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MAST II - Berm Breakwater Structures

Stability of Toe and Scour Protection

Final Report

May 1997

Stability of Toe and Scour Protection

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Introduction

Local scour can occur at a breakwater constructed on a sandy seabed and may endanger the overall stability due to sliding of the main armour layer if the toe and scour protection is failing. The scouring pattern is a function of the water depth, wave conditions, sediment characteristics, and breakwater configuration and reflection characteristics as described by Arneborg et al (1996). A simultaneous current at the breakwater will significantly influence the scouring.

Scouring in front of a berm breakwater constructed without a sufficient scour protection layer may result in berm stones to be moved into the scour hole, which will lead to further reshaping of the protecting berm.

Physical two-dimensional (2D) model tests were made for qualitatively studying the scour development in front of a berm breakwater. Four test series were carried out in order to study the influence on the scouring and breakwater performance of varying the steepness of the incoming waves and of two types of scour protections.

Model Set-up and Test Programme

Model Set-Up

Physical model tests were carried out in a 23m long and 0.60m wide wave flume with the aim of studying scour development and profile reshaping. A fixed bed foreshore with a slope of 1:80 was constructed in the flume, see model set-up in Appendix A.

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In order to make an assessment of the scouring, the seabed below and 1.5 m in front of the breakwater was made of fine sand with d_{50}=0.17 mm.

All four test series were carried out with a berm breakwater having a high crest elevation and wide berm. The profile was the same as used for the 3D tests carried out at DHI, except that the water depth was reduced from 0.55 m to 0.25 m (and in a few tests to 0.20 m). The profiles used in the 4 test series are shown in Appendix A. Each test series consisted of six to nine test runs each with a duration corresponding to 2,000 waves, see test conditions in Appendix A. Test runs were carried out with the following deep water conditions: $H_o=H_{mo}/\Delta D_{n,50}$= 2.0, 2.5, 3.0, 3.5 and 4.0, where H_{mo}(=4*$\sqrt{m_o}$, where m_o is the zero'th moment of the recorded surface elevations) is the deep water wave height, Δ is the relative density, and $D_{n,50}$ is the nominal stone diameter.

The deep water wave steepness is given by the ratio between the wave height, H_{mo}, and the deep water wave length, L_{om}, calculated on basis of the mean wave period, T_{om}:

$$S_{om} = H_{mo}/L_{om} = 2\pi/g*H_{mo}/T_{om}^2$$

Test series 1 and 2 were made with the berm directly constructed on the sandy seabed, but with different wave steepnesses in deep water. Test series 1 consisted of nine tests with a wave steepness of S_{om}=0.05 and test series 2 consisted of six tests with a wave steepness of S_{om}=0.03 and two additional tests with S_{om}=0.02 (the last with the water depth reduced to 0.20 m).

A 0.05 m thick scour protection layer below the berm and extending 0.50 m in front of the berm was introduced in test series 3. In test series 4, the scour protection material was placed as a 0.10 m extension of the berm. The idea being that the first waves hitting the breakwater will reshape the scour material into a combined toe and scour protection. For both test series, four test runs were made with S_{om}=0.03 and two additional test runs with S_{om}=0.02 (the last with the water depth reduced to 0.20 m).

The berm breakwaters were constructed of two stone classes, ie one for the core and scour protection and one for the berm, crest and rear side protection. A relatively wide stone gradation was used for the berm, $D_{n,85}/D_{n,15}$=1.80, having a nominal diameter, D_{n50}, of 0.023. Stones with a sieve diameter of 0.011 m and D_{85}/D_{15} = 2.3 were used for the core. The density of the stone material was measured to ρ_s=2.68t/m^3.

Measurements

The waves were measured by a total of eight resistance type wave gauges, ie three in deep water and five in shallow water in front of the breakwater. A multigauge technique was used for separating the incoming and reflected waves, and subsequently determining the incoming significant wave height and the reflection coefficient both in deep water and in front of the breakwater.

The waves reflected from the breakwater were absorbed by the wave generator applying DHI's AWACS system (Active Wave Absorption Control System).

The breakwater profile was measured in fixed positions for every 0.10 m across the flume (five profiles) before initiation of the tests and after each test run. The profiling was made by two lasers, one laser running on a beam placed across the breakwater for measuring the vertical distance to the breakwater and another laser for measuring the horizontal position of the other laser.

Data analysis

Analysis of the five profiles measured after each test run (for each 0.10 m across the flume) showed that the differences were very small, and thus the five profiles were averaged for the subsequent analysis. The measured profile developments are presented in Appendix C.

Presentation of Results

Test conditions and measured wave heights, wave periods and reflection coefficients both in deep water and in shallow water in front of the breakwater are enclosed in Appendix A.

Photos taken before and after testing are for all four test series shown in Appendix B.

Plots of the profile development are presented in Appendix C together with comparisons of results from the four test series.

Finally, Appendix D includes a plot of the reflection coefficients measured in front of the breakwaters.

Test series 1

Only a very little scouring took place during the first five tests with S_{om}=0.05, ie for wave conditions up to H_o=4.0. Testing was extended to include another 10,000 waves with H_o=3.5, but only a small scour hole (about 0.03 m deep) developed in front of the berm. Sand was deposited inside the berm as seen from photos in Appendix B.

Test series 2

This test series was made with longer waves, ie a smaller deep water wave steepness of S_{om}=0.03. A scour depth of about 0.04 m was found after the first five test runs, ie after testing with wave conditions up to H_o=4.0. After exposure of another 2,000 waves with H_o=4.0, the scour depth was increased to about 0.05 m. Two additional tests were made with a wave steepness of 0.02, and after 4,000 waves with H_o=3.5 a significant increase in the extension of the scour hole was found (a scour hole with a depth of about 0.07 m was measured).

Test series 3

Based on the findings of the two first test series, it was decided to continue testing only with wave steepnesses of S_{om}=0.03 and 0.02. After testing with H_o=4.0, the outer edge of the scour protection layer was smoothed out and a scour hole with a depth of about 0.04 m was registered in front of the scour protection layer.

The depth of the scour hole increased to about 0.05 m after another 2,000 waves with H_o=4.0. A significant increase in the extent and depth of the scour hole was found after exposure of 4,000 waves with S_{om}=0.02 and H_o=3.5; scour hole depth increased to 0.08 m and somewhat more smoothing out of the outer edge of the protection layer was found.

Test series 4

Instead of constructing a wide scour protection layer, an alternative solution with the scour protection material placed as an extension of the berm was studied.

The first waves reshaped the scour material into a toe for the berm material, but at the same time, some of this finer material mixed with the berm stones resulting in a reduced permeability. Compared to the other test series, a significant increase in wave over-topping was experienced.

After testing with H_o=4.0, a scour depth of about 0.04 m was found in front of the developed toe consisting of finer material covered with berm stones. A scour hole depth of 0.06 was measured after another 2,000 waves with H_o=4.0. After additional 4,000 waves with S_{om}=0.02 and H_o=3.5, the extent and depth of the scour hole was increased (a scour depth of about 0.07 m was measured).

Comparison of profiles

The measured profiles after testing with S_{om}=0.03 and H_o=4.0 and also after testing with S_{om}=0.02 and H_o=3.5 were compared for test series 2, 3 and 4, see Appendix C.

The recession of the berm was found to be largest for the profile without any scour protection (due to the subsidence of berm stones into the sandy seabed). The recession of the berm was a little larger for profile 3 compared to profile 4, which is influenced by the extension of the berm with 0.10 m of finer material for profile 4 also resulting in a larger volume of deposited stone material.

Reflection coefficients

Comparing test series 1 and 2 showed that the reflection coefficient was larger for the tests with the longest wave periods, ie lowest wave steepness. No significant difference in the reflection coefficient was found between the last three test series, for which the reflection coefficient varied from 0.37 to 0.43 for the tests up to H_o=4.0, whereas a decrease was found for the additional tests due to the more reshaped profile.

Conclusions

Four test series were carried out in a wave flume for studying the influence of a scour protection on the scouring and behaviour of the berm breakwater.

A berm breakwater with a high crest and a wide berm was used for all four test series. The tests were made with a water depth of 0.25 m (and a few tests with a water depth of 0.20 m), ie the largest waves were breaking in front of the breakwater.

Test series 1 and 2 were made for studying the scouring for a profile without any scour protection under the exposure of waves with deep water wave steepnesses of S_{om}=0.05 and 0.03, respectively. The subsequent two test series were made with S_{om}=0.03 and a few additional tests with S_{om}=0.02. Test series 3 was made with a profile including a scour protection layer extending 0.50 m in front of the berm. Test series 4 was made with the scour protection material placed as a 0.10 m extension of the berm, the idea being that the material under the exposure of the first waves will reshape into a toe and scour protection for the berm material.

A summary of the findings is presented below:

- The scouring was found to increase by decreasing the wave steepness from 0.05 to 0.03 (test series 1 and 2, respectively). A significant increase in the extent of the scour hole was found by decreasing the wave steepness to 0.02.

- Subsidence of berm stones into the sandy seabed was found for the profiles without a scour protection layer (test series 1 and 2).

- Introduction of a scour protection layer (test series 3) moved the scour hole out in front of this and no subsidence of berm stones into the sandy seabed was found. Consequently, the reshaping of the berm, and thus also the berm recession, was reduced.

- During reshaping of the scour protection material placed as an extension of the berm (test series 4), some of this finer material was mixed into the berm material. The resulting reduced permeability lead to increased wave run-up and overtopping.

- No significant difference in the reflection coefficients was found for test series 2, 3 and 4. The reflection coefficients varied from 0.37 to 0.43 for the tests with increasing wave height parameter, H_0, up to 4.0, whereas a decrease was found for the additional tests due to the more reshaped profile.

Acknowledgements

The present study was carried out as part of the research project on Berm Breakwater Structures co-sponsored by the European Commission under contract MAS2-CT94-0087.

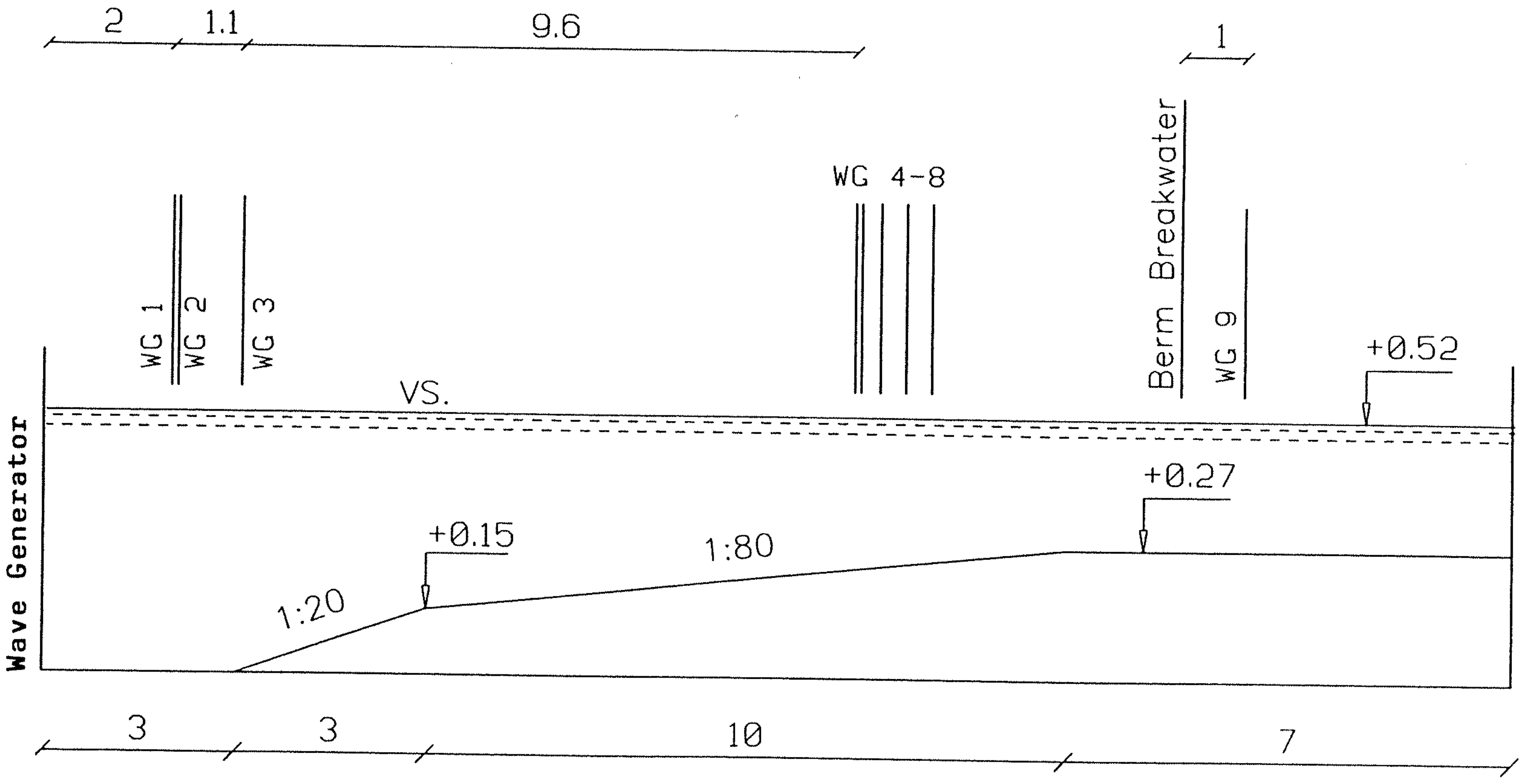
The model tests were carried out at the Danish Hydraulic Institute by the authors. Mr Nikolay Lissev from the University of Architecture, Civil Engineering on Geodesy, Sofia, Bulgaria, is thanked for assistance in the analysis and presentation of the measurements.

