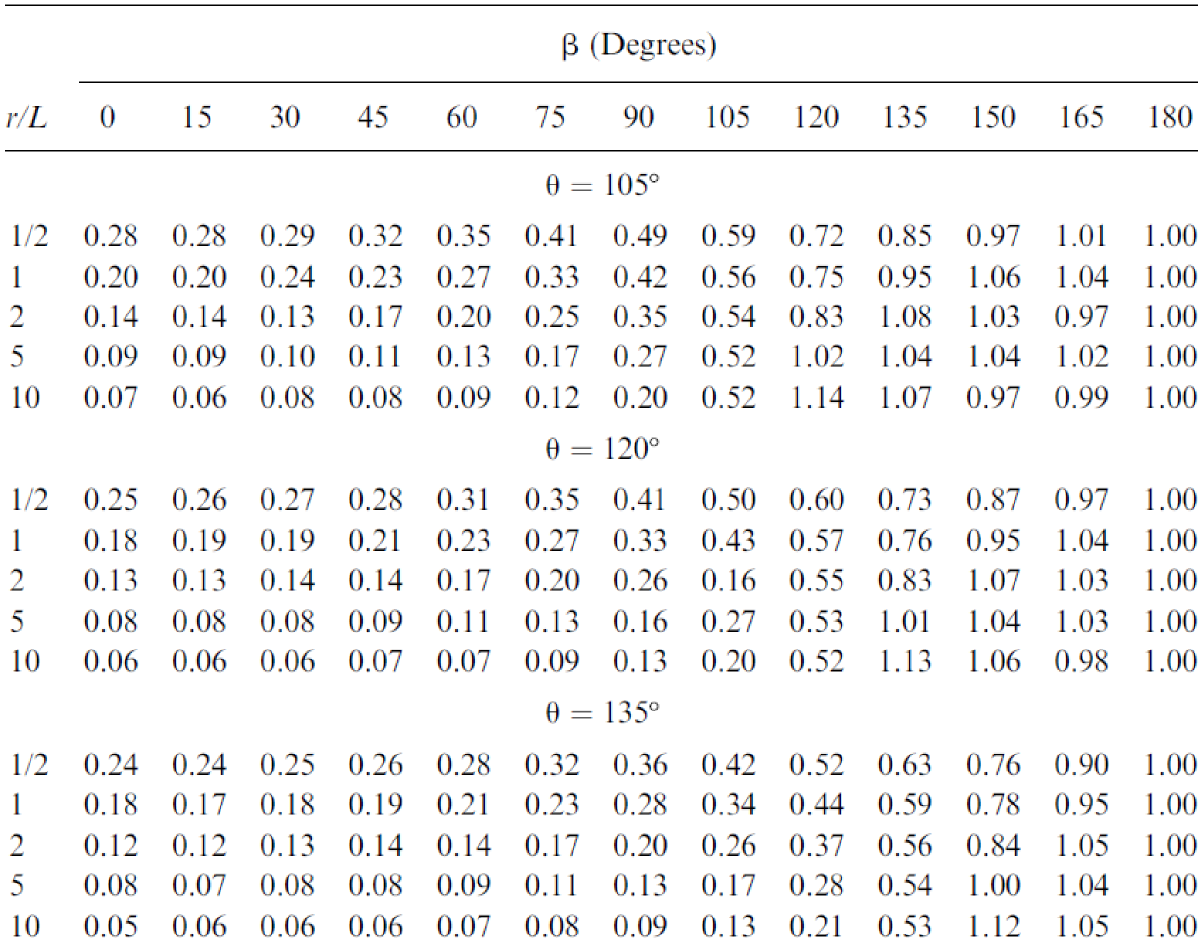


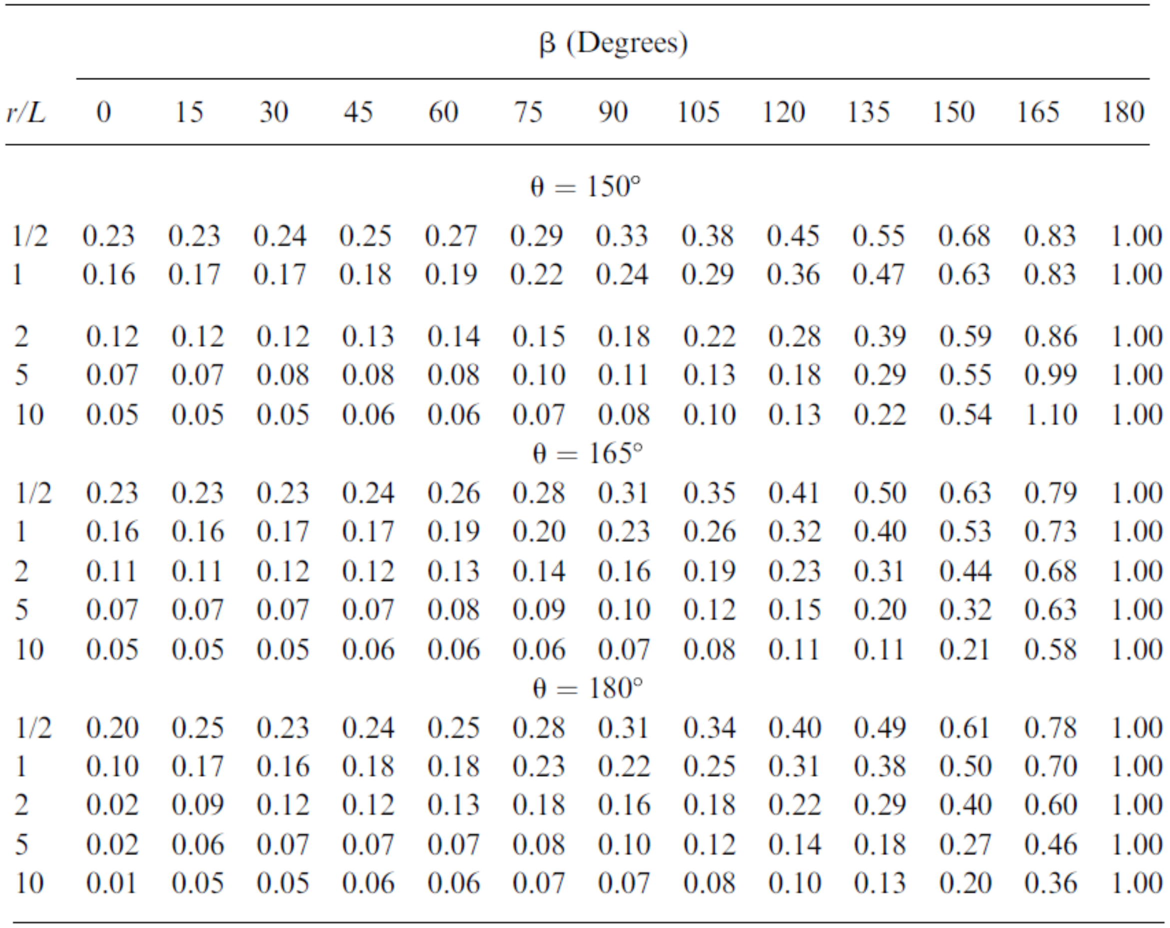
Table 4.1. K_d versus θ, β, r/L for Semi-Infinite Breakwater

