CHAPTER 24

CRITICAL TRAVEL DISTANCE OF WAVES IN SHALLOW WATER

by

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Abstract

A new criterion for shallow water wave analysis is evaluated from prototype data off the German coast on the reef and wadden sea areas south of the outer Elbe river.

Correlations of mean wave heights $\overline{H}$ with mean wave periods $\overline{T}$, and wave height distribution factors $C_{1/3} = \frac{H_{1/3}}{\overline{H}}$ respectively show that the mean periods and both complete height and period distributions of waves in shallow water can be expressed as functions of mean height and topography. So the mean wave height $\overline{H}$ proves to be the characteristic parameter for the description of the complete shallow water wave climate. The upper envelop of the values $\overline{H}$ = f (meteorology, topography) is defined as the case of fully developed sea, which leads to the function of the highest mean wave heights $\overline{H}_{max}$. This parameter is plotted with 3 topographical parameters:

depth of water d,
distance s from deep water area, and
mean wave steepness δ .

The curves $\frac{\overline{H}_{max}}{d}$ versus s for different d show distinct maxima for varying distances $s_{crit.}$ from the deep water

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area. This critical travel distance of waves in shallow water is dependent on the depth of water only. It represents the length, on which the waves grow before the beginning decay due to shoaling effects:

$$s_{crit.} = 0{,}264 \cdot (d + 1)$$

with s in kilometres and d in metres. It points out that the distance from deep water, where the shallow water wave spectrum reaches its critical maximum, grows with the depth of water. Storm tides with extreme water levels transfer the line of critical travel distances coastward, and the probability of destruction rises, as this effect brings a larger increase in wave height than usually recognized.

Introduction

The Port of Hamburg Authority is planning a deep sea harbor at the outer entrance of the Elbe river. Much preliminary work has been done concerning tides, currents, wind conditions etc. and also waves. Investigations in the estuary, off the German North Sea coast, in water depths between 0.3 m and 10 m for more than 10 years at 29 wave stations (fig. 1) provided the basic material for the evaluation of a new criterion for shallow water wave analysis. Before this can be treated in detail, some general remarks are necessary:

Analyses of about 15,000 wave records in terms of S-M-B-method showed that mean periods and both complete height and period distributions of waves in shallow water can be expressed as functions of mean height $\bar{H}$ and topography.

The dependence upon the meteorological situation is not analyzed here because of the following aspects:
From the engineer's point of view often the highest possible waves are of special interest, i.e. the upper envelop of the strongly scattering values