References

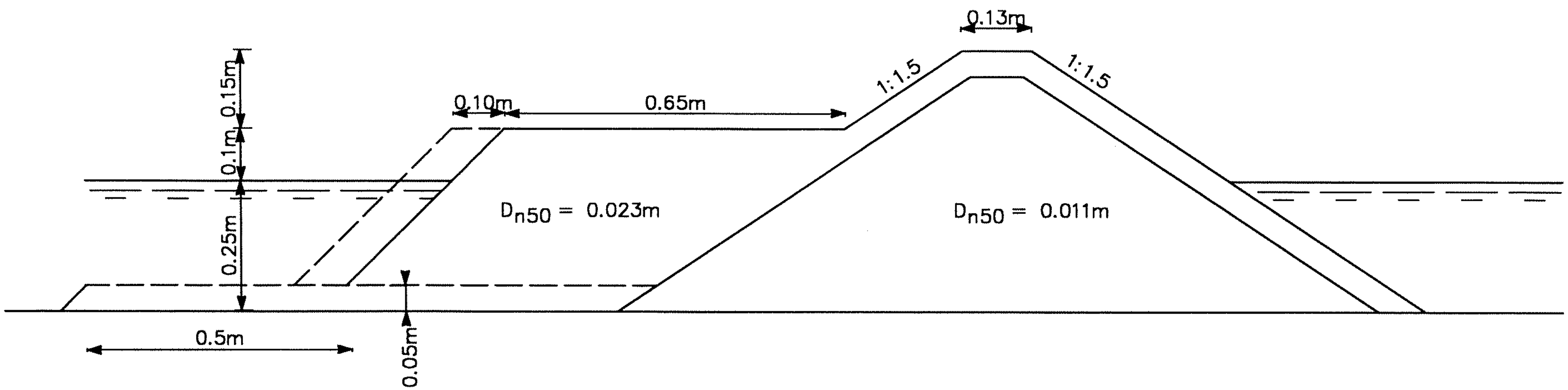
Arneborg, L; Asp Hansen, E; Juhl, J (1996): *Modelling of local scour in front of vertical breakwaters*. Submitted to Coastal Engineering.

Appendices

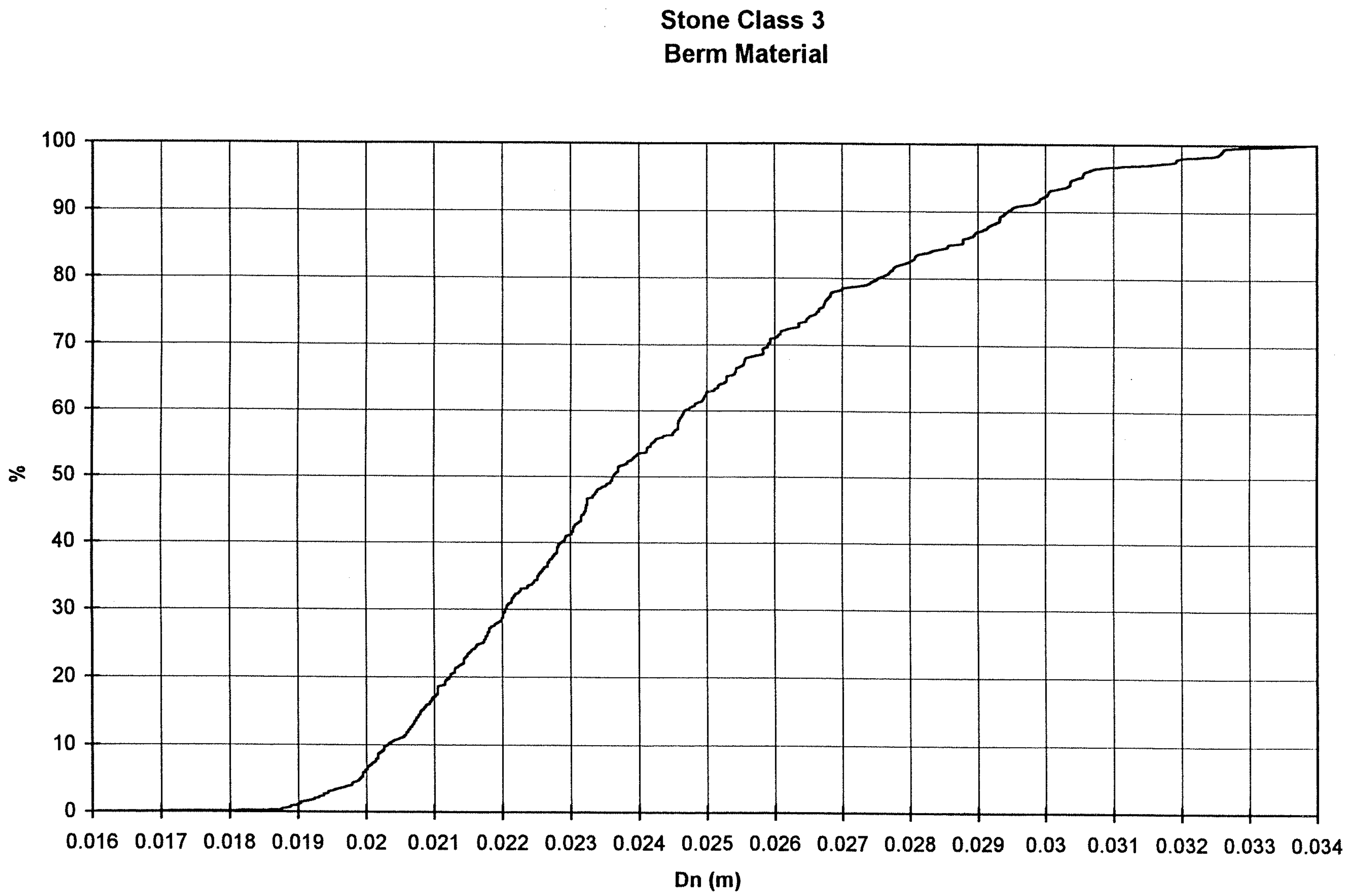
Appendix A Model set-up and test conditions



All Measures in m.



MTD5.97.DWG8081-3

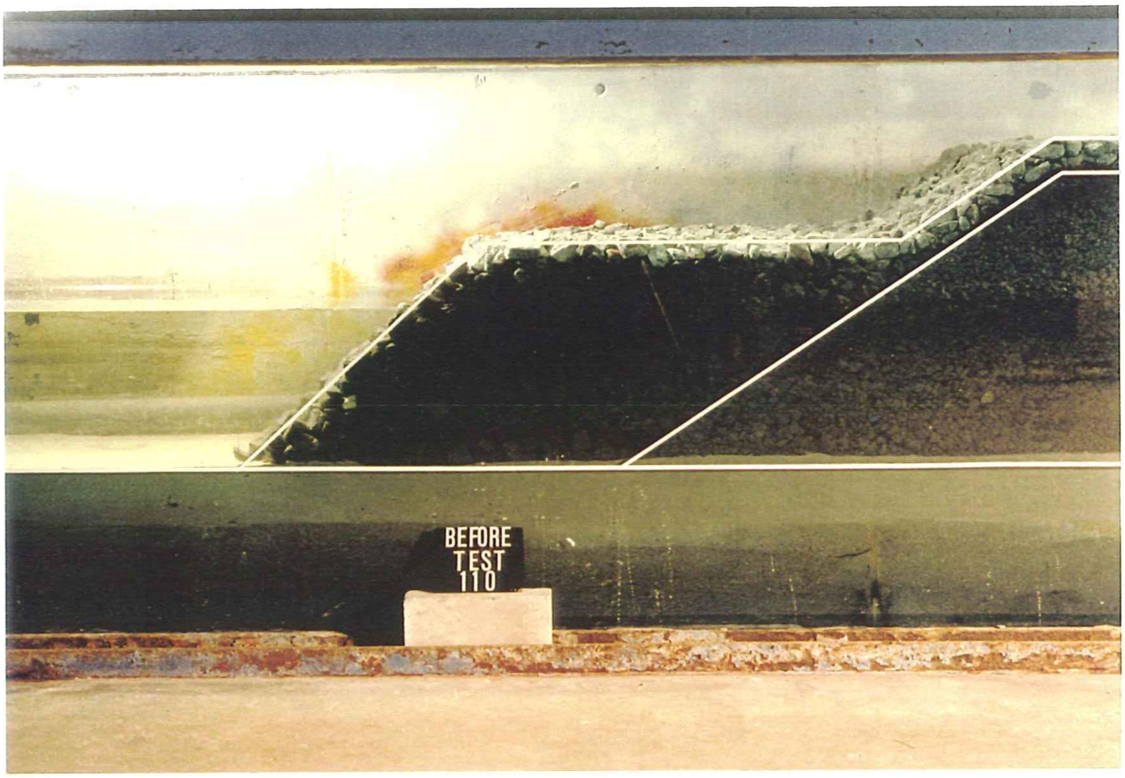

Stone Class 3
Berm Material
%
100
90
80
70
60
50
40
30
20
10
0
0.016
0.017
0.018
0.019
0.02
0.021
0.022
0.023
0.024
0.025
0.026
0.027
0.028
0.029
0.03
0.031
0.032
0.033
0.034
Dn (m)

	TEST CONDITIONS									
	N test	beta (°)	Ho	N. waves	sm	delta	Dn50	Hs=Ho*delta*Dn50(m)	Tm=((2pi*Hs)/g*sm)^0.5)(s)	depth in deep water
	0110	0°	2,0	2000	0,05	1,69	0,023	0,078	0,998	0,520
	0120	0°	2,5	2000	0,05	1,69	0,023	0,097	1,116	0,520
without	0130	0°	3,0	2000	0,05	1,69	0,023	0,117	1,222	0,520
scour protection	0140	0°	3,5	2000	0,05	1,69	0,023	0,136	1,320	0,520
	0150	0°	4,0	2000	0,05	1,69	0,023	0,155	1,411	0,520
	0160	0°	3,5	2000	0,05	1,69	0,023	0,136	1,320	0,520
long duration test	0170	0°	3,5	2000	0,05	1,69	0,023	0,136	1,320	0,520
	0180	0°	3,5	2000	0,05	1,69	0,023	0,136	1,320	0,520
	0190	0°	3,5	4000	0,05	1,69	0,023	0,136	1,320	0,520
	0210	0°	2,0	2000	0,03	1,69	0,023	0,078	1,288	0,520
	0220	0°	2,5	2000	0,03	1,69	0,023	0,097	1,440	0,520
without	0230	0°	3,0	2000	0,03	1,69	0,023	0,117	1,578	0,520
scour protection	0240	0°	3,5	2000	0,03	1,69	0,023	0,136	1,704	0,520
	0250	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
	0260	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
	0270	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,520
	0280	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,470
	0310	0°	3,0	2000	0,03	1,69	0,023	0,117	1,578	0,520
	0320	0°	3,5	2000	0,03	1,69	0,023	0,136	1,704	0,520
with	0330	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
scour protection	0340	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
	0350	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,520
	0360	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,470
	0410	0°	3,0	2000	0,03	1,69	0,023	0,117	1,578	0,520
	0420	0°	3,5	2000	0,03	1,69	0,023	0,136	1,704	0,520
alternative toe	0430	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
scour protection	0440	0°	4,0	2000	0,03	1,69	0,023	0,155	1,822	0,520
	0450	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,520
	0460	0°	3,5	2000	0,02	1,69	0,023	0,136	2,087	0,470