	β (Degrees)												
r/L	0	15	30	45	60	75	90	105	120	135	150	165	180
θ = 15°													
1/2	0.49	0.79	0.83	0.90	0.97	1.01	1.03	1.02	1.01	0.99	0.99	1.00	1.00
1	0.38	0.73	0.83	0.95	1.04	1.04	0.99	0.98	1.01	1.01	1.00	.100	1.00
2	0.21	0.68	0.86	1.05	1.03	0.97	1.02	0.99	1.00	1.00	1.00	1.00	1.00
5	0.13	0.63	0.99	1.04	1.03	1.02	0.99	0.99	1.00	1.01	1.00	1.00	1.00
10	0.35	0.58	1.10	1.05	0.98	0.99	1.01	1.00	1.00	1.00	1.00	1.00	1.00
θ = 30°													
1/2	0.61	0.63	0.68	0.76	0.87	0.97	1.03	1.05	1.03	1.01	0.99	0.95	1.00
1	0.50	0.53	0.63	0.78	0.95	1.06	1.05	0.98	0.98	1.01	1.01	0.97	1.00
2	0.40	0.44	0.59	0.84	1.07	1.03	0.96	1.02	0.98	1.01	0.99	0.95	1.00
5	0.27	0.32	0.55	1.00	1.04	1.04	1.02	0.99	0.99	1.00	1.01	0.97	1.00
10	0.20	0.24	0.54	1.12	1.06	0.97	0.99	1.01	1.00	1.00	1.00	0.98	1.00
θ = 45°													
1/2	0.49	0.50	0.55	0.63	0.73	0.85	0.96	1.04	1.06	1.04	1.00	0.99	1.00
1	0.38	0.40	0.47	0.59	0.76	0.95	1.07	1.06	0.98	0.97	1.01	1.01	1.00
2	0.29	0.31	0.39	0.56	0.83	1.08	1.04	0.96	1.03	0.98	1.01	1.00	1.00
5	0.18	0.20	0.29	0.54	1.01	1.04	1.05	1.03	1.00	0.99	1.01	1.00	1.00
10	0.13	0.15	0.22	0.53	1.13	1.07	0.96	0.98	1.02	0.99	1.00	1.00	1.00
θ = 60°													
1/2	0.40	0.41	0.45	0.52	0.60	0.72	0.85	1.13	1.04	1.06	1.03	1.01	1.00
1	0.31	0.32	0.36	0.44	0.57	0.75	0.96	1.08	1.06	0.98	0.98	1.01	1.00
2	0.22	0.23	0.28	0.37	0.55	0.83	1.08	1.04	0.96	1.03	0.98	1.01	1.00
5	0.14	0.15	0.18	0.28	0.53	1.01	1.04	1.05	1.03	0.99	0.99	1.00	1.00
10	0.10	0.11	0.13	0.21	0.52	1.14	1.07	0.96	0.98	1.01	1.00	1.00	1.00
θ = 75°													
1/2	0.34	0.35	0.38	0.42	0.50	0.59	0.71	0.85	0.97	1.04	1.05	1.02	1.00
1	0.25	0.26	0.29	0.34	0.43	0.56	0.75	0.95	1.02	1.06	0.98	0.98	1.00
2	0.18	0.19	0.22	0.26	0.36	0.54	0.83	1.09	1.04	0.96	1.03	0.99	1.00
5	0.12	0.12	0.13	0.17	0.27	0.52	1.01	1.04	1.05	1.03	0.99	0.99	1.00
10	0.08	0.08	0.10	0.13	0.20	0.52	1.14	1.07	0.96	0.98	1.01	1.00	1.00
θ = 90°													
1/2	0.31	0.31	0.33	0.36	0.41	0.49	0.59	0.71	0.85	0.96	1.03	1.03	1.00
1	0.22	0.23	0.24	0.28	0.33	0.42	0.56	0.75	0.96	1.07	1.05	0.99	1.00
2	0.16	0.16	0.18	0.20	0.26	0.35	0.54	0.69	1.08	1.04	0.96	1.02	1.00
5	0.10	0.10	0.11	0.13	0.16	0.27	0.53	1.01	1.04	1.05	1.02	0.99	1.00
10	0.07	0.07	0.08	0.09	0.13	0.20	0.52	1.14	1.07	0.96	0.99	1.01	1.00

WAVE DIFFRACTION COEFFICIENT



	β (Degrees)												
r/L	0	15	30	45	60	75	90	105	120	135	150	165	180
							θ = 105°						
1/2	0.28	0.28	0.29	0.32	0.35	0.41	0.49	0.59	0.72	0.85	0.97	1.01	1.00
1	0.20	0.20	0.24	0.23	0.27	0.33	0.42	0.56	0.75	0.95	1.06	1.04	1.00
2	0.14	0.14	0.13	0.17	0.20	0.25	0.35	0.54	0.83	1.08	1.03	0.97	1.00
5	0.09	0.09	0.10	0.11	0.13	0.17	0.27	0.52	1.02	1.04	1.04	1.02	1.00
10	0.07	0.06	0.08	0.08	0.09	0.12	0.20	0.52	1.14	1.07	0.97	0.99	1.00
							θ = 120°						
1/2	0.25	0.26	0.27	0.28	0.31	0.35	0.41	0.50	0.60	0.73	0.87	0.97	1.00
1	0.18	0.19	0.19	0.21	0.23	0.27	0.33	0.43	0.57	0.76	0.95	1.04	1.00
2	0.13	0.13	0.14	0.14	0.17	0.20	0.26	0.16	0.55	0.83	1.07	1.03	1.00
5	0.08	0.08	0.08	0.09	0.11	0.13	0.16	0.27	0.53	1.01	1.04	1.03	1.00
10	0.06	0.06	0.06	0.07	0.07	0.09	0.13	0.20	0.52	1.13	1.06	0.98	1.00
							θ = 135°						
1/2	0.24	0.24	0.25	0.26	0.28	0.32	0.36	0.42	0.52	0.63	0.76	0.90	1.00
1	0.18	0.17	0.18	0.19	0.21	0.23	0.28	0.34	0.44	0.59	0.78	0.95	1.00
2	0.12	0.12	0.13	0.14	0.14	0.17	0.20	0.26	0.37	0.56	0.84	1.05	1.00
5	0.08	0.07	0.08	0.08	0.09	0.11	0.13	0.17	0.28	0.54	1.00	1.04	1.00
10	0.05	0.06	0.06	0.06	0.07	0.08	0.09	0.13	0.21	0.53	1.12	1.05	1.00

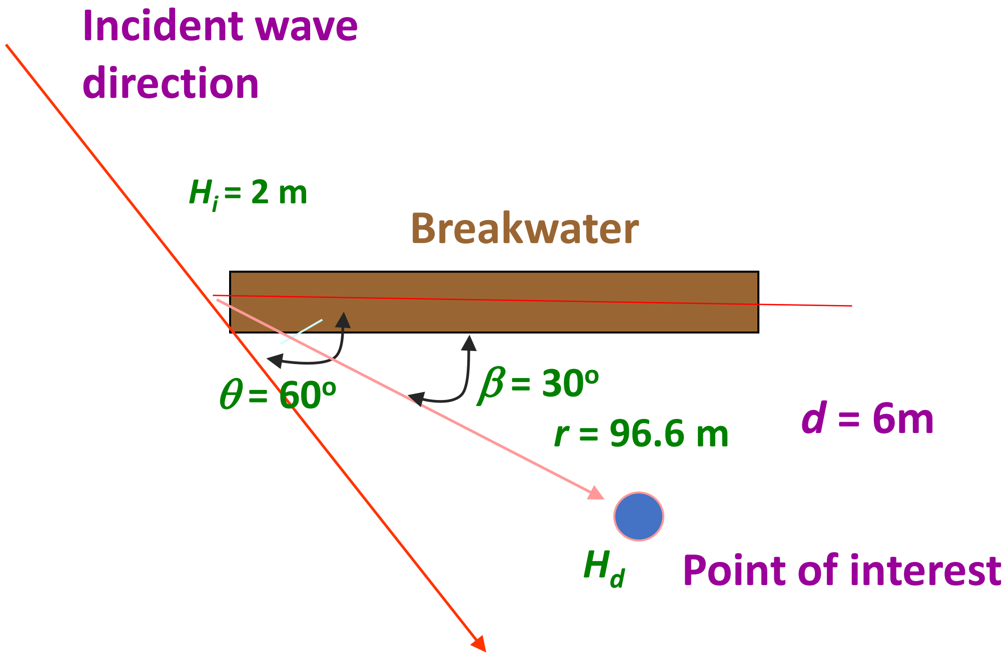


	β (Degrees)												
r/L	0	15	30	45	60	75	90	105	120	135	150	165	180
							θ = 150°						
1/2	0.23	0.23	0.24	0.25	0.27	0.29	0.33	0.38	0.45	0.55	0.68	0.83	1.00
1	0.16	0.17	0.17	0.18	0.19	0.22	0.24	0.29	0.36	0.47	0.63	0.83	1.00
2	0.12	0.12	0.12	0.13	0.14	0.15	0.18	0.22	0.28	0.39	0.59	0.86	1.00
5	0.07	0.07	0.08	0.08	0.08	0.10	0.11	0.13	0.18	0.29	0.55	0.99	1.00
10	0.05	0.05	0.05	0.06	0.06	0.07	0.08	0.10	0.13	0.22	0.54	1.10	1.00
							θ = 165°						
1/2	0.23	0.23	0.23	0.24	0.26	0.28	0.31	0.35	0.41	0.50	0.63	0.79	1.00
1	0.16	0.16	0.17	0.17	0.19	0.20	0.23	0.26	0.32	0.40	0.53	0.73	1.00
2	0.11	0.11	0.12	0.12	0.13	0.14	0.16	0.19	0.23	0.31	0.44	0.68	1.00
5	0.07	0.07	0.07	0.07	0.08	0.09	0.10	0.12	0.15	0.20	0.32	0.63	1.00
10	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.08	0.11	0.11	0.21	0.58	1.00
							θ = 180°						
1/2	0.20	0.25	0.23	0.24	0.25	0.28	0.31	0.34	0.40	0.49	0.61	0.78	1.00
1	0.10	0.17	0.16	0.18	0.18	0.23	0.22	0.25	0.31	0.38	0.50	0.70	1.00
2	0.02	0.09	0.12	0.12	0.13	0.18	0.16	0.18	0.22	0.29	0.40	0.60	1.00
5	0.02	0.06	0.07	0.07	0.07	0.08	0.10	0.12	0.14	0.18	0.27	0.46	1.00
10	0.01	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.10	0.13	0.20	0.36	1.00

PROBLEM 6

Consider a train of 6 s period waves approaching a breakwater so that the angle of approach at the breakwater head is 60°. The water depth in the lee of the breakwater is 10 m. Determine the wave height at an angle of 30° from the breakwater and a distance of 96.6 m from the breakwater head if the incident wave height at the head is 2.2 m.