$$\bar{H} = f\ (\text{meteorology, topography}).$$

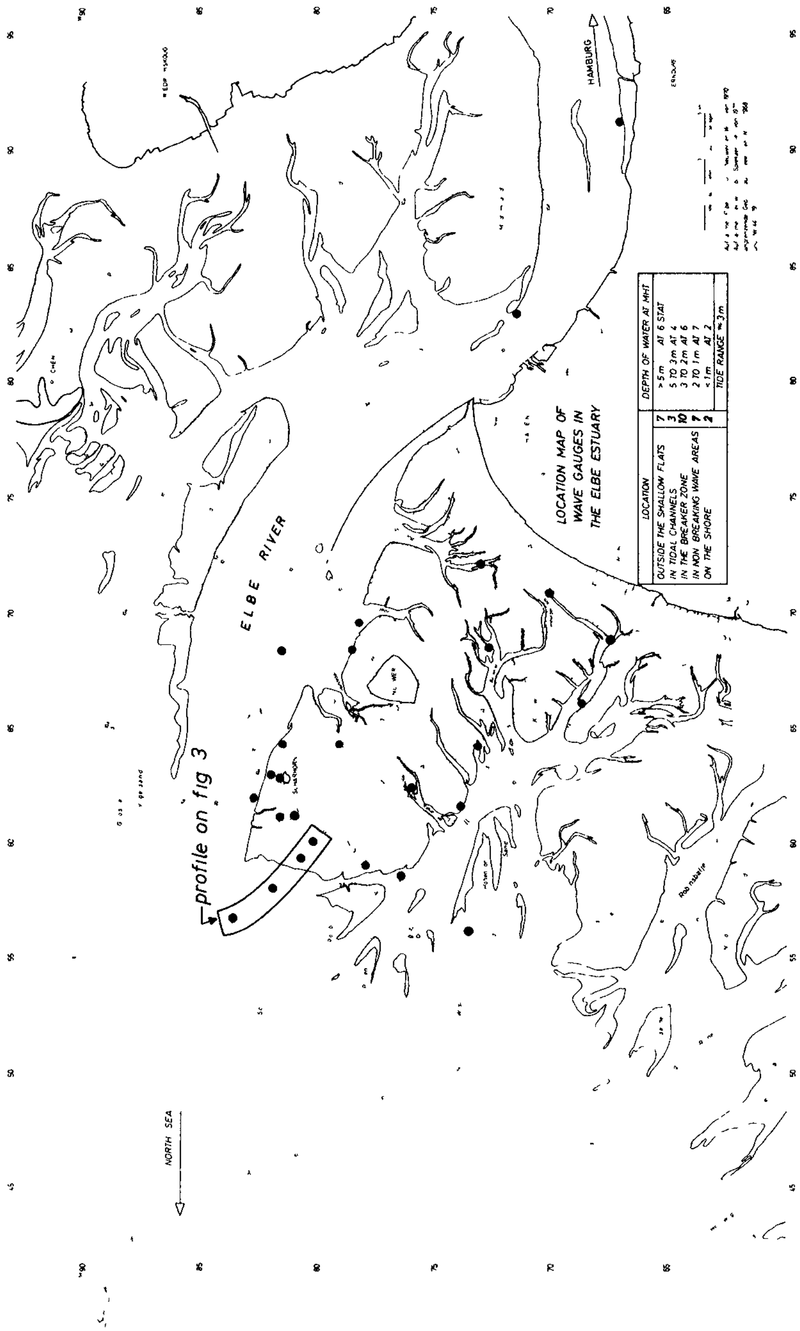

Fig. 1
Wave Investigations in the Elbe Estuary

This leads to functions for the highest possible mean wave heights $\overline{H}_{max}$ for fully arisen sea, which become almost horizontal in shallow water (i.e. independent of the wind conditions) at high wind forces from 6 to 7 Bft onwards.

As structural design is nearly always concerned with wave conditions at higher wind speeds, the simplification of neglecting special meteorological characteristics proves to be admissable.

Topographical Parameters

Under this supposition the knowledge of $\overline{H}_{max}$ as the representative wave parameter is decisive. As its value can be calculated as a function of topography, the latter has to be expressed by parameters. The most common topographical parameter is the depth of water d, but it is surely not the only important one. This may be stressed by fig. 2, showing the highest single wave H_{max} in a natural spectrum as a function of d. There is a wide range of offers with a scattering up to 100%, indicating that important connections were neglected. Fig. 3 with a typical profile of decreasing water depth in the breaker zone of the Scharhornriff (see fig. 1) leads to the conclusion that there is of course a strong influence of d, but not all of the shown parameters do change continuously with d, especially the steepness factor and the wave height distribution factor $C_{1/3} = H_{1/3}/\overline{H}$. Wave steepness decreases from 0.005 to 0.0025 and then remains constant. It turns out that the mean steepness is only a weak function of d and much more an indicator for the dominating wave character, i.e. whether waves are breaking or not, for instance.

The wave height distribution factor also decreases, from 1.52 to 1.40, but then increases to 1.45, i.e. the wave height distribution at first narrows and then widens again (SIEFERT, 1973).

Data from different regions indicate that there are influences of other topographical parameters that have

