# CHAPTER 115

## WAVE FORCES ON BREAKWATER ARMOUR UNITS

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## Abstract

The authors have carried out a research project for investigation of the wave forces acting on breakwater armour units. The project included a literature study, hydraulic model testing and analysis of the test results. The hydraulic model testing was made in a wave flume on a 2-dimensional idealised breakwater structure with an armour layer consisting of two rows of horizontal pipes.

## Introduction

Many researchers have for many years looked into the question of wave forces on breakwater armour units. Most of the research has concentrated on studying the stability of breakwater slopes armoured with various types of armour units.

Only a few researchers have directly studied the wave forces on armour units by making measurements on idealised armour units in a hydraulic model. Sigurdsson (1962) and Sandström (1974) have made measurements on idealised breakwaters consisting of spherical balls exposed to regular waves.

The present work is of the same nature, but is a pure 2-dimensional case and included testing with irregular waves.

The maximum measured forces on an armour unit, both during run-up and run-down, has been studied as function of wave height, wave period, and position of the unit on the breakwater slope.

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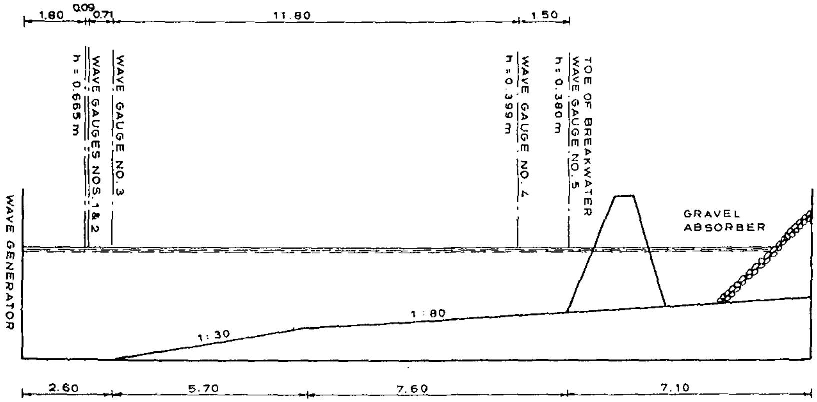
In order to make a simplified representation of the acting forces, stability calculations including both measured force components have been carried out.

During run-up large forces in the direction into the breakwater have been measured. These slamming forces were measured both for regular and irregular waves, but are generally more pronounced for irregular waves. The slamming forces are characterised by a rapid growth and a short duration, and occur when the water hits onto the units. This type of forces is not considered to be dangerous for the stability of armour units, but may be dangerous for breakage of slender and fragile concrete armour units.

Results of the study have been published by the authors in Refs. /1/ and /2/.

## The Model

The model tests were conducted in a 23 m long and 0.6 m wide wave flume. The flume set-up is shown in Fig. 1.



NOTE:
ALL MEASURES IN METERS

**Fig. 1 Set-up of wave flume.**

The model tests were conducted on a 2-D breakwater model with a slope of 1:2 of the armour layer. The crest height was chosen not to allow for wave overtopping. The armour layer consisted of two layers of horizontal steel pipes with diameter 50 mm to form an idealised and purely 2-dimensional representation of a breakwater armour layer. The porosity of the armour layer was selected to p = 0.40. Details of the model are shown in Fig. 2.

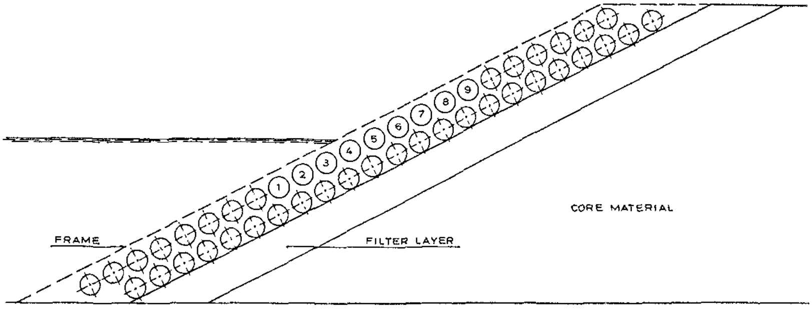


**Fig. 2 Details of test set-up.**

The wave forces on three of the pipes in the upper layer were measured simultaneously by use of strain gauge transducers giving two force components, i.e. vertically and horizontally. Nine of the pipes in the upper layer were prepared for force measurements. The forces were measured on the 0.2 m wide middle section of the horizontal pipes.