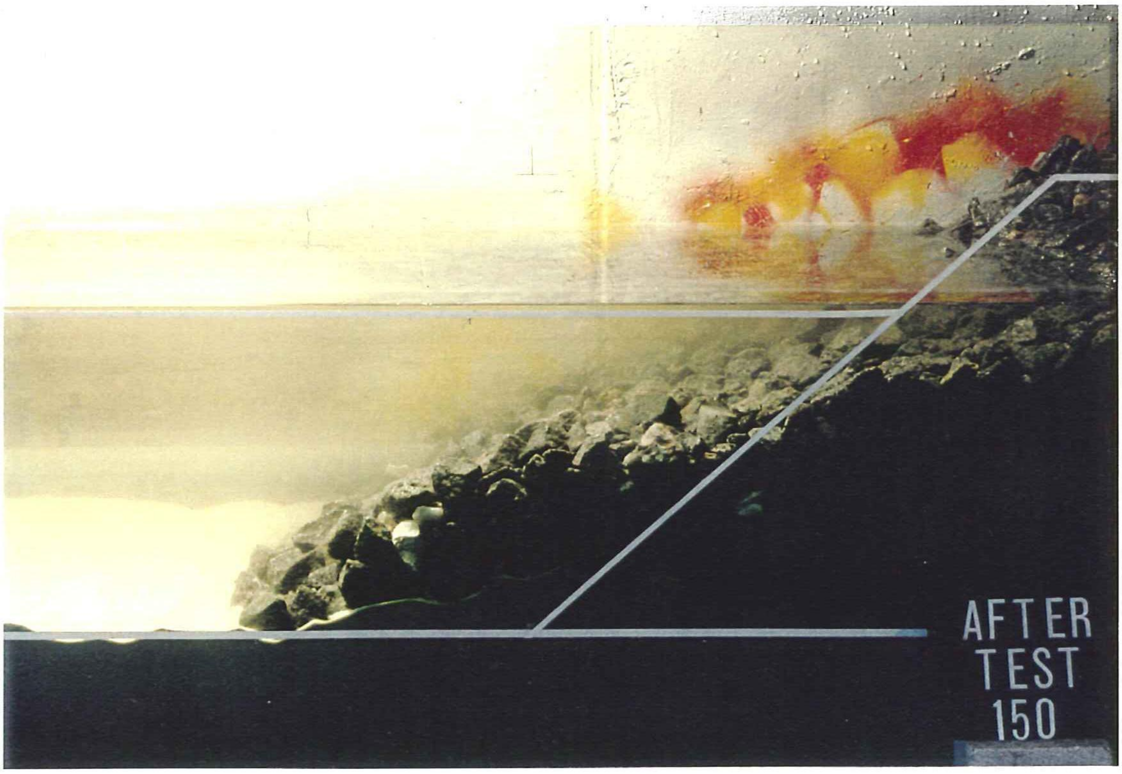
				REFLECTION ANALYSIS [WG 1-2-3]				REFLECTION ANALYSIS [WG 4-5-6-7-8]			
N test	depth in front of the berm b.	Duration [s]	AF	Hs (m)	To2 (s)	Tp (s)	R	Hs (m)	To2 (s)	Tp (s)	R
0110	0,250	1996	1,0								
0120	0,250	2231	1,1	0,089	1,170	1,600	0,36	0,085	1,230	1,550	0,40
0130	0,250	2444	1,2	0,126	1,250	1,620	0,32	0,116	1,320	1,730	0,37
0140	0,250	2640	1,1	0,134	1,320	1,700	0,30	0,124	1,380	1,890	0,35
0150	0,250	2823	1,1	0,150	1,380	2,040	0,30	0,132	1,420	2,040	0,35
0160	0,250	2640	1,1	0,134	1,320	1,700	0,31	0,124	1,370	1,890	0,31
0170	0,250	2640	1,1	0,134	1,320	1,700	0,27	0,124	1,370	1,890	0,30
0180	0,250	2640	1,1	0,134	1,320	1,700	0,26	0,123	1,370	1,890	0,29
0190	0,250	5280	1,1	0,132	1,320	1,700	0,26	0,120	1,360	1,890	0,29
0210	0,250	2577	1,1	0,079	1,320	1,650	0,36	0,078	1,380	1,930	0,41
0220	0,250	2881	1,1	0,097	1,450	1,970	0,36	0,096	1,480	2,090	0,41
0230	0,250	3156	1,1	0,114	1,550	2,180	0,36	0,112	1,510	2,180	0,41
0240	0,250	3409	1,1	0,131	1,630	2,430	0,34	0,123	1,520	2,380	0,41
0250	0,250	3644	1,1	0,148	1,690	2,430	0,32	0,130	1,510	2,560	0,39
0260	0,250	3644	1,1	0,148	1,700	2,430	0,31	0,130	1,530	2,560	0,39
0270	0,250	4175	1,1	0,130	1,950	3,190	0,31	0,119	1,590	2,920	0,40
0280	0,200	4175	1,1	0,129	1,900	2,920	0,27	0,104	1,450	2,920	0,37
0310	0,250	3156	1,1	0,114	1,550	2,180	0,36	0,111	1,520	2,180	0,43
0320	0,250	3409	1,1	0,131	1,630	2,430	0,32	0,123	1,500	2,380	0,39
0330	0,250	3644	1,1	0,148	1,700	2,430	0,31	0,128	1,530	2,560	0,38
0340	0,250	3644	1,1	0,148	1,700	2,430	0,30	0,128	1,530	2,560	0,37
0350	0,250	4175	1,1	0,130	1,950	2,920	0,30	0,117	1,590	2,920	0,38
0360	0,200	4175	1,1	0,130	1,890	2,920	0,26	0,104	1,470	2,920	0,36
0410	0,250	3156	1,1	0,115	1,550	2,170	0,34	0,111	1,510	2,170	0,39
0420	0,250	3409	1,1	0,133	1,630	2,430	0,32	0,124	1,530	2,380	0,37
0430	0,250	3644	1,1	0,150	1,700	2,430	0,32	0,131	1,520	2,560	0,39
0440	0,250	3644	1,1	0,152	1,690	2,430	0,32	0,129	1,510	2,560	0,38
0450	0,250	4175	1,1	0,133	1,930	2,920	0,32	0,118	1,570	2,920	0,40
0460	0,200	4175	1,1	0,131	1,890	2,920	0,27	0,104	1,460	2,920	0,37

Appendix B Selected photos

SCOUR TESTS



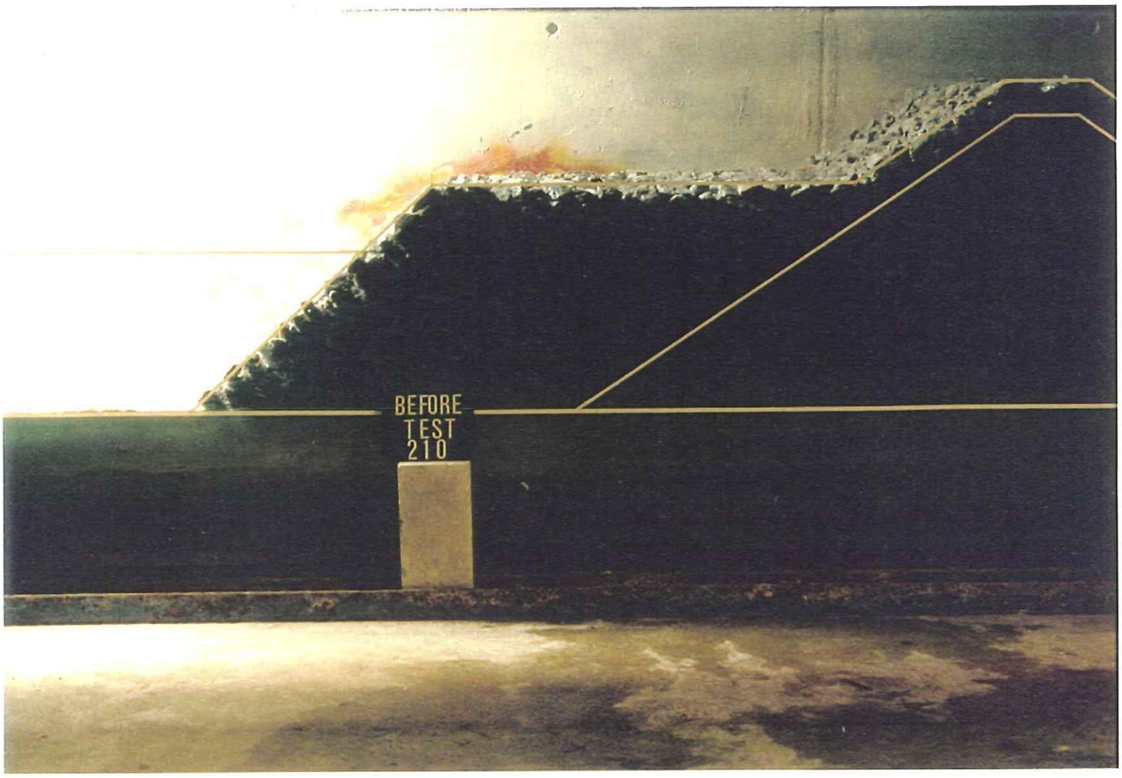
Profile 1 - Before testing



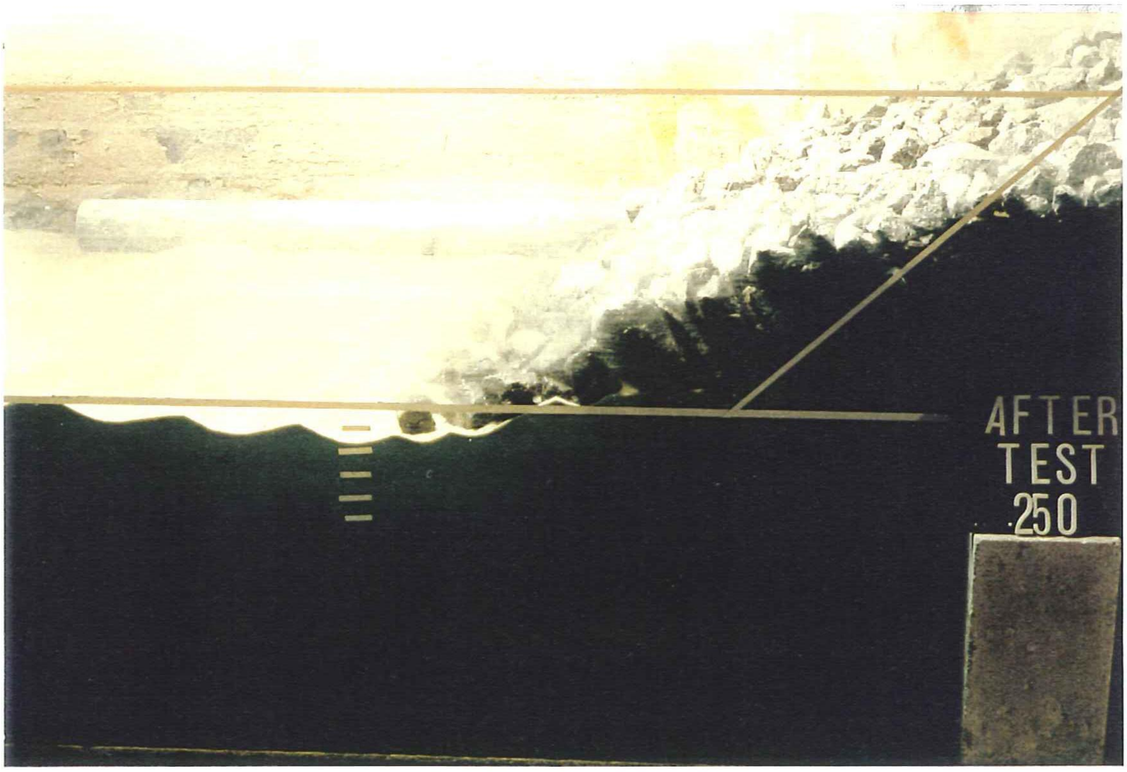
Profile 1 - After test with $H_o=4.0$, $S_m=0.05$

