waterloopkundig laboratorium
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Stability of rubble mound breakwaters

Stability formula for breakwaters armoured with ACCROPODE (R)

Report on basic research

H 546

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Stability formula for breakwaters armoured with ACCROPODE (R)

1. Introduction

Delft Hydraulics has performed an extensive investigation on the stability of rubble mound revetments and breakwaters under random wave attack. Two stability formulae have been derived which describe the stability of rock slopes as a function of wave height, wave period, slope angle, storm duration, permeability and damage level. The complete investigation is described in Dutch in the Delft Hydraulics Report M 1983. The investigation has further been described by Van der Meer and Pilarczyk (1987).

In extension of the investigation on rock slopes Delft Hydraulics has set-up an investigation on the stability of artificial armour units. The first part of this investigation concerned the stability of breakwaters armoured with Cubes and is described by Van der Meer (1986). The second part was focussed on stability of Tetrapods and is described by Van der Meer (1987). Cubes were chosen as these elements are bulky units which have good resistance against impact forces. Tetrapods are widely used all over the world and have a fair degree of interlocking.

ACCROPODE (R) can be regarded as the latest development, showing high interlocking, strong elements and a one layer system. Therefore, the ACCROPODE (R) was chosen to be investigated next. The study was partly financed by SOGREAH, France and partly by Delft Hydraulics as an internal research project.

This study has been performed in March 1987 under the supervision of Mr. J.W. van der Meer, who also wrote the present report.

2. Stability of rock slopes

The investigation on rock slopes was used as a basis for the investigation of ACCROPODE(R). Therefore, the results for the rock slopes will be considered first.

The stability formulae derived are:

$$H_s/\Delta D_{n50} * \sqrt{\xi_z} = 6.2\ P^{0.18}\ (S/\sqrt{N})^{0.2} \qquad (2.1)$$

for plunging waves, and

$$H_s/\Delta D_{n50} = 1.0\ P^{-0.13}\ (S/\sqrt{N})^{0.2}\ \sqrt{\cot\alpha}\ \xi_z^P \qquad (2.2)$$

for surging waves

where:

H_s	= significant wave height	(m)
ξ_z	= surf similarity parameter, $\xi_z = \tan\alpha/\sqrt{2\pi H_s/g\ T_z^2}$	(-)
T_z	= zero up-crossing wave period	(s)
α	= slope angle	(degrees)
Δ	= relative mass density of stone, $\Delta = \rho_a/\rho - 1$	(-)
ρ_a	= mass density of stone or unit	(kg/m^3)
ρ	= mass density of water	(kg/m^3)
D_{n50}	= nominal diameter of stone, $D_{n50} = (W_{50}/\rho_a)^{1/3}$	(m)
W_{50}	= 50% value of mass distribution curve	(kg)
P	= permeability coefficient of the structure	(-)
S	= damage level, $S = A/D^2_{n50}$	(-)
A	= erosion area in a cross-section	(m^2)
N	= number of waves (storm duration)	(-)

The influence of the wave height, wave period and slope angle on stability is shown in Figure 1. The breaker parameter, ξ_z, has been plotted on the horizontal axis and the significant wave height on the vertical. Fixed parameters in this graph are the nominal diameter, D_{n50} = 1 m (average weight, W_{50} = 2.6 t), the relative mass density, Δ = 1.6, the permeability, P = 0.5 and the storm duration, N = 3000 waves. Curves are shown for the damage level, S = 5. This damage level can be described by "tolerable damage". Start of damage is found for S = 2-3 and failure (filter layer visible) for S > 8-17.

The influence of the wave period in the plunging waves region is large. A longer wave period decreases stability. The minimum is found for the transition from plunging to surging waves, the so-called collapsing waves. The stability for plunging waves is very well described by the ξ_z-parameter, as different slope angles have the same curve on the left side of Figure 1. For surging waves, different curves are shown on the right side of Figure 1 for different slope angles. Minimum of stability is lower for a steeper slope.

The parameters investigated for rock slopes were:
$H_s/\Delta D_{n50}$; ξ_z; cotα; S; N; permeability P; spectrum shape and groupiness of waves, and stone gradation.

The spectrum shape and groupiness of waves has no influence on stability when the average period (and not the peak period) was used to calculate ξ_z. It is possible that this influence is not negligible for armour layers with ACCROPODE (R).

The grading of the stone also has no or only minor influence on stability and the stability can be described by the nominal diameter, D_{n50}, only. Armour layers with artificial units consist usually of one size of units. The nominal diameter can be calculated in the same way as for a rock grading, but now without the subscript 50:

$$D_n = (W/\rho_a)^{1/3} \tag{2.3}$$

where:
D_n = nominal diameter for artificial units (m)
W = mass of artificial units (kg)

For a cube the nominal diameter equals the side of the cube. For the ACCROPODE (R) the nominal diameter is equal to 0.7H, where H is the height of the ACCROPODE (R).

For breakwater research, the actual number of displaced units is usually counted. This number can be related to the width of one nominal diameter, (damage level No.). Than the same kind of damage level is defined as for S. The difference is that S is related to the erosion area and No to the actual number of displaced units.

The investigation on ACCROPODE (R) (and also on Cubes and Tetrapods) was restricted to only one cross-section. Therefore, the influence of the slope angle and the permeability of the structure were not considered. This means that the parameters investigated for breakwaters armoured with the ACCROPODE (R) are:

$H_s/\Delta D_n$; ξ_z; S or No and N.

3. Test set-up

3.1 Cross-section of the breakwater

Only one cross-section was investigated for each type of armour unit (Cubes, Tetrapods or ACCROPODE (R)). This cross-section was defined in such a way that it corresponded with most breakwaters built in nature. Breakwaters investigated by Delft Hydraulics in the last decade have been evaluated, therefore, together with SOGREAH's experience on the construction of breakwaters with the ACCROPODE (R). This evaluation resulted in the following dimensions for the cross-section:

Slope angle. Almost all slope angles, applied with Cubes or Tetrapods were 1:1.5. This slope angle was used for the tests on these units. The ACCROPODE (R) is generally built on a slope of 1:4/3 and this slope was used for the present tests.

Ratio armour/filter. The ratio in mass between armour units and stones in the filter layer ranged from 7 to 15. Usually 10 to 20 is recommended. A ratio of 8 was used for the present tests (armour units 161 gr. and filter stones 20 gr.).

Crest height. The crest height can have a substantial effect on stability. The front of low crested breakwaters is more stable than for high crested breakwaters. The evaluation showed that about 5 to 10 percent of overtopping waves could be expected for a ratio of $H_s/h_c = 0.75$ where H_s is the significant wave height and h_c is the crest height above the still water level (SWL). The applied crest height was 0.25 m. Start of damage was expected to occur for $H_s = 0.10$ to 0.15 m and serious damage for $H_s = 0.15$ to 0.25 m. For start of damage the breakwater was not overtopped. Severe overtopping occurred for waves higher than 0.20 m. In the last part of the programme, the crest height was increased to 0.45 m above SWL, resulting in only small overtopping.

Foreshore, water depth. Waves are usually generated on deep water and reach the structure on a sloping foreshore. A uniform slope of 1:30 was chosen as foreshore. The water level was chosen according to $d/H_s = 2$ to 3, where d = water depth at the toe of the structure. These values are reached with a water depth, d, of 0.40 m and wave heights between 0.13 and 0.20 m. Breaking of waves can be expected for waves higher than 0.20 m, depending on the wave period.

3.2 Test equipment, materials and procedure

All tests were conducted in a 1.0 m wide, 1.2 m deep and 50.0 m long wave flume with test sections installed about 44 m from the random wave generator, see Figure 2. This wave generator is capable of performing both translatory and rotational motions by means of a hydraulic actuator, programmed by a closed loop servo-system. The command signal of this loop is obtained from a punched tape, representing a random signal with a predetermined wave energy spectrum. A new system developed by Delft Hydraulics was used to measure and compansate for reflected waves at the wave board. With this system standing waves and basin resonance are avoided.

Damage was measured with a surface profiler which consisted of nine gauges placed 0.10 m apart on a computer controlled-carriage. The surface along the slope was measured every 0.040 m. Every survey consisted of about 400 data points. Successive soundings were taken at exactly the same points using the relocatability of the profiler. An average profile was calculated and plotted by computer and used for determining the erosion damage, S.

The ACCROPODE (R) used for the armour layer has a mass of 0.161 kg and a mass density of 2320 kg/m^3. This means that the nominal diameter, D_n, or side of an ACCROPODE (R) was 0.0411 m and that the relative mass density, Δ, was 1.32. The cross-section of the breakwater is shown in Figure 3. The armour layer consisted of one layer width a thickness of 0.9 H (where H = 0.06 m). The 0.06 m thick filter layer consisted of stones 0.020-0.025 m width an average mass of 0.020 kg. The core consisted of stones with D_{n50} = 0.011 m and D_{85}/D_{15} = 1.50. This core was also used in the investigation on rock slopes, cubes and tetrapods. A slope of 1:30 was present in front of the structure, from the bottom of the flume up to 0.50 m above the bottom. The crest height of the structure was 1.15 m above the bottom of the flume in the first tests and 1.35 above the bottom in the final tests.

SOGREAH assisted with the construction of the armour layer for the first two tests. The ACCROPODE (R) was placed according to the specifications of SOGREAH.

The method of placing is shown in Figure 4.

Each complete test consisted of a bedding-in test, a pre-test sounding, a test of 1000 waves, an intermediate sounding, a test of 2000 more waves and a final sounding. Sometimes the test was extended with another 2000 waves. The bedding-in test was performed in order to let the settlement take place of the newly layed ACCROPODE (R). The wave height of this test was about 0.09-0.10 m the wave period 1.7s, and the duration 15 minutes (about 500 waves). The profiles for all tests are shown in Appendix A, Figures A1 to A26. Together with each sounding the number of displaced ACCROPODE (R) was counted. After each complete test the armour layer was removed and rebuilt. A test series consisted generally of 2-5 tests with the same wave period, but different significant wave heights. Wave heights ranged from 0.12 m to 0.24 m and wave periods from 1.4 to 2.8 seconds. A water depth of 0.90 m was applied for all tests. The water depth at the toe of the structure was 0.40 m.

Each ACCROPODE (R) was marked with a colour. The armour layer was constructed with coloured horizontal bands with a width of two units (1.2 h, see Fig. 4). ACCROPODE (R) displaced out of their coloured band were counted only. The width of the flume was 1 m which equals 24.3 D_n. The damage number No was calculated by dividing the total number of displaced ACCROPODE (R) by 24.3.

3.3 Test programme

The main purpose of the investigation was to establish damage curves for a wide range of wave periods and for different storm durations. Four wave periods were chosen, T_z = 1.4 s, 1.7 s, 2.15 s and 2.8 s. With wave heights between 0.15 and 0.24 m the wave steepness, H_s/L_z, was in the range of 0.015 to 0.06, where $L_z = 1.56\ T_z^2$. For a wave steepness greater than 0.06 waves will break already on deep water, so this value can be regarded as an upper boundary. For the shortest wave period of 1.4 s the maximum significant wave height, therefore, is in the order of 0.18 m.

In total 18 tests were performed, twelf tests with a relatively low crest (0.25 m above SWL and 6 tests with a non-overtopped structure (crest 0.45 m above SWL). The main parameters are shown for each test in Table 1. For each wave period 2 to 5 tests were performed with a different wave height in order to establish the damage curve.

4. Stability of ACCROPODE (R)

4.1 Test results

The wave height at the structure will not be the same as the wave height in deep water, due to shoaling and breaking on the foreshore. The relation between the wave height in deep water and at the structure was established in model without the breakwater in the flume. Waves are dissipated by a wave damper at the end of the flume. The relation for each wave period is shown in Figure 5. During the model tests waves were only measured on deep water. By using the curves of Figure 5 the wave height, H_s, at the structure was established. The wave height at deep water and at the structure are both shown in Table 1. The wave height at the structure was used for further analysis.

Damage was measured by means of a profile indicator, resulting in the damage level S and by means of counting the actual number of displaced ACCROPODE (R) resulting in the damage number No. The damage level S also takes into account the porosity of the armour layer and will be a little greater than the damage number No. The relation between S and No is shown on Figure 6. The linear best fit curve is also drawn on this figure and can be described by:

$$S = 2\ No + 1 \qquad (4.1)$$

The same relationship between S and No was found for Tetrapods.

The coefficient 2 in (4.1) suggests a large difference between S and No. Displaced ACCROPODE (R) were only counted if they were displaced out of their coloured band. Sliding down or displacement of a ACCROPODE (R) less than 1 to 2 diameters was not included in the damage number No. The damage level S takes into account all changes in the slope, where No does not.

Another interesting aspect is the coefficient 1 in equation 4.1. When no ACCROPODE (R) are displaced (No = 0) a damage level of S = 1 is already reached. This is caused by the settlement and slight rearange of the ACCROPODE (R) on the slope which is taken into account with the damage level, S. For Cubes this "no damage" criterion using S amounted to S = 0.5 and for tetrapods S = 1.

Start of damage for a slope with ACCROPODE (R) can be defined for No > 0 or S > 1. This is a difference with rock slopes, where start of damage is defined for S > 2 (for a slope 1:1.5). One allows less damage for a breakwater with ACCROPODE (R) then for a rubble mound revetment or breakwater consisting of rock.

Results of all tests are shown in Table 1. The profiles taken after 1000 and 3000 waves are shown in Appendix A, Figures A 1 to A 26. In tests 13-18 the crest level was increased with 0.20 m and this resulted in a structure which was higher than the side walls of the flume. It was not possible therefore, to use the surface profiler which was mounted on a carriage. This means that profiles for tests 13-18 are not available and that damage was measured by the damage number No only. Damage was plotted versus the wave height for N = 1000 and N = 3000, for each wave period. For the damage level, S, these data points are shown in Figures 7 and 8, and for the damage number, No, in Figures 9-12.

The bedding-in test, described in Section 3.2, was not performed in the first test. The test was directly run with a wave height of 0.15 m. The armour layer showed large damage within 5 minutes of testing. The damage increased slowly when the test was run until 1000 waves had reached the structure.

According to the specifications of SOGREAH an armour layer with ACCROPODE (R) is built in the following way: the ACCROPODE (R) are placed from the toe up to the transition between the slope and the horizontal layer on the crest. The layer on the crest is placed starting from the crest element (if any) to the transition described above. Finally the gap between the two layers of ACCROPODE (R) (one on the slope and one on the crest) is filled up. In prototype this takes places several months after placing the units on the slope. This means that the completion of armour layer construction is realized after settlement of the units on the slope during the first months of construction.

Therefore, a bedding-in test was performed for all other tests. No damage was not found for a wave height lower than 0.20 m (see Table 1 - tests 2-5).

Damage was measured in tests 1-12 by means of a surface profiler. The profiles (Appendix A) showed that the damage was always located above the Still Water Level. This is different for rock slopes and Cube and Tetrapod armour layers, where damage is located around the Still Water Level.

Damage curves for each wave period are shown in Figure 7-12. A few important conclusions can be drawn on these figures.

- If no damage occurred during the first 1000 waves ($S < 1$ or $N = 0$), more waves were not able to cause more damage. This means that the no-damage criterion is independent on the storm duration (or number of waves).
- If some damage occurred during the first 1000 waves it is possible that more waves can cause failure of the structure. Tests 6 and 11 are good examples, see Figures 7 - 10. In test 6 the damage increased from No = 0.21 (N = 1000) to N = 0.29 (N = 3000) and No = 2.5 (N = 3700). Therefore the criterion for large damage should be placed at low damage for short storm durations.
- From the figures it is clear that the difference between no damage and large damage is caused by a small increase in wave height (or $H_s/\Delta D_n$). The damage curve is very steep and dependent on the storm duration.

Based on this last conclusion it is obvious that the description of damage by a damage curve is not useful. It is satisfactory to distinguish two damage levels:

no damage: $S \leq 1$ or $No = 0$
large damage, failure: $S > 2$ or $No > 0.5$

Both damage levels were taken from Figures 7-12 and the $H_s/\Delta D_n$ values for these damage levels are shown in Table 2. Besides these $H_s/\Delta D_n$ values the corresponding ξ_z values are given in Table 2. These values were calculated using the $H_s/\Delta D_n$ value, $\Delta D_n = 0.0543$, $\tan\alpha = 0.75$, the wave period T_z and the formula:

$$\xi_z = \tan /\sqrt{gT_z^2/2\pi H_s} \qquad (4.2)$$

The damage levels with the obtained $H_s/\Delta D_n$ and ξ_z values are shown in Figure 13. The upper plot shows the data for the no damage criterion and the lower one for large damage. The plots can, in fact, be compared with the results on rock slopes, Figure 1.

From Figure 13 it can be concluded that the damage is not influenced by the wave period as horizontal lines can be drawn through the data points. A second conclusion can be derived from Figure 13. The test results of tests 1-12 (overtopping) and of tests 13-18 (non-overtopping) show no significant differences. This means that the damage to ACCROPODE (R) is not influenced by the crest height of the structure or the number of overtopping waves if the number of overtopping waves is less than 40% (range of test results).

4.2 Derivation of stability formula

For practical use the test results must be summarized in a design formula. As described in Chapter 2 stability of ACCROPODE (R) might be a function of the following parameters:

$H_s/\Delta D_n$; ξ_z; S or No and N.

As only two damage levels are used, S and No will not appear in the formula. Furthermore it is assumed that the no-damage criterion is independent of the storm duration. For more than "no damage" the storm duration has a significant influence, but this is taken into account by taking a low value of S or No for this damage level. The results showed no influence of the wave period (Figure 13). As breakwaters armoured with ACCROPODE (R) are generally constructed with a slope of 1:4/3 and the wave period has no influence on damage, the parameter ξ_z (Equation 4.2) will have no influence too.

The only remaining parameter, therefore, is the $H_s/\Delta D_n$. The average of the $H_s/\Delta D_n$ values for both damage levels can be obtained from Table 2:

No damage: $H_s/\Delta D_n = 3.74 \pm 0.22$
Large damage: $H_s/\Delta D_n = 4.10 \pm 0.18$

If no damage is assumed for a value of 3.7 and large damage for a value of 4.1 the stability formula for ACCROPODE (R) becomes:
No damage : $S \leqslant 1$ or $No = 0$

$$H_s/\Delta D_n = 3.7 \qquad (4.3)$$

large damage/failure : $S > 2$ or $No > 0.5$

$$H_s/\Delta D_n = 4.1 \tag{4.4}$$

Equations 4.3 and 4.4 show that the difference between start of damage and failure is small. An increase of the wave height by 10 percent can cause the difference between no damage and failure. The design wave height, therefore, should not be based on Equation 4.3 only. A safety factor should be taken into account using Equation 4.3 if the 1/50 years wave height (for example) is taken. Another possibility is to use Equation 4.4 for a more extreme wave height, for instance the estimated 1/500 years wave height.

The Shore Protection Manual (1977) gives the Hudson formula with different K_D coefficients for various armour units. The Hudson formula can be written as:

$$H_s/\Delta D_n = (K_D \cot\alpha)^{1/3} \tag{4.5}$$

SOGREAH uses a K_D factor of 12 (Vincent (1987)) which gives with $\cot\alpha = 4/3$:
$H_s/\Delta D_n = 2.52$
In comparison with the test results (Equation 4.3) this means a safety coefficient of $3.7/2.52 = 1.47$ for the wave height (or diameter) and a safety coefficient of $1.47^3 = 3.2$ for the mass of the unit.

4.3 Comparison with Cubes and Tetrapods

As mentioned in Chapter 1 Cubes and Tetrapods were investigated earlier (Van der Meer (1986) and (1987)). It is interesting to discuss the differences between the three different armour units: Cubes (bulky units), Tetrapods (world wide application-interlocking) and ACCROPODE (R) (new development, one layer system).

The stability of Cubes and Tetrapods showed to be dependent on the wave period. Stability increased with longer wave periods. For damage levels with $No > 0$ the stability showed to be a function of the storm duration, but less pronounced as for the ACCROPODE (R). For these damage levels rocking of some units could be observed during the tests. After the initial settlement of the ACCROPODE (R) almost no rocking was observed. The ACCROPODE (R) are placed with a large number in a one layer system and almost each unit contacts more than one neighbour in such a way that rocking is hardly possible (after initial settlement).

A $H_s/\Delta D_n - \xi_z$ plot can be used to compare the stability of the three types of units (not considering rocking). The damage levels No = 0 and No = 2 are plotted in Figure 14, using a storm duration of 3000 waves. From this figure it follows that:

- the difference between start of damage for Cubes and Tetrapods with start of damage for ACCROPODE (R) is large.
- the difference for large damage (No = 2) is smaller. For $\xi_z > 6$ stability is more or less equal for Tetrapods and ACCROPODE (R), using No = 2.

4.4 Overtopping

A wave gauge was mounted on top of the breakwater. Each time a wave runup passed this gauge it was recorded on a paper recorder. The times that a wave runup passed the crest was related to the number of waves which reached the structure in the same period. In this way the percentage of overtopping waves was recorded.

The results on overtopping are shown in Table 1 (last column) and Figure 15. The overtopping in tests 1-12 ranged between 2 and 40 percent. In these tests where damage occurred the percentage of overtopping waves was always higher than 20 percent. The tests 13-18 showed much lower overtopping, generally lower than 10 percent and are not shown in Figure 15.

nee! langere periode geeft hogere H_s bij de constructie!

From Figure 15 it follows that a longer wave period causes more overtopping.

(deep water waves)

4.5 Friction between model units

Prototype artificial units are always constructed of concrete. Model units can consist of mortar, plastic, aluminium, porcelain or other materials. Units constructed of different materials will have the same shape and mass, but the contact friction between elements can differ substantially. Model breakwaters constructed with smooth plastic Tetrapods for example are damaged at a much lower wave height than model breakwaters with rough concrete Tetrapods, having the same shape and mass, but higher natural angle of repose (angle of natural slope).

Klein Breteler and Van der Meer (1984) have investigated the influence of contact friction on stability. The relation between contact friction and natural angle of repose was established for Cubes, Tetrapods and Dolosse. Finally tests were performed with the same units (Tetrapods) constructed of different materials. These tests resulted in a stability formula which included the natural angle of repose. These results will be used to evaluate the effect of contact friction on the stability formulae derived in Section 4.2.

The friction coefficient was measured by pulling a wet unit which rested on a horizontal part of another unit. Each test was repeated 10 times to minimize the influence of an individual measurement. The natural angle of repose is determined by use of a tilting box filled with two layers of armour units on a filter layer of 20-40 gr rock. This method was also used by Hedar (1960). The box was filled at a slope of 15° and tilted until partial collaps occurred in the armour layer whereby the natural angle of repose was determined. Each test was repeated 3 times.

The results for Cubes, Tetrapods and Dolosse showed that the angle of repose can be expressed as the sum of two parts, representing the effect of friction and of interlocking. The latter factor turns out to be a constant for a certain type of armour unit which increased with increasing irregularity of the unit. The relation which was found for the above mentioned armour units was as follows:

$$\phi_r = \phi_c + \phi_i, \qquad \text{or:} \tag{4.7}$$

$$\mu = \tan \phi_r = \tan (\phi_c + \phi_i) \tag{4.8}$$

where:

ϕ_r = natural angle of repose
ϕ_c = angle of contact friction determined by: $f = \tan \phi_c$
f = friction coefficient
ϕ_i = angle of interlocking
μ = friction coefficient including interlocking

Tests on large scale units of 20-50 kg showed that the angle of contact friction is independent on size and shape (Cubes, Antifer, Tetrapods) and measured 34-36 degrees. Using (4.7) and assuming no scale effects between the large scale concrete units and prototype units, the natural angle of repose of prototype units can be calculated.

During the present investigation the natural angle of repose and the friction coefficient between units was measured for two sizes of the ACCROPODE (R). Besides the units with a mass of 0.161 kg which were used in the tests on stability, smaller units with a mass of 0.055 kg were tested. These smaller units had a smoother surface. The results on contact friction are as follows:

	mass 0.161 kg	mass 0.055 kg
friction coefficient f	0.74 ± 0.07	0.48 ± 0.07
angle of contact friction ϕ_c	36.5° ± 2.6°	25.4° ± 3.0°

The test with the tilting box was performed in a few different ways. First the standard test was performed which means a full box constructed on an angle of 15°. Only 100 small units were available which gave approximately a ¼ box filled with units (width of six units and 16 rows). For comparison the units of 0.161 kg were tested in the same way. Finally the small units were constructed at an angle of 37° (slope 1 : 4/3) which is the same as the slope angle of the breakwater. The results on measuring the natural angle of repose are as follows:

	mass 0.161 kg	mass 0.055 kg
standard test	52.6° ± 2.0°	-
standard test with only 100 units	64.3° ± 0.8°	61.2° ± 3.4°
construction at 1:4/3 and 100 units	-	62.2° ± 2.5°

The number of units used has a substantial influence on the natural angle of repose. Furthermore it can be concluded that construction at a steeper slope has no influence on the natural angle of repose.

