CHAPTER 42

MODEL INVESTIGATION ON WAVE RUN-UP CARRIED OUT IN THE NETHERLANDS DURING THE PAST TWENTY YEARS

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1. INTRODUCTION

This paper gives a summary of the results of the model studi on wave run-up carried out in the Netherlands since 1936. More detailed information on these studies is to be found in publication H.L.D. No. 11 to be issued shortly by the Delft Hydraulics Laboratory.

The object of the first studies on wave run-up was the establishment of a relationship between the wind velocity W, the fetch F, and the waterdepth D on one hand and the height of wave run-up Z on the other.

Apart from the model investigations on wave run-up, a large number of tests were carried out on the growth of wind-generated waves and, when after the war the now well-known studies of Sverdrup and Munk on deep-water waves, ref. 1, were published, these could be compared with and supplemented by the studies of the Delf Laboratory on wind waves in deep-, as well as in shallow water. These were presented by Thijsse to the General Meeting of the Inte national Association on Physical Oceanography, Oslo 1948, ref. 2.

These studies made it possible to determine the characteristics of the waves in shallow water from those in deep water, so that in the tests carried out after 1942 the wave run-up could be related to the wave height in front of the dike.
In addition to the above mentioned model studies, many tests were carried out to determine the influence of the dike facing on the run-up. Only impermeable facings have been tested.

2. ANALYSIS OF THE PROBLEM

The general problem is to determine, by means of statistical methods, the most unfavourable combination of astronomical tide, piling-up of the water level by wind, and run-up of the waves on the talus of the dike, that is likely to occur with a reasonable degree of frequency. From these three determinant factors for the height of the dike, only the wave run-up is the subject of the present paper.

From the beginning it was realized that many of the factors, involved in this problem, are of a statistical character, requiring statistical methods for their analysis and solution. For this reason most of the tests were carried out with wind-generated waves and the results were plotted on probability paper. The critical value of the run-up, to be used as a basis for the design, will be defined as the height which has a probability of n% to be attained or exceeded (Z_n). The design formulas are based on a frequency of 2%. In certain cases, however, this percentage may be too high or too low, dependent on the required safety of the dike and the duration of the high water periods, so that each case has to be considered separately.

The factors governing the run-up are divided into the following two groups.

a) The factors determined by nature

b) The factors determined by the dike.

The factors sub a) are:

1) the characteristics of the waves in front of the dike

2) the direction of the wave attack,

and the factors sub b);

3) the slope of the dike

4) the shape of the dike

5) the character of the dike facing

6) the artificial-foreshore conditions.

The factors sub a) are in turn dependent on W, F, and D, the latter representing the sea bottom conditions.
Since the ultimate object of the model studies on wave run-up is the safety of the dike under various conditions, not only the height of the run-up is of importance, but also the velocities with which the water runs over the talus of the dike and the magnitude of the masses of water involved.
For notations and dimensions see fig. 1.

3. APPARATUS AND PROCEDURE

The tests were carried out in the wind flume of the Delft Laboratory. In this flume waves can be generated by wind, as well as by means of a wave machine, and the tests were carried out with so called "equilibrium waves". These waves were generated by wind and wave machine together, in such a way that finally a state of equilibrium is reached in which the waves no longer grow and the energy supplied by the wind and by the wave machine is fully dissipated by the friction losses. Theoretically the generation of

equilibrium waves requires an unlimited length of fetch, but in practice it can be taken that the waves no longer grow if the length of the fetch is at least 1000 D.
A description of the wind flume with wave-generating equipment and test procedure is given in publication H.L.D. No. 11.

Regarding the transference of the model results to the prototype, it is assumed that Froude's law may be applied, provided the following conditions are fullfilled:

a) geometrical similarity and negligible influence of molecular forces

b) statistical similarity

c) breaking of the waves under influence of the wind.

Concerning the first requirement, it appeared that mechanically-generated waves, having originally a trochoidal shape, become less steep when they are subjected to a wind current, thus obtaining a proportionally larger length and a greater velocity, while the shape becomes sinusoidal. The run-up of these waves is considerably higher (up to 30%) than that of equivalent waves generated without wind. Since the equilibrium waves are partly generated by wind and partly by the wave machine, these waves are also somewhat too steep resulting in too low values of the run-up.

The second requirement, i.e. statistical similarity, was not fullfilled as, contrary to nature, the direction and the velocity of the wind in the model remained practically constant.