Profile 1 - After additional 10,000 waves with H_o=3.5, S_m=0.05

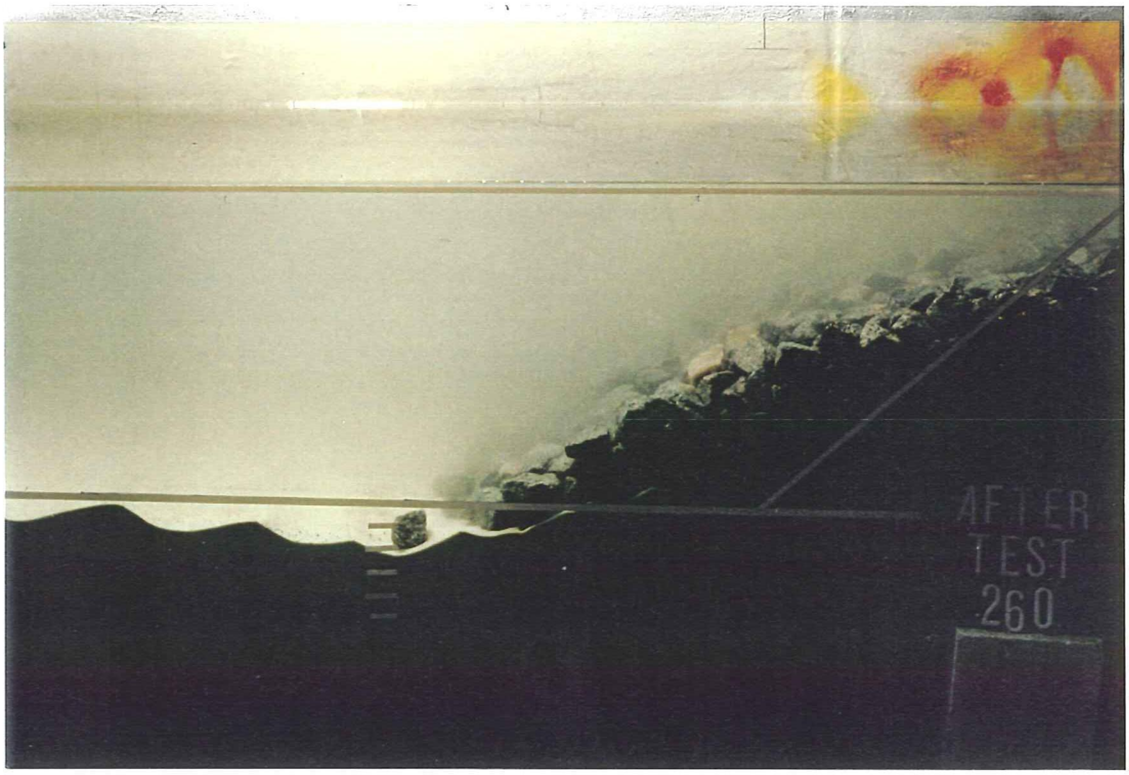
Profile 1 - After additional 10,000 waves with H_o=3.5, S_m=0.05



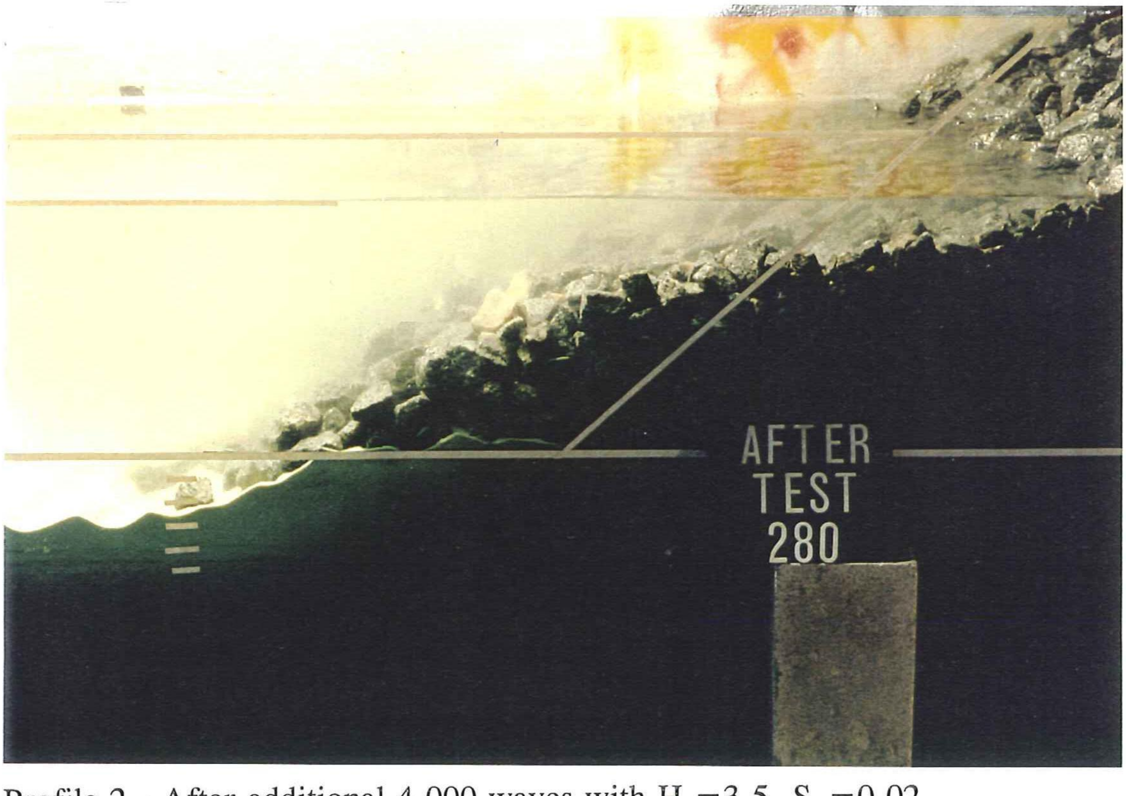
Profile 2 - Before testing



Profile 2 - After test with $H_o=4.0$, $S_m=0.03$



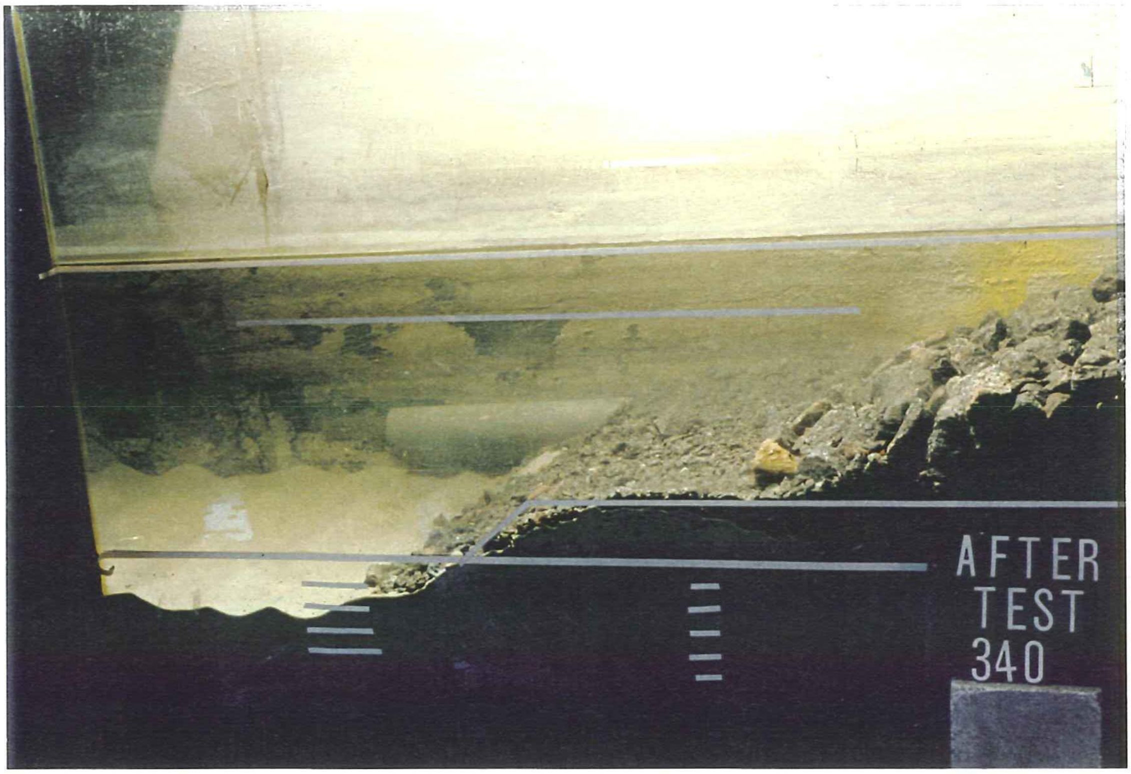
Profile 2 - After additional 2,000 waves with $H_o=4.0$, $S_m=0.03$