The results on contact friction and natural angle of repose are shown in Figure 16. The tests with 100 units show a high degree of interlocking.
Based on these data Equation 4.7 can be written as:

$$\phi_r = \phi_c + 31° \quad (4.9)$$

Based on the standard test (which is the only test for comparison with Cubes, Tetrapods and Dolosse) Equation 4.7 gives:

$$\phi_r = \phi_c + 16°$$ (4.10)

Equation 4.10 gives ϕ_r values which are a little higher than for Cubes and much lower than for Tetrapods or Dolosse. Equation 4.9 gives ϕ_r values which are even higher than for Dolosse. As Equation 4.10 is only based on one size of unit the result must be treated carefully. It might be worthwhile to perform more tests with other sizes of units. In the mean time it is assumed that the actual value of ϕ_i for the ACCROPODE (R) will be between 16° and 26° (found for Tetrapods).

The friction coefficient between the units used in the stability tests amounted to 36.5° which is very close to the values measured for large concrete model units (34°-36°). It can be concluded, therefore, that the results obtained can be used for prototype design.

The influence of natural angle of repose on stability can theoretically be described by the following two formulae (Klein Breteler and Van der Meer, 1984):

downrush: $H_s/\Delta D_n = K_1 \cdot (\mu \cos\alpha - \sin\alpha)/(\mu C_n + C_p)$ (4.11)

and uprush: $H_s/\Delta D_n = K_2 \cdot (\mu \cos\alpha + \sin\alpha)/(\mu C_n + C_p)$ (4.12)

where:

K_1, K_2 = stability coefficients

C_n/C_p = ratio of forces acting normal and parallel to the slope.

Tests on a 1 in 1.5 slope of Tetrapods with $\xi_z = 3$ showed that the uprush was responsible for the initiation of damage and the ratio of C_n/C_p was established at 1/8.5. This means that 4.12 can be rewritten as follows:

$$H_s/\Delta D_n = K (\mu \cos\alpha + \sin\alpha)/(\mu + 8.5) \quad (4.13)$$

Formula 4.13 has two restrictions:

- it was established for Tetrapods
- it was established for the plunging/collapsing region with $\xi_z = 3$.

Only tests on the ACCROPODE (R) for several wave conditions will give the right formula for ACCROPODE (R). In the mean time it is suggested to use 4.13 for all elements and for all wave conditions. Formula 4.13 must now be included in

Formulae 4.3 and 4.4. Therefore the parameter $f(\mu)$ is introduced with:

$$f(\mu) = \frac{\mu_m \cos\alpha + \sin\alpha}{\mu_m + 8.5} * \frac{\mu_p + 8.5}{\mu_p \cos\alpha + \sin\alpha} \tag{4.14}$$

where the subscript m and p refer to model and prototype, respectively.

For prototype units μ_p can be calculated using Equation 4.8 with 4.9 or 4.10. The value μ_m for model units can easily be measured. If ϕ_c of the model units is different from 34°-36° (μ_m is different from 0.67-0.73) stability formula should be corrected with the factor $f(\mu)$ in the following way:

$$H_s/\Delta D_n = 3.7 / f(\mu) \quad \text{or:} \tag{4.15}$$

$$H_s/\Delta D_n = 4.1 / f(\mu) \tag{4.16}$$

As already mentioned above, the model units used in the present investigation showed to have a ϕ_c value of 36.5° which means that $f(\mu)$ is almost unity.

5. Conclusions and recommendations

The main conclusions derived from the results of the stability tests on a breakwater armoured with the ACCROPODE (R) can be summarized as follows:

1. The acceptable damage level for artificial units is lower than for slopes armoured with rock. Start of damage can be assumed if S = 2 to 3 for rock, and S = 1 or No = 0 for the ACCROPODE (R) (No = number of displaced units in a row of one diameter). Severe damage can be assumed for S = 8-10 for rock, and S > 2 or No > 0.5 - 1.0 for the ACCROPODE (R).

2. Both the damage level, S, which is based on the erosion profile, and the damage counted by the number of displaced units, No, showed no influence of the wave period. For the no damage criterion, No = 0 or S = 1, the storm duration showed no influence on stability. If some damage ocurred, however, the storm duration showed to have a substantial influence on stability.

3. Due to the effect of storm duration on damage the stability curves were very steep and the difference in wave height for the no damage criterion and for the failure criterion consequently small. It was decided, therefore, to apply only these two criteria, instead of using S or No in a formula. The stability formula for the ACCROPODE (R) can be written as:

   No damage: No = 0 or S $\leq$ 1

   $$H_s/\Delta D_n = 3.7 \qquad (4.3)$$

   Large damage/failure: No > 0.5 - 1.0 or S > 2

   $$H_s/\Delta D_n = 4.1 \qquad (4.4)$$

   In practical design one should use a safety factor when using Formula 4.3.

4. The steep slope of 1 in 4/3 is favourable for an armour layer constructed with the ACCROPODE (R) as it causes settlement of the units. This settlement is essential for the design of the ACCROPODE (R) and gives a "blanket" of armour units where each unit contacts several neighbours. Therefore rocking was hardly shown during the tests and large wave forces are required to move or displace a unit.

5. In comparison with Cubes and Tetrapods the no damage criterion (Equation 4.3) is much higher for the ACCROPODE (R). This fact is due to the high interlocking of the units after the initial settlement which was described in Conclusion 4. The failure criteria for these units are more close. The damage to an ACCROPODE (R) layer is always situated above the Still Water Level, see the Figures in Appendix A. For Cubes and Tetrapods damage is usely found around the Still Water Level.

6. Model units constructed of different materials have different friction coefficients. The natural angle of repose in model will differ from prototype. For analysis of model tests this effect has to be taken into account. The friction coefficient and the natural angle of the ACCROPODE (R) model units were measured. Due to too few sizes investigated no clear relationship could be established. As the friction coefficient of the model ACCROPODE (R) was very close to prototype, results of the model investigation can directly be used for prototype design.

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SOGREAH Consulting Engineers

test	deep water Hs m	Tz s	Tp s	Hs/ΔDn	at structure Hs s	Hs/ΔDn	results N	S	number	No	over-topping %
1	.143	1.71	1.90	2.63	.153	2.82	1000	10.38	>3	>100	2.70
2	.114	1.67	1.90	2.10	.122	2.25	1000	.56	0	0	.70
							3000	.68	0	0	
3	.143	1.68	1.90	2.63	.153	2.82	1000	–	0	0	2.80
							3000	–	0	0	
4	.165	1.68	1.90	3.04	.174	3.20	1000	.87	0	0	9.00
							3000	.99	0	0	
5	.201	1.68	1.90	3.70	.201	3.70	1000	.91	0	0	16.30
							3000	1.10	0	0	
6	.261	1.76	1.90	4.80	.224	4.12	1000	1.37	5	.21	39.30
							3000	1.26	7	.29	
							3700	6.23	61	2.5	
7	.171	2.15	2.49	3.15	.203	3.74	1000	.33	0	0	18.10
							3000	.42	0	0	
8	.205	2.15	2.49	3.77	.234	4.31	1000	1.01	2	.08	25.90
							3000	1.78	6	.25	
							5000	2.03	8	.33	
9	.159	2.82	3.57	2.93	.210	3.86	1000	.54	0	0	21.60
							3000	1.37	7	.29	
							5000	2.30	13	.53	
10	.142	2.83	3.57	2.61	.188	3.46	1000	.36	0	0	15.20
							3000	.48	0	0	
11	.181	2.78	3.57	3.33	.232	4.27	1000	1.03	1	.04	29.50
							3000	1.44	14	.58	
							4300	3.64	43	1.77	
12	.208	1.43	1.49	3.83	.181	3.33	1000	.36	0	0	11.90
							3000	.64	0	0	
13	.204	1.70	1.90	3.75	.203	3.74	1000	n m	3	.12	3.30
							3000	n m	7	.29	
							5000	n m	7	.29	
14	.169	1.67	1.90	3.11	.178	3.28	1000	n m	1	.04	1.30
							3000	n m	1	.04	
15	.171	2.13	2.53	3.15	.203	3.74	1000	n m	0	0	2.80
							3000	n m	0	0	
							5000	n m	0	0	
16	.188	2.13	2.53	3.46	.220	4.05	1000	n m	2	.08	5.20
							3000	n m	3	.12	
							5000	n m	9	.37	
17	.169	2.76	3.57	3.11	.221	4.07	1000	n m	0	0	8.00
							3000	n m	2	.08	
							5000	n m	2	.08	
18	.190	2.79	3.49	3.50	.241	4.44	1000	n m	25	1.03	13.50
							1100	n m	>50	>2	

Dn = 0.0411 m
delta = 1.322
cotα = 1.33

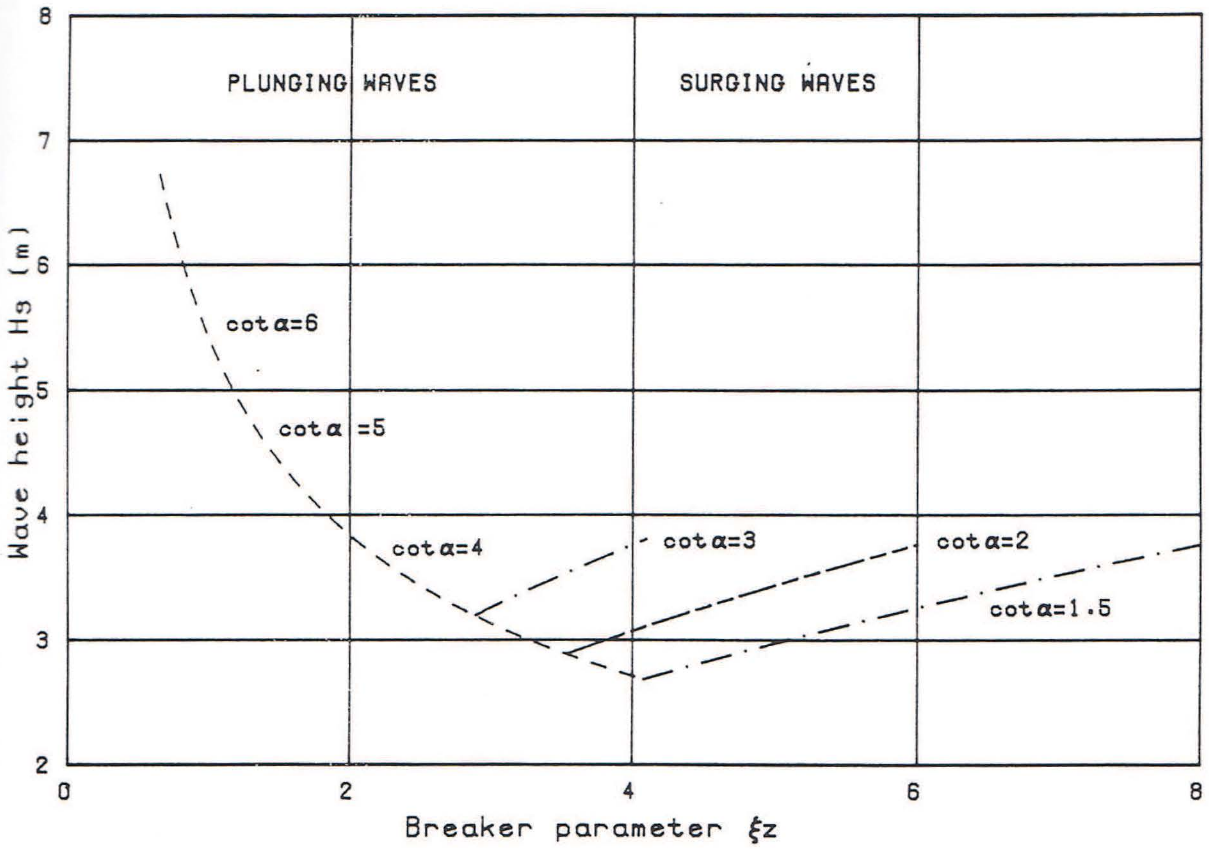
N = number of waves
S = damage measured with profiler
number = total number of displaced accropode
No = total number related to a width of 1 Dn
n m = profile not measured

Table 1 Test results of ACCROPODE (R)

structure	Tz s	no damage, S<1		no damage, No=0	
		Hs/ΔDn	Ksiz	Hs/ΔDn	Ksiz
overtopped	1.70	3.70	3.55	3.70	3.55
overtopped	2.15	4.10	4.27	3.80	4.44
overtopped	2.80	3.70	5.85	3.50	6.02
non-overtopped	1.70			3.40	3.71
non-overtopped	2.13			3.80	4.39
non-overtopped	2.78			4.00	5.59

structure	Tz s	large damage, S>2		large damage, No>0.5	
		Hs/ΔDn	Ksiz	Hs/ΔDn	Ksiz
overtopped	1.70	4.10	3.38	4.10	3.38
overtopped	2.15	4.30	4.17	4.40	4.12
overtopped	2.80	3.90	5.70	3.90	5.70
non-overtopped	1.70			3.90	3.46
non-overtopped	2.13			4.10	4.23
non-overtopped	2.78			4.20	5.46