SOLUTION



$L_o = 56.21$ m

$L = 48.43$ m

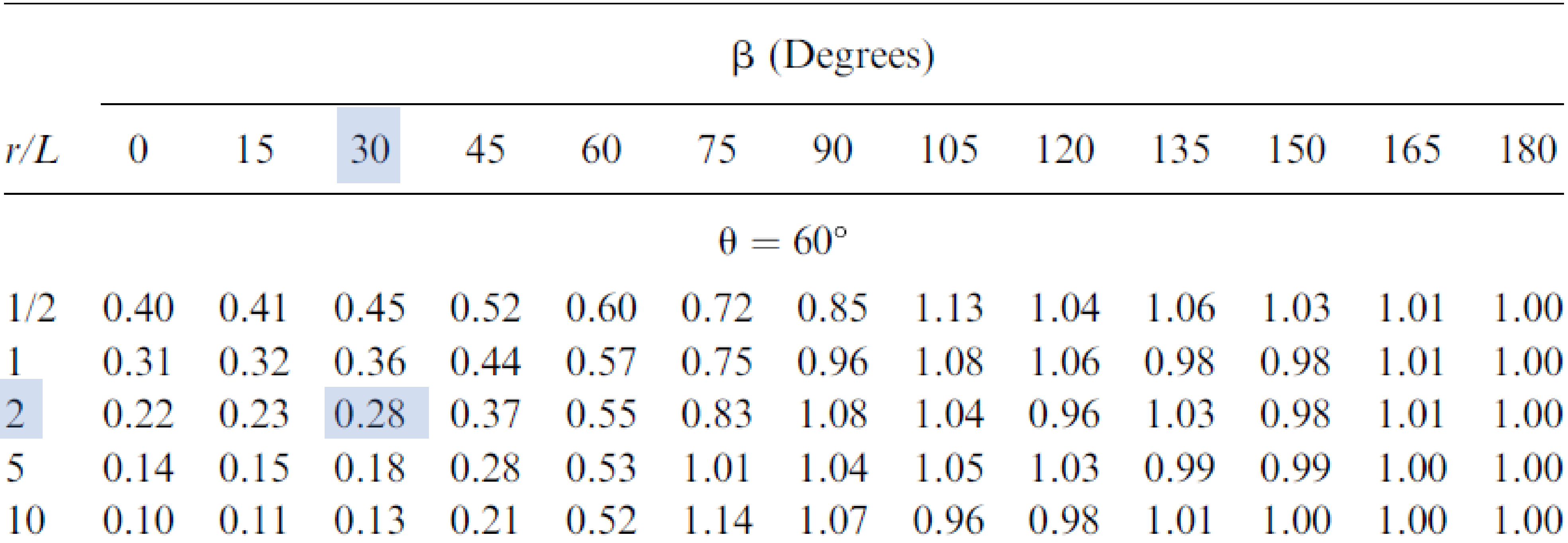
$r/L = 96.6/\ 48.43 = 2$

Referring to Table 4.1,

$K_d = 0.28$

$H_d = 0.28 \times 2.2 = 0.62$ m

WAVE DIFFRACTION COEFFICIENT



	β (Degrees)												
r/L	0	15	30	45	60	75	90	105	120	135	150	165	180
						$\theta = 60°$							
1/2	0.40	0.41	0.45	0.52	0.60	0.72	0.85	1.13	1.04	1.06	1.03	1.01	1.00
1	0.31	0.32	0.36	0.44	0.57	0.75	0.96	1.08	1.06	0.98	0.98	1.01	1.00
2	0.22	0.23	0.28	0.37	0.55	0.83	1.08	1.04	0.96	1.03	0.98	1.01	1.00
5	0.14	0.15	0.18	0.28	0.53	1.01	1.04	1.05	1.03	0.99	0.99	1.00	1.00
10	0.10	0.11	0.13	0.21	0.52	1.14	1.07	0.96	0.98	1.01	1.00	1.00	1.00

PROBLEM

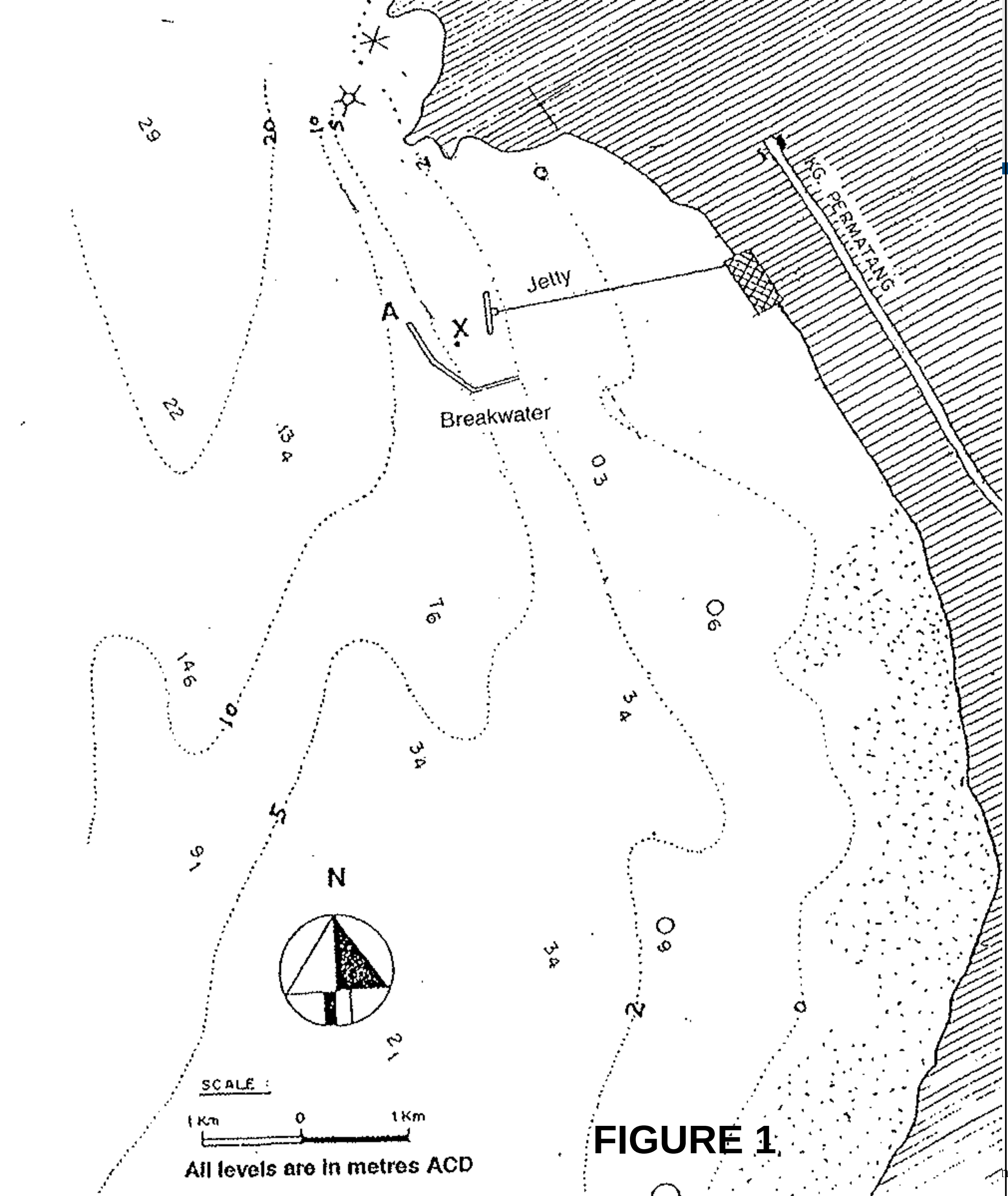


FIGURE 1

FIGURE 1 shows a site location plan of a proposed breakwater project for protection of a jetty near Kg. Permatang. Assume a train of deep water waves of 2.5 m high and 8 sec period propagating to the site area at an incident angle of 270° from the North Bearing. The waves start experiencing shoaling when moving on a bottom slope of 1:50.

a. Estimate the wave height at **A** where the water depth is 8 m.

b. Assume the water depth in the vicinity of the breakwater is fixed at 8 m. Estimate the wave height at **X**. Explain if the presence of the jetty would affect your estimation.