Profile 2 - After additional 4,000 waves with $H_o=3.5$, $S_m=0.02$

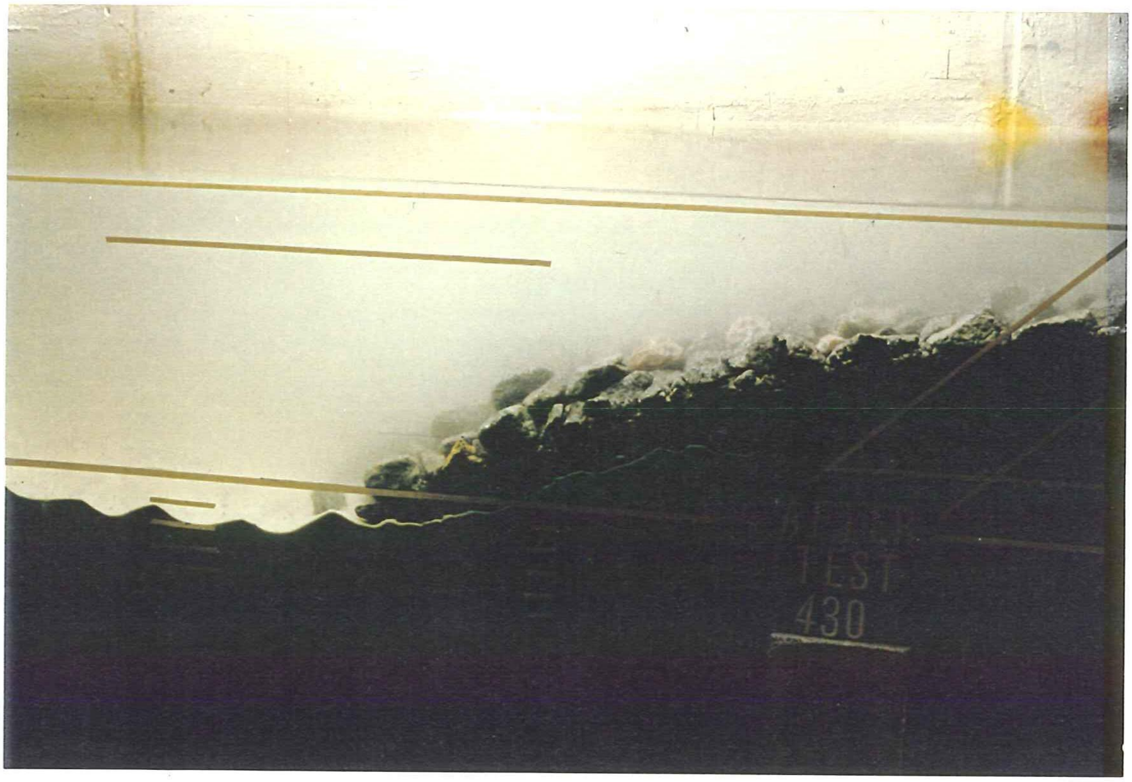
Profile 3 - Before testing

Profile 3 - After test with H_o=4.0, S_m=0.03



Profile 3 - After additional 2,000 waves with H_o=4.0, S_m=0.03

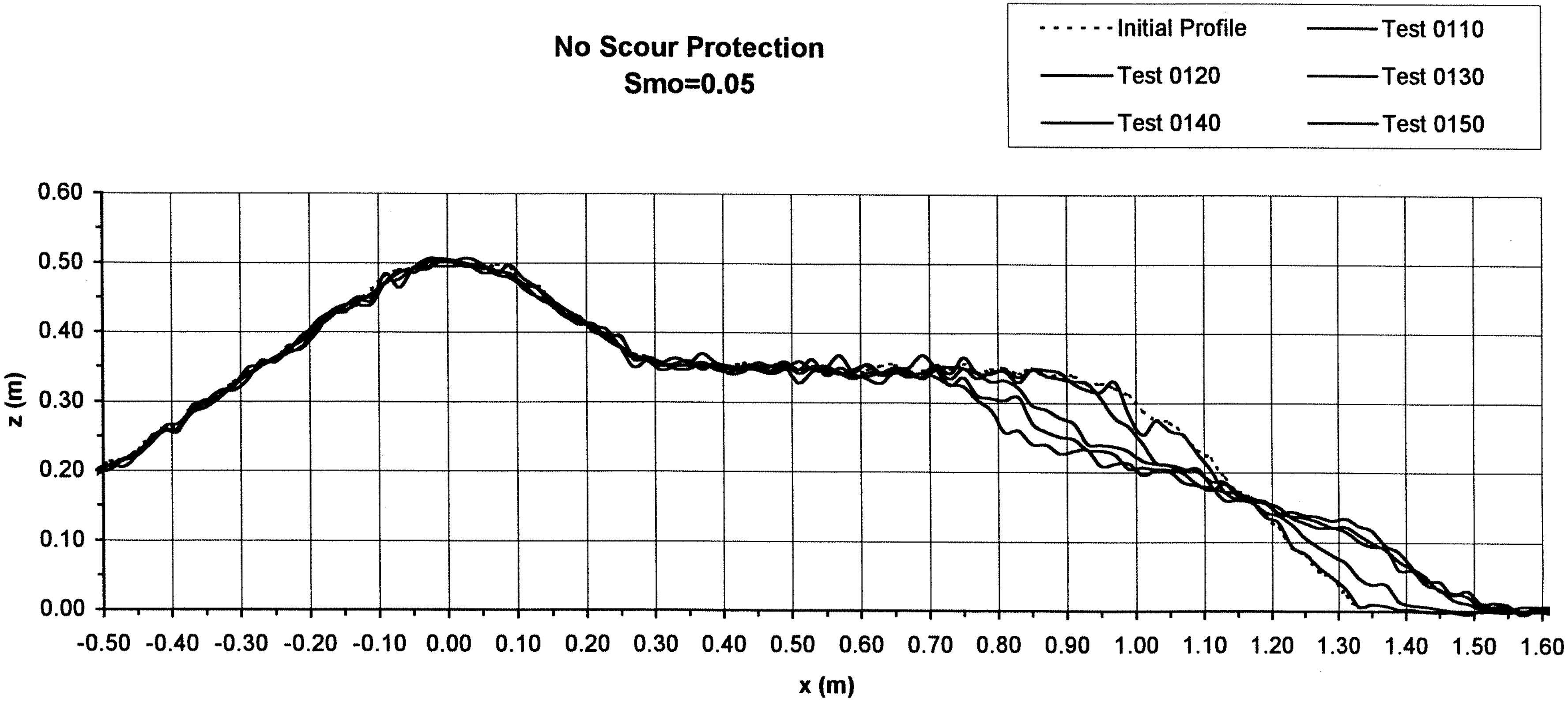
Profile 3 - After additional 4,000 waves with H_o=3.5, S_m=0.02

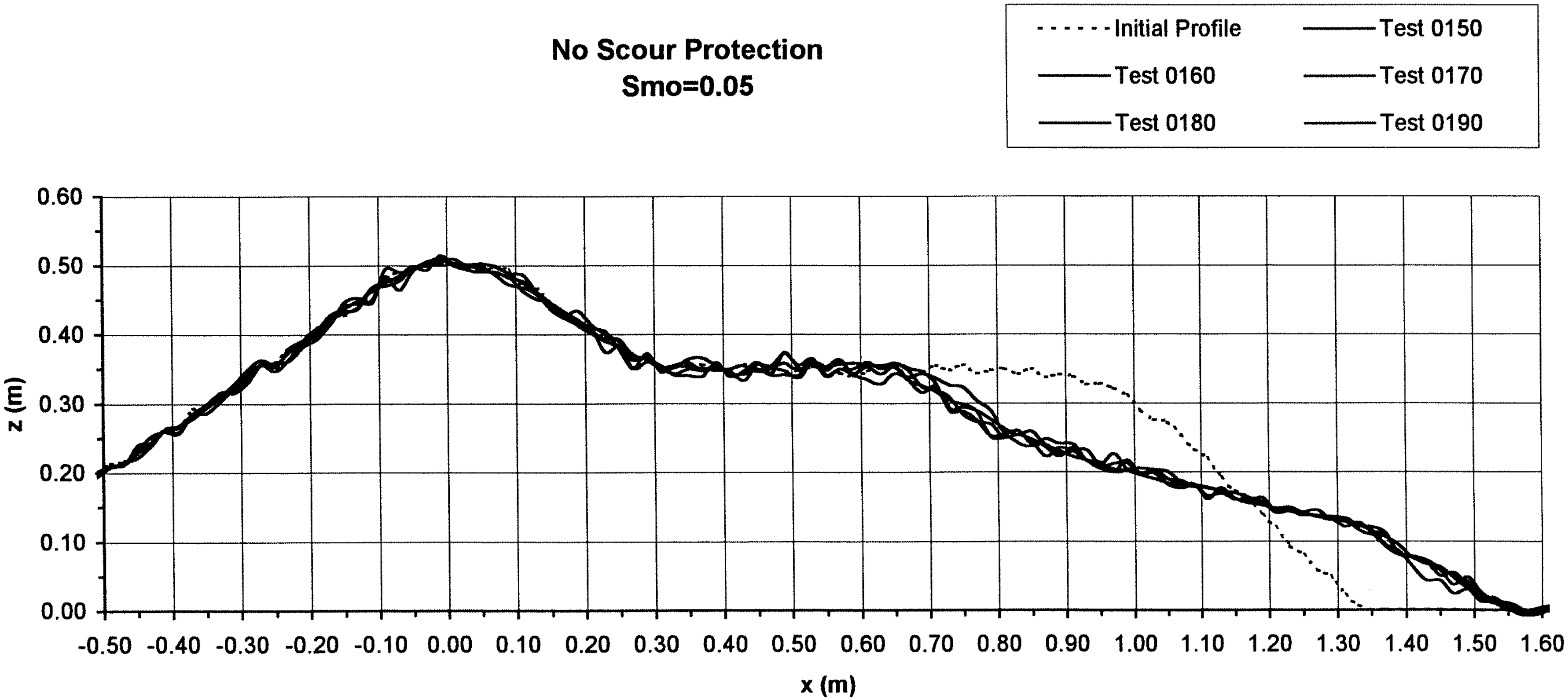


Profile 4 - After test with H_o=4.0, S_m=0.03

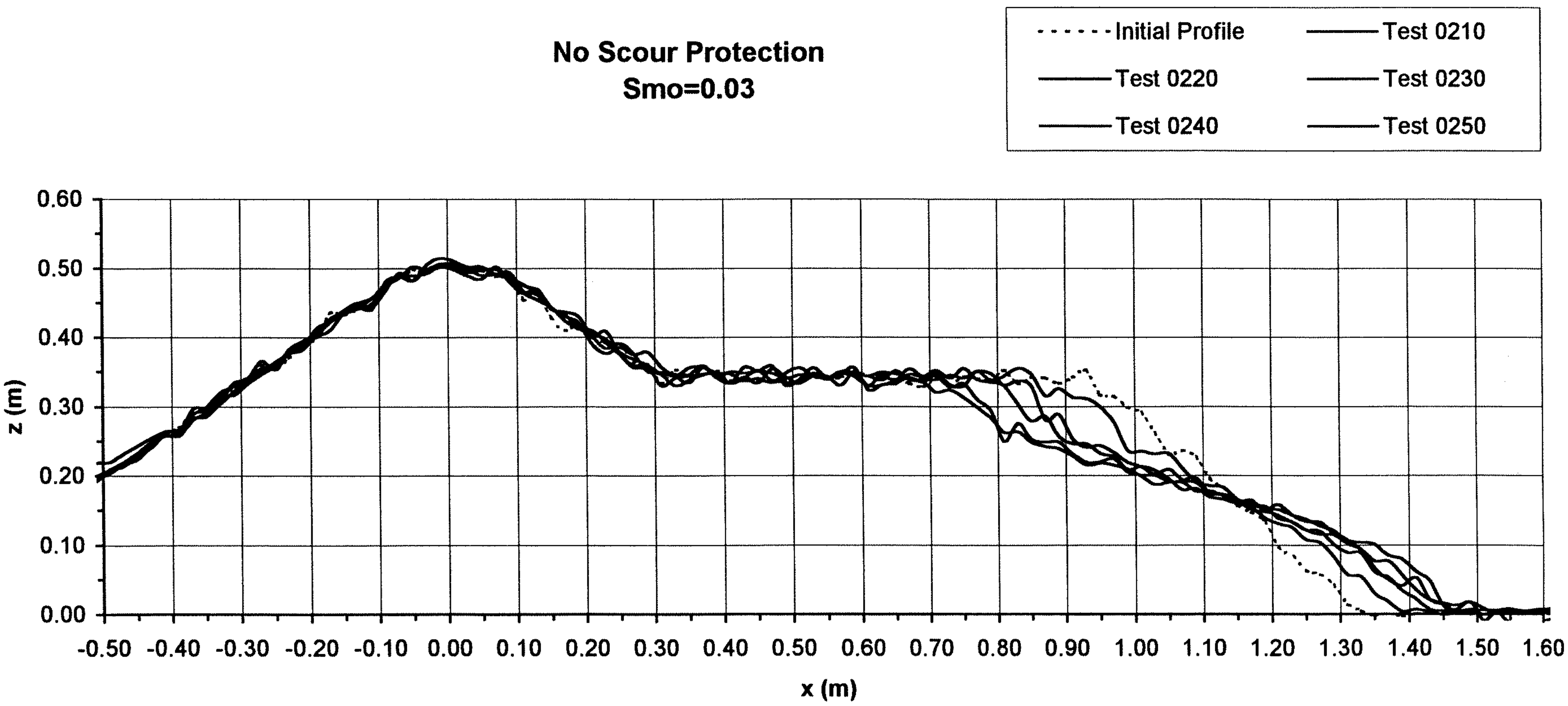
Profile 4 - After additional 4,000 waves with H_o=3.5, S_m=0.02