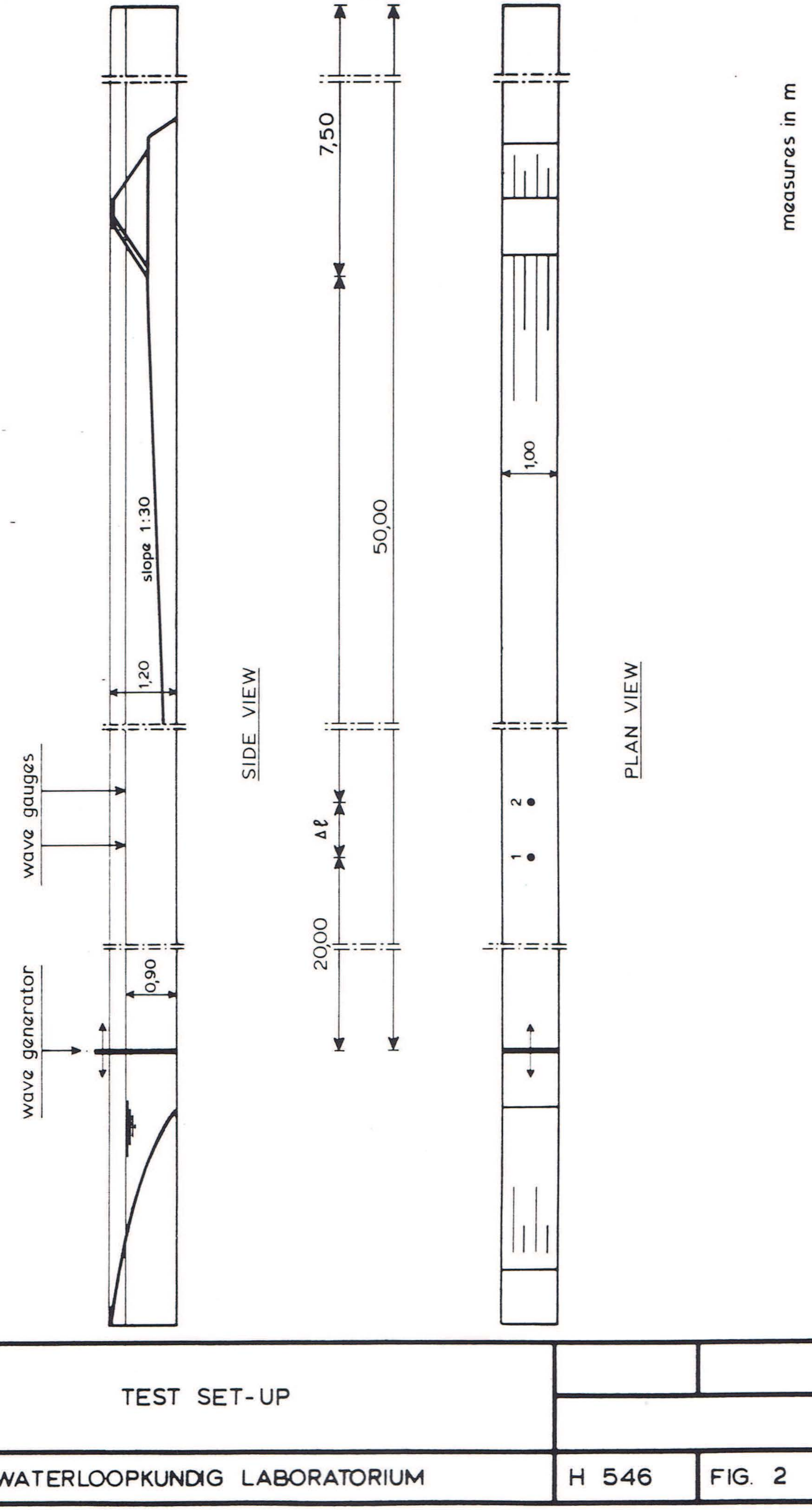
Table 2 Results for fixed damage levels



Dn50=1m Δ=1.6 S=5 P=0.5 N=3000

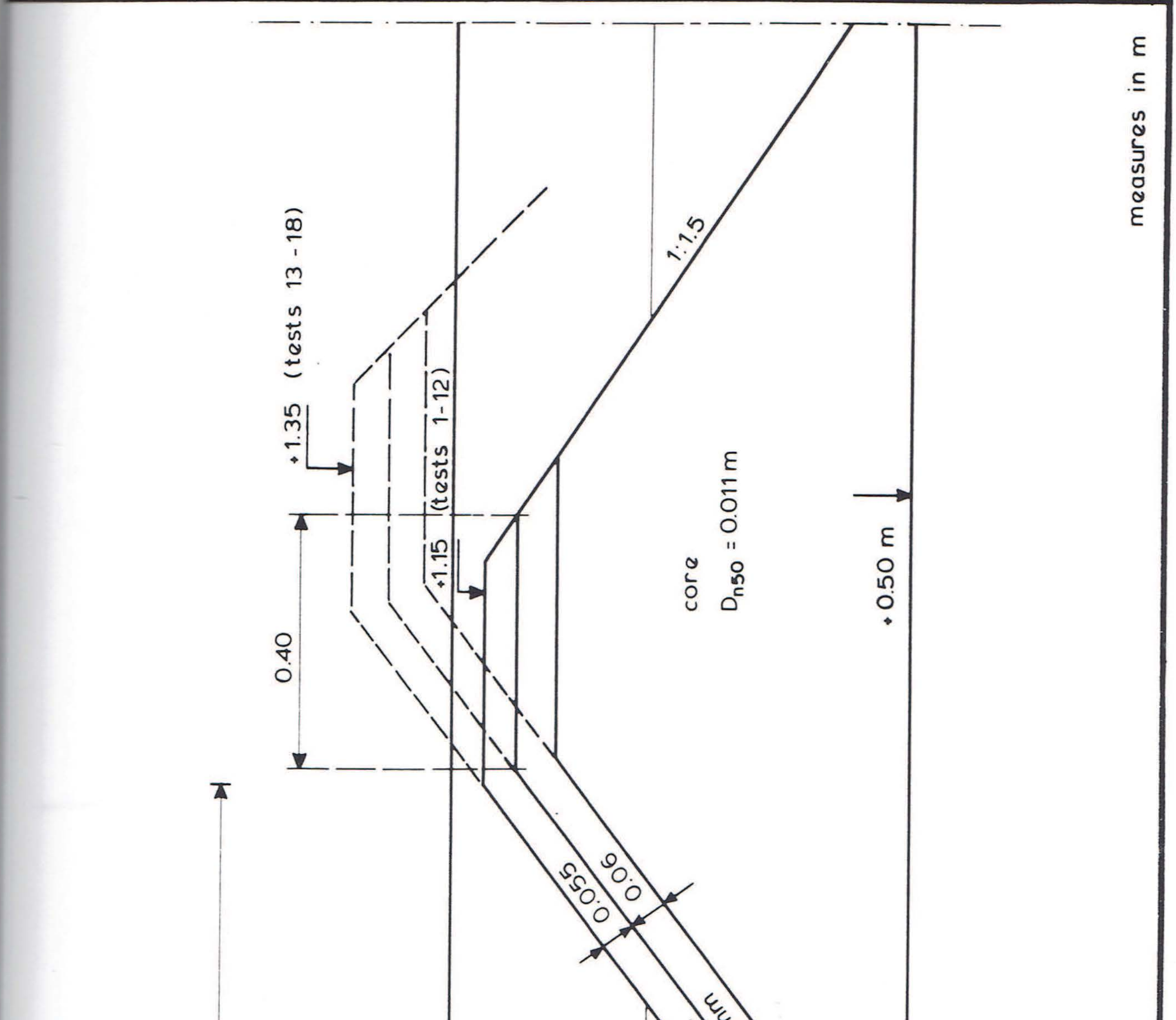
STABILITY OF RUBBLE MOUND BREAKWATERS

DELFT HYDRAULICS LABORATORY | H 546 | FIG. 1



TEST SET-UP

WATERLOOPKUNDIG LABORATORIUM | H 546 | FIG. 2



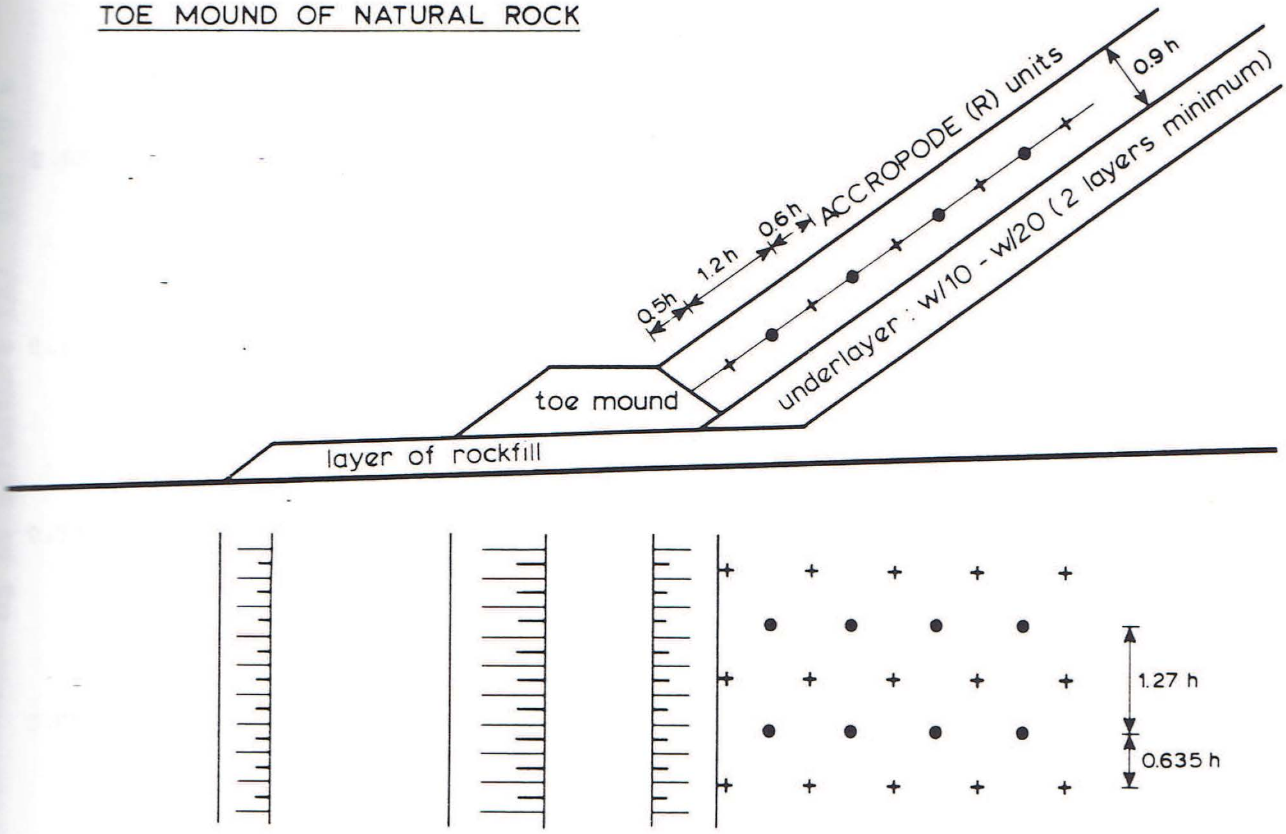
CROSS-SECTION OF BREAKWATER

DELFT HYDRAULICS LABORATORY

H 546

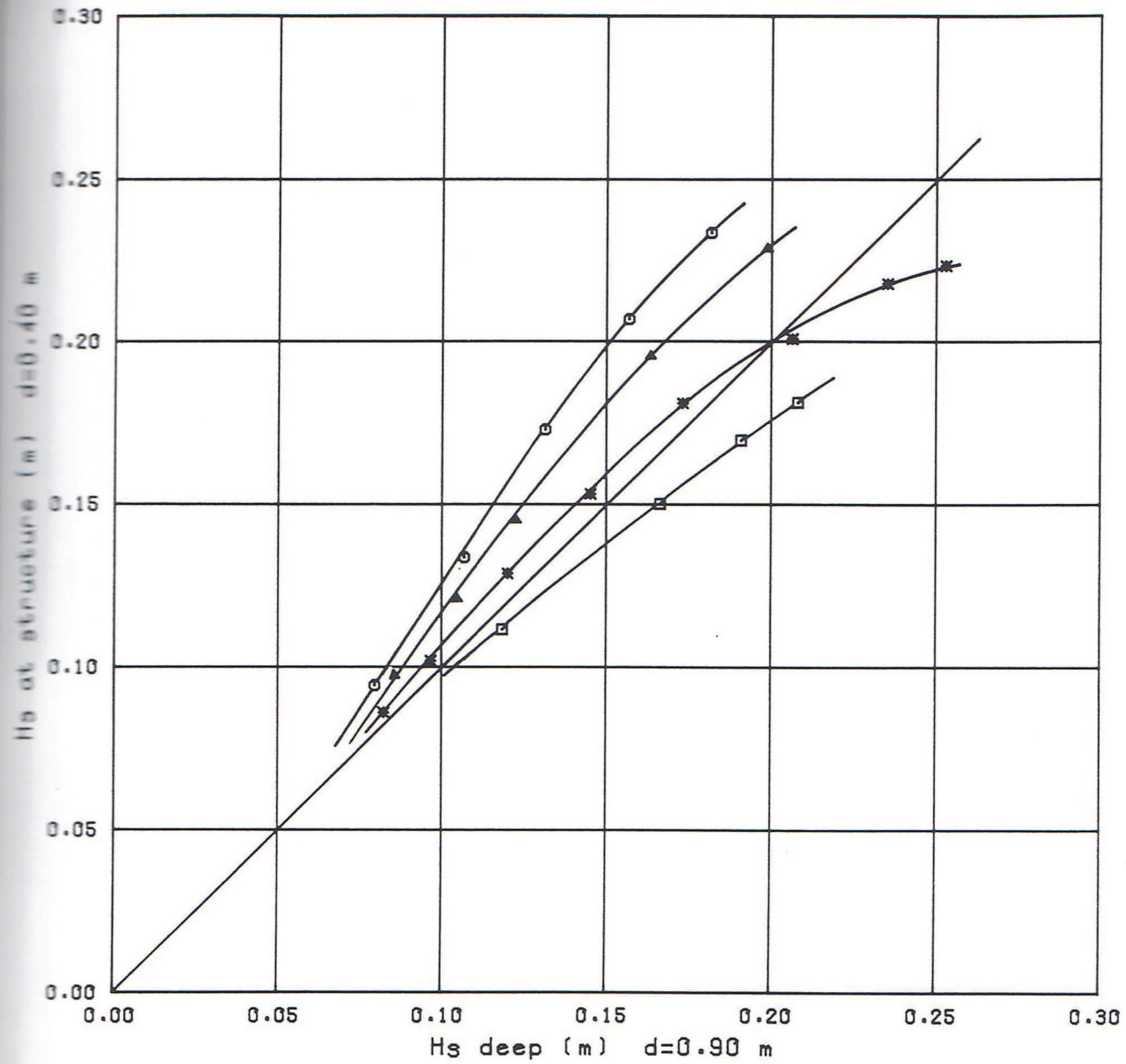
FIG. 3

TOE MOUND OF NATURAL ROCK



h = height of ACCROPODE (R) block
w = weight of ACCROPODE (R) block

POSITIONING PLAN OF ACCROPODE (R) ACCORDING TO SOGREAH		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 4



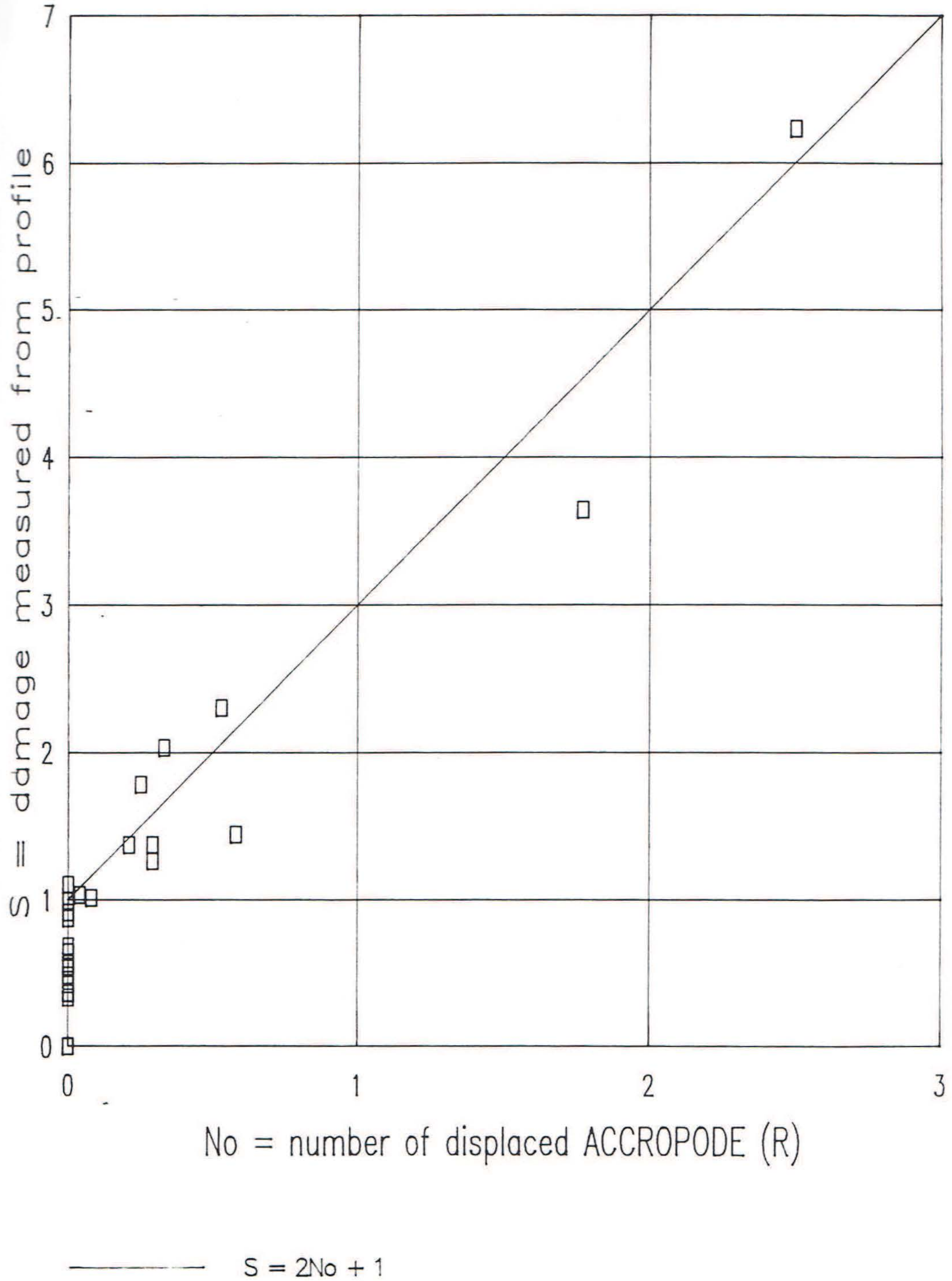
□ = 1.4 s

✱ = 1.7 s

▲ = 2.15 s

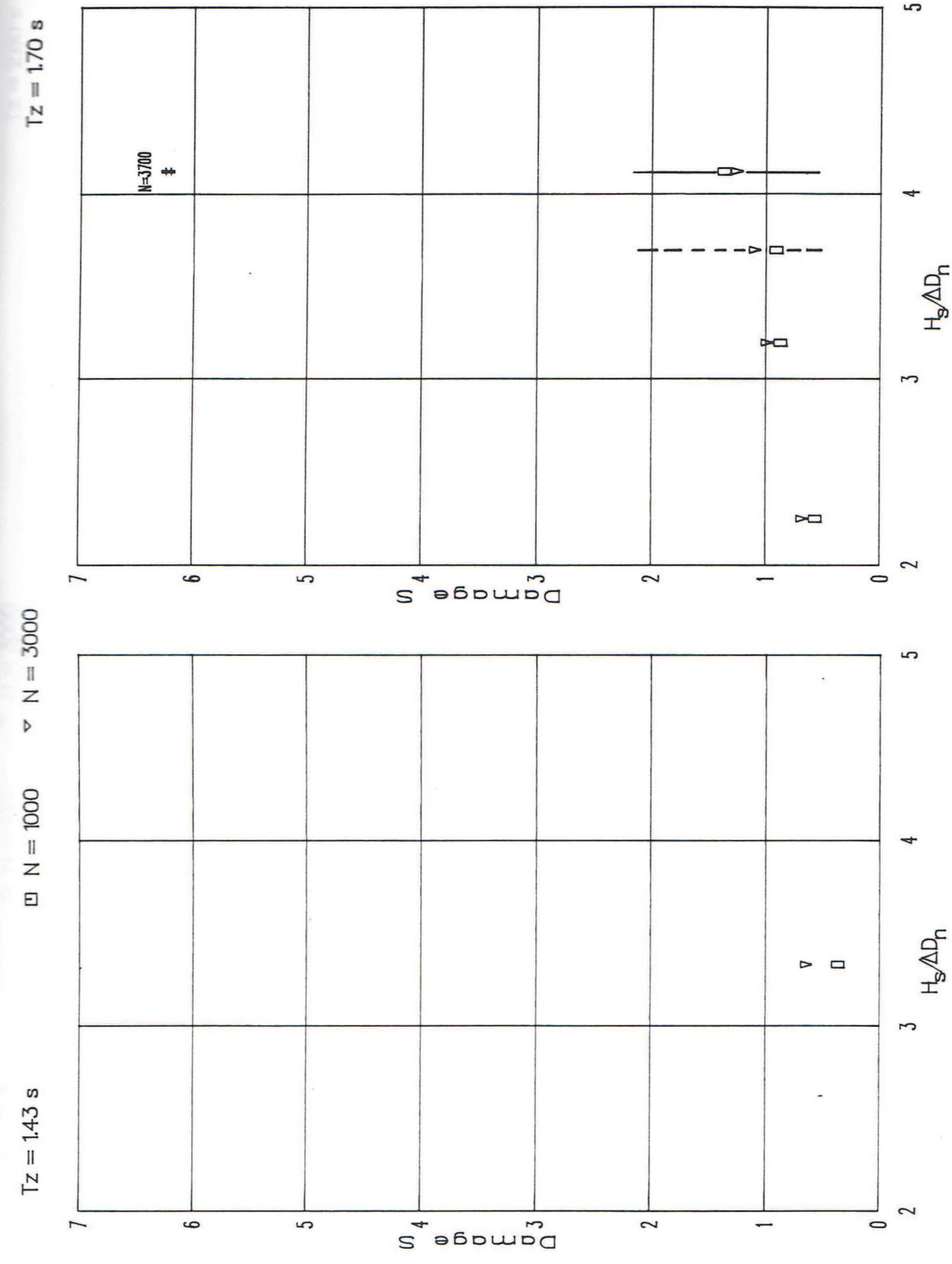
⊙ = 2.8 s

RELATION BETWEEN WAVE HEIGHT ON DEEP WATER AND AT STRUCTURE		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 5



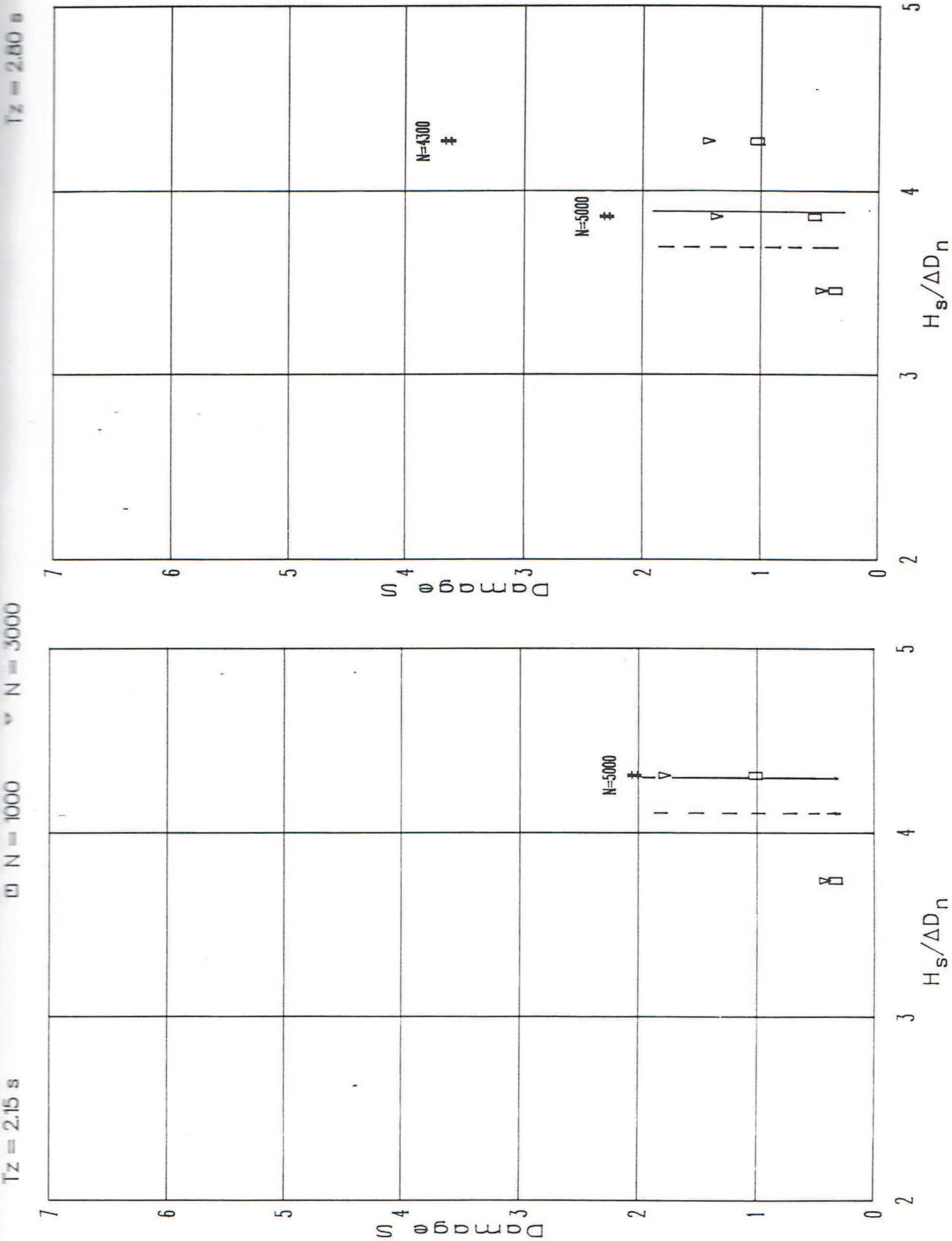
RELATION BETWEEN S AND No

DELFT HYDRAULICS LABORATORY | H 546 | FIG. 6



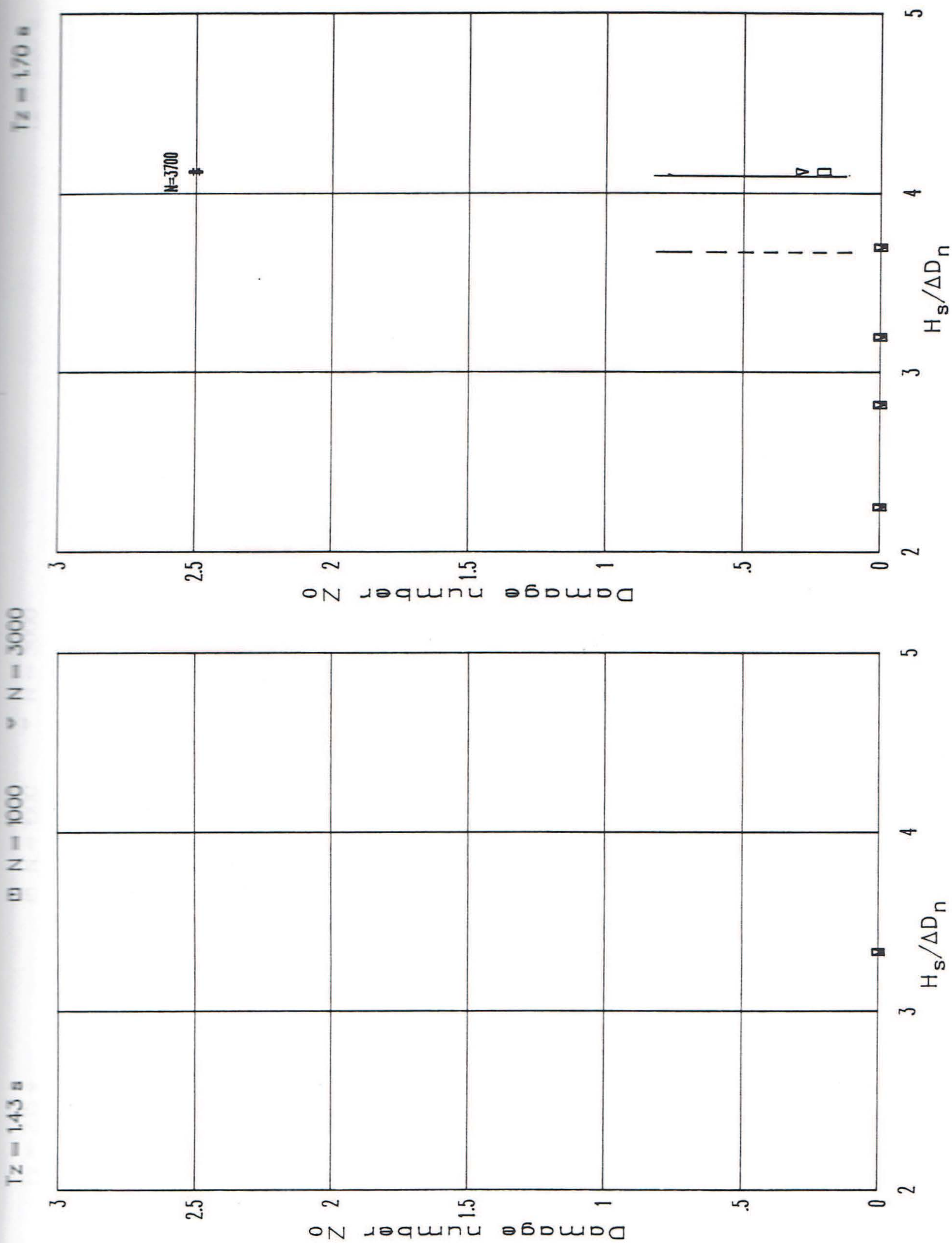
Breakwater with ACCROPODE (R) cot α= 1.33 PM spectrum

WAVE HEIGHT – DAMAGE CURVE FOR OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 7



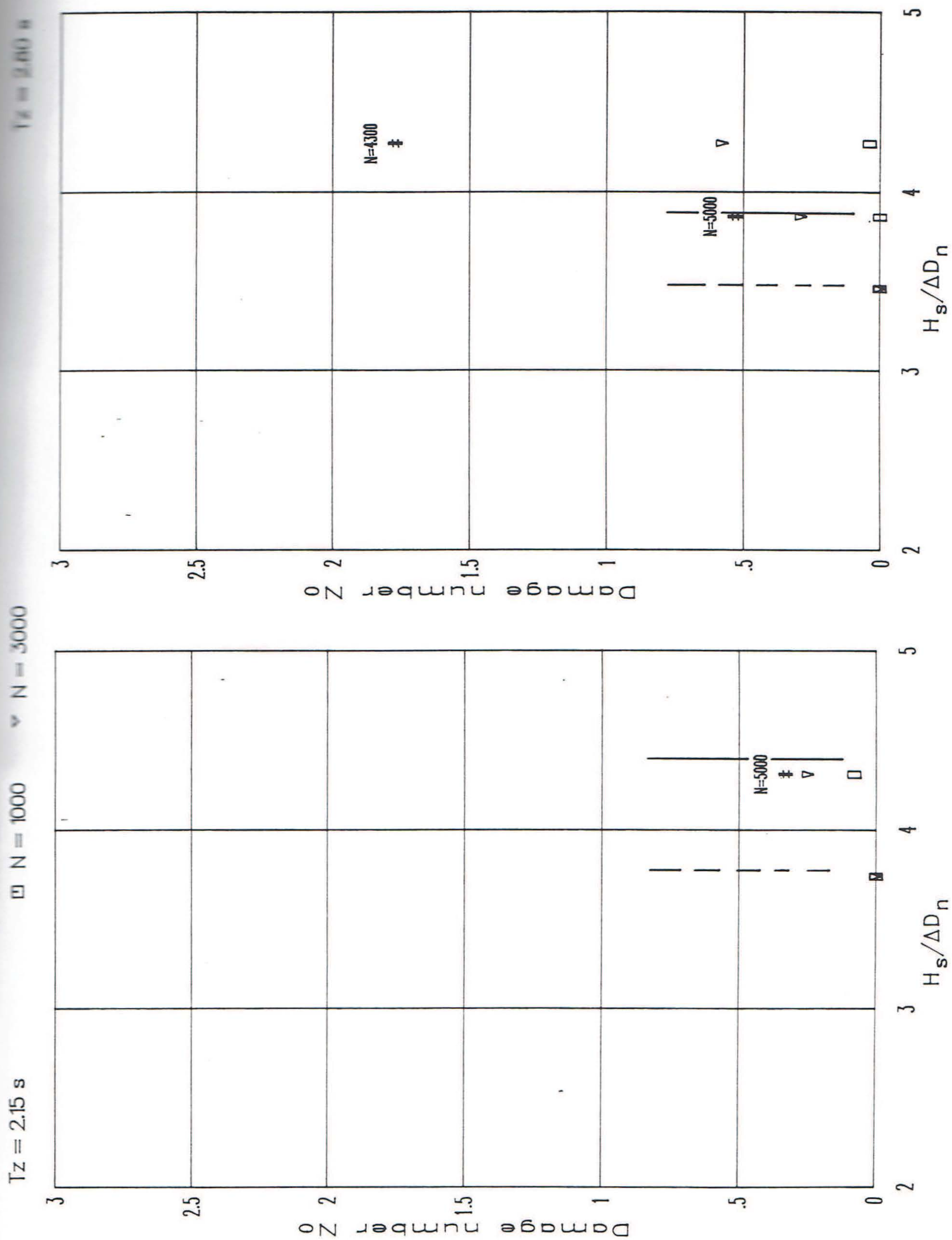
Breakwater with ACCROPODE (R) cotα= 1.33 PM spectrum

WAVE HEIGHT – DAMAGE CURVE FOR OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 8



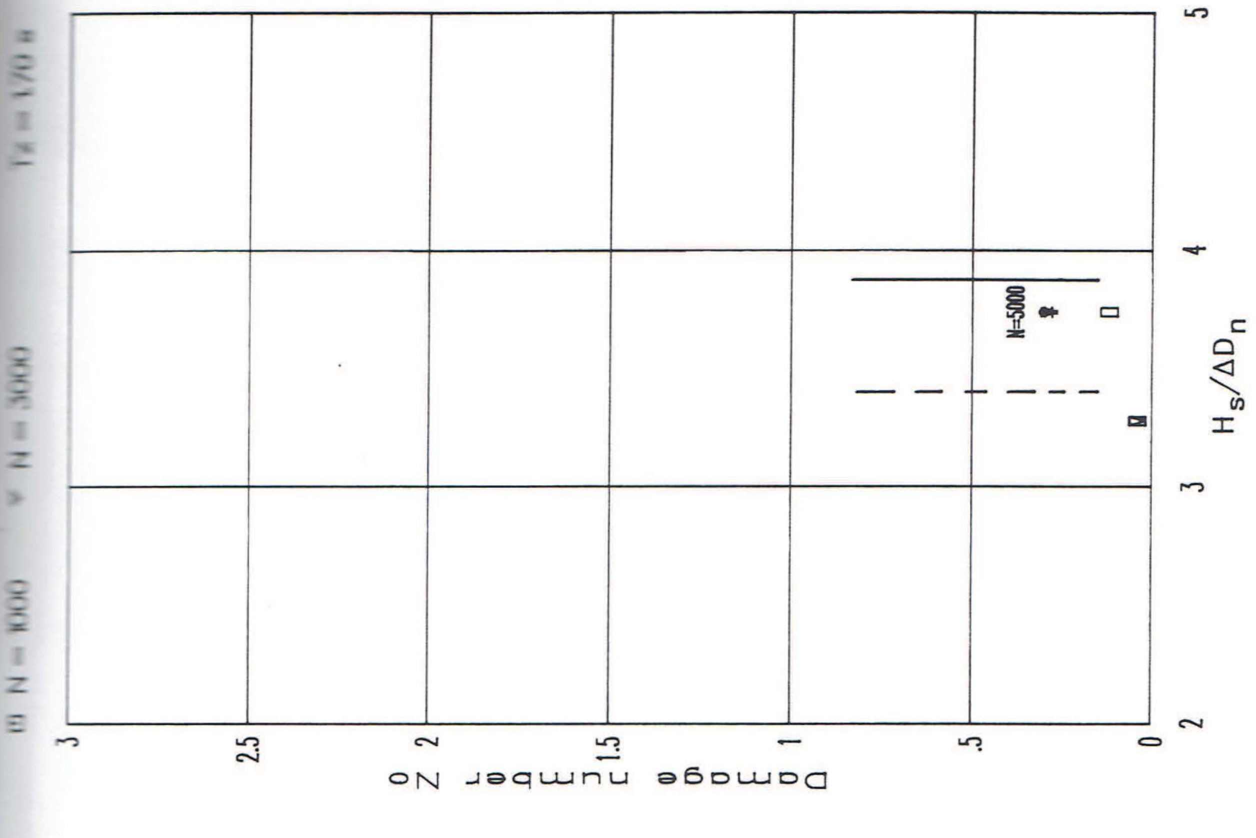
Breakwater with ACCROPODE (R) cot α= 1.33 PM spectrum