WAVE RUN UP

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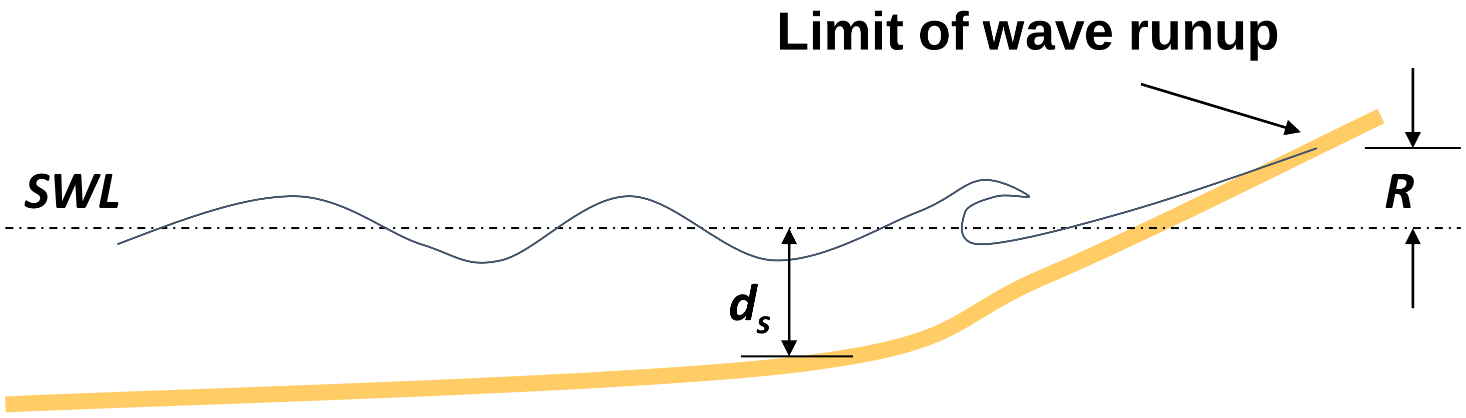
energising futures

LEARNING OUTCOMES

At the end of this lesson, student should be able to:

- describe the influence of wave run-up on the design of coastal and offshore structures.
- estimate the wave run-up on various slope conditions.

WAVE RUN UP

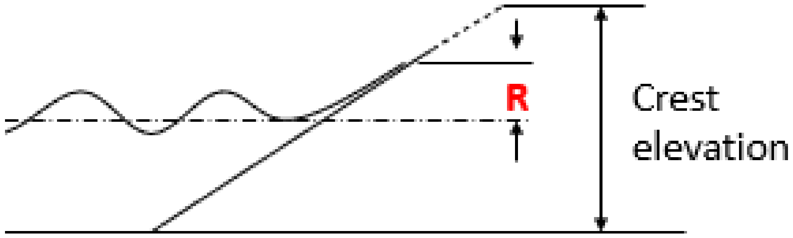


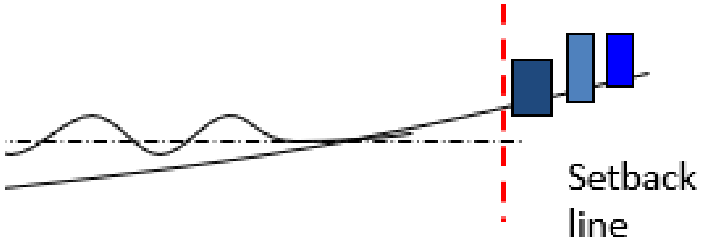
After a wave breaks, a portion of the remaining energy will energize a bore that will run up the face of a beach.

Run-up is the maximum elevation of wave uprush above the still-water level.

WHY IS THE STUDY OF WAVE RUN-UP IMPORTANT?

- Wave run-up is an important process in causing or promoting the bluff and shore erosion.
- To determine the required crest elevation for a sloping coastal structure
- To establish a beach setback line for limiting coastal construction





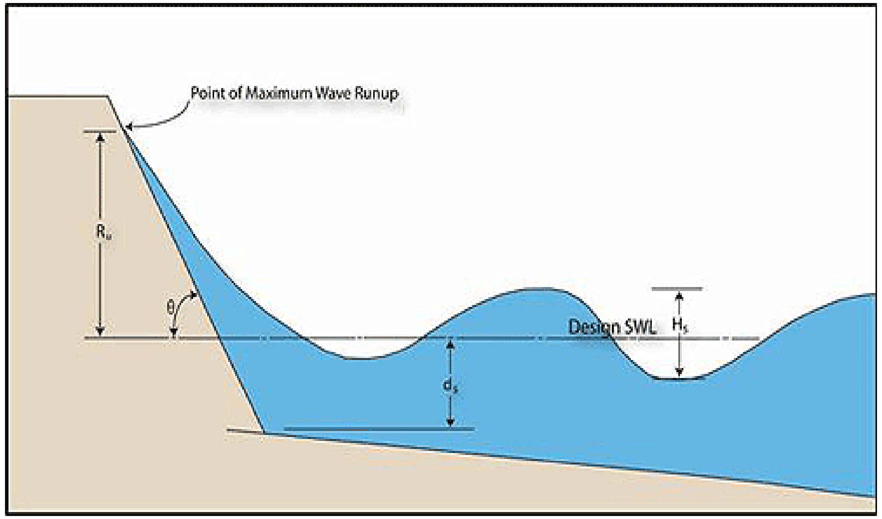
WAVE RUN UP

- Wave run-up consists of two components:

1. Super-elevation of the mean water level due to wave action (wave set-up)
2. Fluctuations about the mean water level (swash)

- The upper limit of run-up is an important parameter for determining the active portion of the beach profile.
- At present, theoretical approaches for calculating run-up on beaches are not viable for coastal design due to difficulties inherent in run-up prediction include nonlinear wave transformation, wave reflection, three dimensional effects (bathymetry), porosity, roughness, permeability, and groundwater elevation.

FACTORS AFFECTING RUN-UP



https://pilebuck.com/highways-coastal-environment-second-edition/chapter-6-coastal-revetments-wave-attack/

$$\frac{R}{H_o'} = f\left(\alpha, \frac{H_o'}{gT^2}, \frac{d_s}{H_o'}\right)$$

Relative run-up

Surface slope

cot α =1/m

Wave Steepness

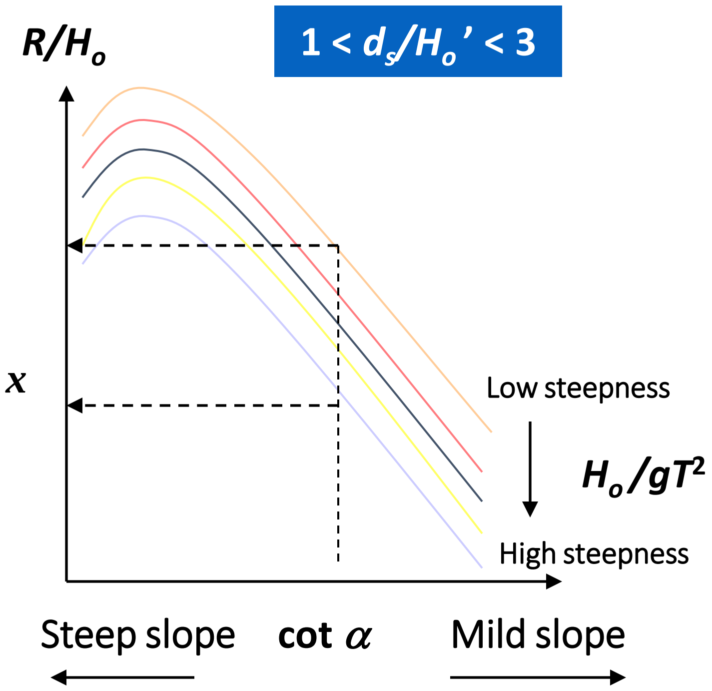
Relative depth

Other affecting parameters:

Roughness of the slope face

Permeability of the slope face

RELATIVE RUN-UP



Dimensionless Run-up on Smooth Impermeable Slope vs. (i) Bottom Slope and (ii) Incident Deep Water Wave Steepness

For a given slope, steeper waves have lower relative run-up.

For most beaches and revetment slopes, the wave run-up increases as the slope becomes steeper.