4. WAVE RUN-UP AS A FUNCTION OF WIND, FETCH, AND WATER DEPTH, ON A SLOPE OF 1 : $3\frac{1}{2}$

In 1936 tests were carried out with the object of establishing a relationship between the 2% run-up and the variables: wind velocity W, fetch F and water depth D, for a dike with straight slope of 1 : $3\frac{1}{2}$, provided with a smooth facing. The tests were carried out with a constant water depth of 0.32 m, so that the wind velocity was the only variable. The wind velocity was expressed in the velocity-head of the wind (wind pressure) : s, measured in mm water column. The tests were conducted with wind pressures of 1.3, 2.0, 3.0, 3.7 and 4.8 mm. The corresponding dimensions of the waves are shown in fig. 2. The average steepness was 0.07.

Based upon these tests the following relationship was derived

$$Z_2 = 41\ s^{\frac{1}{2}} \qquad \text{(in cm)} \qquad (a)$$

This relationship is graphically shown in fig. 3.

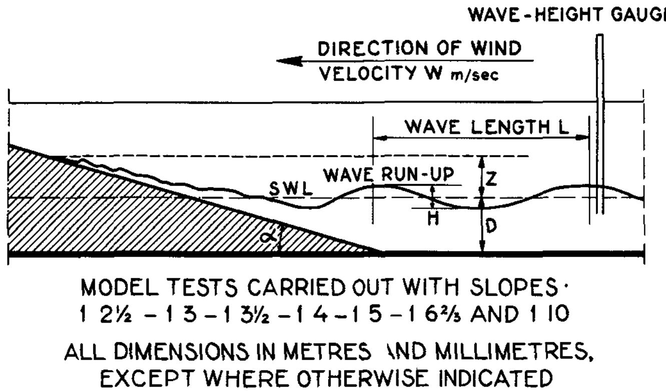


Fig. 1

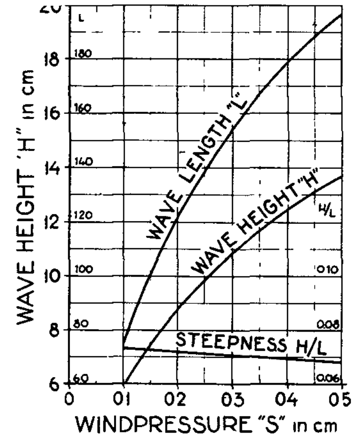


Fig. 2

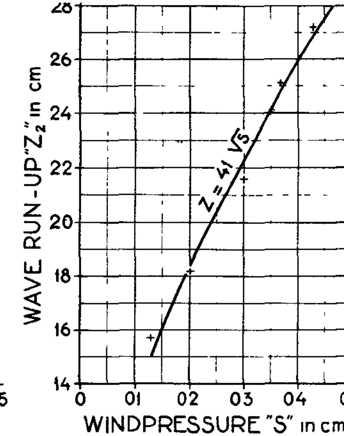


Fig. 3

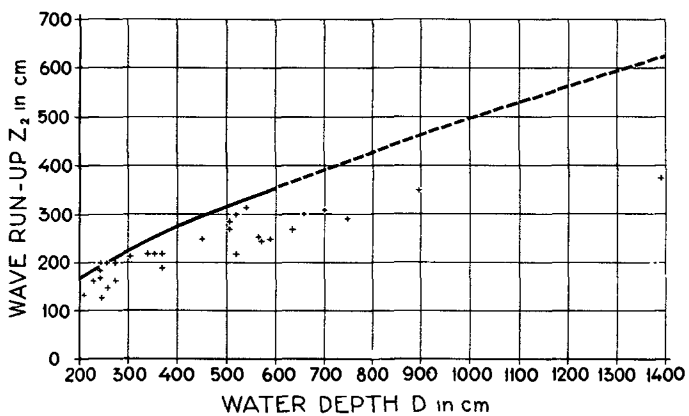


Fig. 4

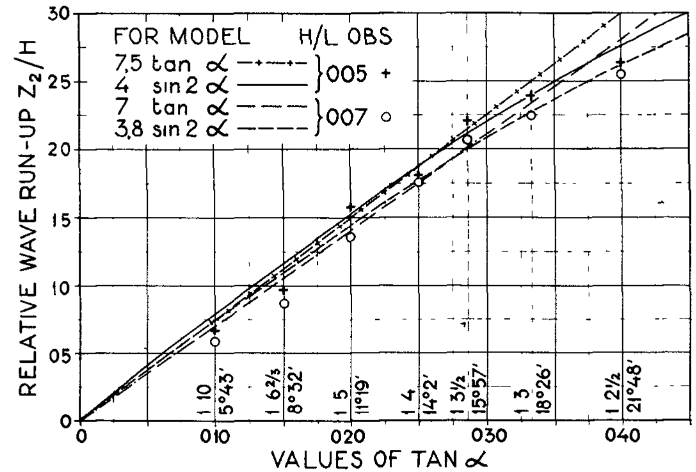


Fig. 5

Fig. 1. Notations and dimensions

Fig. 2. Relationship between wind pressure in model and dimensions of waves

Fig. 3. Relationship between wind pressure in model and wave run-up Z_2

Fig. 4 Comparison of formula: $Z_2 = 4.95\ D_{2/3}$ with observations in nature (Zuiderzee Works)