WAVE HEIGHT – DAMAGE CURVE FOR OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 9



Breakwater with ACCROPODE (R) cot α= 1.33 PM spectrum

WAVE HEIGHT – DAMAGE CURVE FOR OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 10

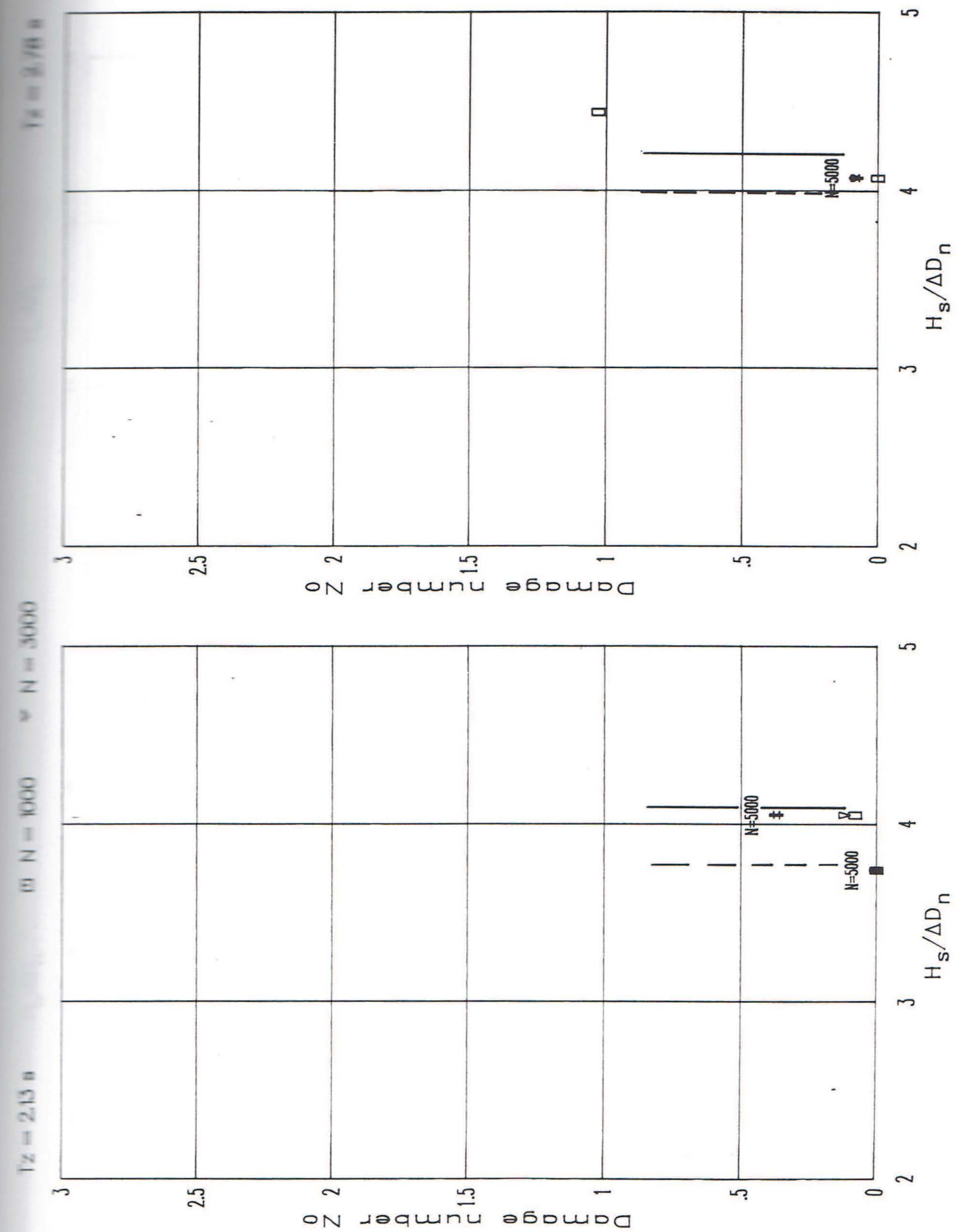


The short wave period of 1.4 s was not tested

as the wave height was limited by wave steepness

Breakwater with ACCROPODE (R) cot α= 1.33 PM spectrum

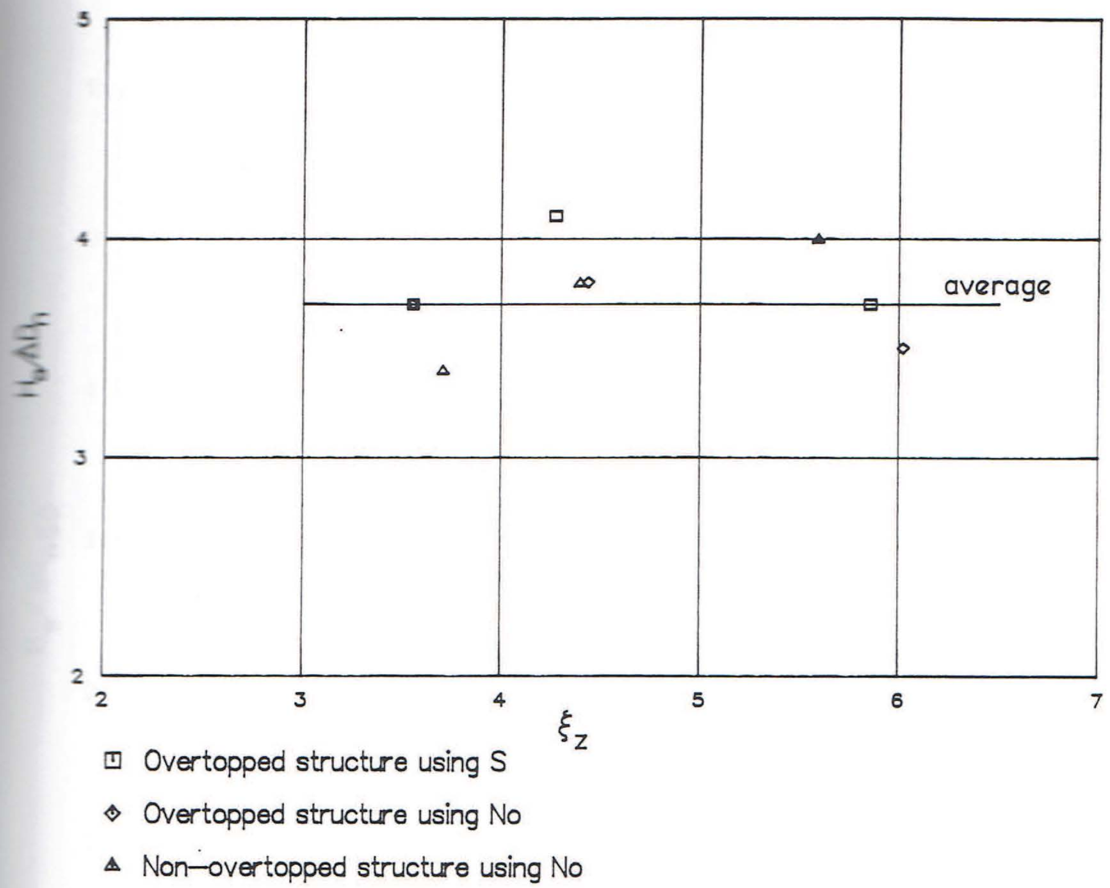
WAVE HEIGHT – DAMAGE CURVE FOR NON–OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 11



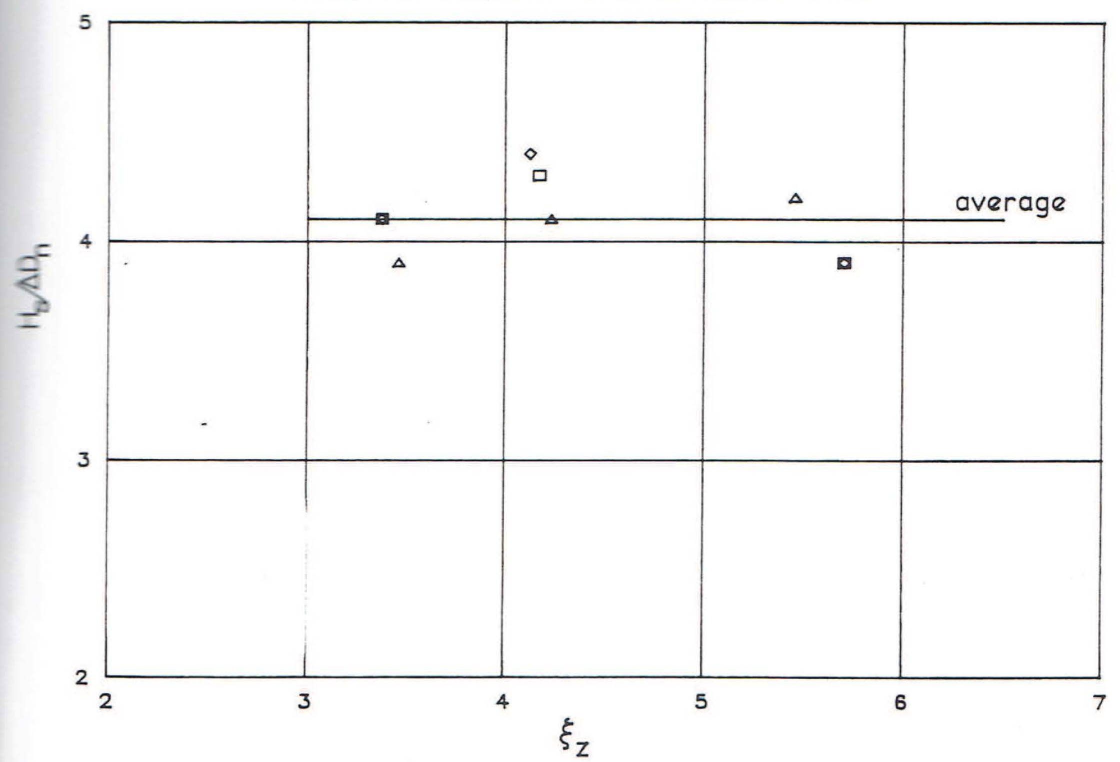
Breakwater with ACCROPODE (R) cot α = 1.33 PM spectrum

WAVE HEIGHT – DAMAGE CURVE FOR NON–OVERTOPPED BREAKWATER		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 12

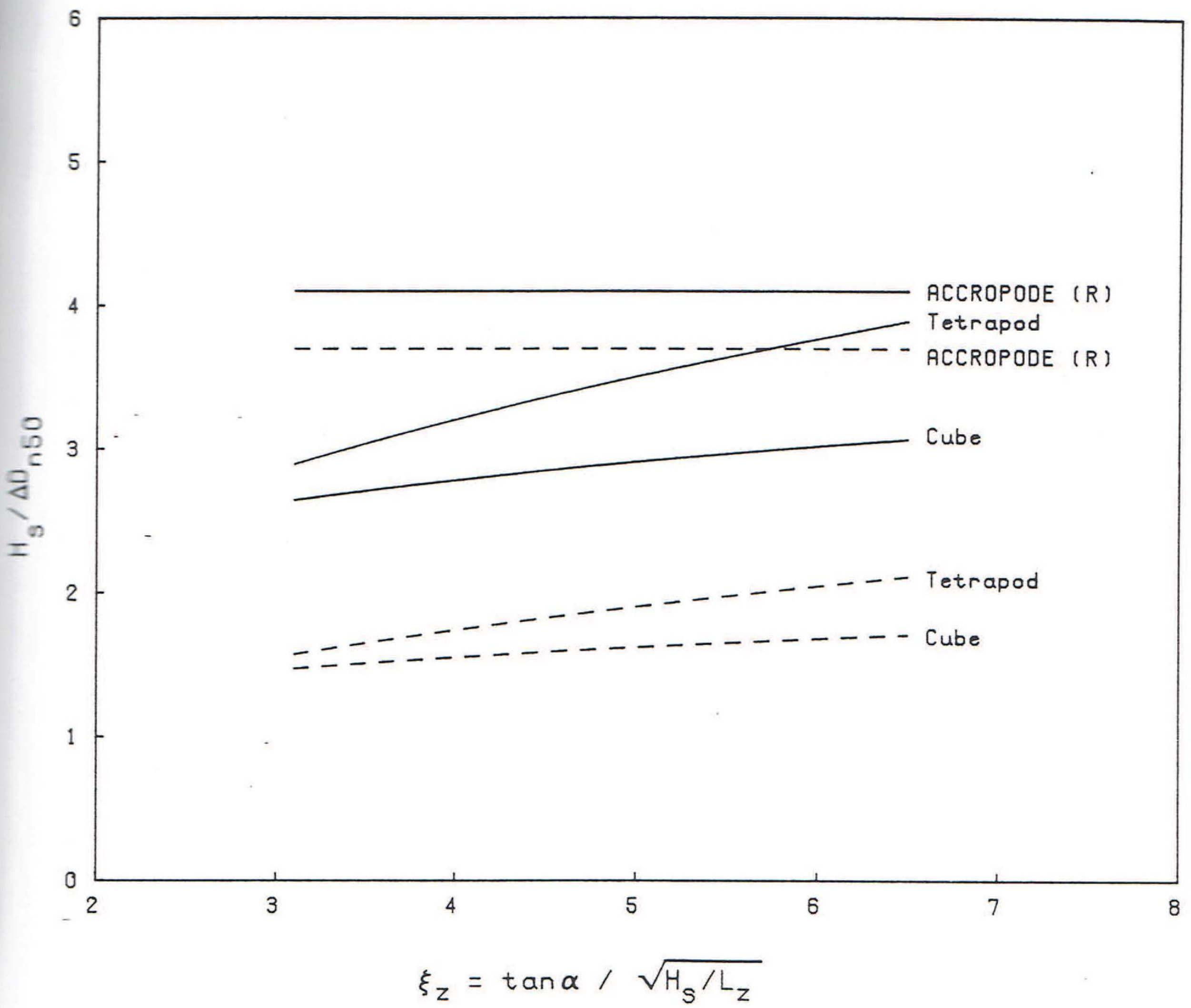
No damage: No=0 or S<1



Large damage, failure: No>0.5 or S>2



STABILITY CURVES FOR NO DAMAGE AND FAILURE		
DELFT HYDRAULICS LABORATORY	H 546	FIG. 13



------ Damage level No = 0

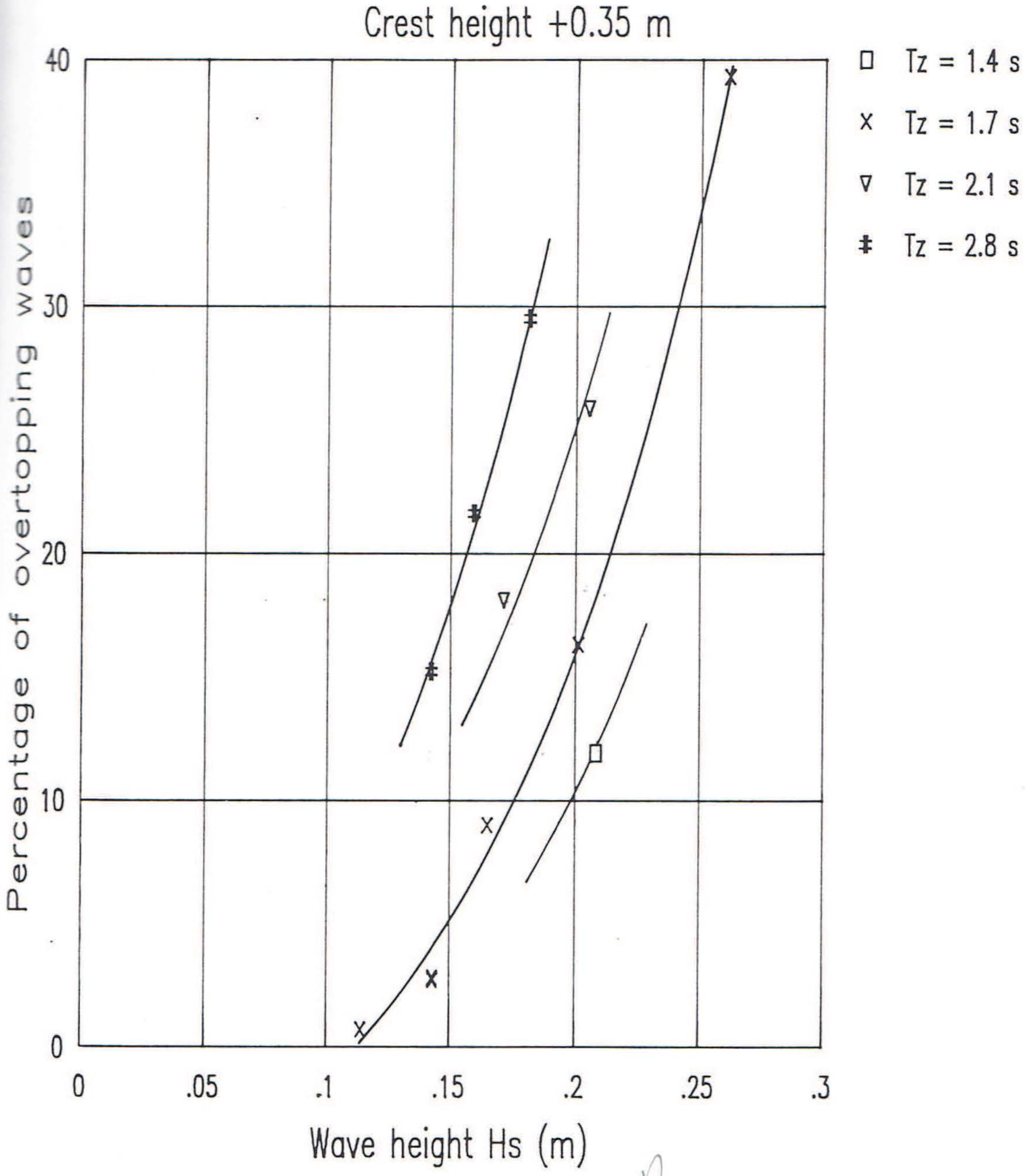
—— Damage level No = 2

Cube and Tetrapod: $\cot\alpha = 1.5$
$N = 3000$

ACCROPODE (R): $\cot\alpha = 4/3$

COMPARISON OF STABILITY FOR
CUBE, TETRAPOD AND ACCROPODE (R)

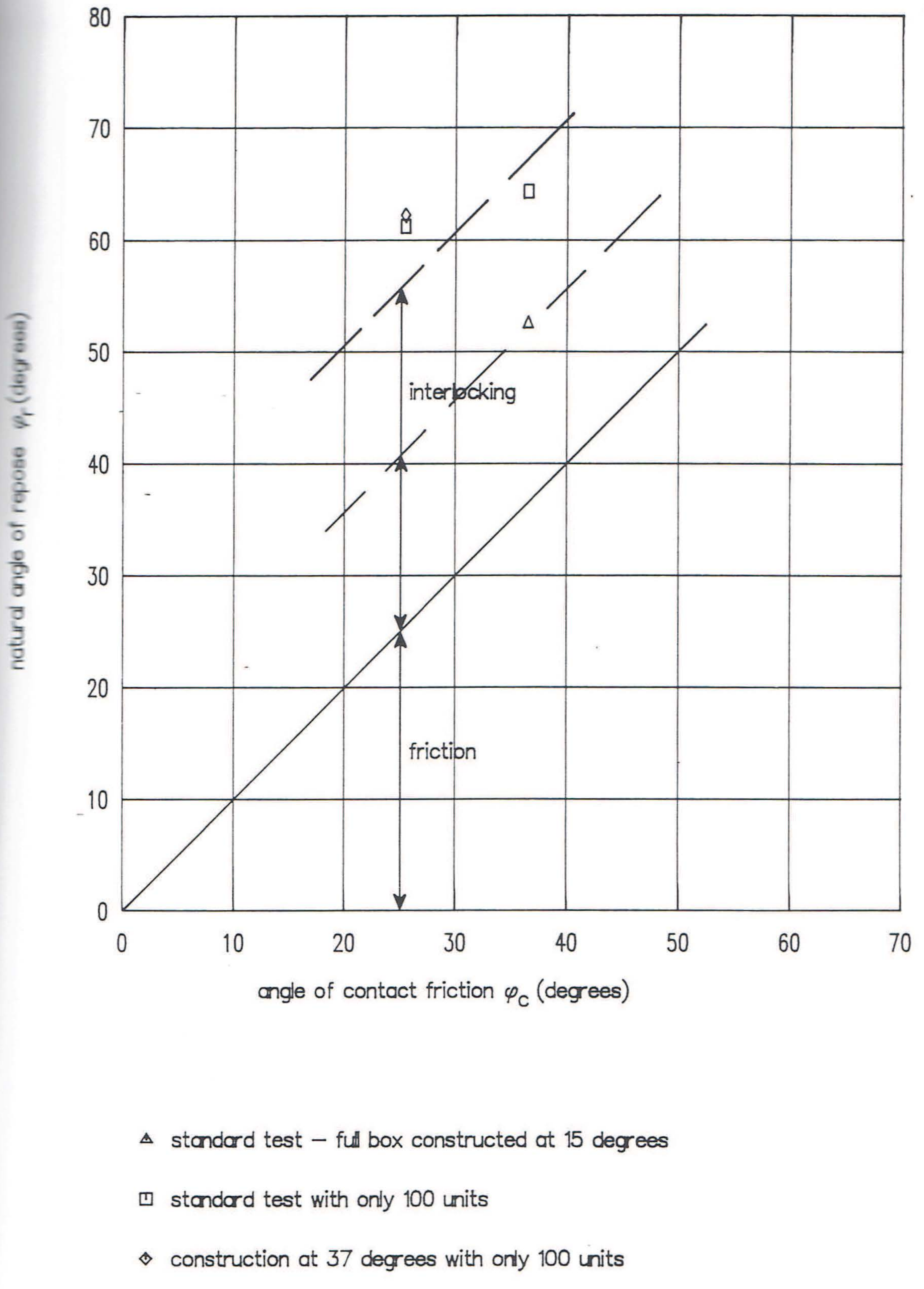
DELFT HYDRAULICS LABORATORY | H 546 | FIG.14



deep water? je.