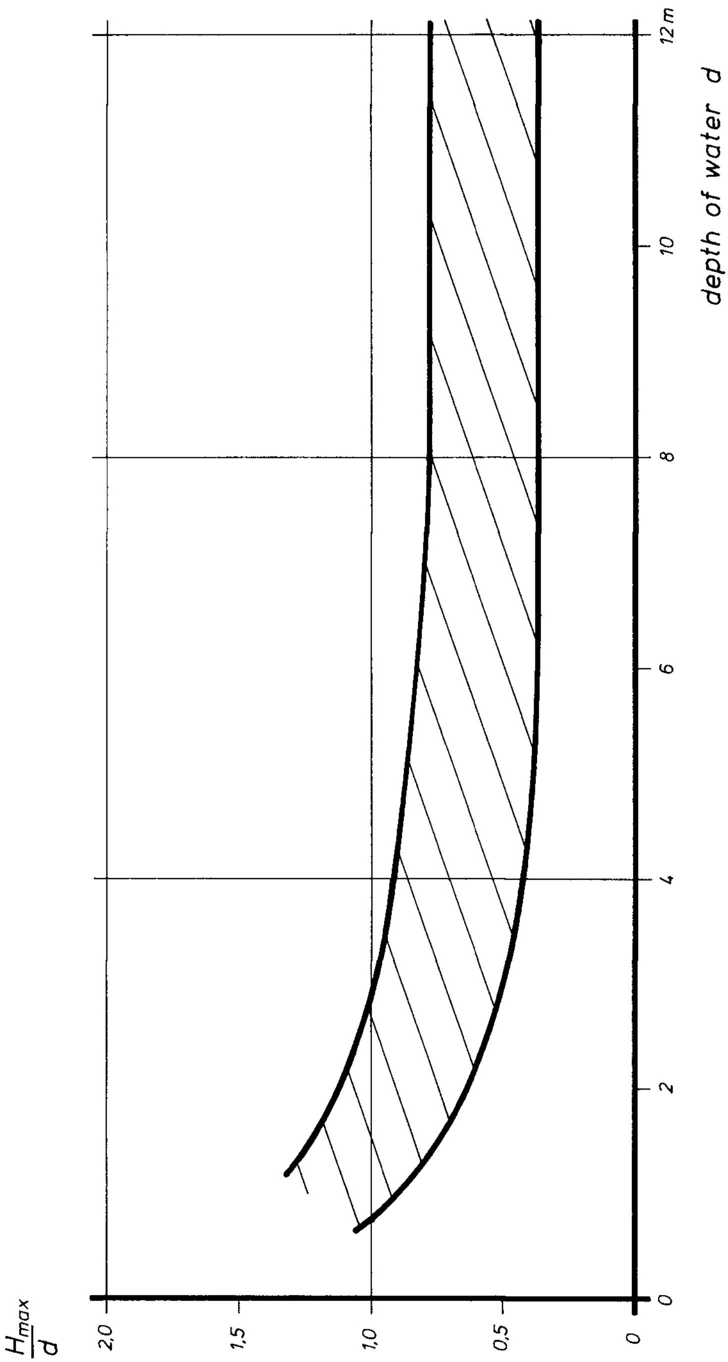

Fig. 2

$\frac{H_{max}}{d}$ vs. d,

Range of Functions from Various Authors

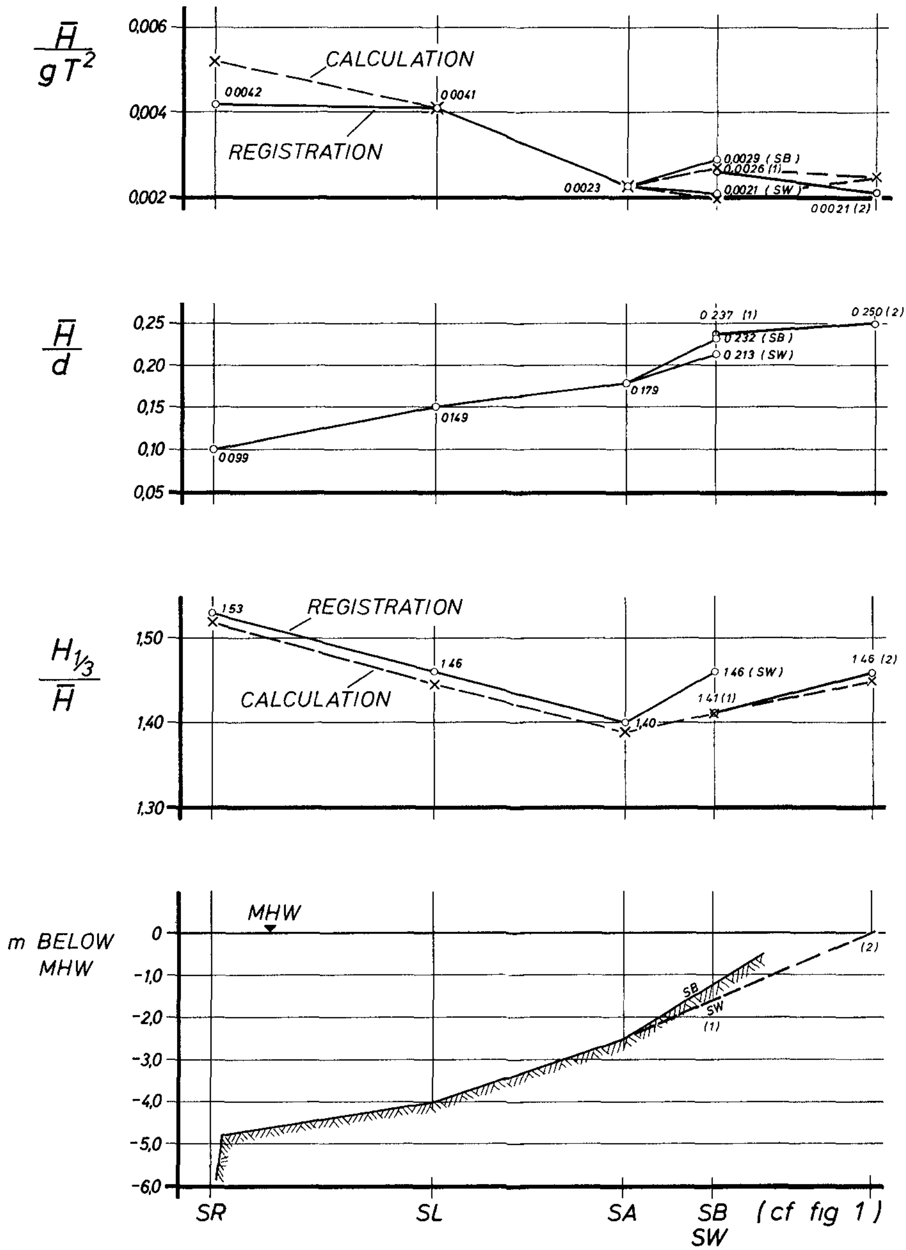

Fig. 3

Variation of Wave Parameters with Decreasing Depth to be regarded. They lead to the calculated best-fit lines on fig. 3. The additional parameters are the mean wave steppness $\delta = \bar{H}/\bar{L}$ and the distance s from deep water areas. So we get some sort of "2nd order parameters", and topography can be expressed by

the depth of water d,
the distance s from deep water areas, and
the mean wave steepness.

The table shows the mean steepnesses of deep water and typical shallow water areas as used in the following derivations:

Mean Steepnesses
of Waves in Shallow Water

AREA	$\delta = \frac{\bar{H}}{\bar{L}} \approx 10 \cdot \frac{\bar{H}}{g\bar{T}^2}$
WATER DEPTH >10 m	0.055
TIDAL CHANNELS	0.060
NON-BREAKING WAVE AREA	0.050
EDGE OF TIDAL FLATS	0.040
BREAKER ZONE	0.025

The influence of this parameter on the value of $\bar{H}_{max}$ was evaluated as

$$\frac{H(\delta)}{H(\delta_o)} = \frac{1}{1 - \frac{\delta_o - \delta}{3\delta_o}} = \frac{3\delta_o}{2\delta_o + \delta}$$

It is obviously not very strong, but leads for example to breaking waves being 20% higher than non-breaking waves in the same depth of water (fig. 4).