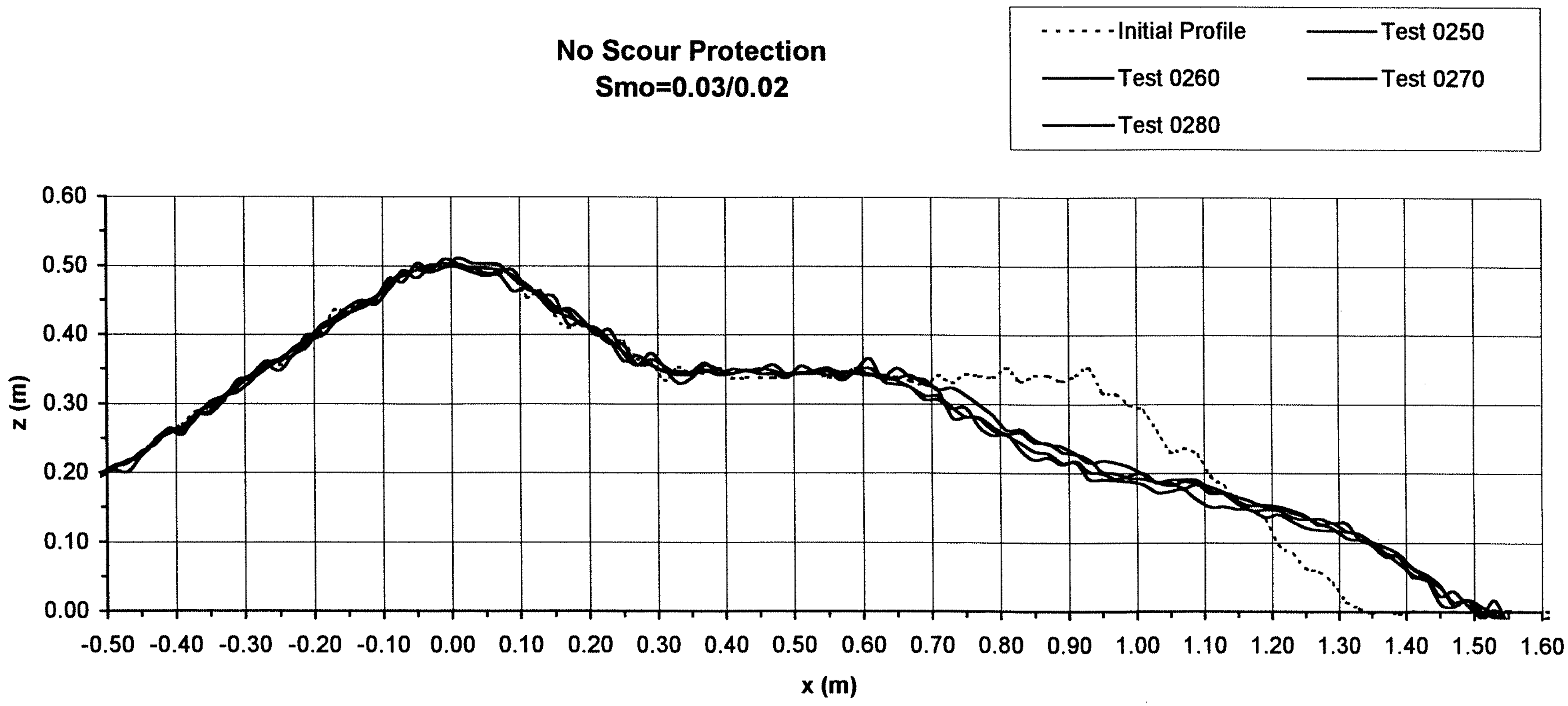
Appendix C Plots of profile developments

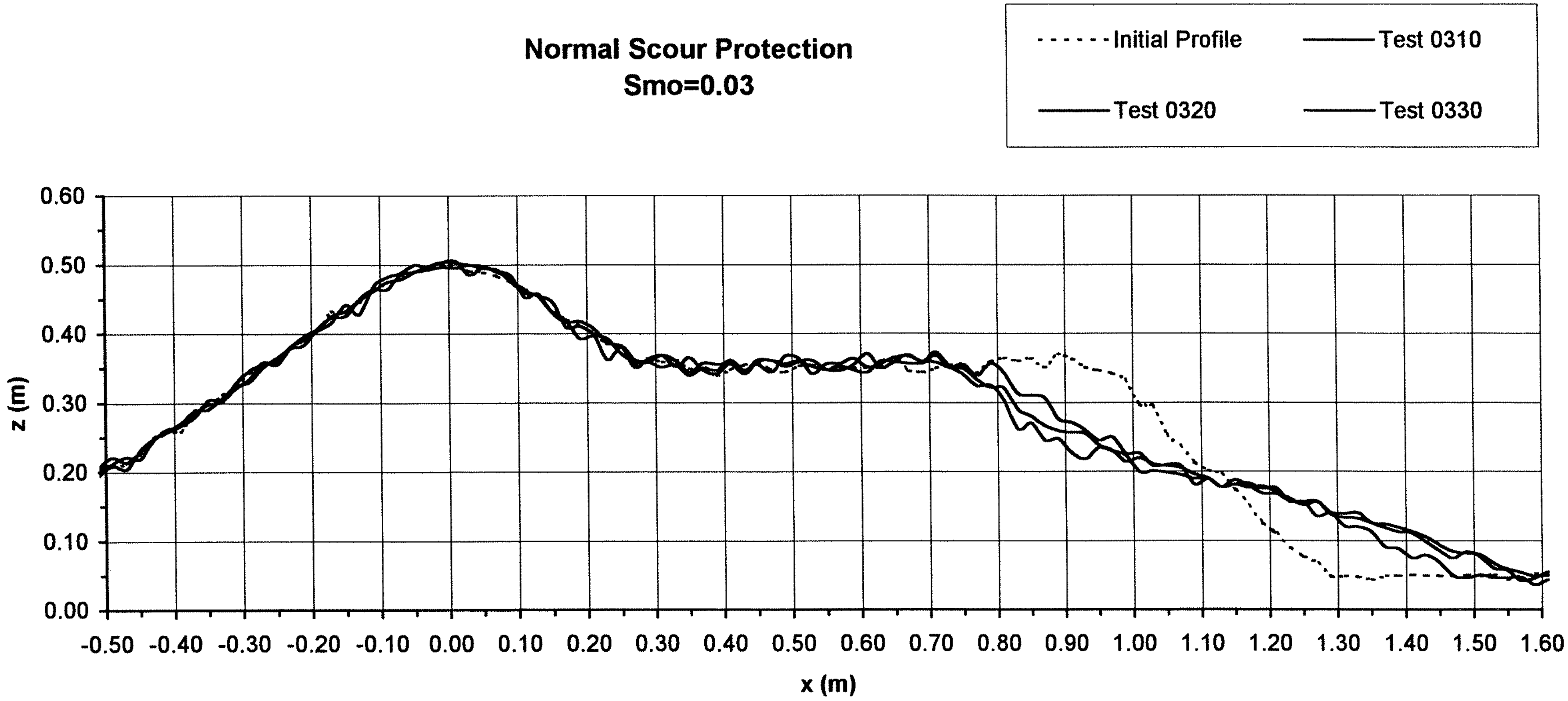

No Scour Protection
Smo=0.05
Initial Profile
Test 0110
Test 0120
Test 0130
Test 0140
Test 0150
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.50 -0.40 -0.30 -0.20 -0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60
x (m)



No Scour Protection
Smo=0.05
Initial Profile
Test 0150
Test 0160
Test 0170
Test 0180
Test 0190
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.50 -0.40 -0.30 -0.20 -0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60
x (m)

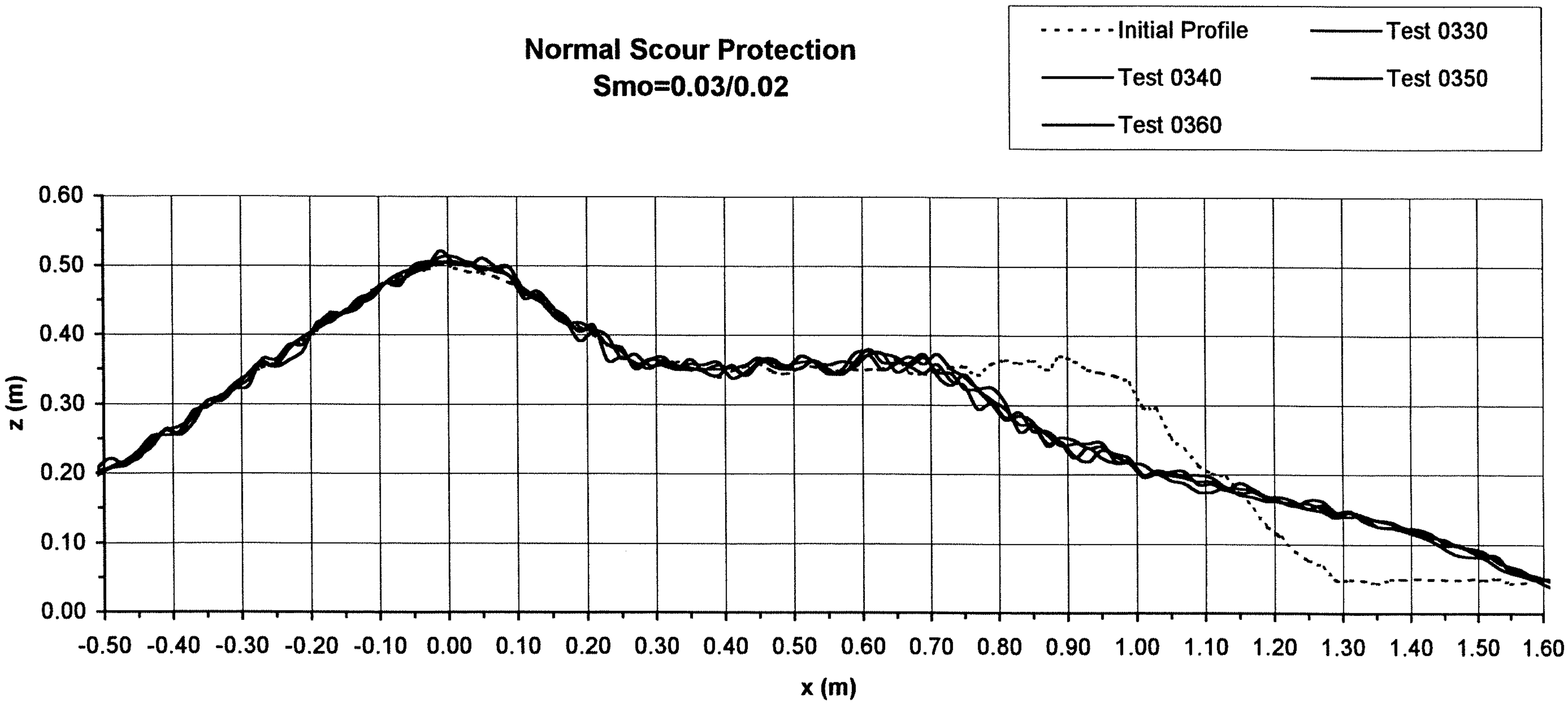

No Scour Protection
Smo=0.03
Initial Profile
Test 0210
Test 0220
Test 0230
Test 0240
Test 0250
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
x (m)

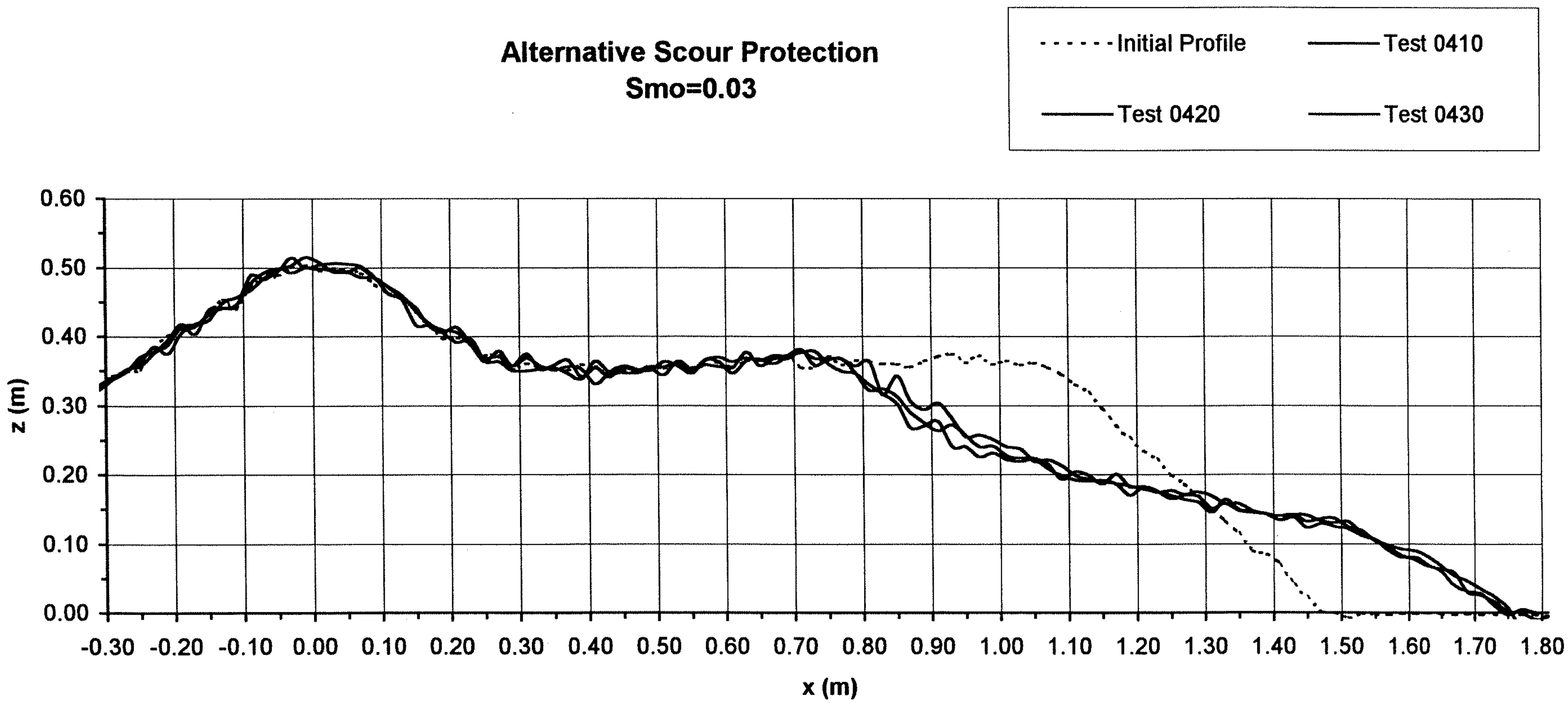

No Scour Protection
Smo=0.03/0.02
Initial Profile
Test 0250
Test 0260
Test 0270
Test 0280
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
x (m)