RESULTS ON OVERTOPPING

DELFT HYDRAULICS LABORATORY | H 546 | FIG. 15

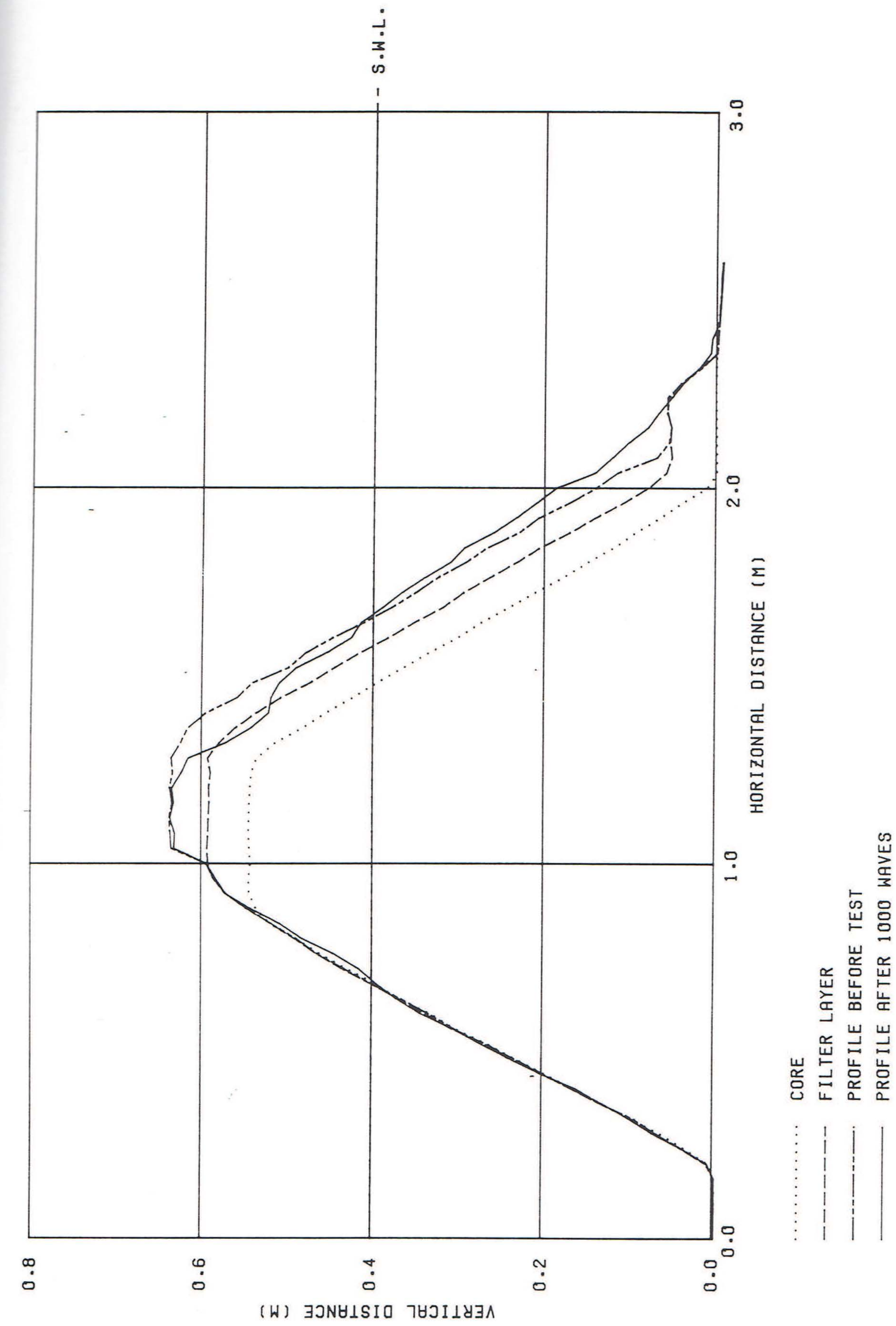


RELATION BETWEEN NATURAL ANGLE OF REPOSE AND ANGLE OF CONTACT FRICTION FOR ACCROPODE (R)

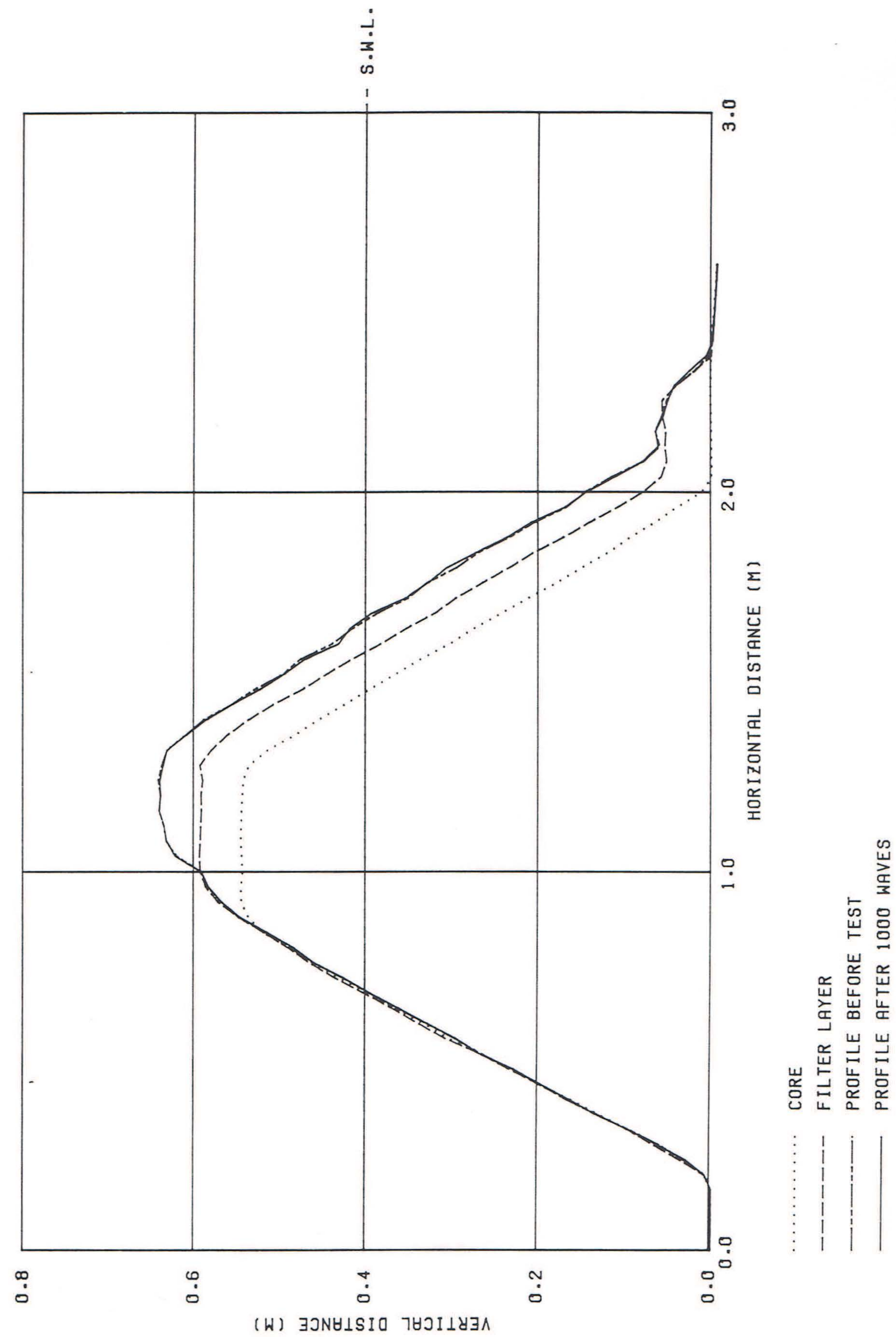
DELFT HYDRAULICS LABORATORY

H 546

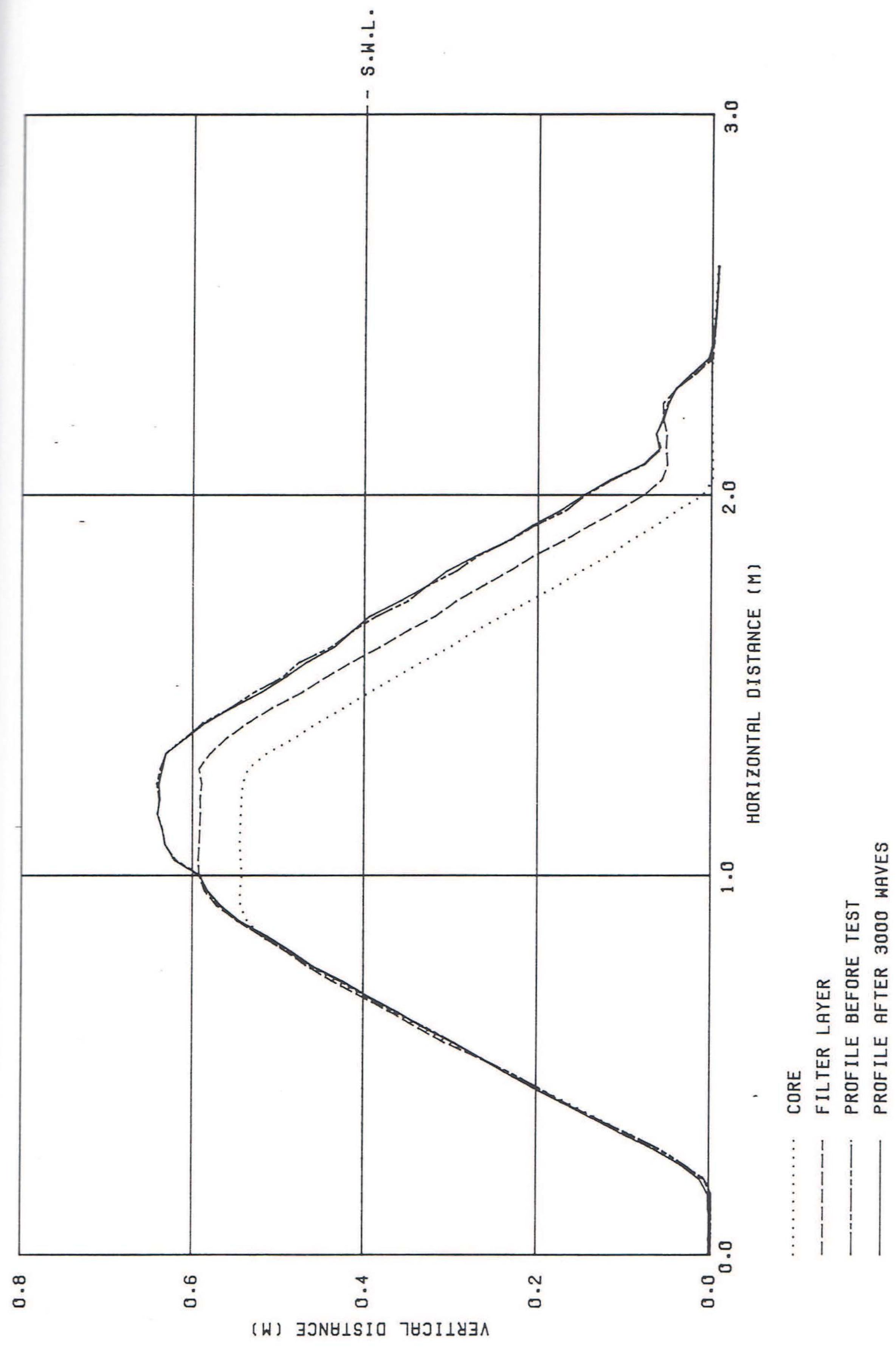
FIG. 16



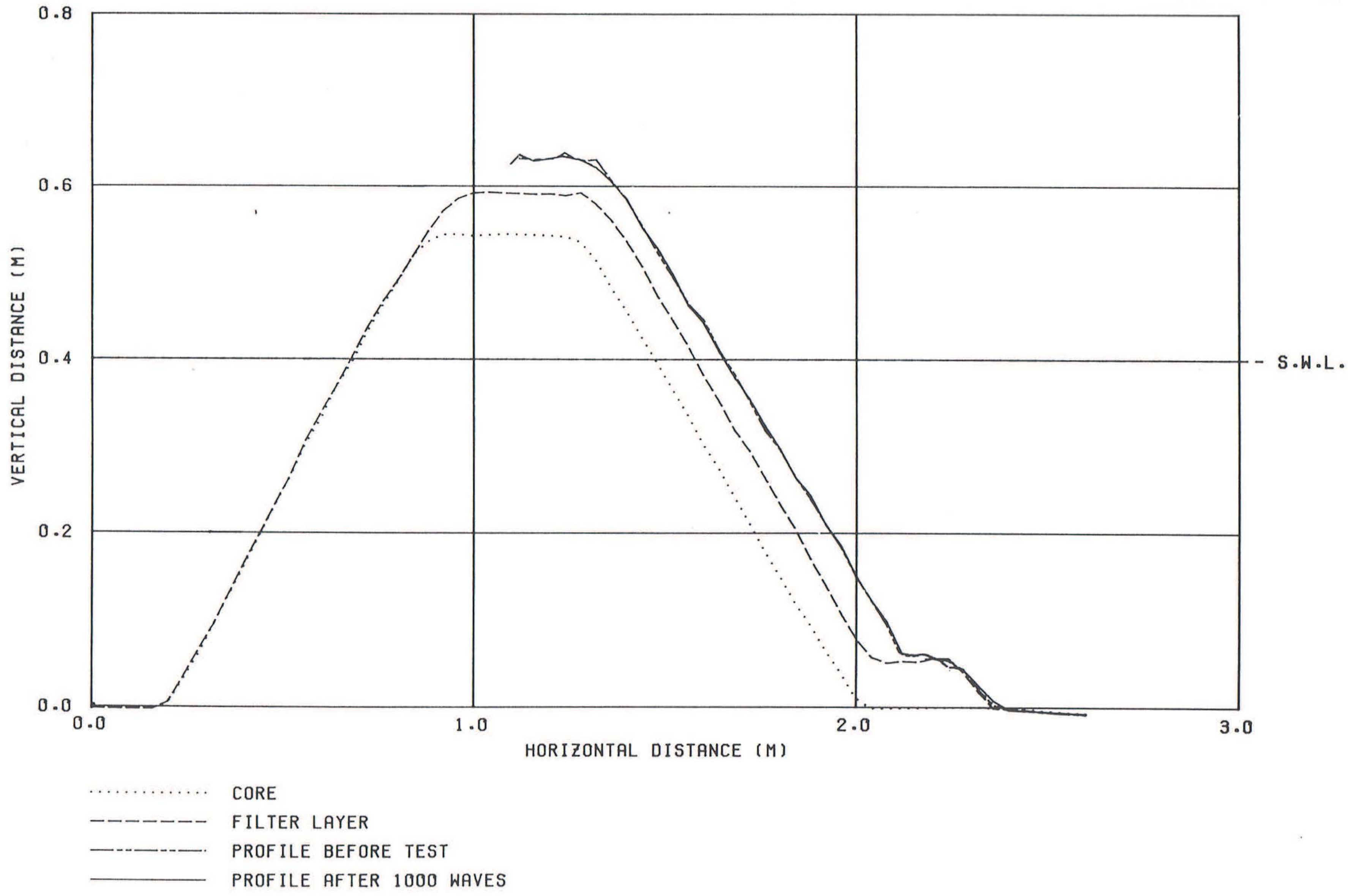
PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P001	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A1



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P002	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A2



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P002	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A3

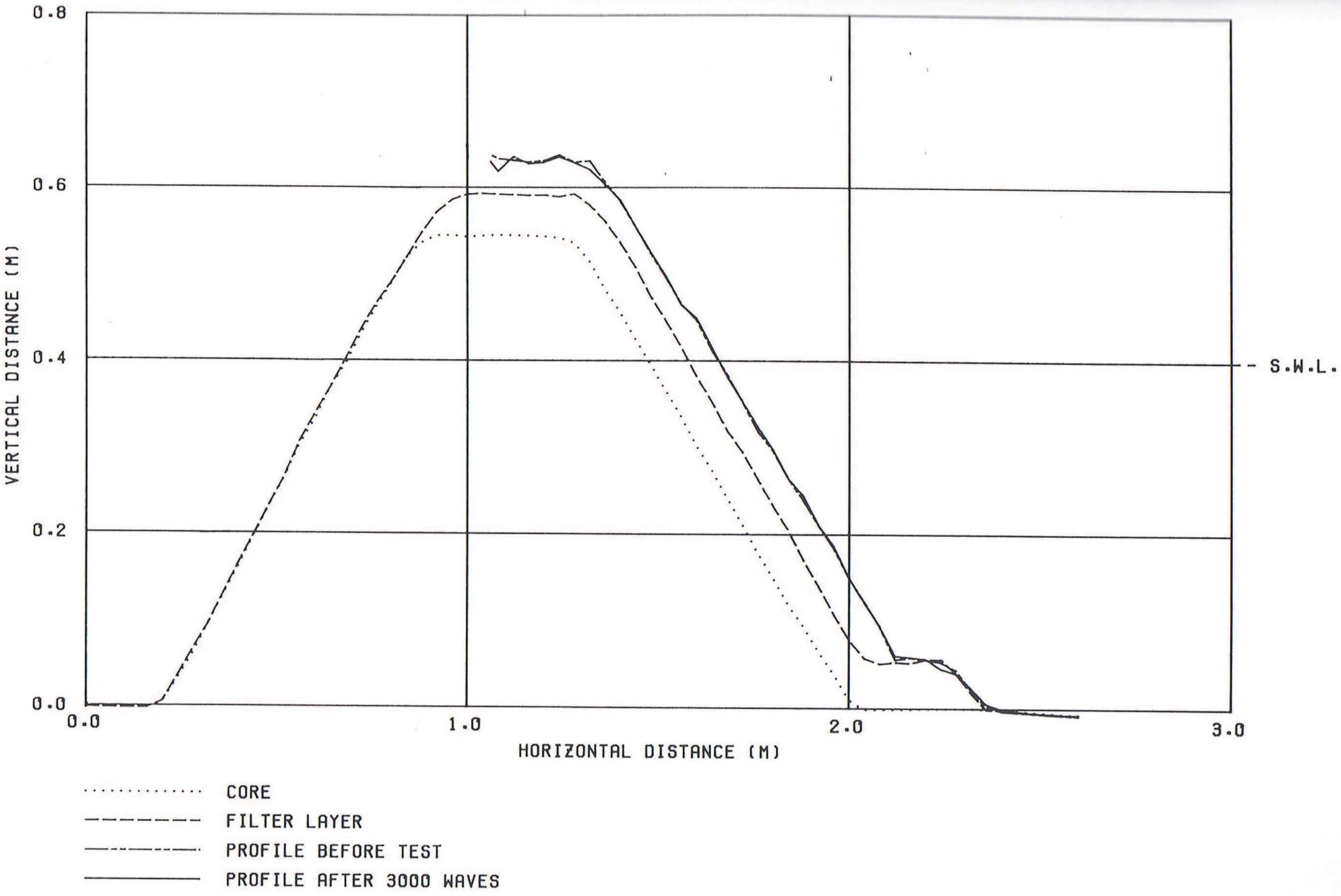


PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)
DELFT HYDRAULICS LABORATORY

P003

H 546

FIG. A4



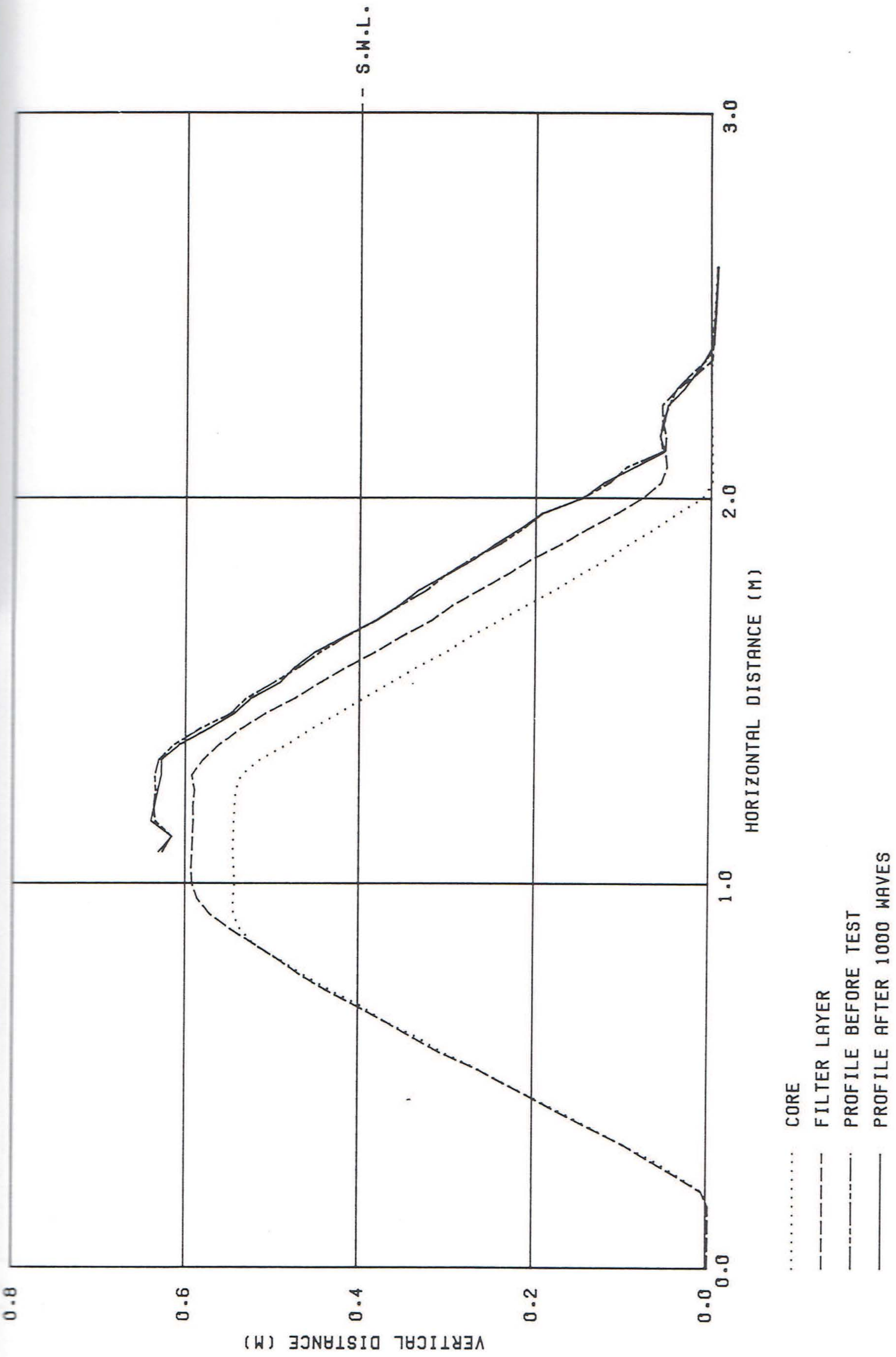
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

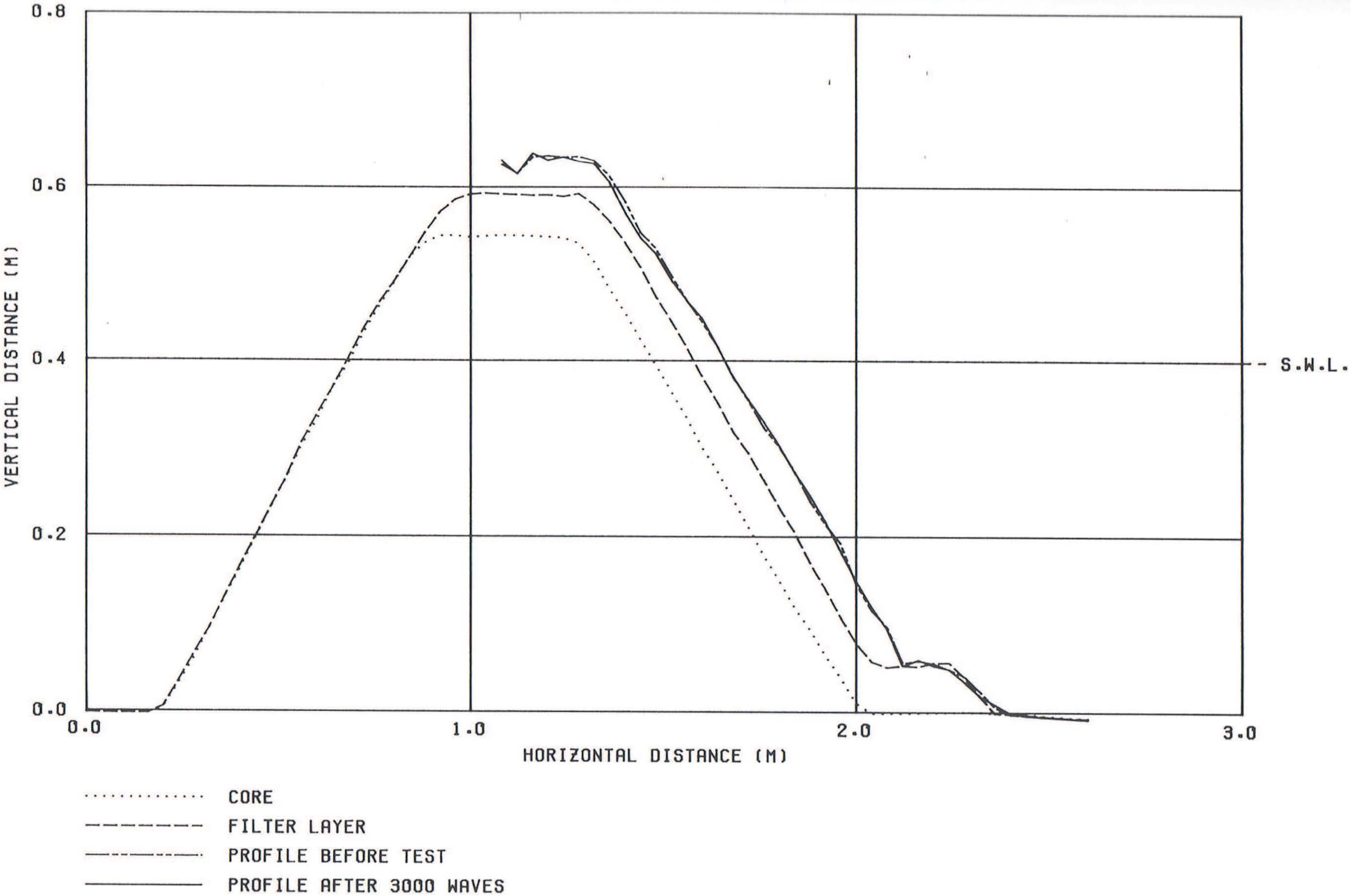
P003

H 546

FIG. A5



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P004	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A6