Fig. 5 Comparison of tangent and sinus formulas for run-up Z_2 with frequency of 2%

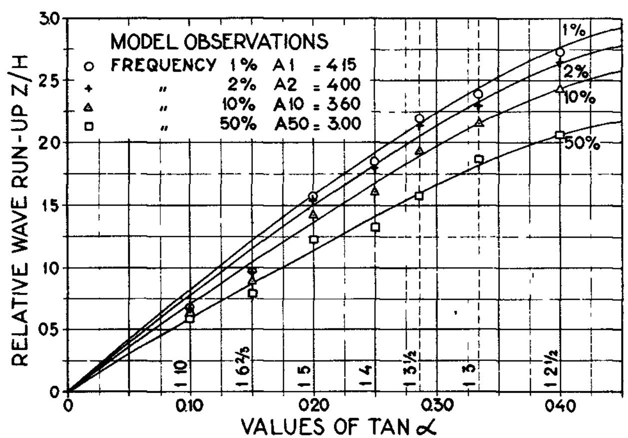


Fig. 6

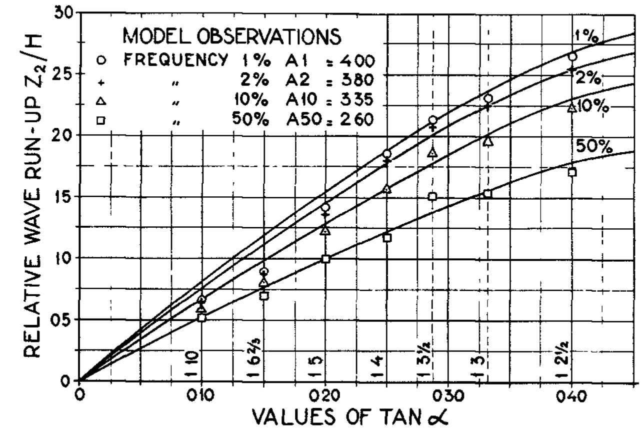


Fig. 7

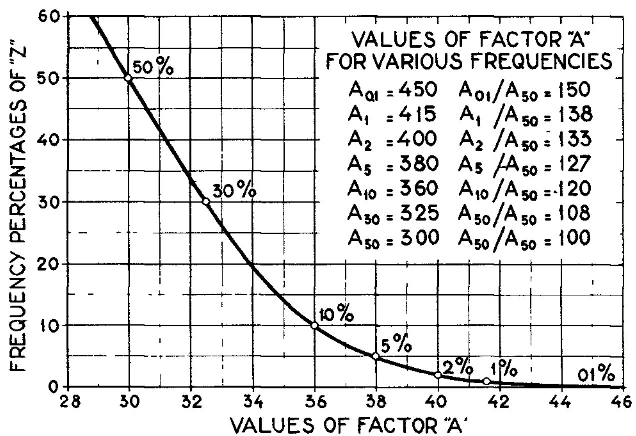


Fig. 8

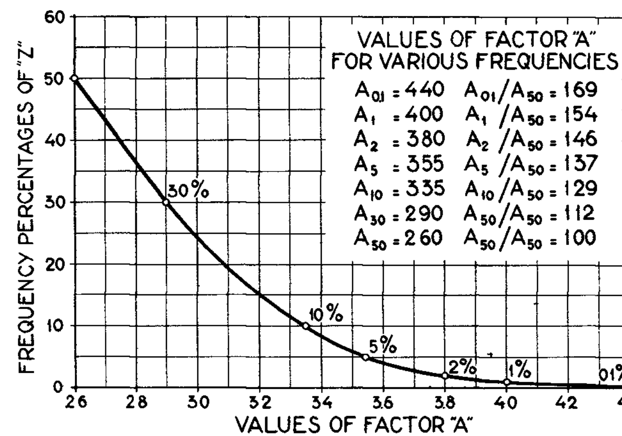


Fig. 9

Fig. 6. Relative wave run-up as a function of slope: $Z/H = A \sin 2\alpha$ for $H/L = 0.05$
Fig. 7. Relative wave run-up as a function of slope: $Z/H = A \sin 2\alpha$ for $H/L = 0.07$
Fig. 8. Relationship between frequency and value of A for $H/L = 0.05$