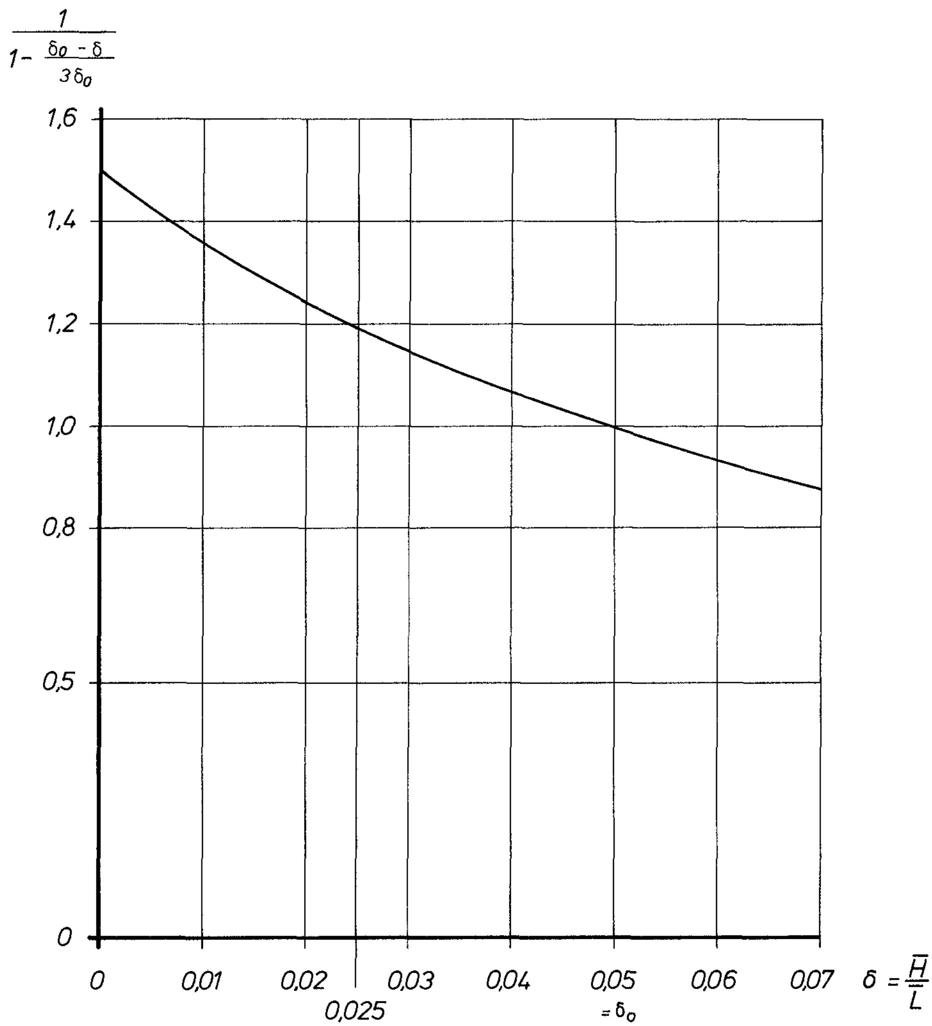

Fig. 4
Influence of Mean Wave Steepness on Wave Height

Wave Height as Function of Travel Distance

The influence of the distance s from deep water areas on the wave height at a shallow water location can be much greater, and the investigation of this led to an interesting conclusion. To consider the importance of this parameter, the ratio $\overline{H}_{max}/s$, corrected by δ , was plotted against d/s in log-log-paper (fig. 5). The values summarize at an upper envelop that can be expressed by the equation

$$\frac{\overline{H}_{max}}{s} \cdot \left(1 - \frac{\delta_o - \delta}{3\,\delta_o}\right) = 0.2 \cdot \left(\frac{d+1}{s}\right)^{1.16 - 0.06 \cdot \ln \left(\frac{d+1}{s}\right)}$$

This function leads to special curves for different d and δ . Fig. 6 contains the curves for a water depth of 2 m as an example. They rise to a maximum at a certain distance s and then - with increasing distance from deep water - decrease asymptotically to the height of pure wind waves originated in the shallow water area. Doubtlessly the most interesting point is the maximum. It indicates that waves, running from deep onto shallow water, relatively quickly increase in height and thereafter, under the influence of bottom friction and energy dissipation, slowly decrease. So at first there is no wave height decay to be expected when waves have reached shallow water. This zone of decay begins behind a zone of wave height increase at the edge of the shallow water area.

For constant wave characteristic the locality of the peak is a function of d. In prototype however waves are changing their character, expressed by different δ . Fig. 7 demonstrates that in these cases there are peaks as well, though it is a little bit more complicated to fix them exactly.