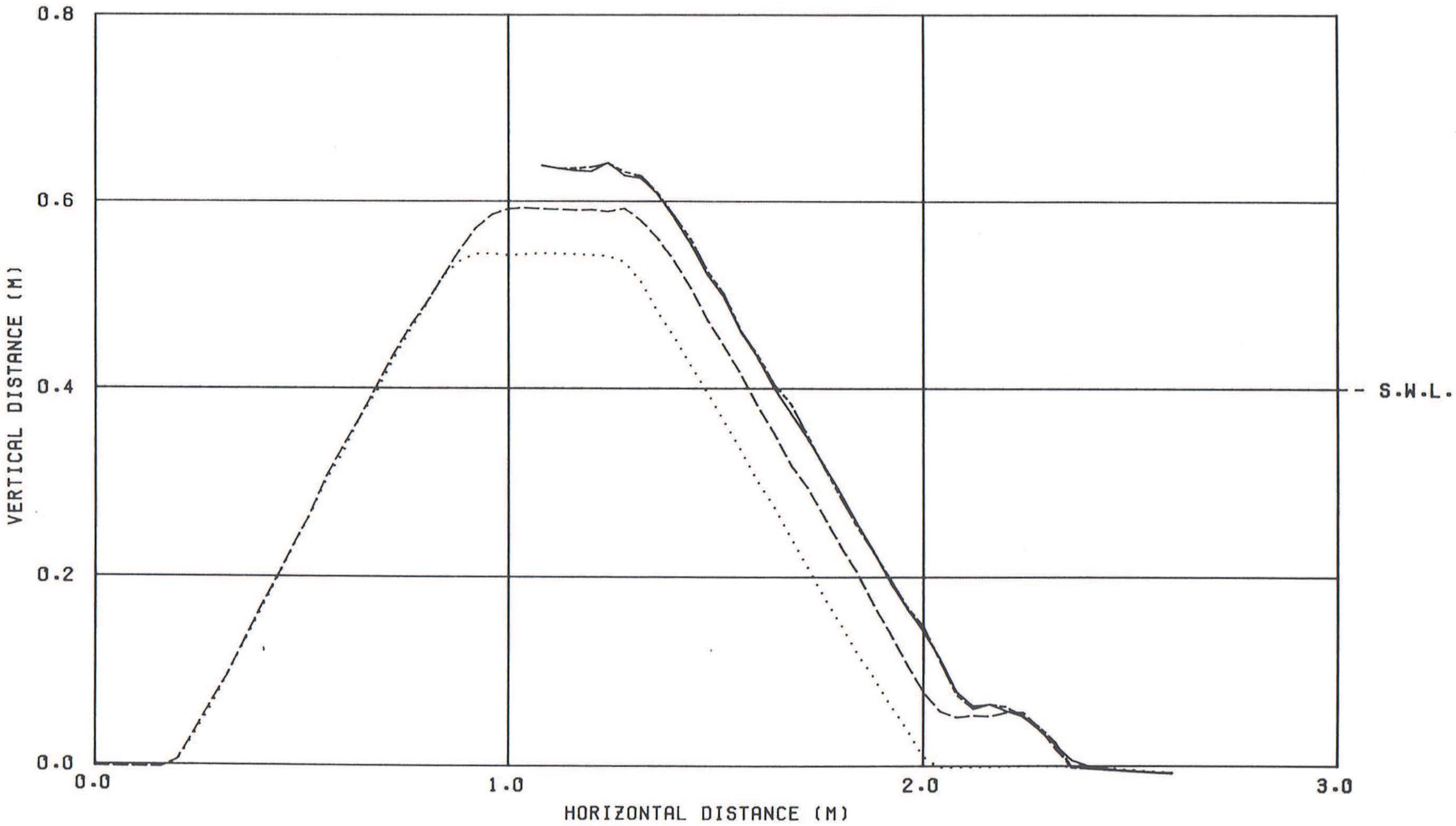
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

P004

H 546

FIG. A7



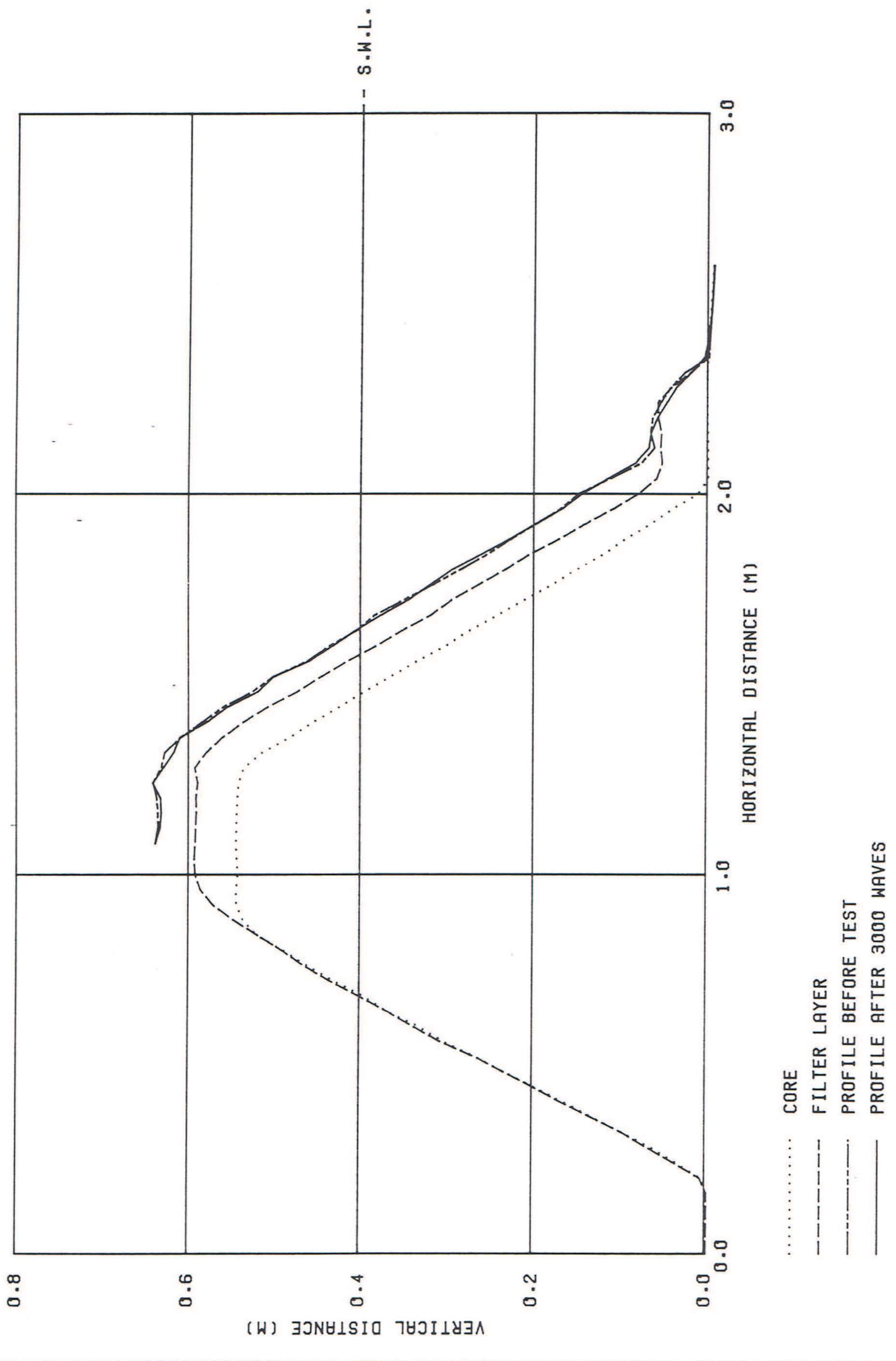
CORE
FILTER LAYER
PROFILE BEFORE TEST
PROFILE AFTER 1000 WAVES

PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)
DELFT HYDRAULICS LABORATORY

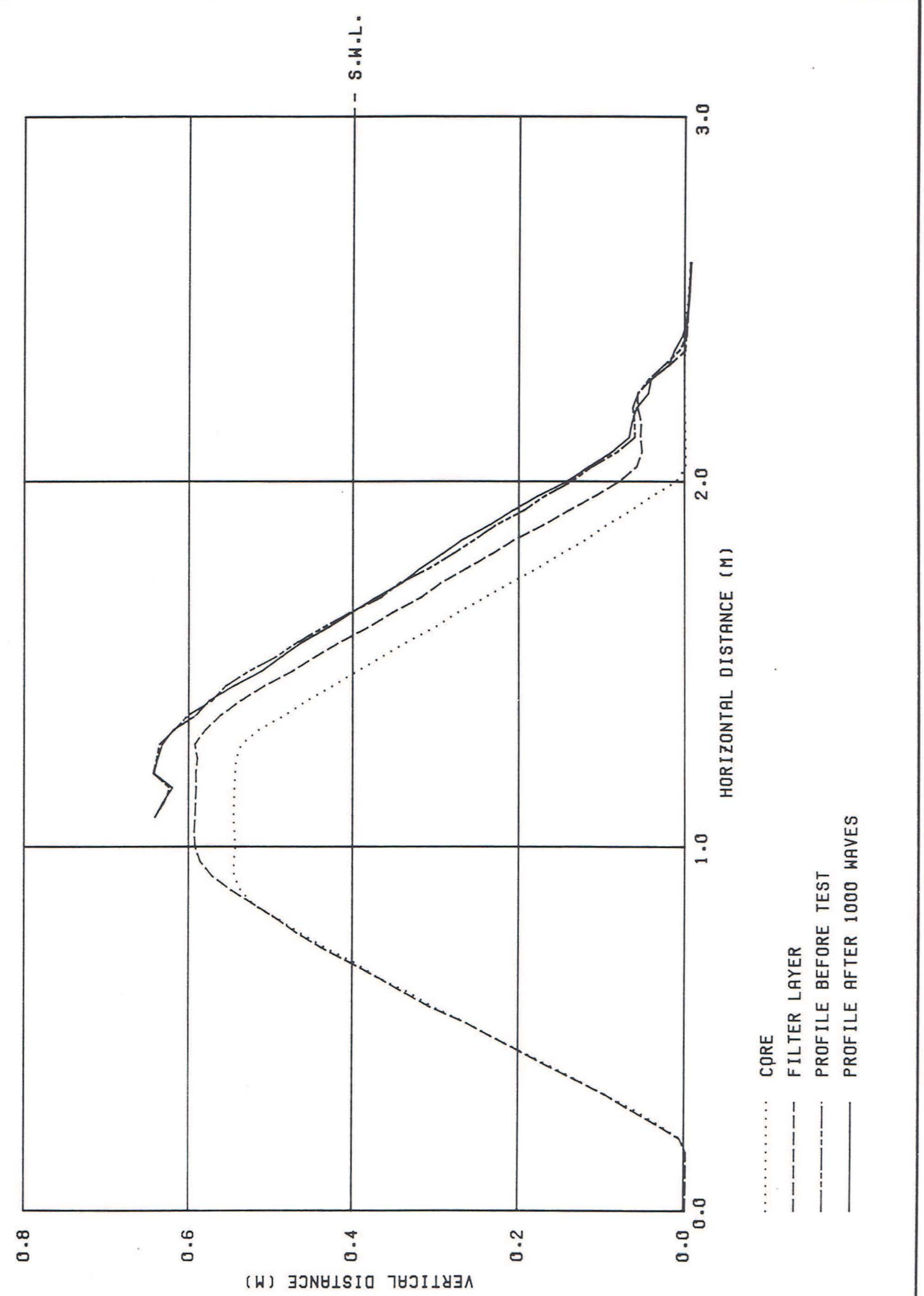
P005

H 546

FIG. A8



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P005	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A9



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P006	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A10

PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

P006

H 546

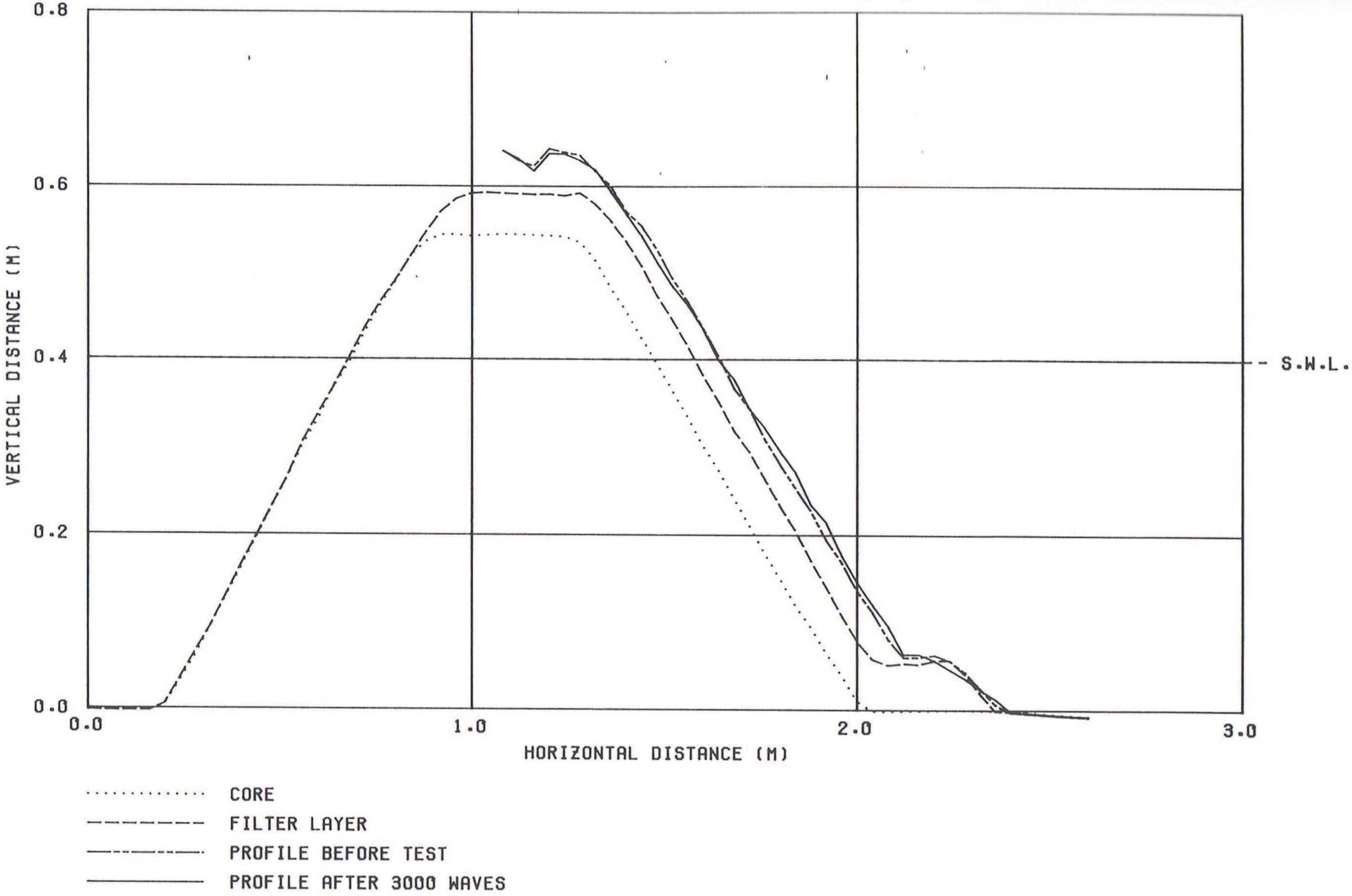
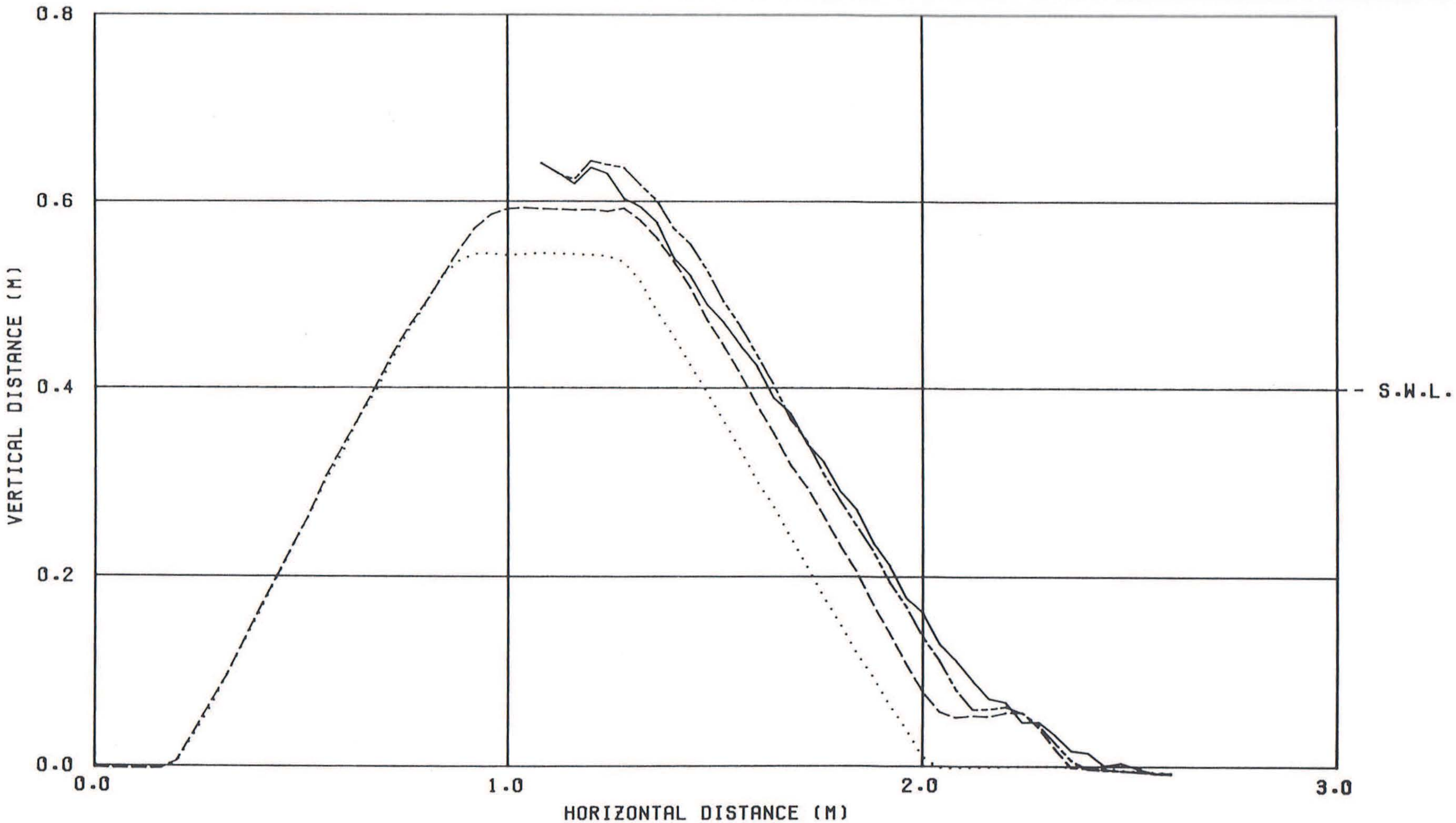


FIG. A11

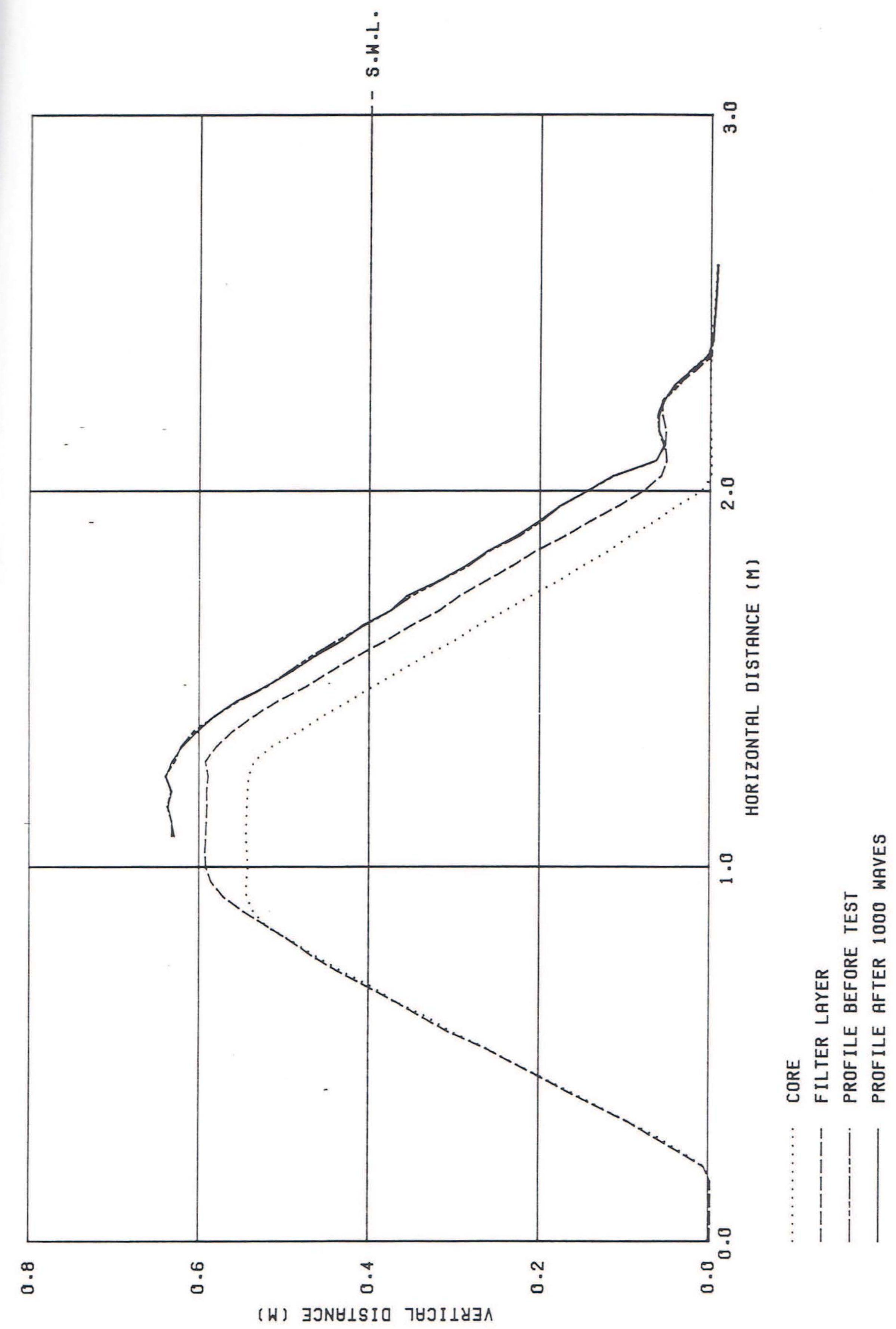
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