Using the relationship:

$$s_1/s_2 = y_1^{2/7} \,/\, y_2^{2/7} \qquad \text{(b)}$$

between the wind pressures s_1 and s_2 at heights y_1 and y_2, the following expression was found for the 2% run-up:

$$Z_2 = 7\ D^{2/3}\ s^{\frac{1}{2}}\ y^{-1/7} \qquad \text{(in cm)} \qquad (1)$$

Assuming a wind velocity of: $W = 25$ m/sec at a height of: $y = 15$ m, the wind pressure is 4 cm, so that
$s^{\frac{1}{2}} = 2$ and $y^{-1/7} = 1500^{-1/7} = 0.3533$. After substituting these values in (1) the following equation is obtained:

$$Z_2 = 4.95\ D^{2/3} \qquad \text{(in cm)} \qquad (2)$$

Equation (2) is graphically shown in fig. 4, together with the observations in nature used as a basis for the Zuiderzee works and mentioned in the report of the "Staatscommissie Lorentz", ref. 3.

As may be seen from fig. 4, the values of formula (2) are well in accordance with the observations in nature for water depths below 6 m. If the fetch is less than 1000 D, the values of Z_2 must be multiplied by a correction coefficient which was determined by model tests.

5. WAVE RUN-UP ON SLOPES WITH VARYING ANGLES OF INCLINATION, AS A FUNCTION OF THE ANGLE OF INCLINATION AND THE WAVE CHARACTERISTICS IN FRONT OF THE DIKE

In 1942 the model studies on the growth of wind-generated waves were sufficiently far advanced to establish a direct relationship between the wave run-up and the wave height in front of the dike.

For this purpose two series of tests were carried out on dikes with slopes of 1 : 2½, 1 : 3, 1 : 3½, 1 : 4, 1 : 5, 1 : 6⅔ and 1 : 10, viz: with waves of steepness 0.05 and of steepness 0.07 respectively. The water depth was kept constant at 0.35 m.

For the 2% run-up the results of these tests are shown in fig. 5. Straight lines were drawn through the plotted points expressing the various observations, and from these it appeared that for values of α ranging from 7° to 16°, the relationship between the relative run-up Z_2/H and the angle of inclination α can be expressed by the equations:

$$Z_2/H = 7.5 \tan\alpha \qquad (\text{for } H/L = 0.05) \qquad (3a)$$

and:

$$Z_2/H = 7.0 \tan \alpha \qquad (\text{for } H/L = 0.07) \qquad (3b)$$

In the above formulas the wave height H is the average height of the equilibrium waves in the model which did not vary very much.

Since the waves in the model were proportionally too steep (resulting in too small values of Z_2), the difficulty arose how to transfer the model results to the prototype.
After considering all factors involved, it was decided to increase the factor 7.5 in the model to 8 in the prototype, for the 2% run-up on a dike provided with a stone revetment and waves of a steepness of 0.05. The run-up is thereby expressed in the "significant wave height" $H_{1/3}$. In this way the following formula was obtained:

$$Z_2/H_{1/3} = 8 \tan \alpha \qquad (\text{for } H/L = 0.05) \qquad (4)$$

This formula, which was published for the first time in a paper presented to the 18th International Navigation Congress, Rome 1953, ref. 4, proved to be in good agreement with the prototype observations carried out in the Netherlands for slopes not steeper than 16 degrees.

As may be seen from fig. 5, this was also the case with the model observations. A trial was therefore made to find a better formula for slopes steeper than 16°. Partly based on the theoretical considerations of Miche, ref. 5, and partly on the results of new model tests on a dike provided with a berm, the following formula was developed:

$$Z_2/H_{1/3} = 2.7 \sin \left(\frac{90^\circ}{\alpha}\right)^{\frac{1}{2}} \left(\cos \beta - \frac{b}{L}\right)$$

in which:

b = width of the berm

L = wave length

α = angle of inclination of the upper slope

β = angle between the direction of the wave crests and the axis of the dike.

The above formula, which was mentioned in a paper presented to the 5th Conference on Coastal Engineering, Grenoble 1954, ref. 6 proved not to be in accordance with observations carried out in nature and should, therefore, be discarded. One of the reasons that the above formula cannot be generalized comes from the fact that the term $(\cos \beta - \frac{b}{L})$ was based on earlier tests on a berm dike, with equal upper and lower slopes, while in the tests on which the above formula is based the upper and lower talus had a different slope. Moreover, the width of the berm was kept constant during the latter tests, so that the factor $(\cos \beta - \frac{b}{L})$ could not be verified.