Smooth Impermeable Slope

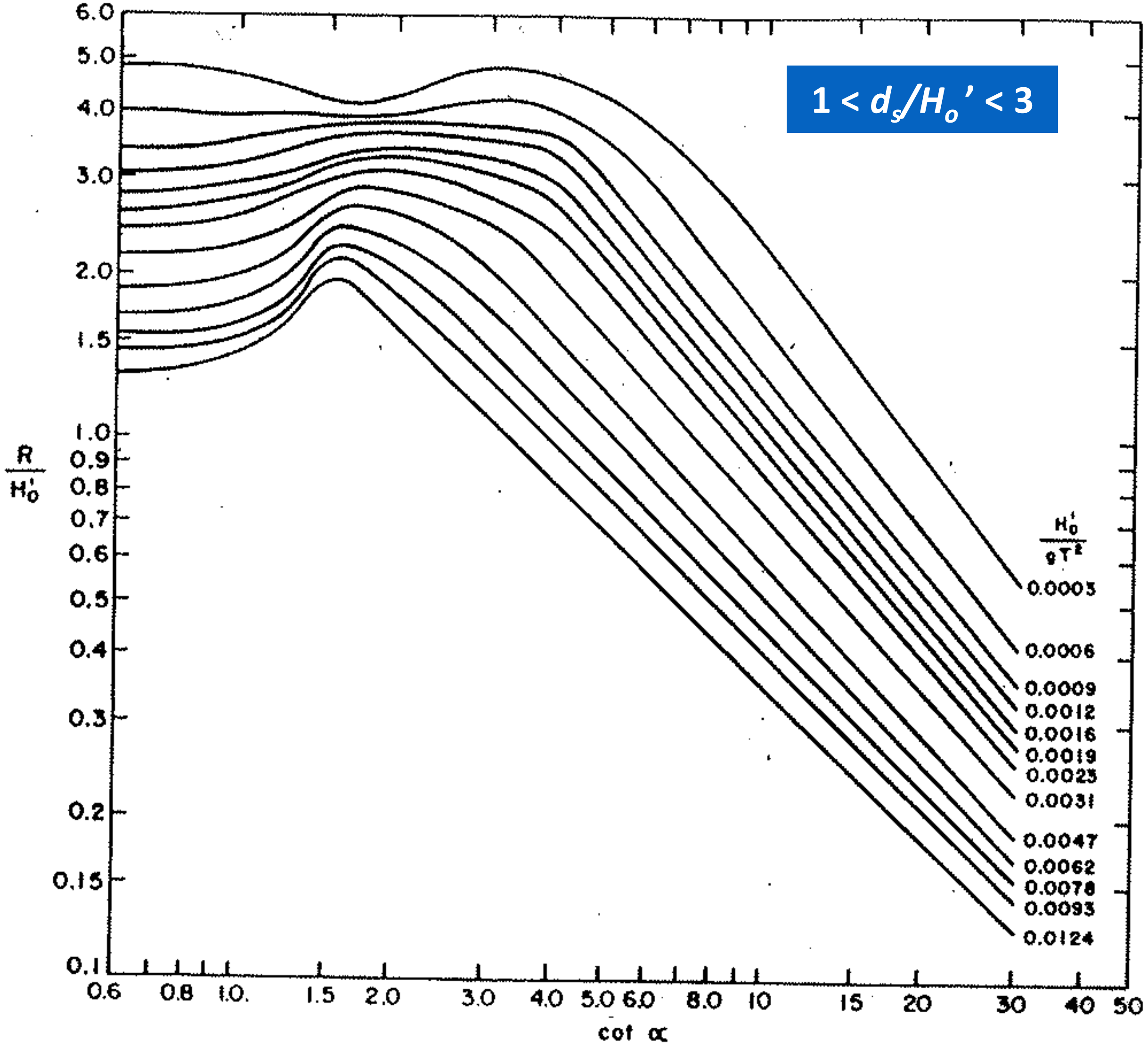
$$\boxed{R = x\,H_o}$$

For other slope conditions ⇒ use **run-up factor (*r*)**

Other Slopes

$$\boxed{R = x\,H_o\,r}$$

RELATIVE RUN-UP



$1 < d_s/H_o' < 3$

RUN-UP FACTORS

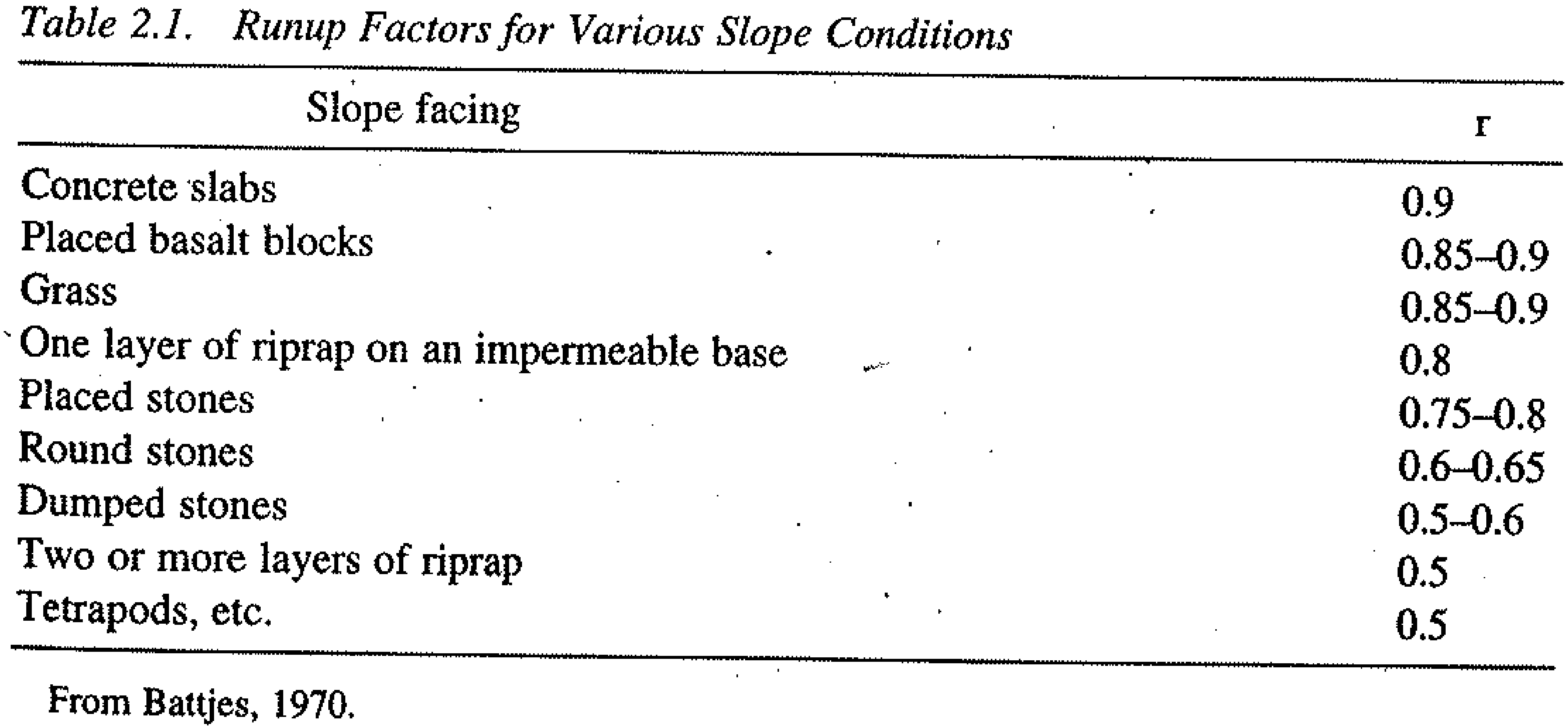


Table 2.1. Runup Factors for Various Slope Conditions

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.

PROBLEM 9

A wave in water 100 m deep has a period of 10 s and a height of 2 m, 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.

Determine:

(i) the breaking wave height, and
(ii) the wave run-up elevation on the grass-covered slope.