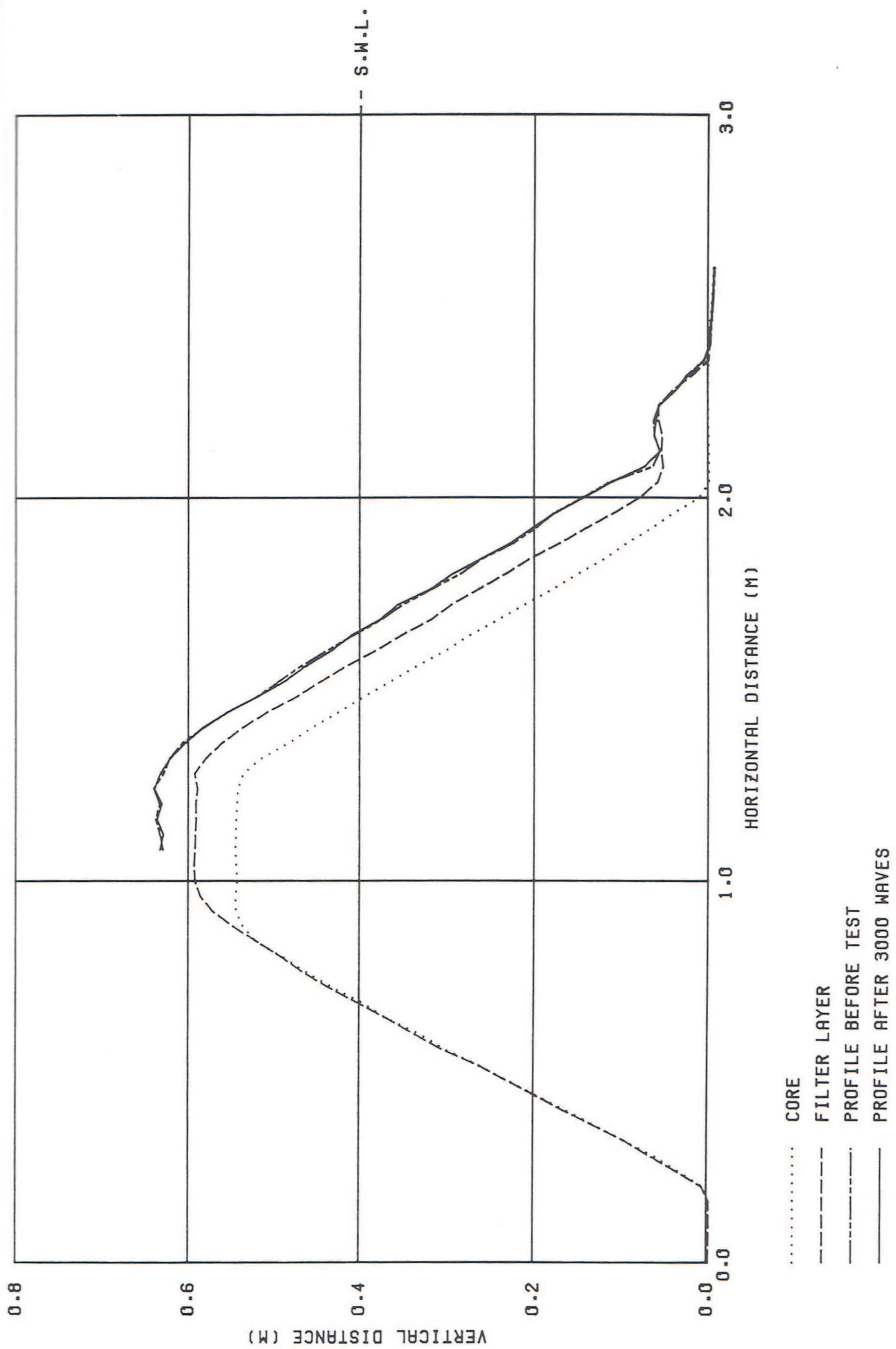
H 546	FIG. A12
P006	



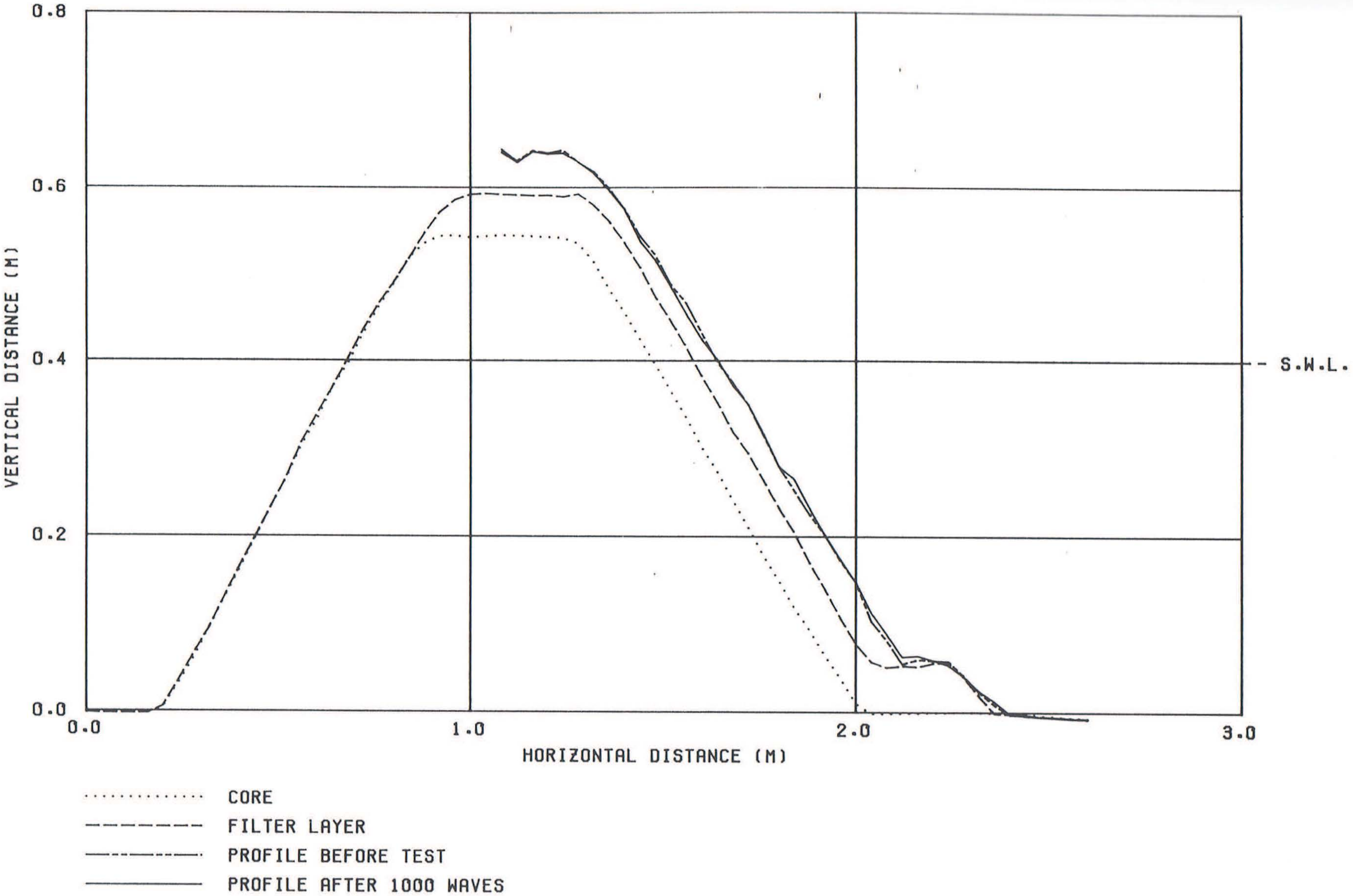
CORE
FILTER LAYER
PROFILE BEFORE TEST
PROFILE AFTER 3700 WAVES



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P007	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A13



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P007	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A14



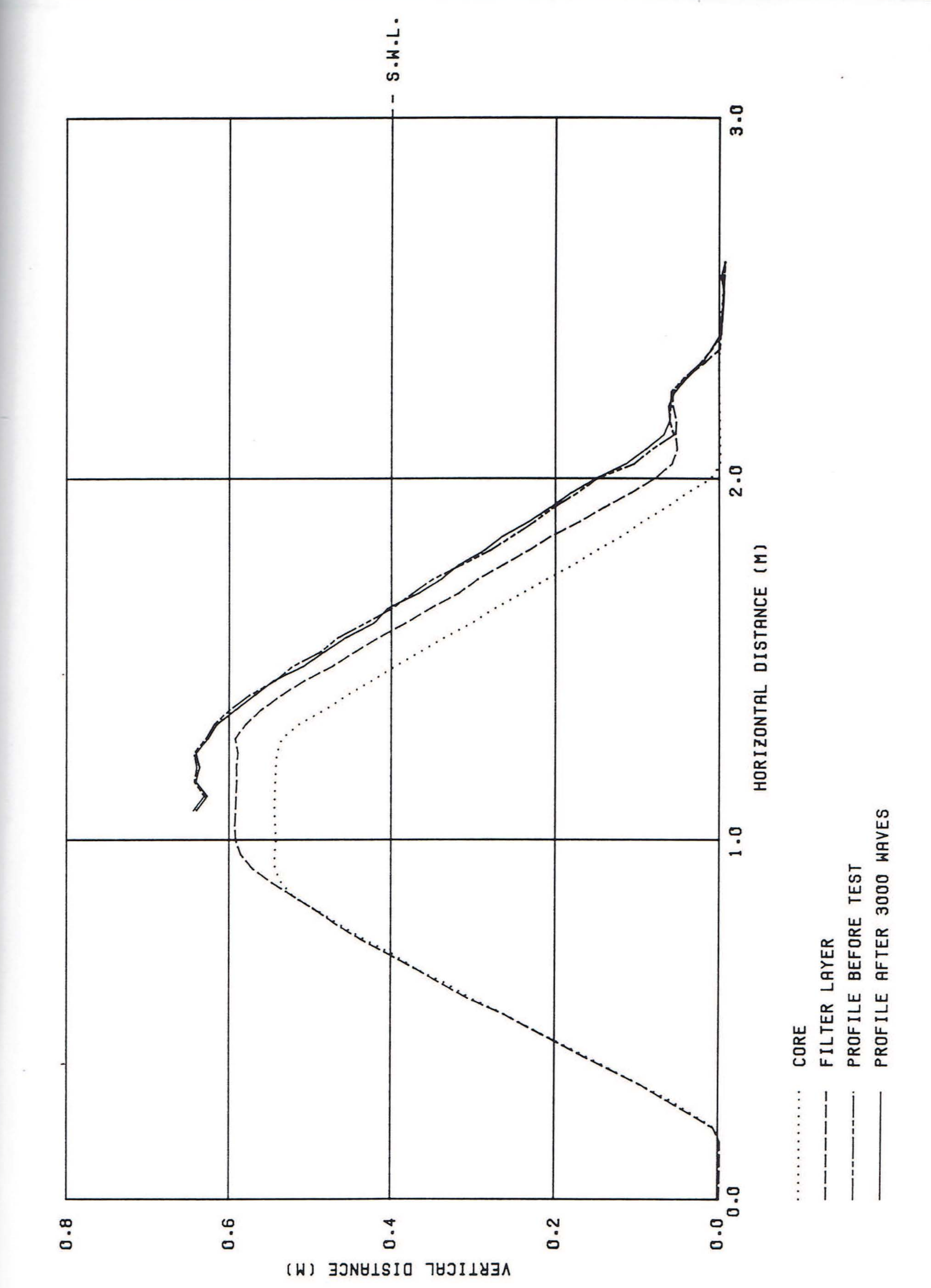
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

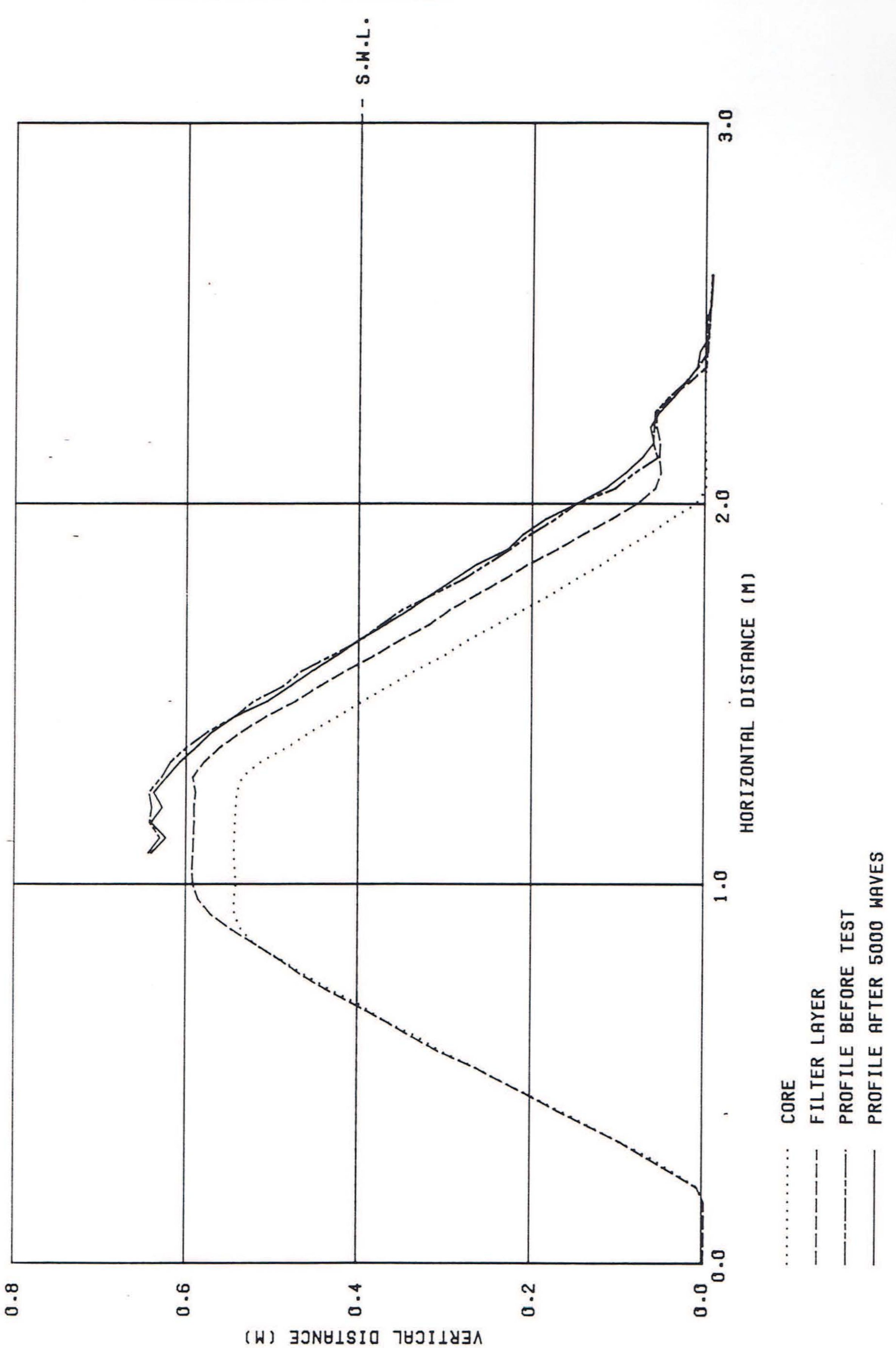
P008

H 546

FIG. A15



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P008	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A16



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P008	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A17

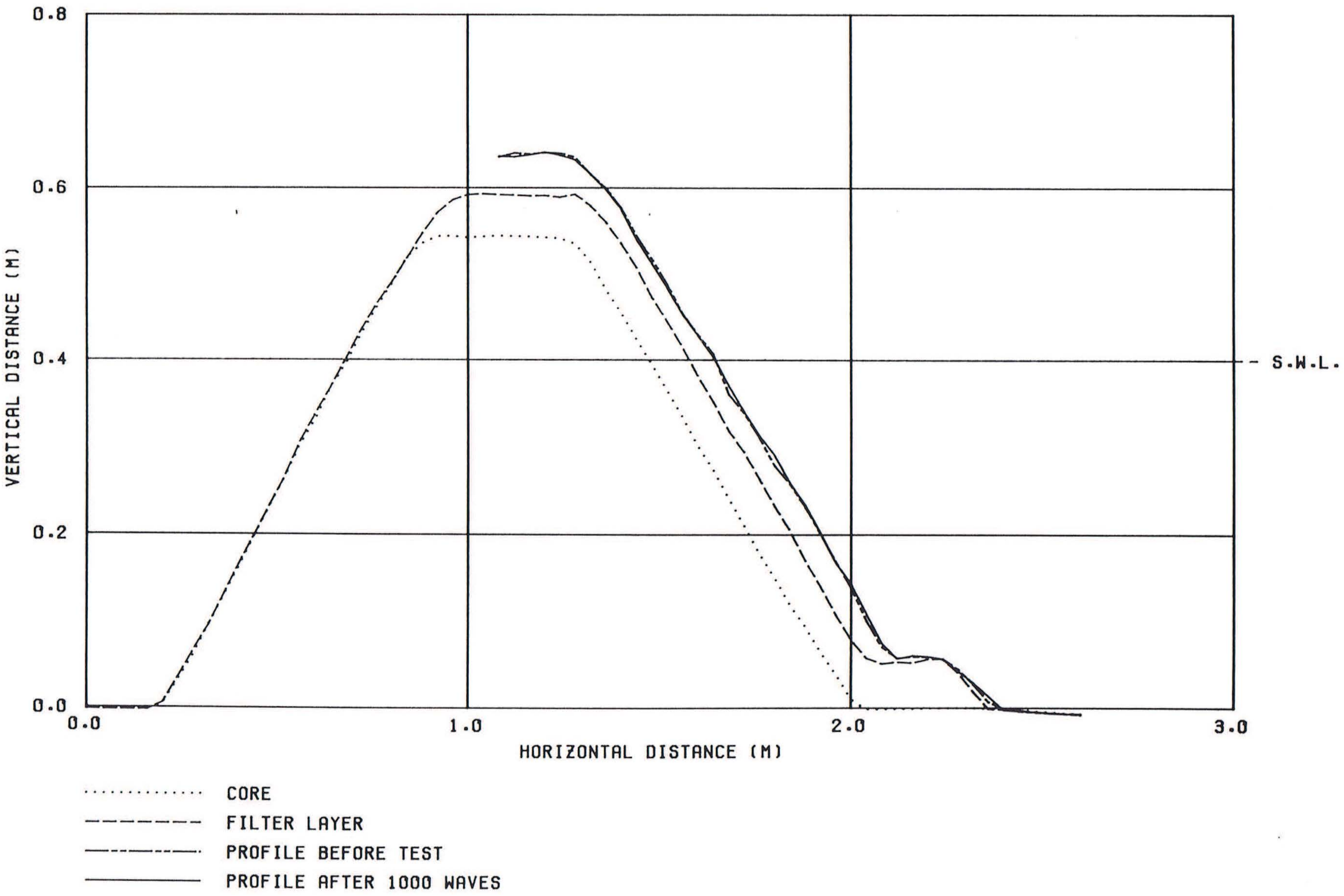
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

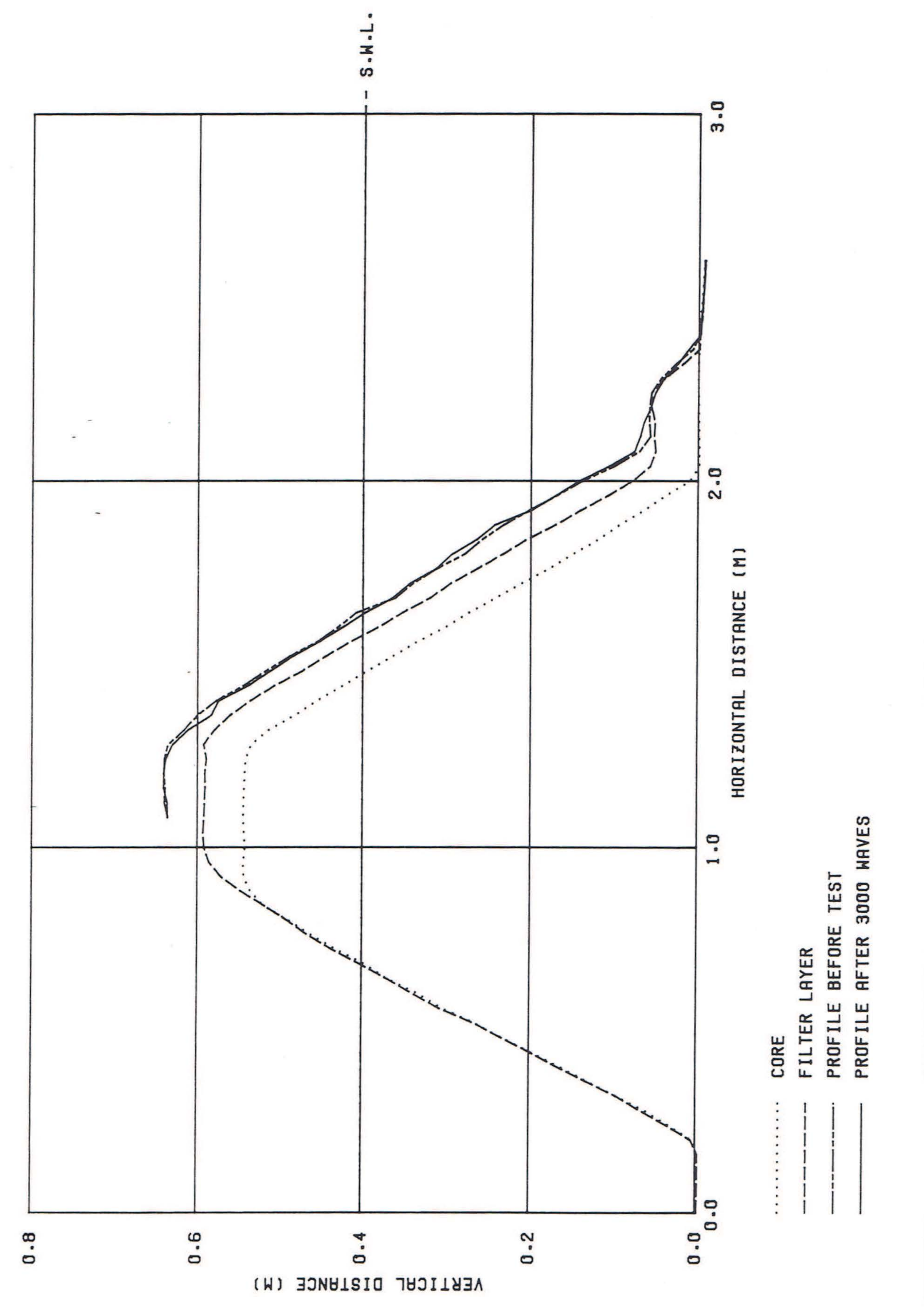
DELFT HYDRAULICS LABORATORY

P009

H 546

FIG. A18





PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P009	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A19

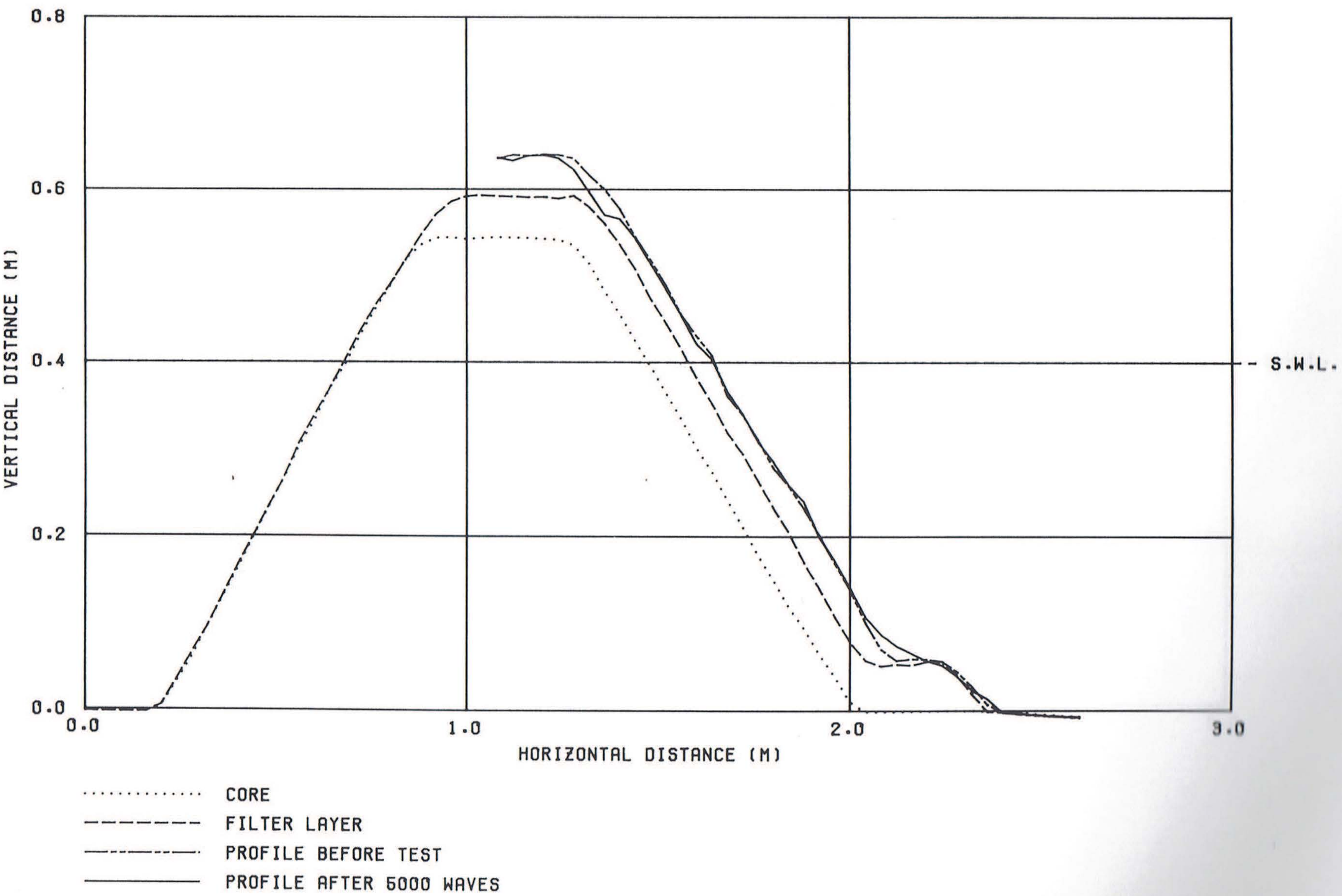
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