A fresh trial was made by multiplying tan α by $\cos^2 \alpha$, thus obtaining a formula of the following general form:

$$Z_n/H = A \sin 2\alpha \qquad (5)$$

The value of A can be determined in such a way that, for $\alpha = 15^\circ$, with formula (5) the same value for Z_2 is obtained as with formula (3a). The value of 7.5 tan 15° must then be equal to A sin 30°, or: 7.5 x 0.268 = 0.5 A. so that:

$$A = \frac{7.5 \times 0.268}{0.5} = 4.0$$

Hence:

$$Z_2/H = 4.0 \sin 2\alpha \qquad (\text{for } H/L = 0.05) \qquad (6a)$$

In the same way has been calculated:

$$Z_2/H = 3.8 \sin 2\alpha \qquad (\text{for } H/L = 0.07) \qquad (6b)$$

The curves representing formulas (6a) and (6b) are also shown in fig. 5 and from this it may be seen that they are well in accordance with the model observations for values of $\alpha > 15^\circ$. For values of $\alpha < 15^\circ$, the difference between the tangent and the sinus formulas is so small, that also for values of $\alpha < 15^\circ$ the sinus formula could be used. The max value of α for which the sinus formula was investigated is 22°.
For other frequencies than 2% the values of the factor A have also been determined and the curves representing the relationship between Z_n/H and α, for frequencies of 1%, 2%, 10% and 50%, for H/L = 0.05 and H/L = 0.07 respectively, are shown in figs. 6 and 7. The relationship between the factor A and the frequencies of A is shown in figs. 8 and 9.

The above values of A are for the model observations and again the difficulty arose how to transfer these results to the prototype. For Z_2 this could be done by giving A such a value that, for $\alpha = 15^\circ$, the sinus formula gives the same value for Z_2/H as the tangent formula.
Then is:

$$A = \frac{8 \times 0.268}{0.5} = 4.3$$

so that:

$$Z_2/H_{1/3} = 4.3 \sin 2\alpha \qquad (\text{for } H/L = 0.05) \qquad (7)$$

For other frequencies, however, the values of A for the prototype conditions can only be determined by means of observations in nature, since the frequency distribution in the model is different from that in nature. Taking the same ratio of the prototype values to the model values as assumed for Z_2, then the following values of A are obtained.

Run-up	H/L = 0.05	H/L = 0.07
$Z_{0.1}$	$A_{0.1} = 4.90$	$A_{0.1} = 4.75$
Z_1	$A_1 = 4.50$	$A_1 = 4.30$
Z_2	$A_2 = 4.30$	$A_2 = 4.10$
Z_5	$A_5 = 4.10$	$A_5 = 3.85$
Z_{10}	$A_{10} = 3.90$	$A_{10} = 3.60$
Z_{30}	$A_{30} = 3.50$	$A_{30} = 3.10$
Z_{50}	$A_{50} = 3.25$	$A_{50} = 2.80$

Due to the difference in frequency distributions, however, the above values of A may not be considered as correct, and they should be corrected as soon as more prototype data are becoming available.

Formula (5) can be written in the general form:

$$Z_n/H = A.B \sin 2\alpha \qquad (8)$$

in which formula the value of factor A depends on:
1) the steepness of the waves in front of the dike
2) the value of H in which the run-up is expressed
3) the frequency of Z

and the value of factor B on:

1) the shape of the dike (factor B_1)
2) the character of the dike facing (factor B_2)
3) the foreshore conditions (factor B_3)
4) the direction of the wave propagation (factor B_4)

For a "normal" dike the value of each of the factors B_1, B_2, B_3 and B_4 will be taken as "one". By definition this will be the case for the following conditions:

$B_1 = 1$: dike without berm and straight talus.
$B_2 = 1$: dike facing of neatly-set stone
$B_3 = 1$: if the foreshore conditions have no influence on the run-up
$B_4 = 1$: if the direction of the wave propagation makes an angle of 90° with the axis of the dike.

Hence, for the reference dike the above formula becomes again:

$$Z_n/H = A \sin 2\alpha \qquad (5)$$

6. INFLUENCE OF THE SHAPE OF THE DIKE

One of the first model studies on the influence of the shape of the dike on the run-up was carried out in 1946, in connection with the reconstruction of the sea wall on the island of Walcheren, which was badly damaged by war activities and severe storms. The results of these tests are briefly shown in fig. 10.

Fig. 11 shows a number of schematical cross sections of modern Dutch dikes. From various model tests on berm dikes, it was found that a berm has a benificial influence on the run-up, if it is placed at approximately storm water level and of its width is approximately equal to 1/4 L.