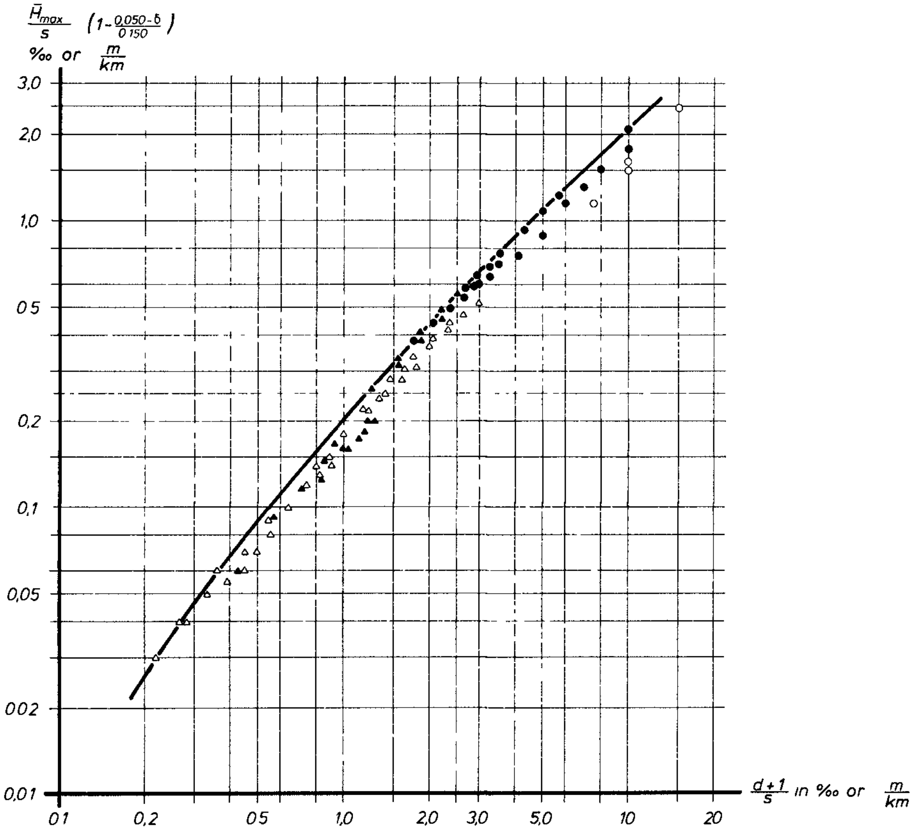

Fig. 5

$\overline{H}_{max} = f(d,s,\delta)$ with depth of water d(in m), distance from deep water area s(in km), mean wave steepness $\delta = \frac{\overline{H}}{\overline{L}}$