Waves

Regular and irregular waves were used for model testing. The wave combinations covered both non-breaking and breaking waves.

The tests with irregular waves covered a range of wave combinations: Peak periods, $T_p$, from approximately 1.0 to 3.0 s and significant wave heights, $H_s$, from approximately 0.05 m to 0.20 m.

The wave heights for the irregular waves were determined as $H_s = 4 \times h_{rms}$, where $h_{rms}$ is calculated as

$$h_{rms} = \sqrt{1/m \sum_{i=1}^{m} h_i^2}$$

m being the total number of samples and $h_i$ being the surface elevation.

Wave Measurements

The waves in the flume were measured in 5 points by resistance type wave gauges as shown in Fig. 1.

The coefficient of reflection, R, has been determined for each test by a standard three gauge method, wave gauges Nos. 1, 2, and 3.

The measured wave heights have been corrected by a factor of $\sqrt{1+R^2}$ to take into account waves reflected from the breakwater.

The wave height measured 1.5 m in front of the breakwater (wave gauge No. 4) has been used as reference wave height for all test runs.

Measurements of the run-up/run-down was carried out with a wave gauge placed parallel to the breakwater slope and in a distance of 50 mm (one pipe diameter) to ensure no effect from the steel pipes.

## Force Measurements

Strain gauge transducers were used for measurements of two force components, i.e. vertically and horizontally.

The natural periods for the 0.2 m test section of the pipes fixed to the strain gauge transducers have been determined:

| | | |
|---|---|---|
| (a) | In air | 100 Hz |
| (b) | In water | 55 Hz |
| (c) | In half air/half water (pipe No. 5) | 60 Hz |

It should be noted that the transducers were calibrated to zero-force for still water level. This means that the buoyancy acting vertically upwards has been subtracted for pipes Nos. 1-5 being either totally or partly submerged.

The buoyancy for a totally submerged pipe was 19.30 N/m and for the partly submerged pipe No. 5 the buoyancy was 9.65 N/m. This fact is important in the interpretation and comparison of the test results for the different pipes.

## Test Conditions

All tests were carried out with fixed wave conditions, i.e. stationary wave height ($H$, $H_s$) and wave period ($T$, $T_p$). The water level was identical during all test runs, i.e. a water level of 0.38 m at the toe of the breakwater.

The test runs with regular waves had a duration of 300 s, while the test runs with irregular waves had a duration corresponding to approximately 500 zero-crossing waves.

The signals from the wave gauges and the strain gauge transducers were recorded (with a logging frequency of 40 Hz) and stored by a micro computer.

## Wave Forces on a Two-Dimensional Breakwater

The determination of forces acting on the idealised armour units can be compared with forces acting on a pipeline located on or close to the seabed. The following points indicate the complexity for the present model set-up.

(a) The flow pattern around the pipes is very complex, each individual pipe is influenced by the presence of neighbouring pipes.
(b) Air entrainment occurs which makes the velocity field uncertain and decreases the density of the fluid.
(c) The buoyancy varies with time as a result of run-up/run-down. This means that it is impossible to separate the hydrostatic force and hydrodynamic forces.
(d) Wave breaking results in wave slamming forces.

The positive orientation of the measured forces is shown in Fig. 3.