In order to establish the influence of the shape of the dike on the run-up, the various dike profiles have been divided into the following 8 types, shown in the figures 12 and 13.

Type	Fig.	Description
p o	12 A	Straight talus with angle α
p 1	12 B	Convex talus
p 2	12 C	Concave talus
p 3	12 D	Berm dike with equal slopes
p 4	13 A	Ditto, with "stilling basin"
p 5	13 B	Berm dike with unequal slopes
p 6	13 C	Ditto, with "stilling basin"
p 7	13 D	Ditto, with parabolic transition

For the 2% run-up the following reduction factors have been found.

Type	
p 0:	$B_1 = 1$ (Reference)
p 1:	$B_1 = 0.95$ for convexity of 3%
p 2:	Not investigated
p 3:	$B_1 = 0.75$ for equal slopes of 1 : $3\frac{1}{2}$ en b = 1/4 L
p 4:	$B_1 = 0.65 - 0.70$
p 5:	The tests showed that changes in slope of the upper talus, as well as in that of the lower one, have a considerable influence on the run-up
p 6:	Not investigated
p 7:	A few tests showed that a smooth transition between berm and upper slope has a benificial influence on the run-up.

7. INFLUENCE OF THE CHARACTER OF THE DIKE FACING

Since 1936 a large number of model tests on the influence of the character of the dike facing on the run-up have been carried