SOLUTION

Determination of breaker height, H_b

$H_o'/gT^2 = 2/[9.81 \times 100] = 0.0020$

$m = 0.1$

$H_b/H_o' = 1.6$

$H_b = 1.6 \times 2 = 3.2$ m (plunging breaker)

Determination of wave runup, R

$d_s/H_o' = 4/2 = 2$

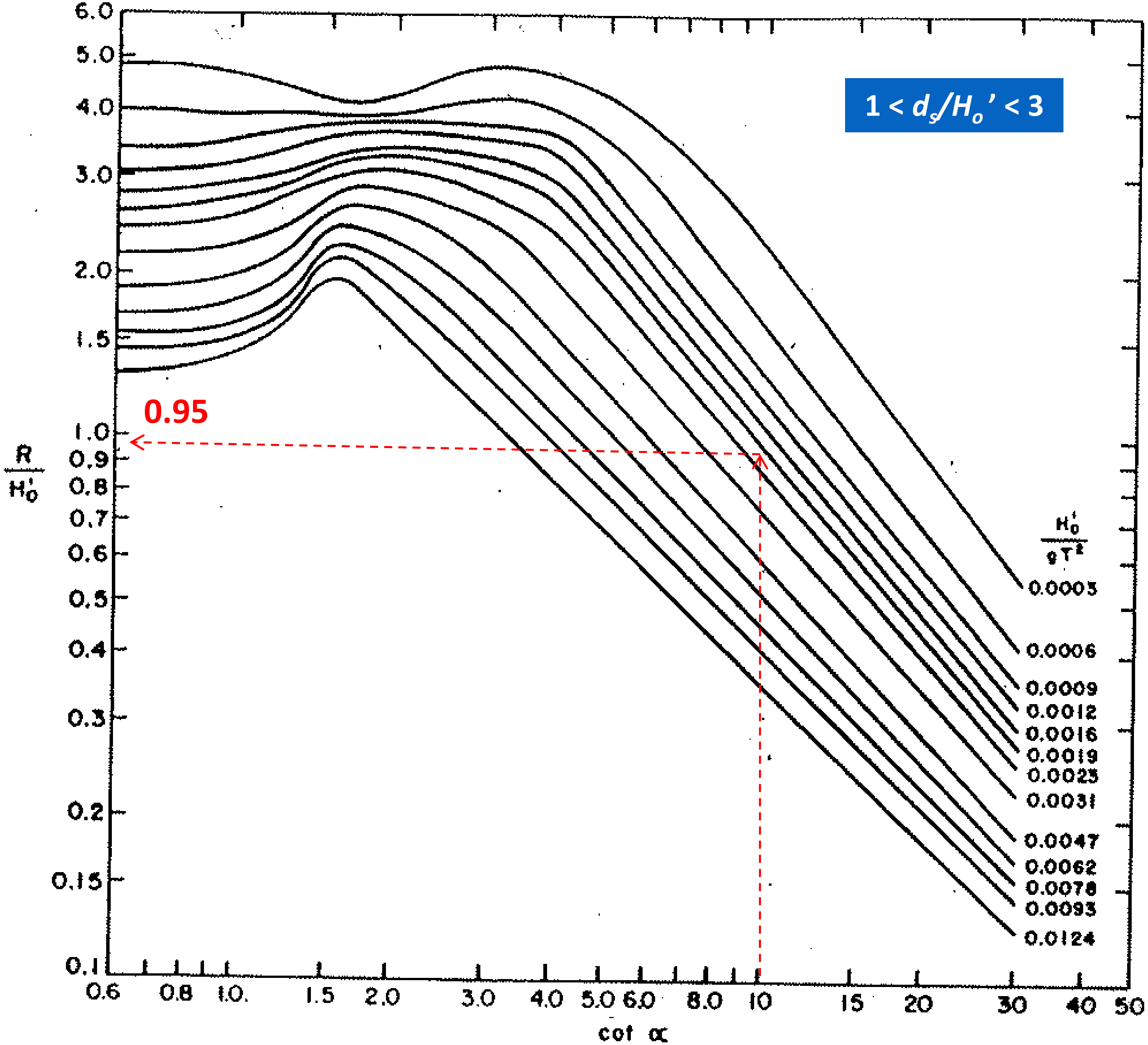
$\cot \alpha = 10$

$H_o'/gT^2 = 0.0020$

$R/H_o' = 0.95$

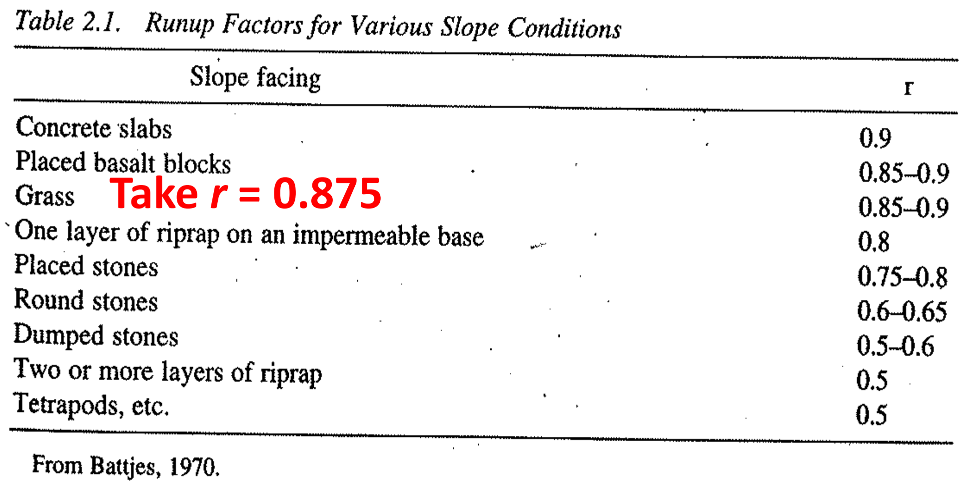
The uncorrected **smooth slope** runup: $R = 0.95\ (2) = 1.9$ m

The corrected **grass-covered slope** runup : $R = 0.875\ (1.9) = 1.66$ m



$1 < d_s/H_o' < 3$

0.95



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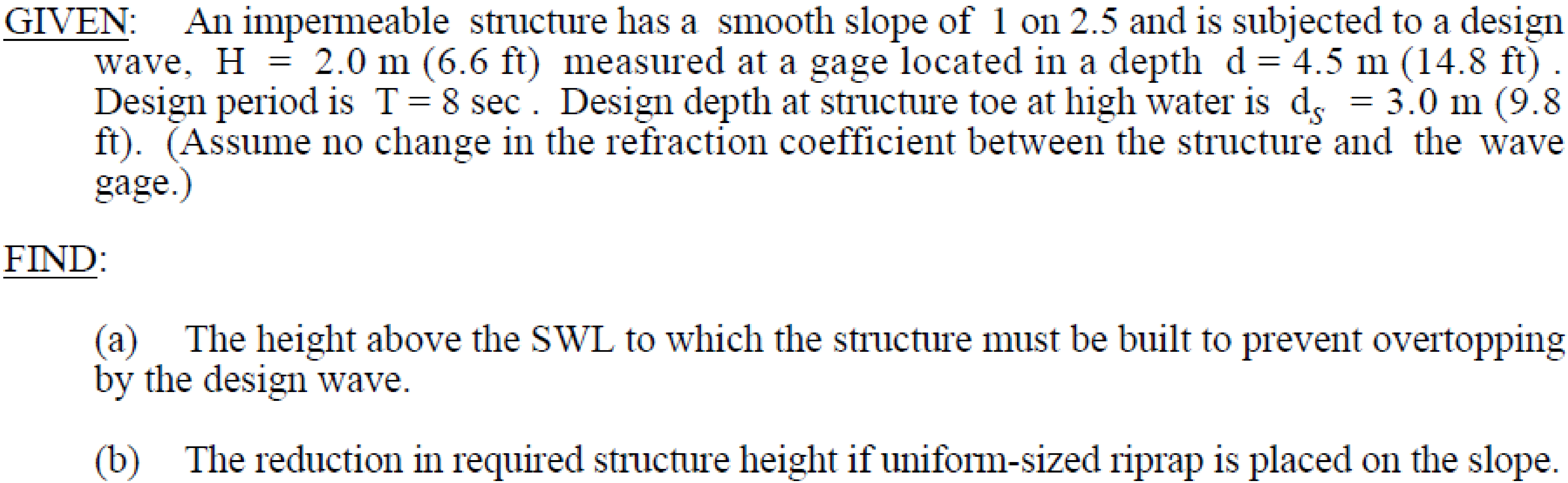
Round stones	0.6–0.65
Dumped stones	0.5–0.6
Two or more layers of riprap	0.5
Tetrapods, etc.	0.5

From Battjes, 1970.

Take $r = 0.875$

PROBLEM



GIVEN: An impermeable structure has a smooth slope of 1 on 2.5 and is subjected to a design wave, H = 2.0 m (6.6 ft) measured at a gage located in a depth d = 4.5 m (14.8 ft). Design period is T = 8 sec. Design depth at structure toe at high water is d_s = 3.0 m (9.8 ft). (Assume no change in the refraction coefficient between the structure and the wave gage.)

FIND:

(a) The height above the SWL to which the structure must be built to prevent overtopping by the design wave.

(b) The reduction in required structure height if uniform-sized riprap is placed on the slope.