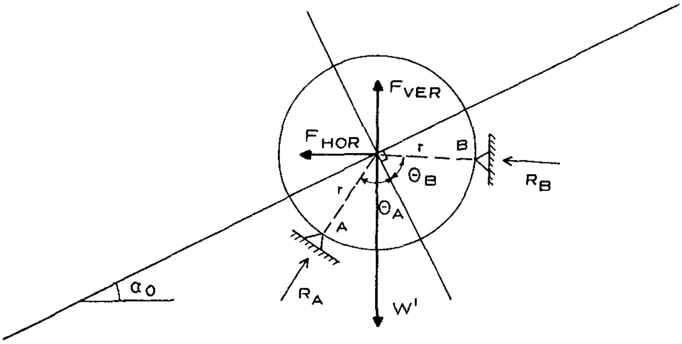


**Fig. 3 Definition sketch of the used coordinate system, and simplified stability calculations.**

## Velocity and Acceleration in Run-up/Run-down

The wave gauge for measuring run-up/run-down was installed 0.05 m above the slope and calibrated so that the run-up/run-down was measured vertically in agreement with the standard procedure for reporting of run-up heights.

The velocity and acceleration of the water in the run-up/run-down front has been calculated by a filter technique as described by Hamming (1977). The filters represented single and double differentiation of the measured time series of run-up/run-down.

It should be noted that the calculated velocity and acceleration refers to the run-up/run-down and not to the flow conditions around the individual pipes.

## Stability Calculations

Stability calculations including both force components have been carried out with the aim of making a simplified representation of the acting forces. It is assumed that the armour unit is supported in two contact points as shown in Fig. 3. Only symmetric contact points have been used for the calculations, i.e. $\theta = \theta_A = \theta_B$.

An example of the measured run-up/run-down and measured horizontal and vertical forces is shown in Fig. 4 together with the calculated required weight for no movements. The required effective weight to withstand roll-down, $W'_d$, is positive whereas the required effective weight to withstand roll-up, $W'_u$, is plotted as negative values. The required weights presented throughout the paper have been calculated for $\theta$ = 60 deg.

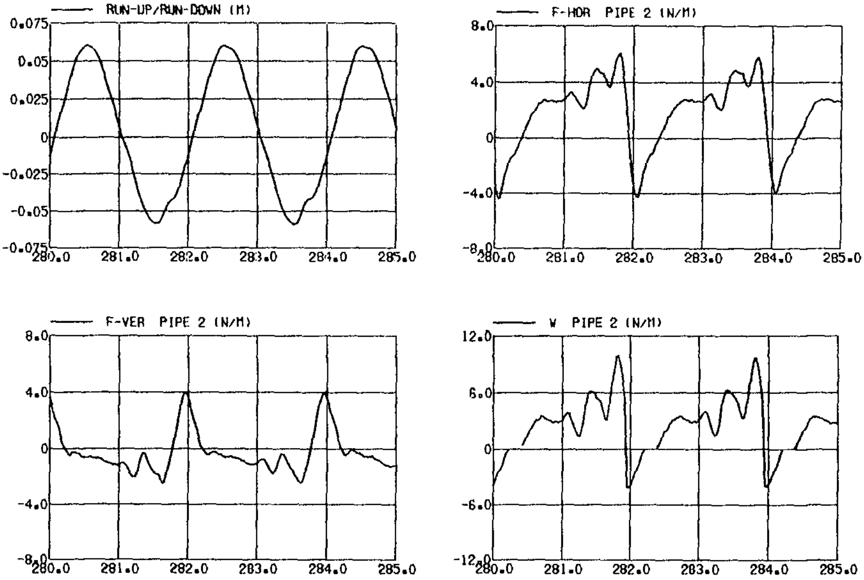


**Fig. 4** **Recorded and calculated time series for a regular wave with H = 0.07 m and T = 2.0 s.**

## Test results for Regular Waves

The following paragraphs include results from testing with regular waves.

### Required Weights in Relation to Pipe Position

For regular waves with a wave period of 2.0 s, a series of tests has been carried out for studying the effect of pipe position.

Fig. 5 shows the calculated required weights to withstand roll-up and roll-down, respectively. $W'_u$ and $W'_d$ are presented for the nine pipes on which wave forces have been measured.

The calculated required weights to withstand roll-down shows that a maximum of $W'_d$ is reached at pipes Nos. 1, 2, or 3 depending on the wave height. Also for roll-up, a maximum in required weight is found at pipe No. 1, 2 or 3 and further, a local maximum is found at pipe No. 5. The test results show that the required calculated weights to withstand roll-up are generally less than the required weights to withstand roll-down. This is in good agreement with the experience from physical model tests of rubble mound breakwaters, i.e. the major part of damage occurs during run-down for a slope of 1:2.0.