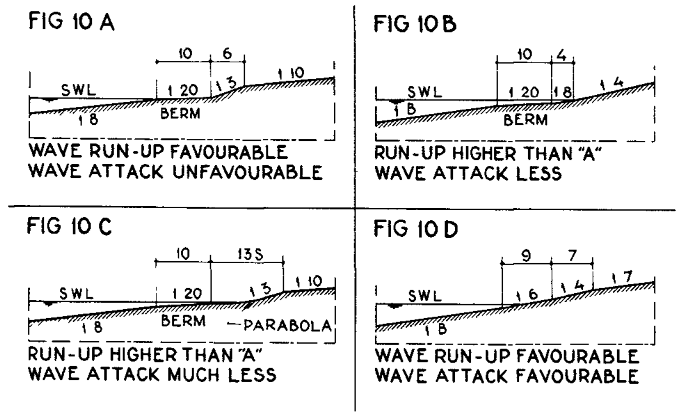


Fig. 10

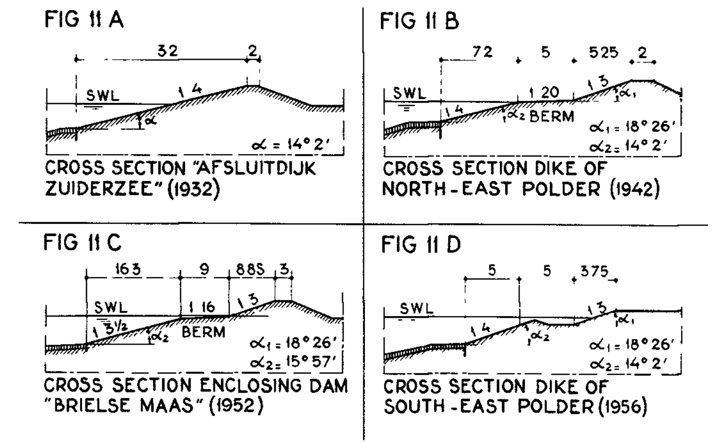


Fig. 11

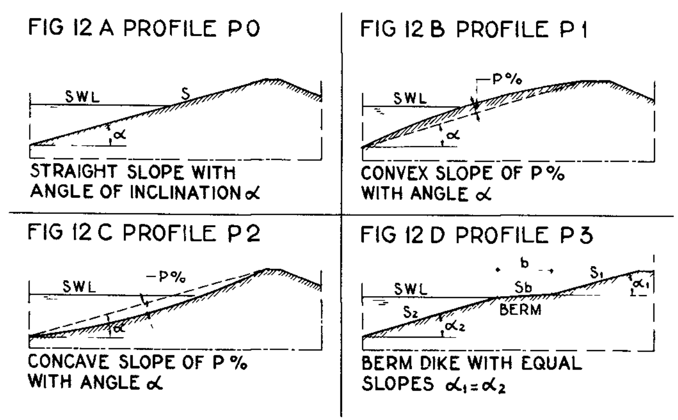


Fig. 12

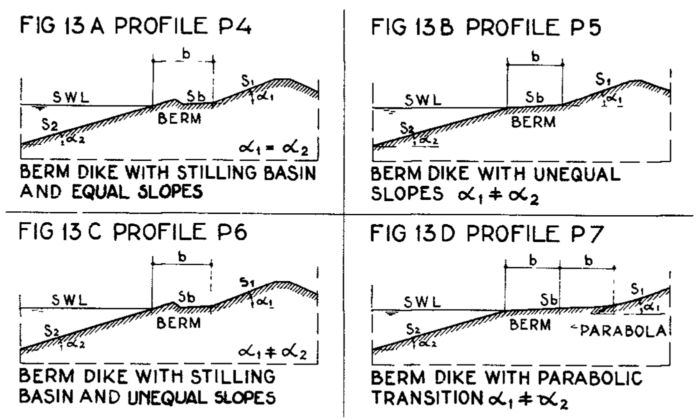
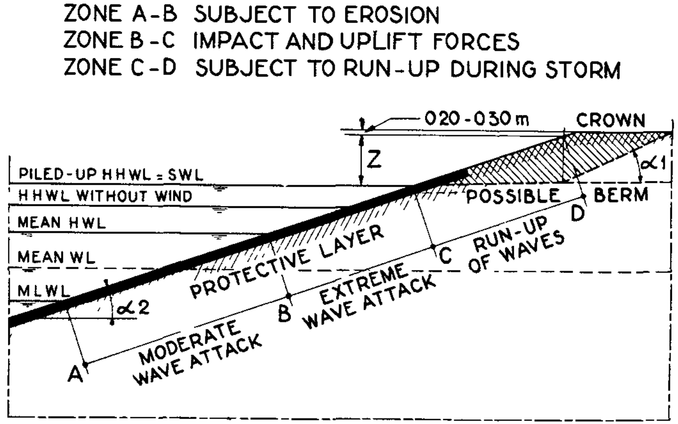


Fig. 13

Fig. 10. Modelstudy of sea wall on the Island of Walcheren
Fig. 11. Cross sections of modern Dutch dikes
Fig. 12. Dike profiles types P 0 to P 3, inclusive



Figs. 14

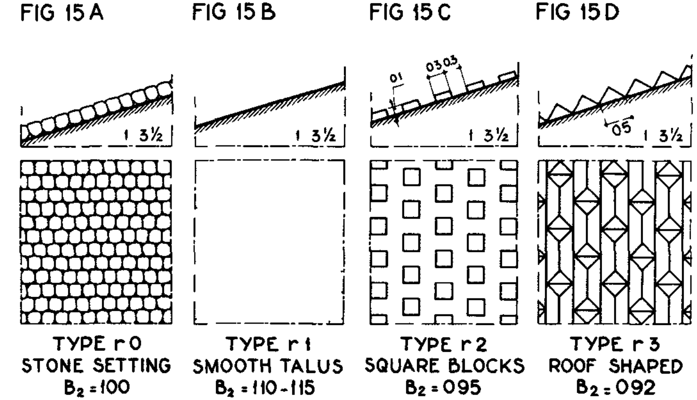


Fig. 15

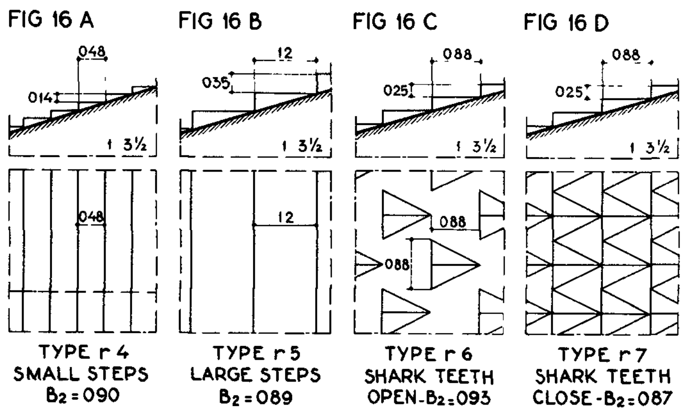


Fig. 16

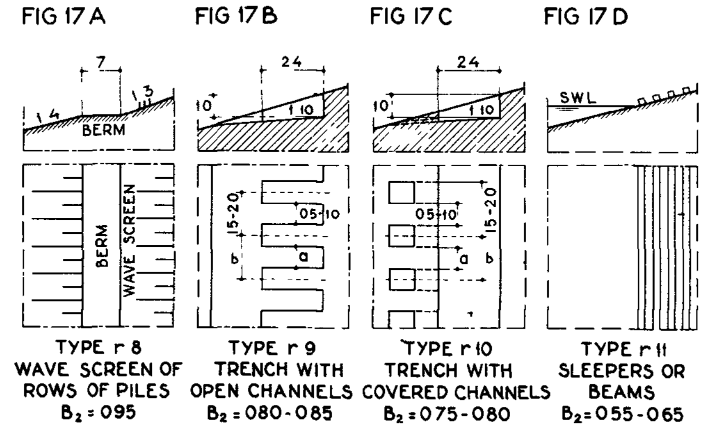


Fig. 17

Fig. 14. Diagram of impermeable sloping sea wall
Fig. 15. Dike facings types R 0 to R 3, inclusive
Fig. 16. Dike facings types R 4 to R 7, inclusive
Fig. 17. Dike facings types R 8 to R 11, inclusive