(a) The height above the SWL to which the structure must be built to prevent overtopping by the design wave.

$$\frac{d}{L_o} = \frac{2\pi d}{gT^2} = \frac{2\pi(4.5)}{(9.8)(8)^2} = 0.0451$$

From Table C-1, Appendix C, for

$$\frac{d}{L_o} = 0.0451$$

$$\frac{H}{H'_o} = 1.041$$

Therefore

$$H'_o = \frac{H}{1.041} = \frac{2.0}{1.041} = 1.9 \text{ m } (6.2 \text{ ft})$$

To determine the runup, calculate

$$\frac{H'_o}{gT^2} = \frac{1.9}{(9.8)(8)^2} = 0.0030$$

and using the depth at the structure toe

$$d_s = 3.0 \text{ m } (9.8 \text{ ft})$$

$$\frac{d_s}{H'_o} = \frac{3.0}{1.9} = 1.58$$

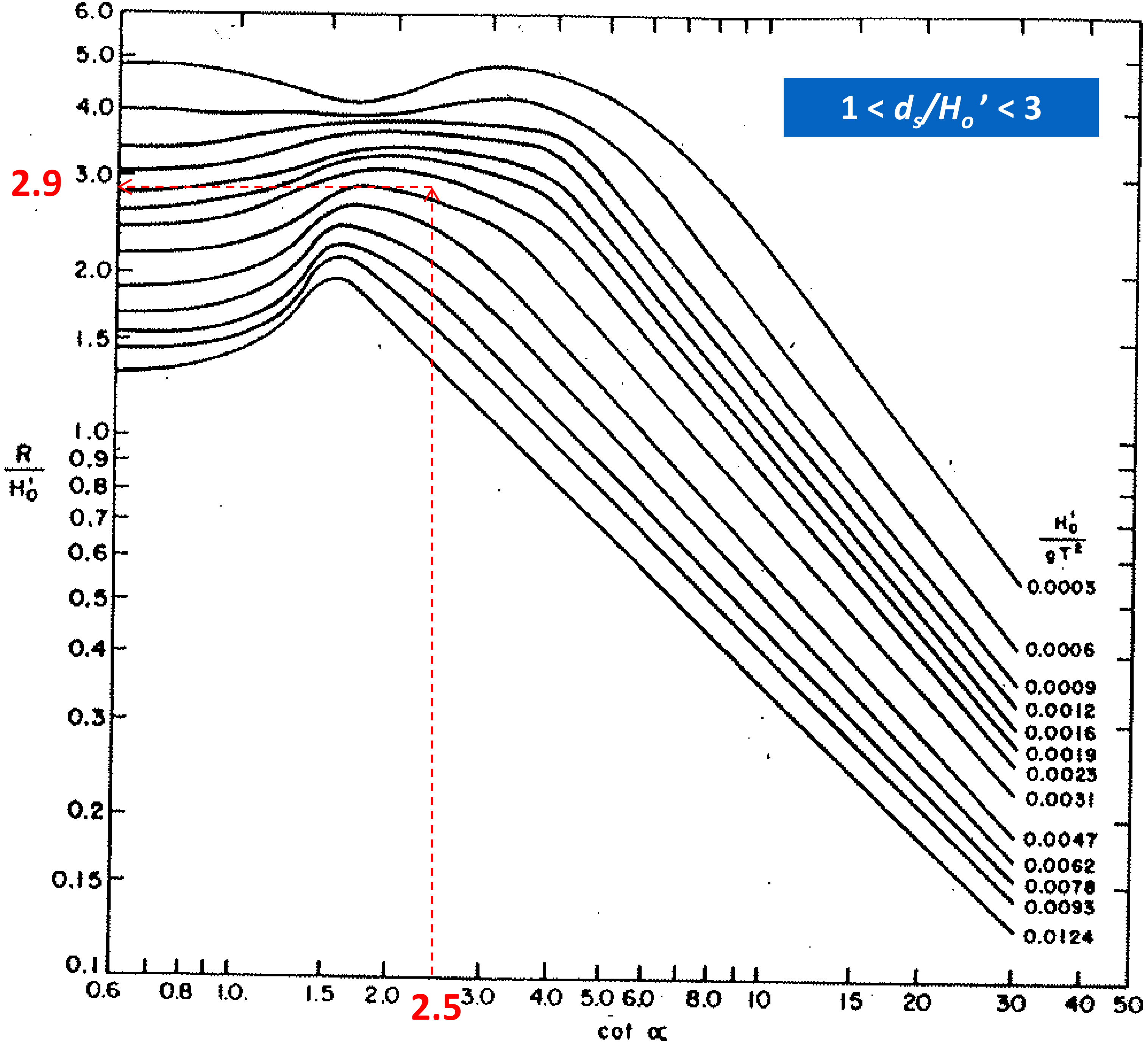
$1 < d_s/H_o' < 3$

OK!

$R/H_o' = 2.9$

$R = 2.9 \times 1.9 = 5.51$ m

Since R = 5.51 m above the SWL, the height of the structure must be built beyond R in order to prevent wave overtopping.


2.9
2.5
R / H'0
cot α
H'0 / gT²
6.0
5.0
4.0
3.0
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.15
0.1
0.6
0.8
1.0
1.5
2.0
3.0
4.0
5.0
6.0
8.0
10
15
20
30
40
50
0.0003
0.0006
0.0009
0.0012
0.0016
0.0019
0.0023
0.0031
0.0047
0.0062
0.0078
0.0093
0.0124

$1 < d_s/H_o' < 3$

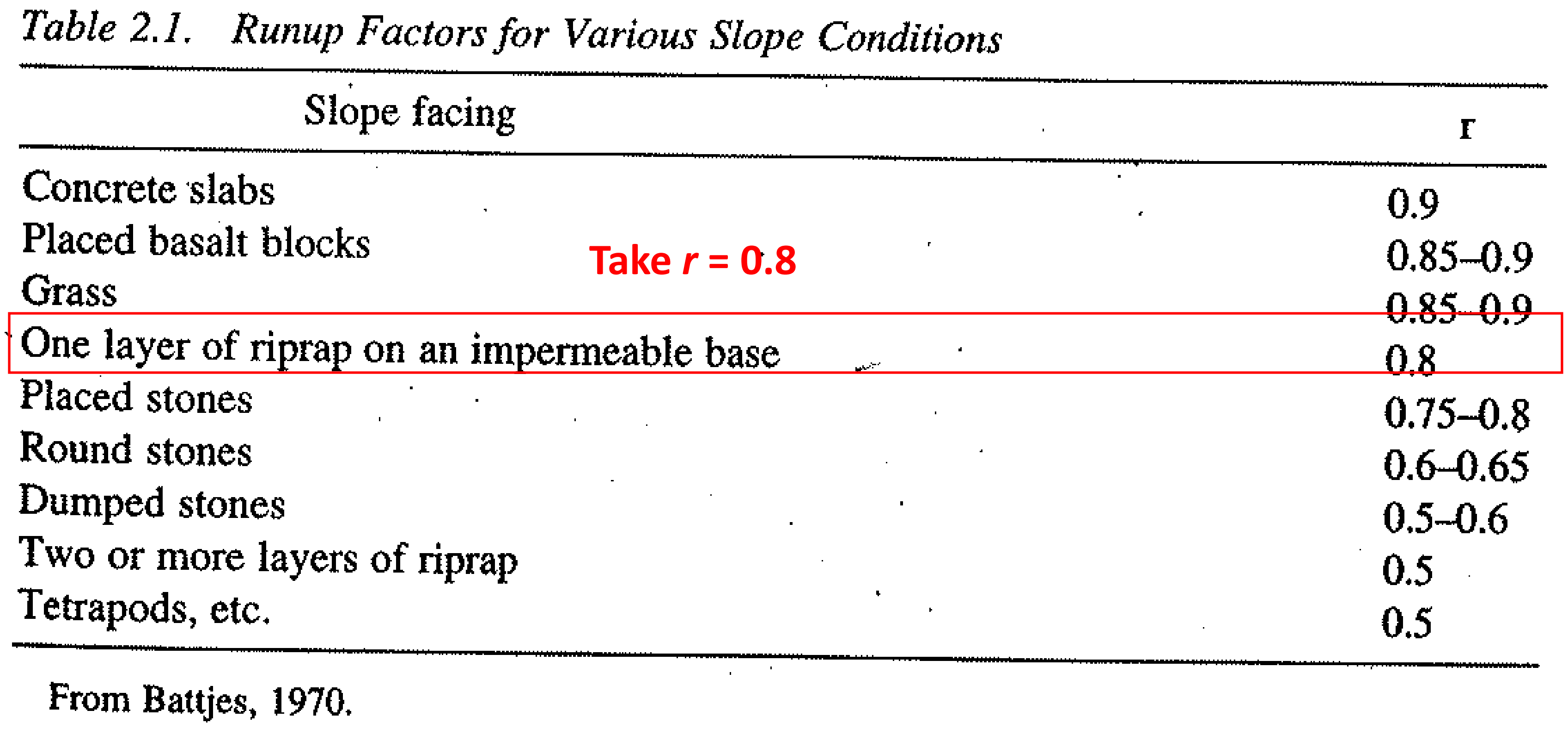

(b) The reduction in required structure height if uniform-sized riprap is placed on the slope.