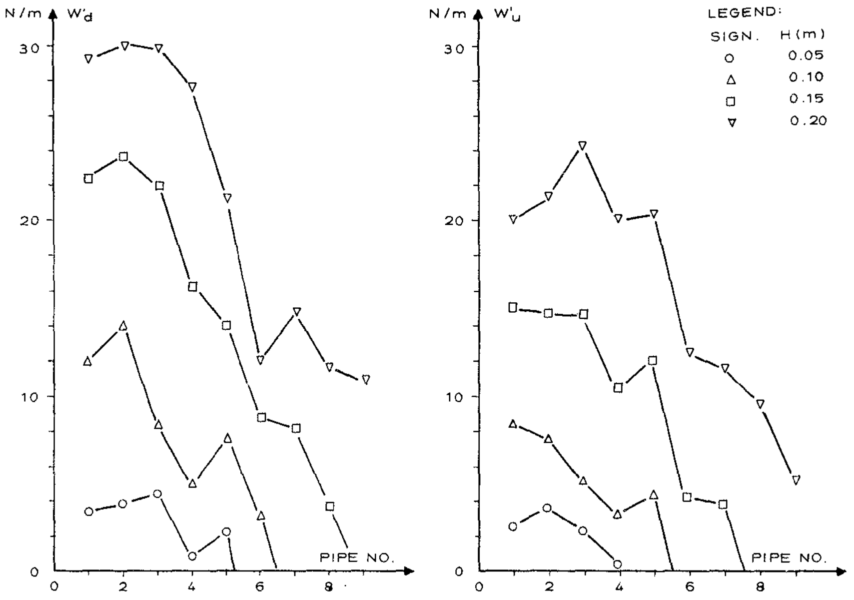


**Fig. 5 Required weights to withstand roll-up/roll-down for the nine pipes. Wave period T = 2.0 s.**

## Influence of Wave Period

The calculated required weights to withstand roll-down, $W'_d$, for pipes Nos. 2 and 5 are shown in Fig. 6 as function of the wave period. The results show that for pipe No. 2, the largest required weight occurs for T = 1.5 s, whereas a minimum is found for T = 2.5 s. For pipe No. 5, the required weight only varies slightly with the wave period, whereas for pipe No. 8, an increase with the wave period is found, which is due to increasing wave run-up for increasing wave periods. Similar dependencies of the wave period are found for the required weights to withstand roll-up.

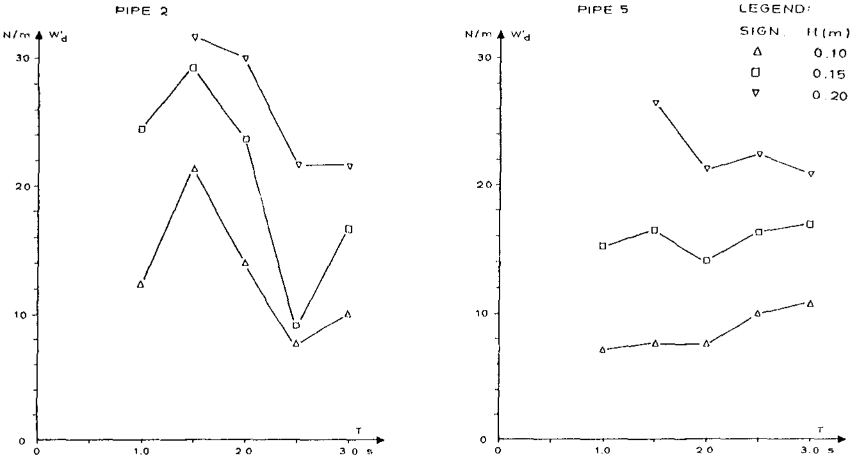


**Fig. 6 Required weights as function of the wave period. Regular waves.**

The measurements show that it is a rough simplification to aim for one stability formula for description of the stability of the entire seaward armour layer of a rubble mound breakwater.