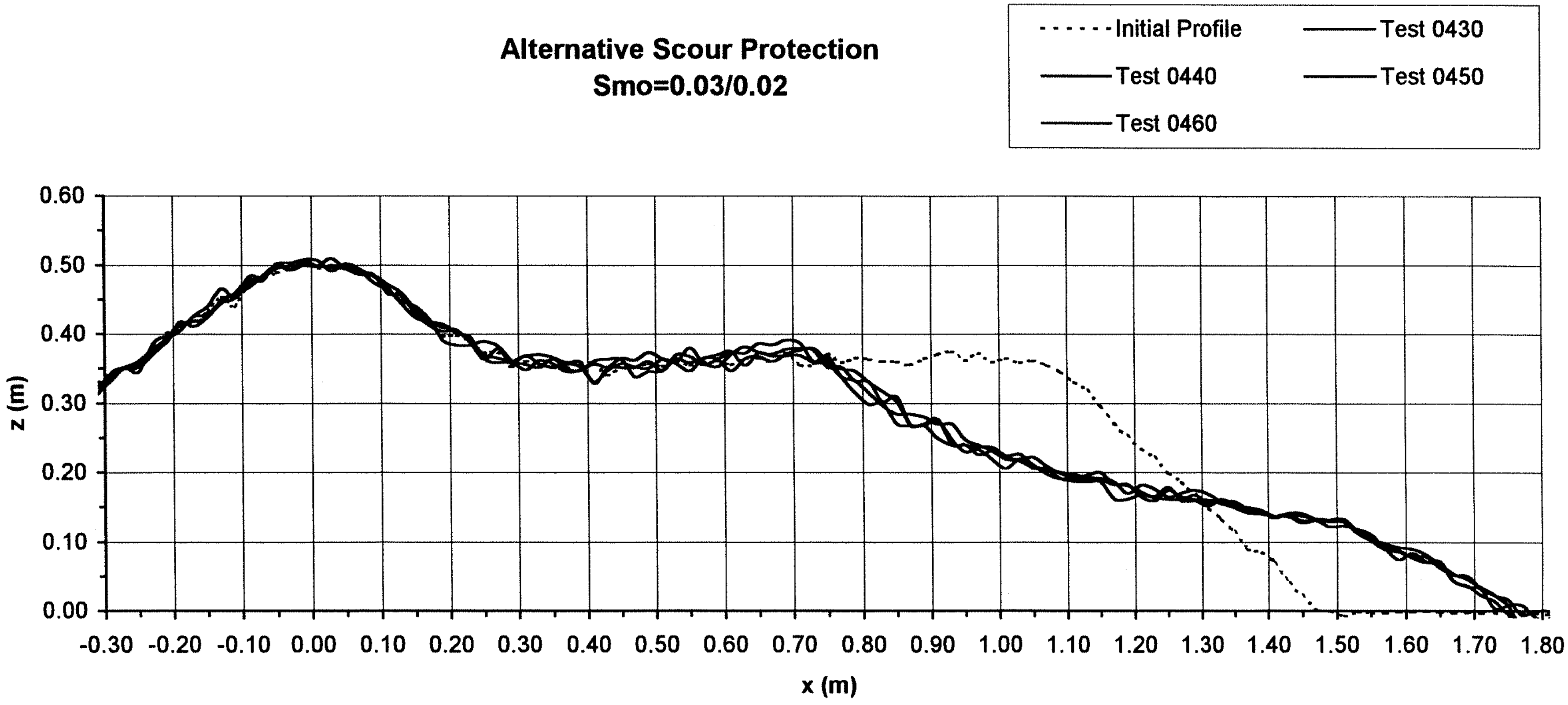
Normal Scour Protection
Smo=0.03
Initial Profile
Test 0310
Test 0320
Test 0330
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.50 -0.40 -0.30 -0.20 -0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60
x (m)

Normal Scour Protection
Smo=0.03/0.02

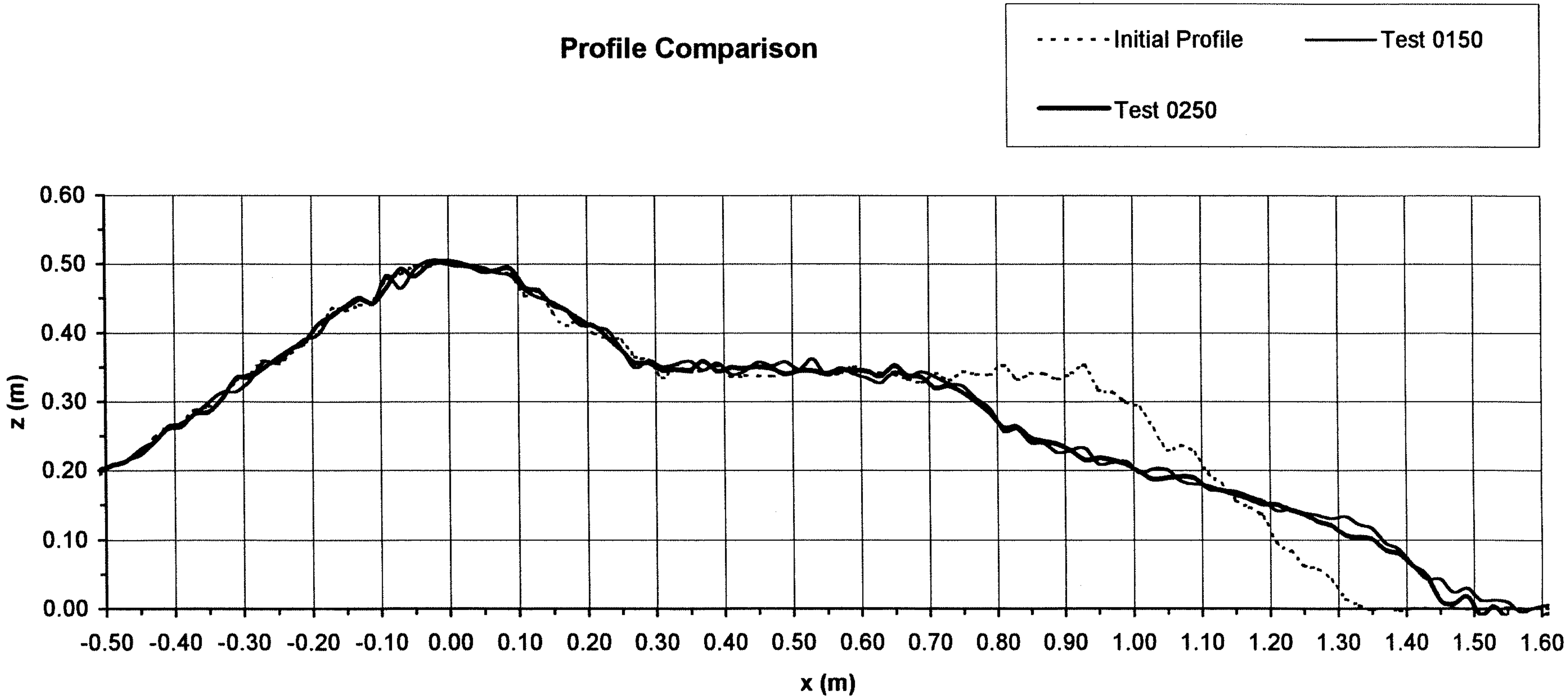


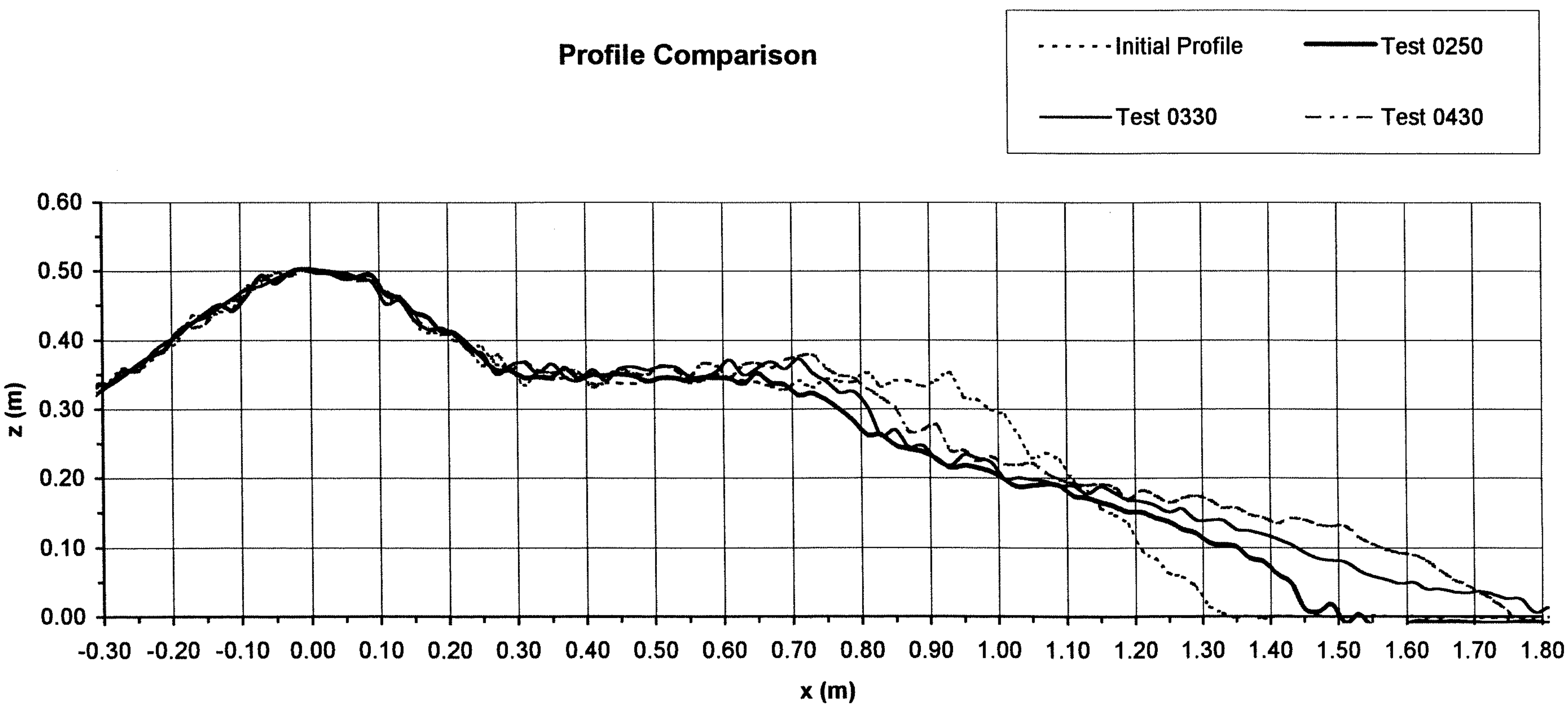


Alternative Scour Protection
Smo=0.03
Initial Profile
Test 0410
Test 0420
Test 0430
z (m)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
x (m)