out. In order to facilitate comparison of the various kinds of facing the following types will be distinguished.
The values of the reduction factor B 2 are for the 2% run-up Z_2.

Type	Fig.	Description	B_2.
r 0	15 A	Revetment of neatly-set stone	1
r 1	15 B	Smooth protective layer	1.10-1.15
r 2	15 C	Square concrete blocks, 0.3 x 0.3 sq.m, protruding 0.1 m	0.95
r 3	15 D	Roof-shaped blocks, 0.5 x 1 sq.m, high 0.25 m	0.92
r 4	16 A	Small steps, 0.14 x 0.48 m	0.90
r 5	16 B	Large steps, 0.35 x 1.2 m	0.89
r 6	16 C	Shark teeth, 0.88 x 0.88 m, high 0.25 m, open setting	0.93
r 7	16 D	Ditto, close setting	0.87
r 8	17 A	Rows of piles, acting as a wave screen	0.95
r 9	17 B	Trench 2.4 m wide and 1 m deep, provided with open drainage channels	0.80-0.85
r10	17 C	Ditto, provided with covered drainage channels	0.75-0.80
r11	17 D	Beams or sleepers on the talus of the dike	0.55-0.65

As may be seen from the diagram shown in fig. 14, the zone above S.W.L. is only subject to the run-up of waves during storm ar for this reason this part of the dike needs only a light protectior for which in most cases a grass cover will be sufficient. Unfortunately, however, it is just in this region that the artificial roughness must be placed to be efficient.

8. INFLUENCE OF THE FORESHORE CONDITIONS

In the foregoing tests the models were arranged in such a way that the conditions of foreshore and sea bottom had no influence or the wave run-up, so that the waves were breaking on the dike.

Tests on the influence of the foreshore conditions on the rur up are at present in progress.

9. INFLUENCE OF THE DIRECTION OF THE WAVE ATTACK

For a dike without berm the following formula was derived, based upon a limited number of model tests:

$$B_4 = \frac{1 + \sin \beta}{2}$$

where: β = angle between the direction of the wave propagation and the axis of the dike. For a frontal wave attack is $\beta = 90^o$ and $B_4 = 1$.

For values of $\beta > 45^o$, the values calculated by means of the above formula are higher than the ones observed in the tests. Due to reflection of the waves in the wind flume these observations are not fully reliable and additional tests are required to investigate this influence.

The attempt made in point 5 to express the influence of the wave direction, for a berm dike with varying width of the berm, by means of the factor

$$(\cos \beta - \frac{b}{L})$$

has to be discarded for the reasons mentioned before.

For the investigated case of b = 1/4 L and upper and lower talus of 1 : 3½, the following formula is in agreement with the model tests

$$B_4 = 0.0075 \beta + 0.325 .$$

However, to generalize this formula additional model tests should be carried out.

10. PROGRAM OF FURTHER INVESTIGATIONS ON WAVE RUN-UP

It is desirable to carry out the following additional investigations on the influence of the various factors on the wave run-up.

a. Slope of the dike

1) Additional investigations on the influence of the upper slope, as well as that of the lower one, for a dike provided with a berm.

2) Influence of the steepness H/L on the run-up.

3) Relationship between the values of the factor A and the frequency of the wave height, for equal frequencies of run-up and wave height.

b. Shape of the dike (B_1)

1) Influence of convexity and concavity, for dikes without berm.

2) Influence of a parabolic transitien between berm and upper talus, for a dike provided with a berm.

3) Influence of the berm width.

c. Facing of the dike (B_2)

Beams or sleepers on a berm dike.

d. Foreshore conditions (B_3)

Influence of foreshore and sea bottom conditions.

e. Direction of the wave attack (B_4)

1) Verification of the reduction factor: $B_4 = (\frac{1 + \sin \beta}{2})$ for a dike without berm.

2) Influence of the wave direction on the run-up for a berm dik with varying width of the berm.

f. Safety of the dike

Investigation of the velocity with which the water runs over th talus and of the magnitude of the masses of water involved.

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