## Influence of Surf Similarity Parameter, $\xi = \tan\alpha_o / \sqrt{H/L_o}$

The influence of the surf similarity parameter on stability has been studied. For fixed values of the required weights to withstand roll-up and roll-down, the corresponding wave heights have been found and the results are for pipe No. 2 presented in Fig. 7. It was found that a minimum in stability occurs for a surf similarity parameter in the order of 2 to 4, which corresponds to peak wave periods in the order of 1.5 s to 2.0 s. It is very important to notice that this range of the $\xi$-factor corresponds approximately to the transition between plunging and surging wave breaking.

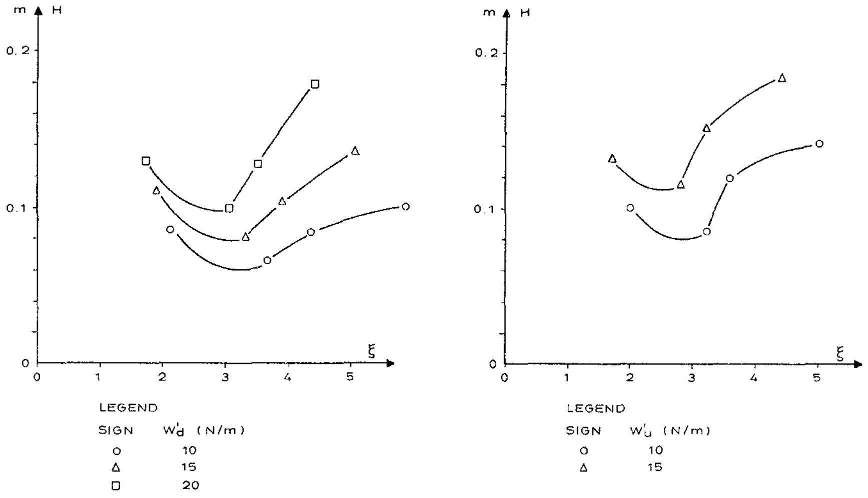


**Fig. 7** **Relationship between wave height and surf similarity parameter, $\xi$, for fixed required weights to withstand roll-up and roll-down. Pipe No. 2.**

## Test Results for Irregular Waves

All results presented in this section are based on model tests with irregular waves generated on basis of a JONSWAP spectrum. The forces were during all tests measured on pipes Nos. 2, 3, and 5.

### Analysis of Results

The measured forces and calculated required weights have been analysed statistically by plotting the results on semi-logarithmic paper as shown in Fig. 8. From these plots, the most probable forces and required weights have been found and used for further analyses.

### Influence of Wave Height

The calculated required weights to withstand roll-up and roll-down have been plotted for each wave period as function of the wave height. It was found that the relationship between the required weights and the wave height to a high degree depends on the peak wave period and location on the slope.

### Influence of Wave Period

The test results for irregular waves show the same tendency, but less pronouced as for regular waves, i.e. a maximum in required weight for $T_p$ = 1.5 s for pipe No. 2, whereas the required weight for pipe No. 5 is almost independent of the wave period.

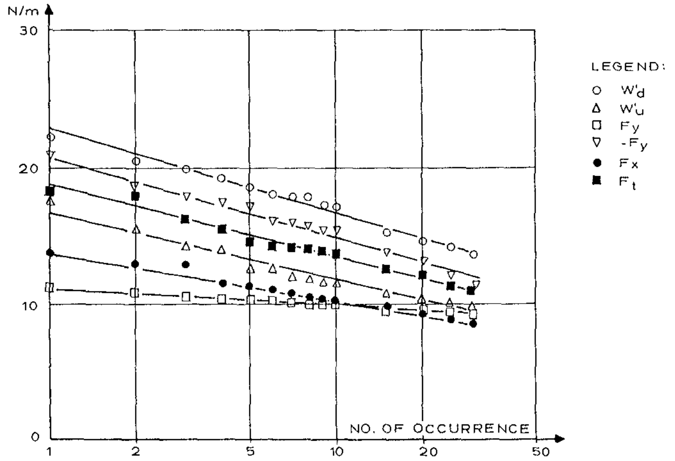


**Fig. 8 Distribution of maximum forces and required weights on pipe No. 3. $H_s$ = 0.13 m, $T_p$ = 2.0 s.**

### Influence of Surf Similarity Parameter, $\xi = \tan\alpha_0/\sqrt{H_s/L_{op}}$

In Fig. 9, the influence of the surf similarity parameter on the stability is shown for pipe No. 2. For fixed values of the required weights to withstand roll-up and roll-down, the corresponding wave heights have been found.