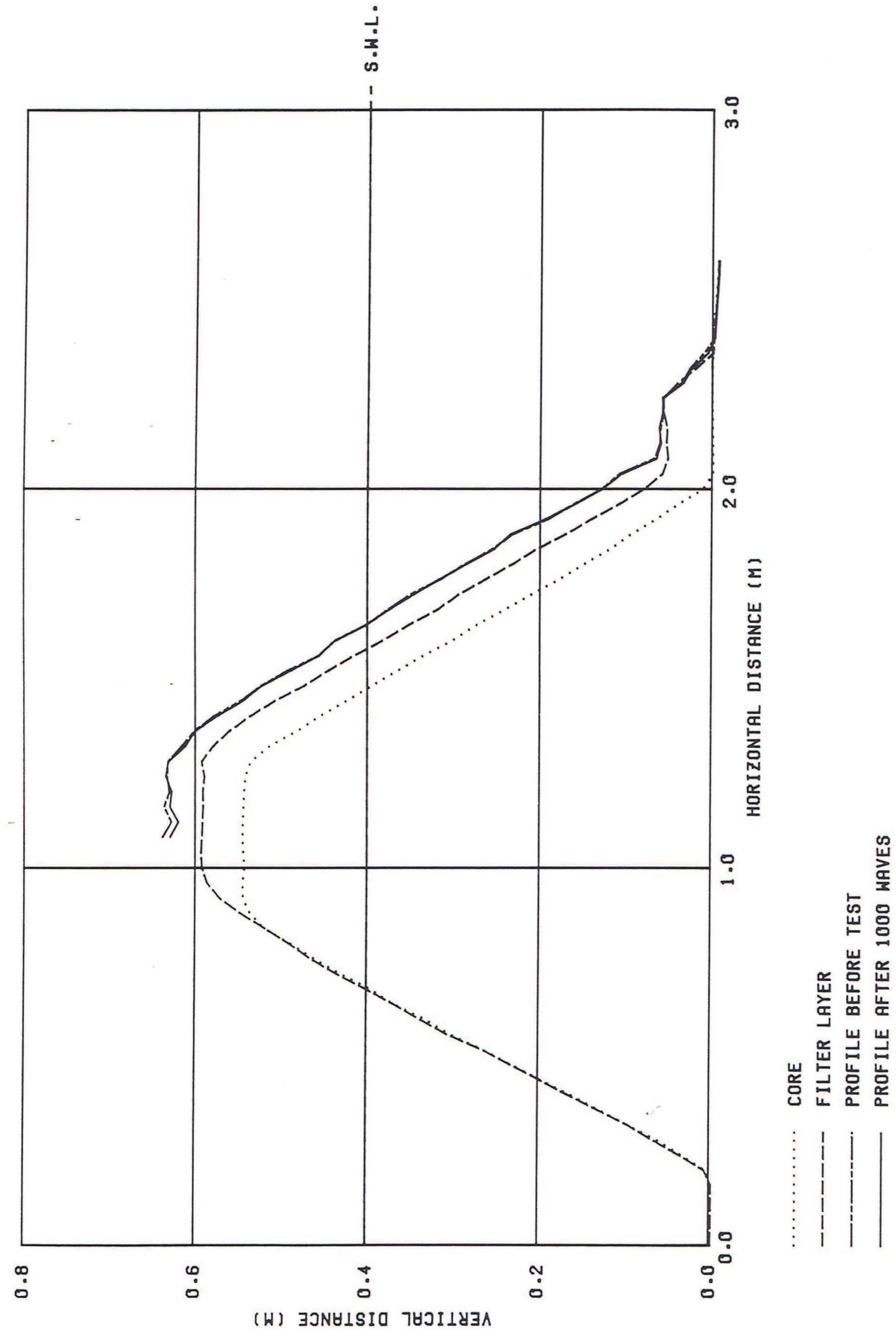
DELFT HYDRAULICS LABORATORY

P009

H 546

FIG. A20





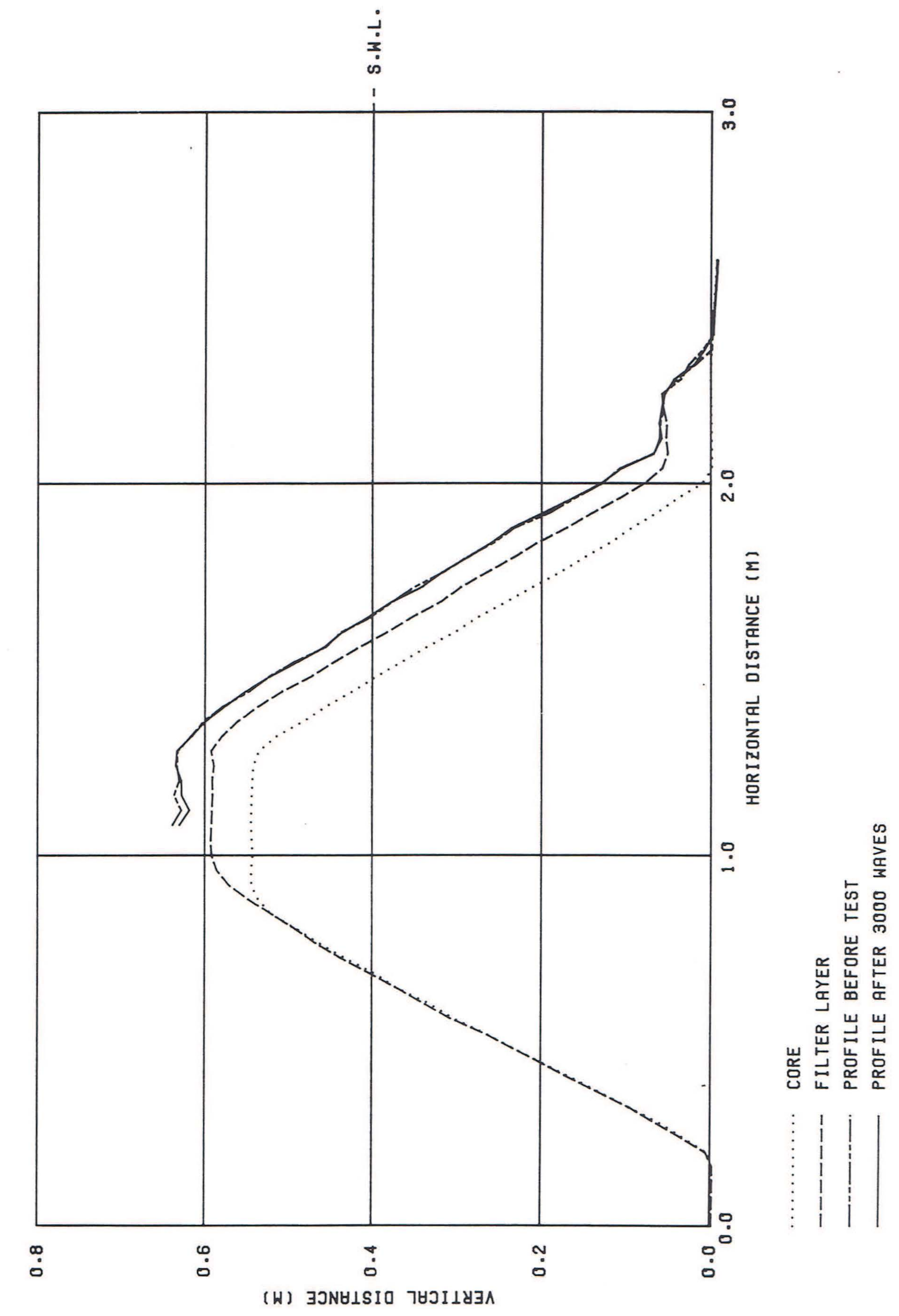
PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

P010

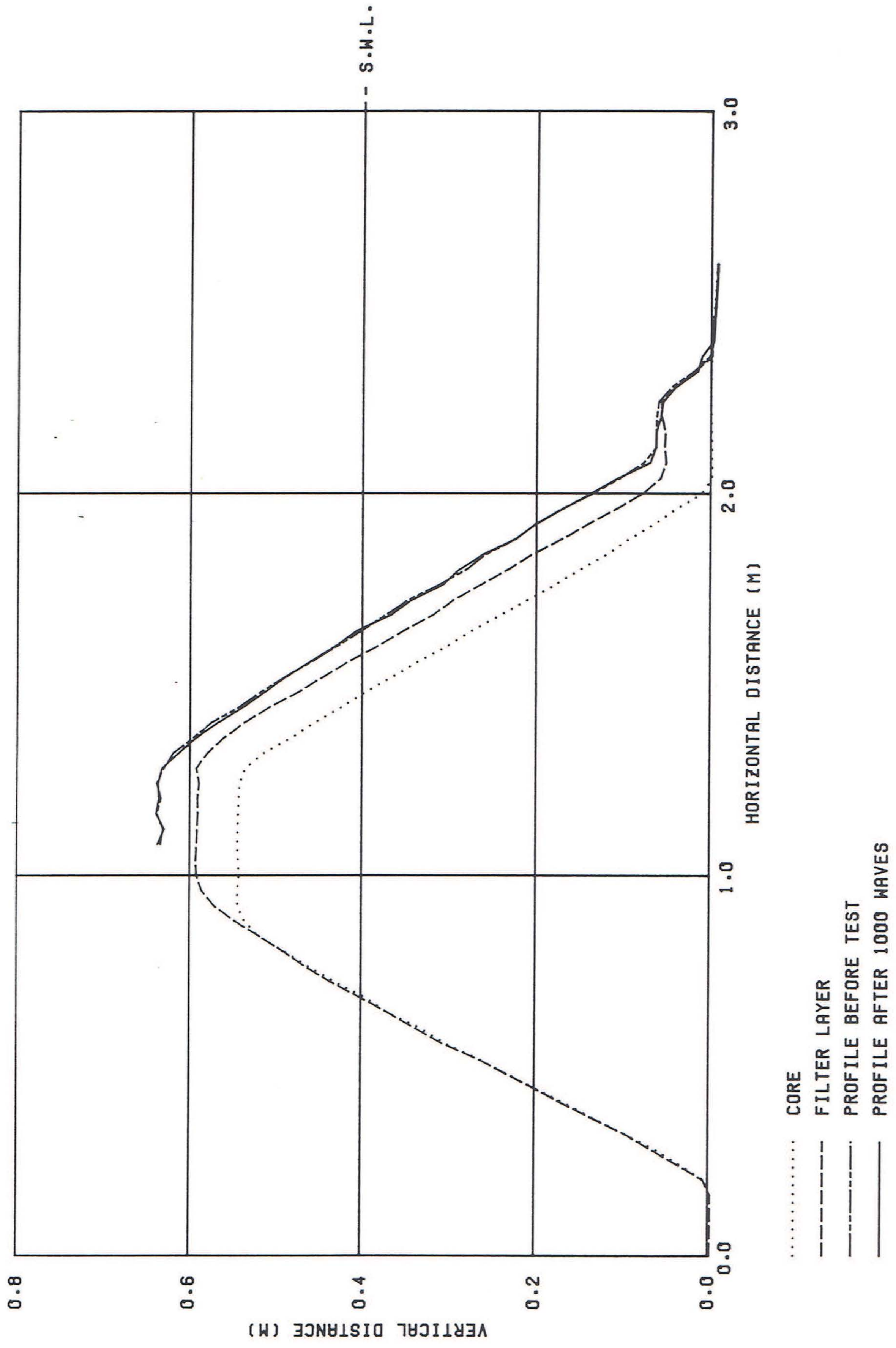
DELFT HYDRAULICS LABORATORY

H 546

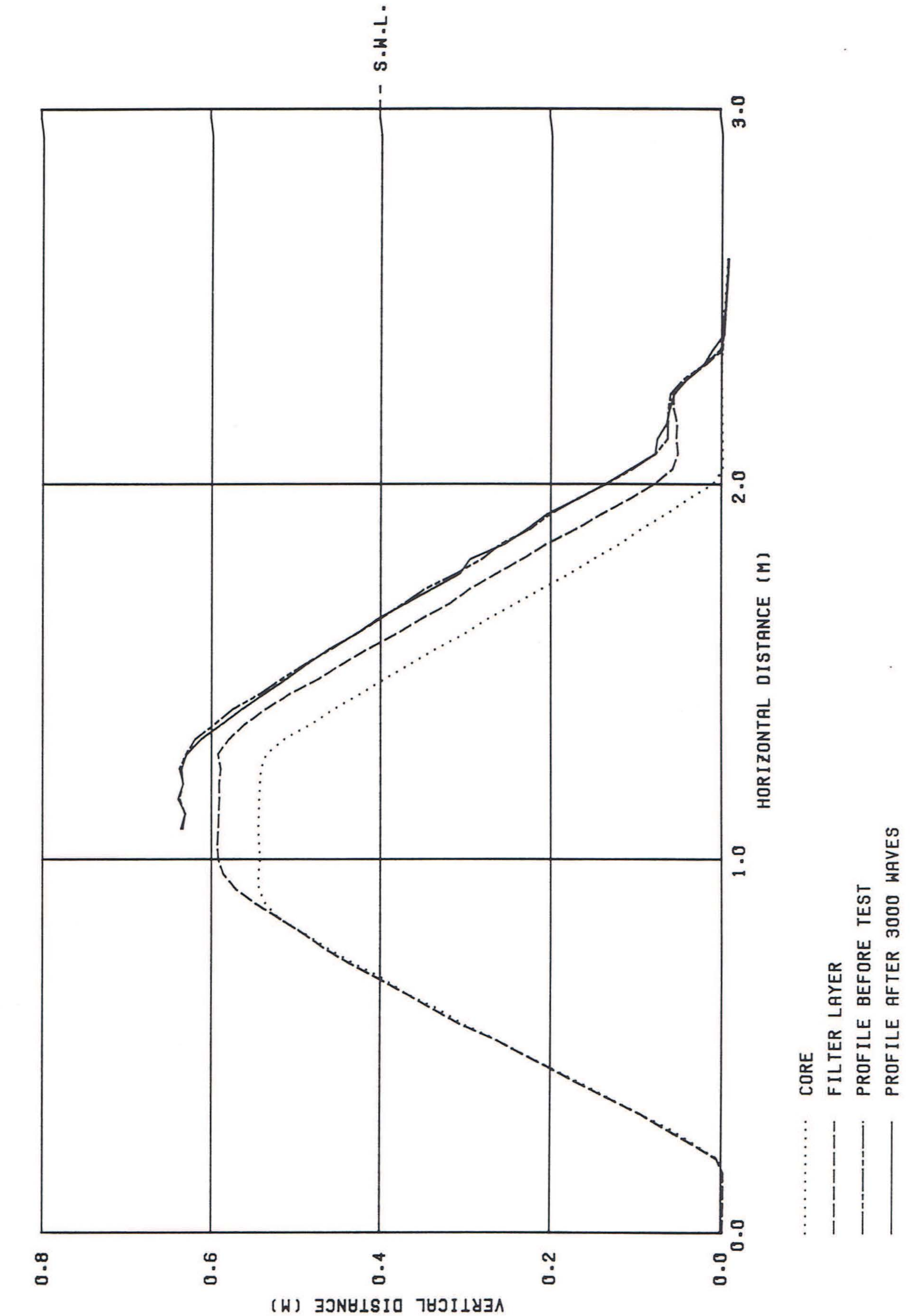
FIG. A21



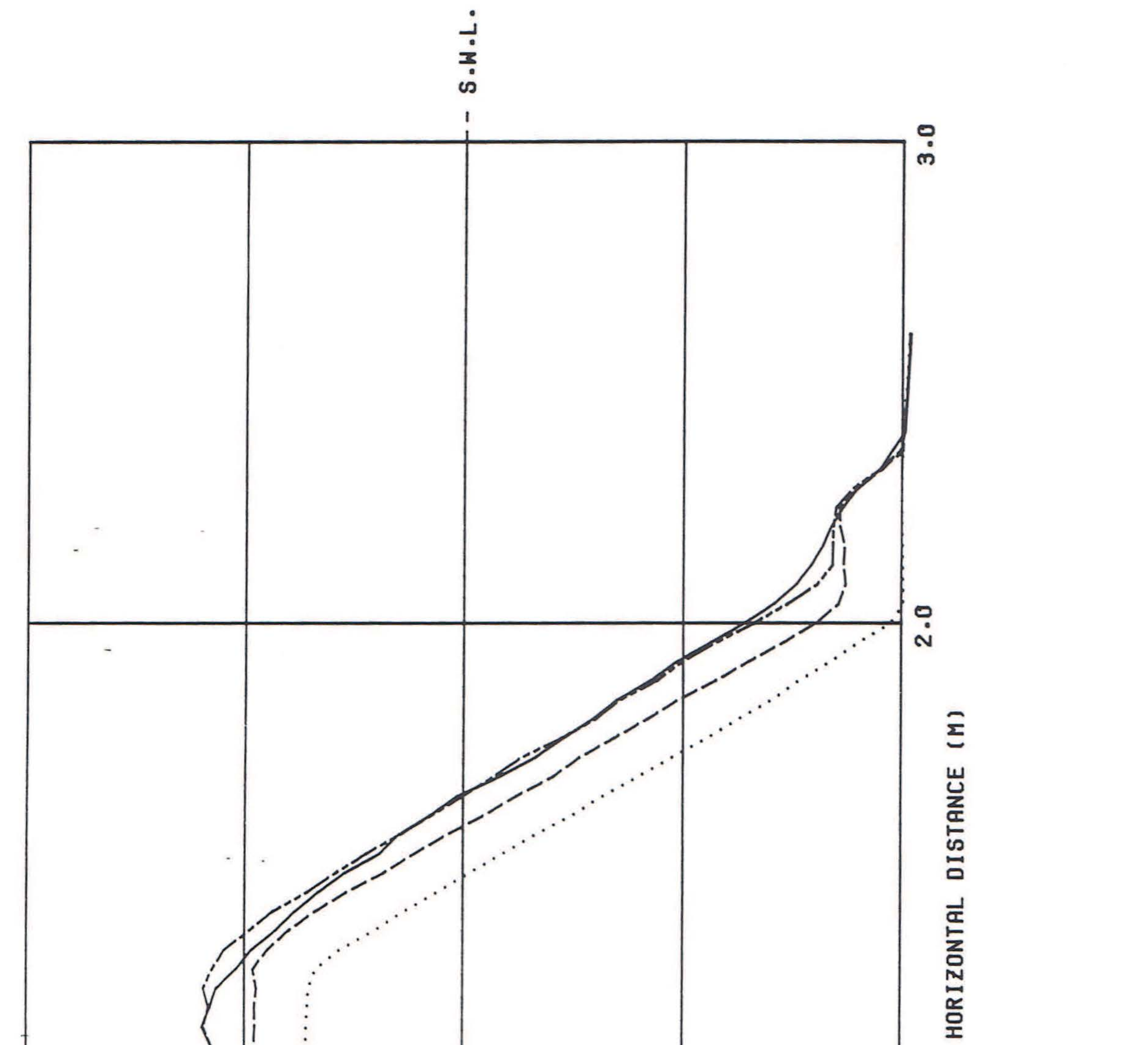
PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P010	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A22



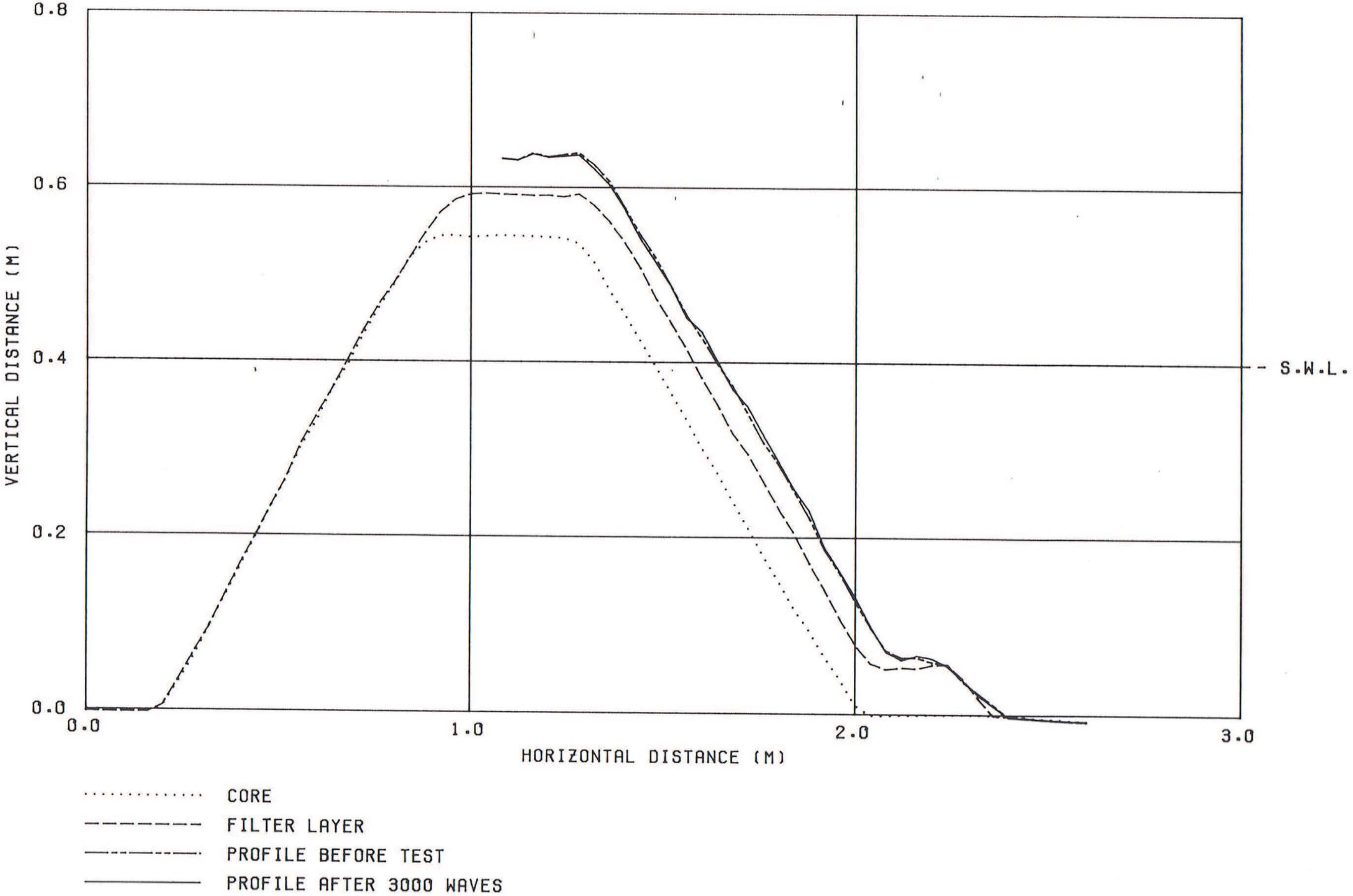
PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P011	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A23



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P011	
DELFT HYDRAULICS LABORATORY	H 546	FIG. A24



PROFILES OF STABILITY TESTS BREAKWATER WITH ACCROPODE (R)	P011	
DELFT HYDRAULICS LABORATORY	H 546	FIG.A25



PROFILES OF STABILITY TESTS
BREAKWATER WITH ACCROPODE (R)

DELFT HYDRAULICS LABORATORY

P012

H 546

FIG. A27