Run-up correction factor due to a layer of rip-rap, $r = 0.8$

The uncorrected **smooth slope** runup: R = 5.51 m

The corrected **rip-rap slope** runup : R = 0.8 (5.51) = 4.41 m

Run-up Factors for Various Slope Conditions



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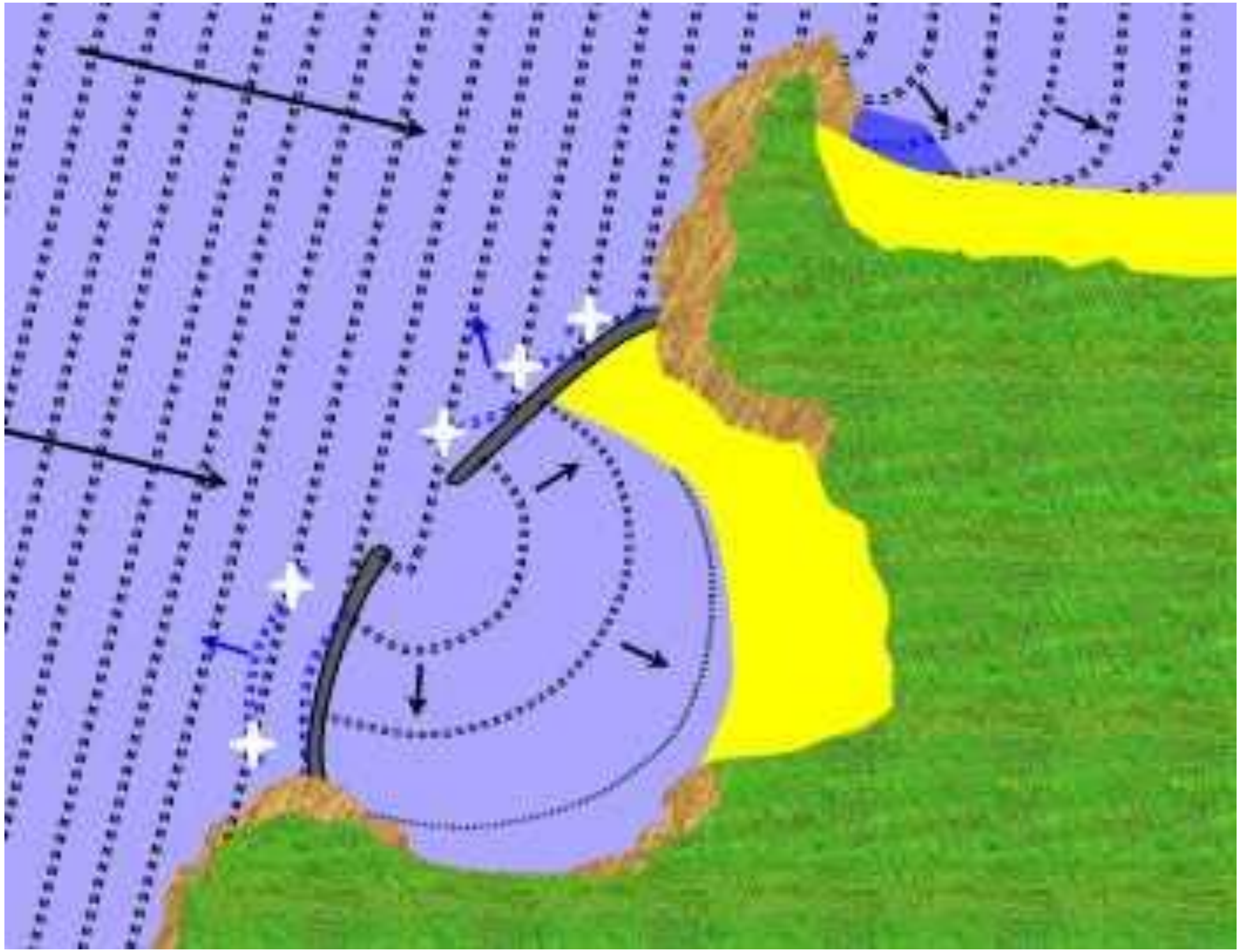
Round stones	0.6–0.65
Dumped stones	0.5–0.6
Two or more layers of riprap	0.5
Tetrapods, etc.	0.5

From Battjes, 1970.

Take *r* = 0.8

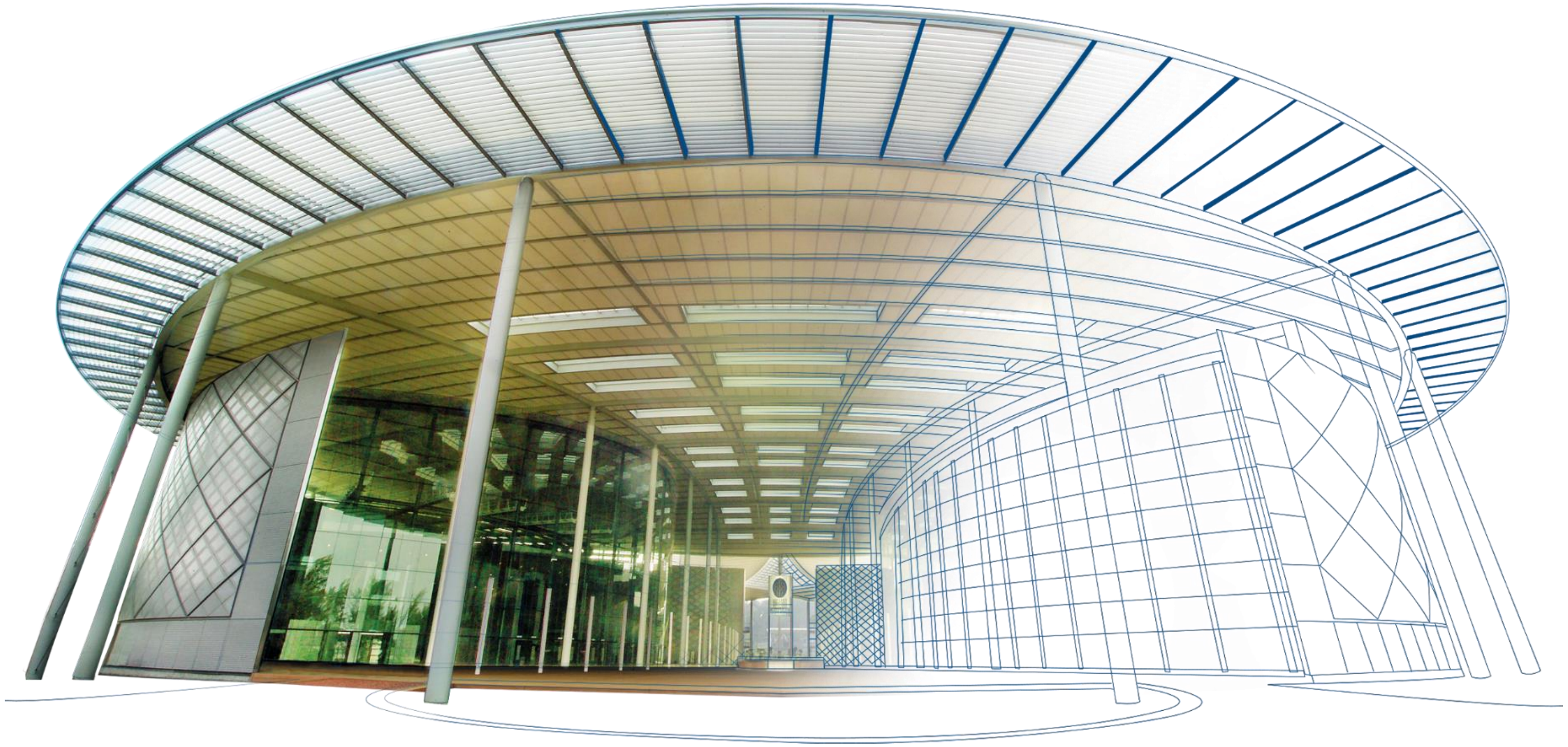
PROBLEM



Describe the nearshore wave transformation processes that you can observe from this figure.

WAVE RUNUP & OVERTOPPING DEMONSTRATION

Wave tank demonstration showing the impact of coastal defences on flood risk



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