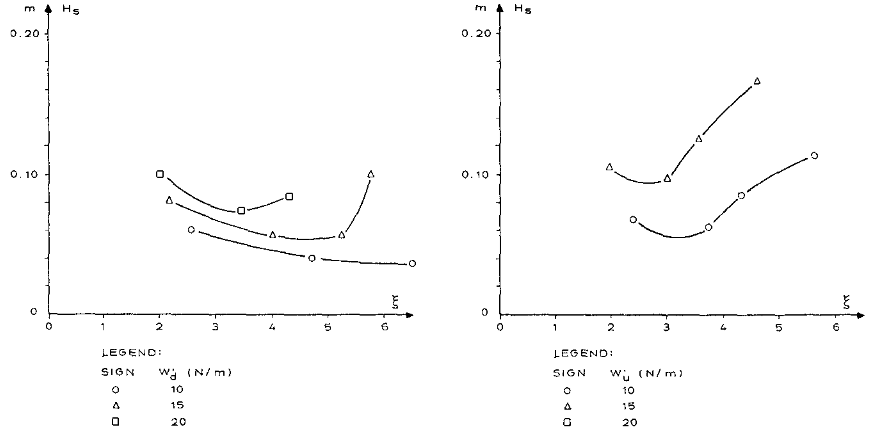


**Fig. 9 Relationship between significant wave height and surf similarity parameter, ξ, for fixed required weights to withstand roll-up and roll-down. Pipe No. 2.**

For roll-up, a minimum in stability is found for a surf similarity parameter in the order of 2 to 4.

For roll-down, the minimum in stability is not so pronounced as for roll-up or as was the case for regular waves. A minimum in stability was found for a surf similarity parameter of 3-5.

## Wave Slamming Forces

The wave slamming forces on the pipes have been analysed by studying the horizontal forces acting into the breakwater, i.e. when $F_{hor} < 0$. The advantage of this method is elimination of the varying buoyancy. It can, however, not be excluded that small buoyancy effects occur due to asymetrical buoyancy and air entrainment. The duration of the measured slamming forces was approximately 0.1 s with a rising time of approximately half, i.e. 0.05 s. This is significantly longer than slamming forces on a vertical wall, most probably due to the circular shape of the pipe.

## Maximum Horizontal Force in Relation to Pipe Position

For regular waves with a period of 2.0 s, a series of tests has been carried out for studying the relationship between the maximum inwards acting horizontal force ($-F_{hor}$) and the pipe position. Fig. 10 shows the results for the nine pipes on which wave forces have been measured.

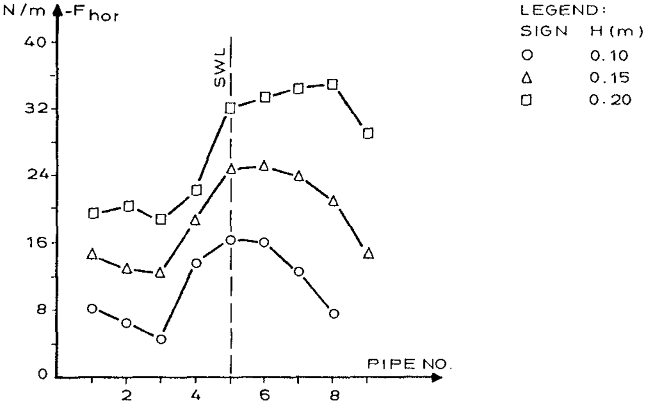


**Fig. 10** **Maximum inwards acting horizontal forces in relation to pipe position. T = 2.0 s. Regular waves.**

The results show that for H = 0.10 m the largest force is acting on pipe No. 5. When the wave height is increasing, the wave run-up is increasing and thus the largest force is acting on a pipe further up the slope. For H = 0.20 m, the largest force is found to act on pipe No. 8, but this force is only slightly larger than the largest forces acting on pipes Nos. 5, 6, and 7.