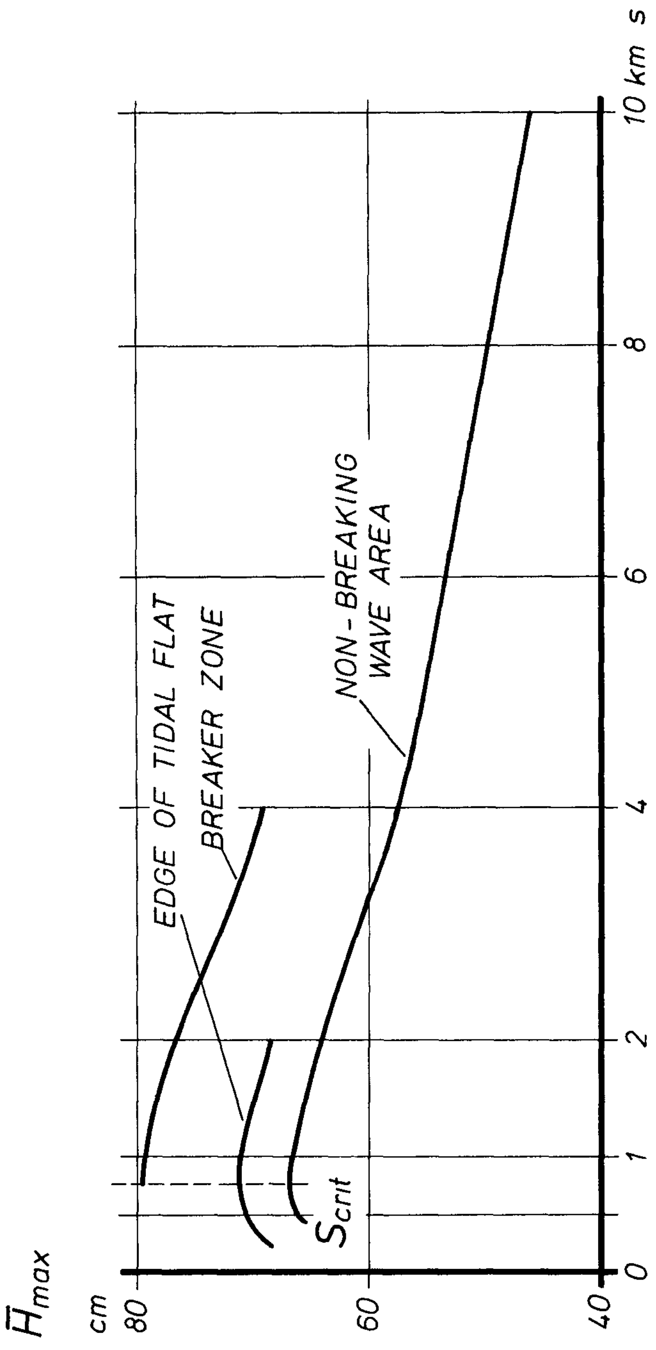

Fig. 6

Example for Evaluation of Critical Travel Distance in Shallow Water of Constant Depth (d = 2,0 m)

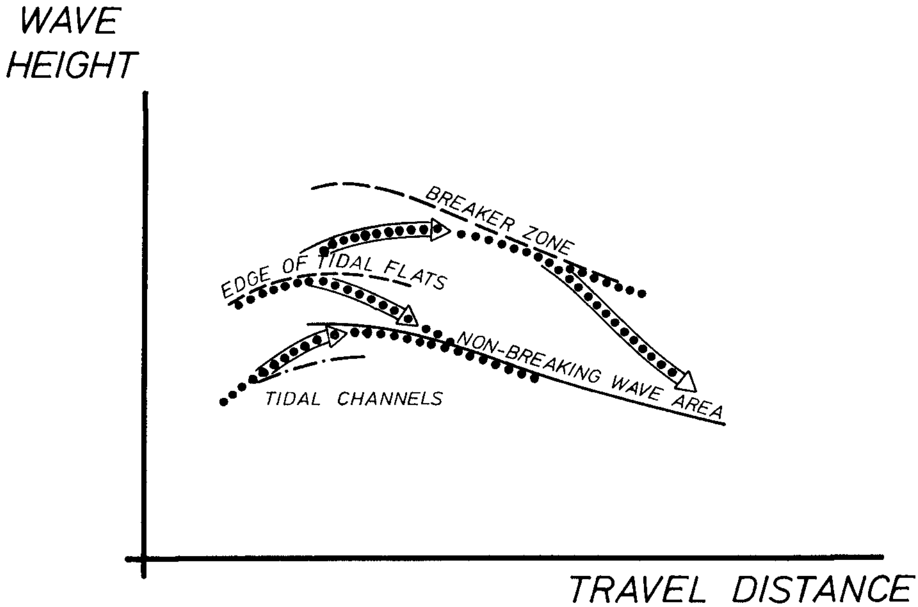

Fig. 7
Example for Evaluation of
Critical Travel Distance
in Transitional Waters

Discussion

For the idealized case of waves running from deep water over a relatively steep slope into an area of constant water depth, the location of the peaks can be expressed as a function of d (fig. 8). As at these points the waves reach their highest values, this location is defined as

"critical travel distance $s_{crit.}$"