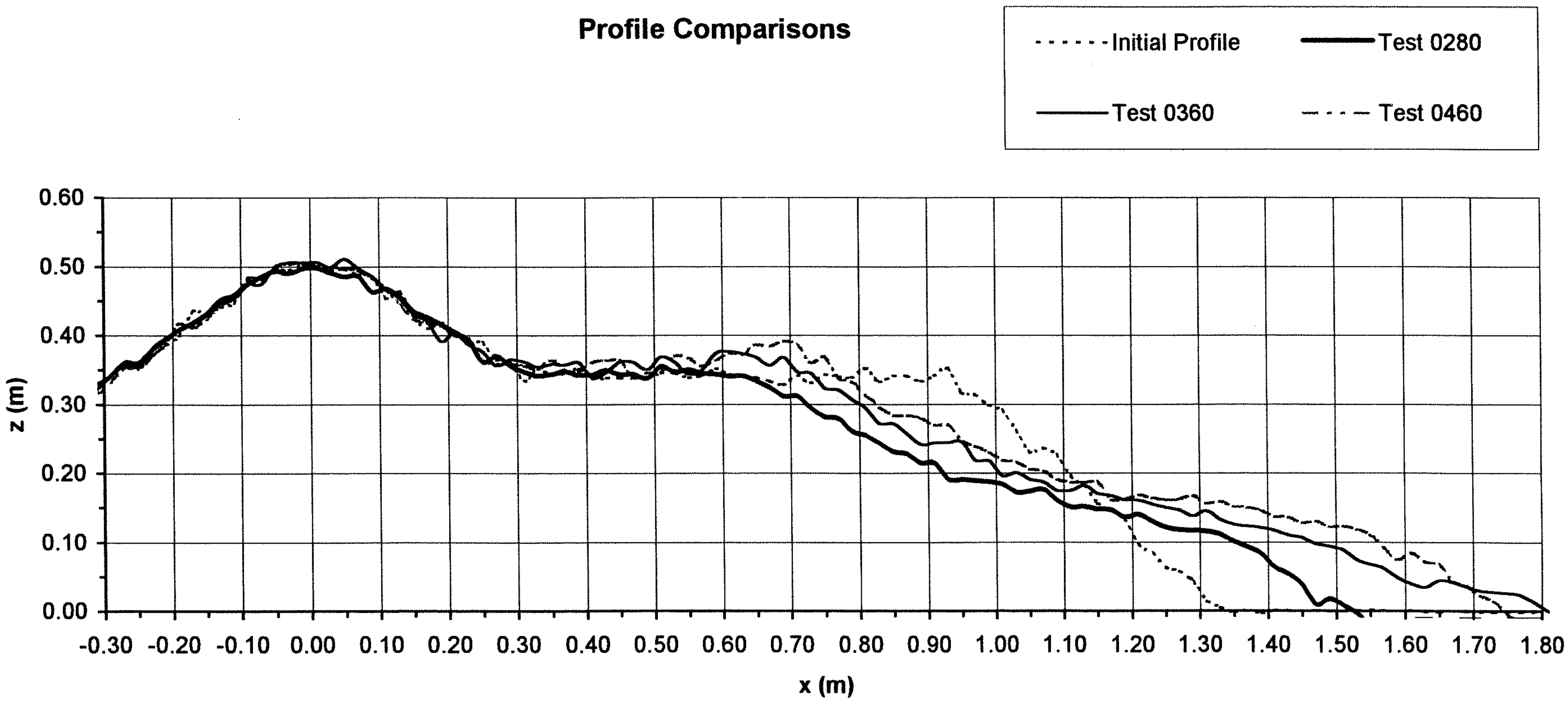


Alternative Scour Protection
Smo=0.03/0.02
Initial Profile
Test 0430
Test 0440
Test 0450
Test 0460
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
x (m)


Profile Comparison
Initial Profile
Test 0150
Test 0250
z (m)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
x (m)

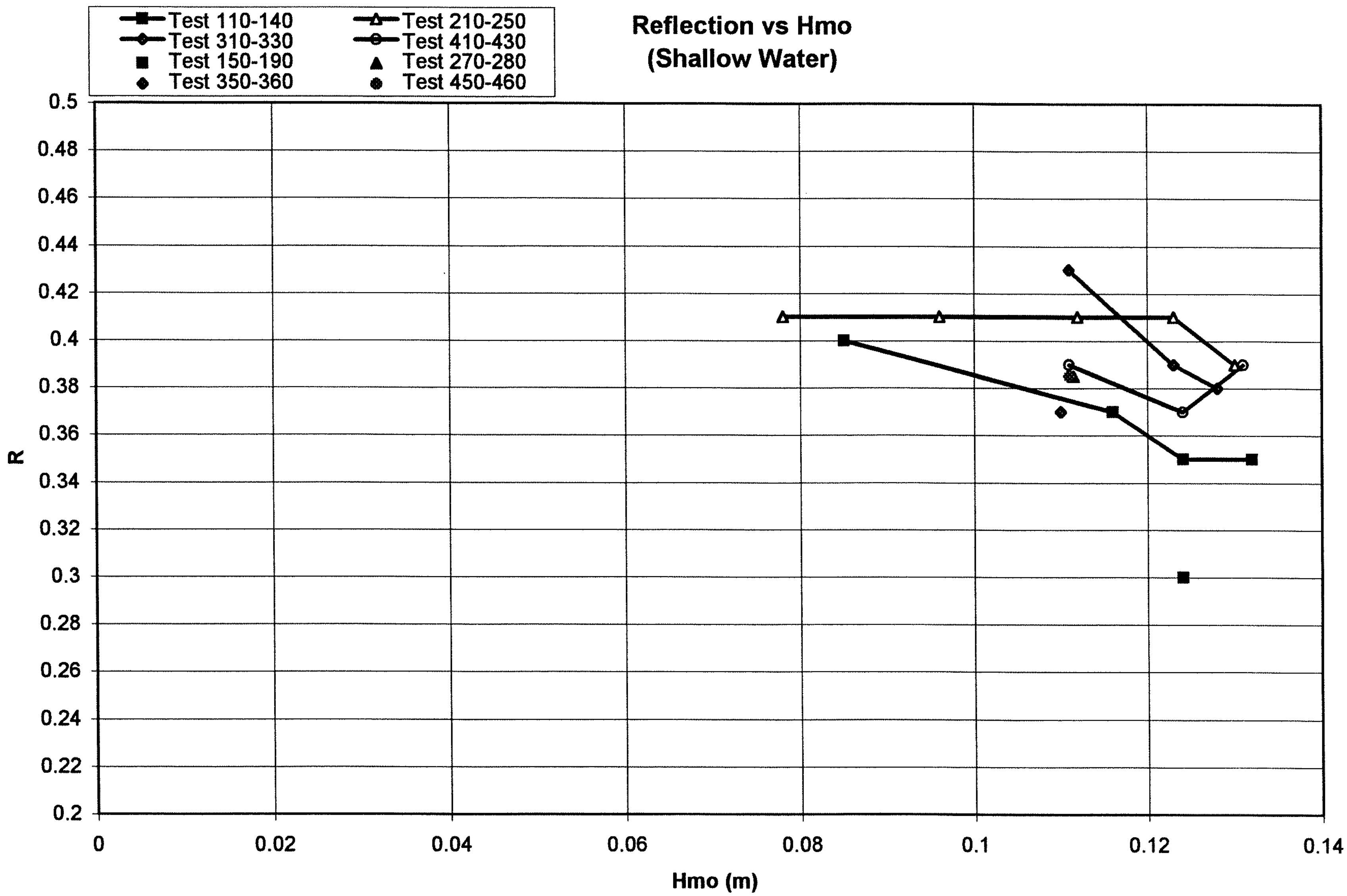


Profile Comparison
Initial Profile
Test 0250
Test 0330
Test 0430
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
x (m)

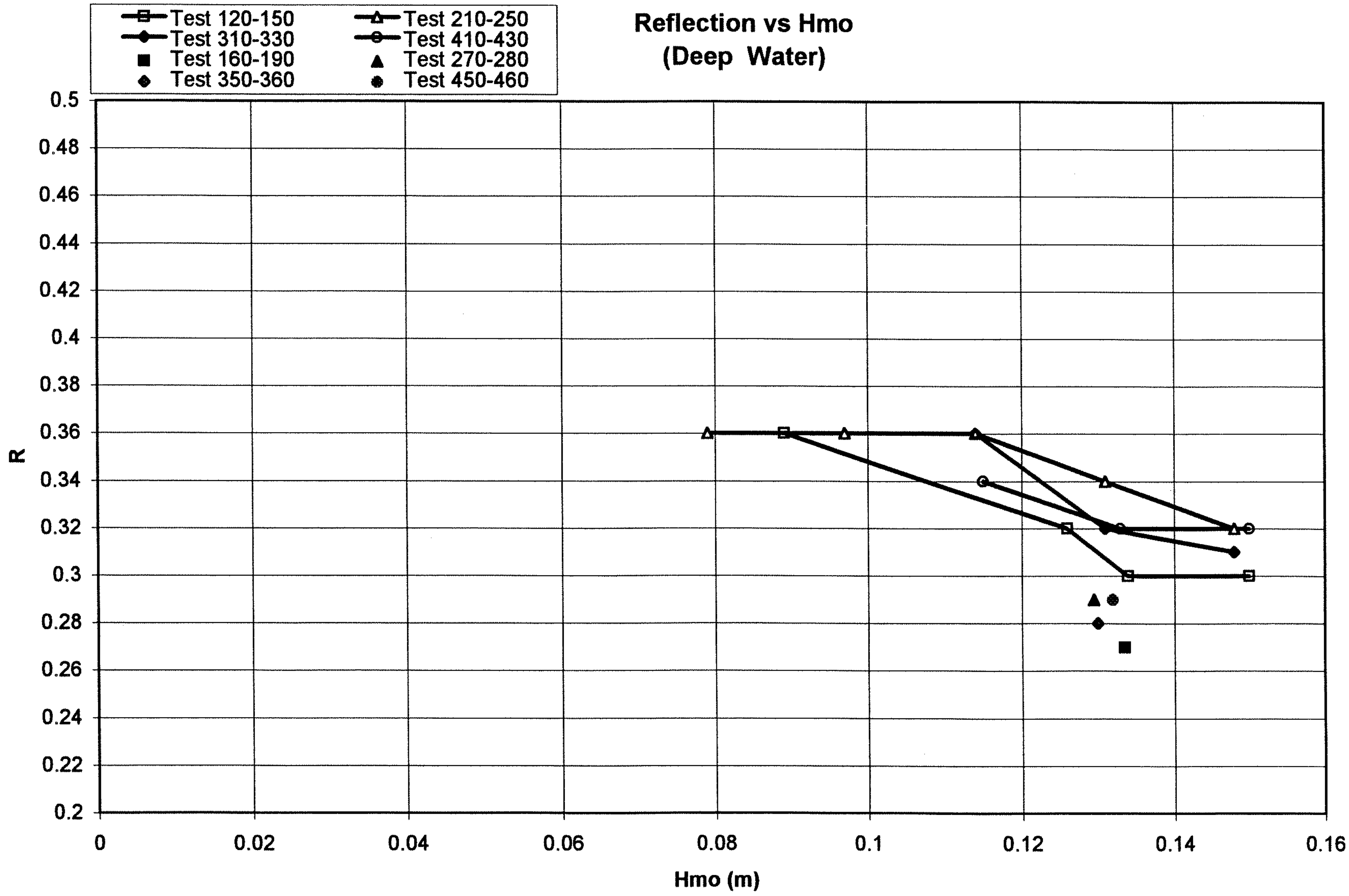


Profile Comparisons
Initial Profile
Test 0280
Test 0360
Test 0460
0.60
0.50
0.40
0.30
0.20
0.10
0.00
z (m)
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
x (m)

Appendix D Plots of reflection coefficients



Reflection vs Hmo
(Shallow Water)
Test 110-140
Test 210-250
Test 310-330
Test 410-430
Test 150-190
Test 270-280
Test 350-360
Test 450-460
R
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Hmo (m)


Reflection vs Hmo
(Deep Water)
Test 120-150
Test 210-250
Test 310-330
Test 410-430
Test 160-190
Test 270-280
Test 350-360
Test 450-460
R
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Hmo (m)