For all three wave heights, it was found that the maximum forces acting on pipes Nos. 1, 2, and 3 are approximately half the largest maximum force.

### Slamming Forces as Function of Run-Up Velocity

In order to analyse if the run-up velocity is the dominant factor for the horizontal wave impact on the pipes, the maximum measured horizontal force during each run-up period has been determined.

A scatter diagram of the correlation between run-up velocity and maximum inwards acting horizontal force, $-F_{hor}$, on pipe No. 5 is shown in Fig. 11.

The results show that the maximum horizontal force increases almost linearly with the run-up velocity. This result is very surprising as $-F_{hor}$ is expected to be proportional to $U^2$.

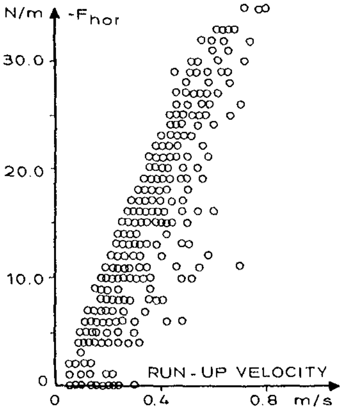


**Fig. 11** **Scatter diagram of run-up velocity and maximum inwards acting horizontal force on pipe No. 5. $H_s$ = 0.18 m, $T_p$ = 2.0 m. JONSWAP spectrum.**

### Summary and Conclusion

Calculations of the required weights to withstand roll-up and roll-down showed that the maximum required weights occur for pipes Nos. 1, 2 or 3 (below SWL), depending on the wave height.

For roll-down, a maximum in required weight for pipe No. 2 is found for a wave period of 1.5 s, whereas the required weight for pipe No. 5 is almost independent of the wave period.

For roll-up, a minimum in stability was found for a surf similarity parameter, $\xi$, of 2 to 4 for both regular and irregular waves. For roll-down, a minimum in stability was found for a $\xi$ of 2 to 4 for regular waves, whereas the minimum is less pronounced for irregular waves and occurs for a $\xi$ of 3 to 5.

The results show that the slamming forces acting on the pipes vary to a high degree with the wave period resulting in different types of wave breaking and on the position of the pipe relative to SWL.

The largest horizontal slamming forces were measured at the pipes from still water and upwards on the slope. There was a tendency that waves with a period of 1.5 s to 2.0 s caused the largest forces which corresponds to a surf similarity parameter in the order of 2 to 4. This range of the $\xi$-factor corresponds approximately to the transition between plunging and surging wave breaking.

Analyses have shown that the measured horizontal slamming forces are increasing almost linearly with the run-up velocity.

## Acknowledgement

The research study of wave forces on idealised breakwater armour units was partly financed by the Danish Technical Research Council. The support is graciously acknowledged.

## Appendix 1 - Reference

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## Appendix 2 - Notation

The following symbols are used in this paper:

$g$ = acceleration due to gravity
$F_{hor}$ = horizontal force component (outwards from the breakwater)
$-F_{hor}$ = horizontal force component (inwards the breakwater)
$F_{ver}$ = vertical force component (upwards)
$-F_{ver}$ = vertical force component (downwards)
$F_t$ = total force. Negative when acting into the breakwater
$H$ = wave height at wave gauge No. 4
$H_s$ = significant wave height at wave gauge No. 4
$h$ = water depth
$h_i$ = surface elevation
$h_{rms}$ = rms-value of the water surface elevation
$L_o$ = deep water wave length, $L_o = g/2\pi \cdot T^2$
$L_{op}$ = deep water wave length, $L_{op} = g/2\pi \cdot T_p^2$
$m$ = number of samples
$p$ = porosity of armour layer
$R$ = reflection coefficient
$T$ = wave period
$T_p$ = spectral peak wave period
$W'_d$ = required weight to withstand roll-down
$W'_u$ = required weight to withstand roll-up
$\alpha$ = slope of breakwater, $\tan\alpha_o = \frac{1}{2}$
$\theta$ = angle for contact points
$\xi$ = surf similarity parameter