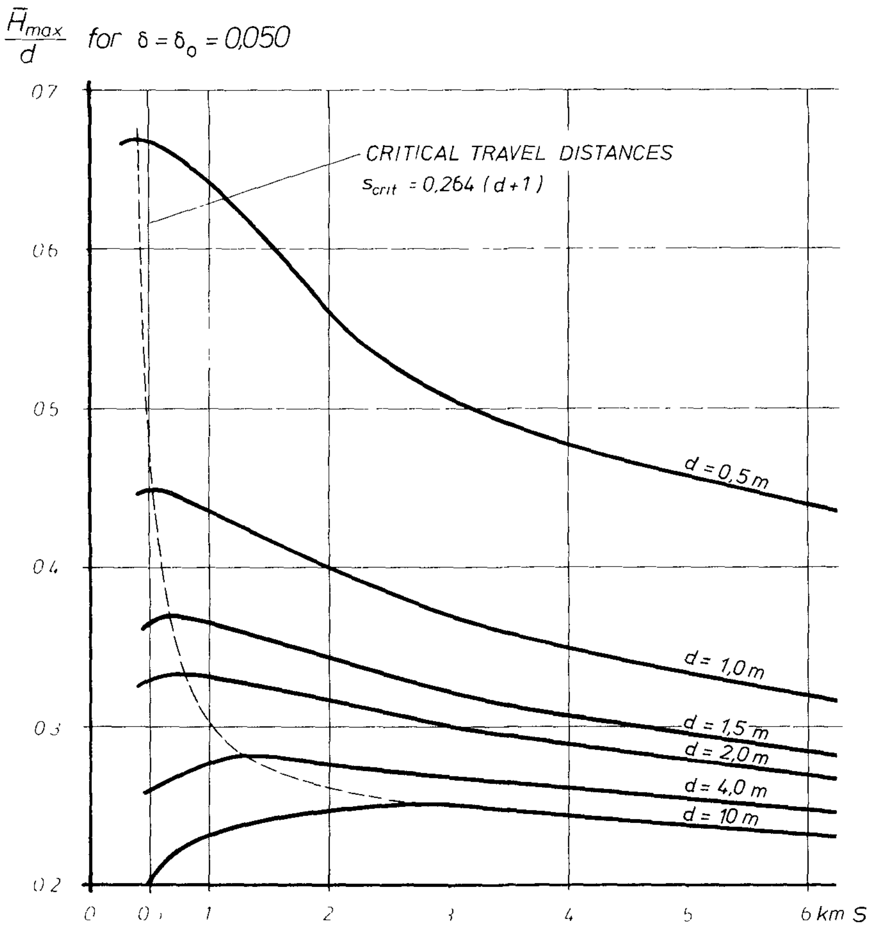

Fig. 8
Critical Travel Distances

With

$$s_{crit.} = 0.264\ (d+1)$$

$s_{crit.}$ increases linearly with d, i.e. relatively higher waves can proceed the further landward the deeper the water is. Besides this the influence of s on the ratio $\bar{\bar{H}}_{max}/d$ decreases with increasing d as a result of weaker influence of bottom friction etc. So this graph enables us to demonstrate, in what amount storm tides with extreme water levels transfer the line of critical travel distances coastward, and the probability of destruction rises, as this effect brings a larger increase in wave height than usually recognized. So during rise and fall of the water level the critical travel distance varies and leads to a range that should be avoided by coastal structures.

$s_{crit.}$ is a function of d only, but the height of the highest mean wave height $\bar{\bar{H}}_{max}$ at the critical travel distance is a function of d and δ:

$$\bar{\bar{H}}_{max}\,(s_{crit.}) = 0.223 \cdot \frac{3\delta_o}{2\,\delta_o+\delta} \cdot (d+1)$$

with $\delta_o = 0.050$.

The results as a whole may be surprising, but they are for instance in agreement with and similar to the analysis of GALVIN (1969) for breaker travel on slopes: There waves do not immediately acquire the height theoretically due to d, but only after travelling a certain distance. The energy transfer from wave to bottom and the shoaling effect need a certain time to develop the wave character that may be theoretically derived.

Some other investigations, undertaken in the US some years ago, may be mentioned in this connection: Theoretical approaches and laboratory tests with waves running from deep water over a steep slope into shallow water of constant depth (MADSEN and MEI, 1969; ZABUSKY and GALVIN, 1968). They indicate that single waves are devided into 2 or 3 secondary waves with the first wave being the highest one, slowly decreasing on its way in shallow water. Moreover the ratio H over deep water wave height H_o increases more quickly the smaller the depth is. This is a verification of the statement that the critical travel distance is reached earlier with decreasing water depth.

Summary

As the critical travel distance of waves in shallow water can obviously be fixed or be at least estimated, its knowledge may lead to a certain revision of today's dimensioning criteria: The location of buildings should not be $s_{crit.}$, possibly landward of $s_{crit.}$, but maybe planning demands a location near a deep water area. In this case a point seaward of $s_{crit.}$ can be more suitable avoiding steepening of waves in front of it and perhaps even shoaling.

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