Scour and Scour Protection for Bucket Foundations

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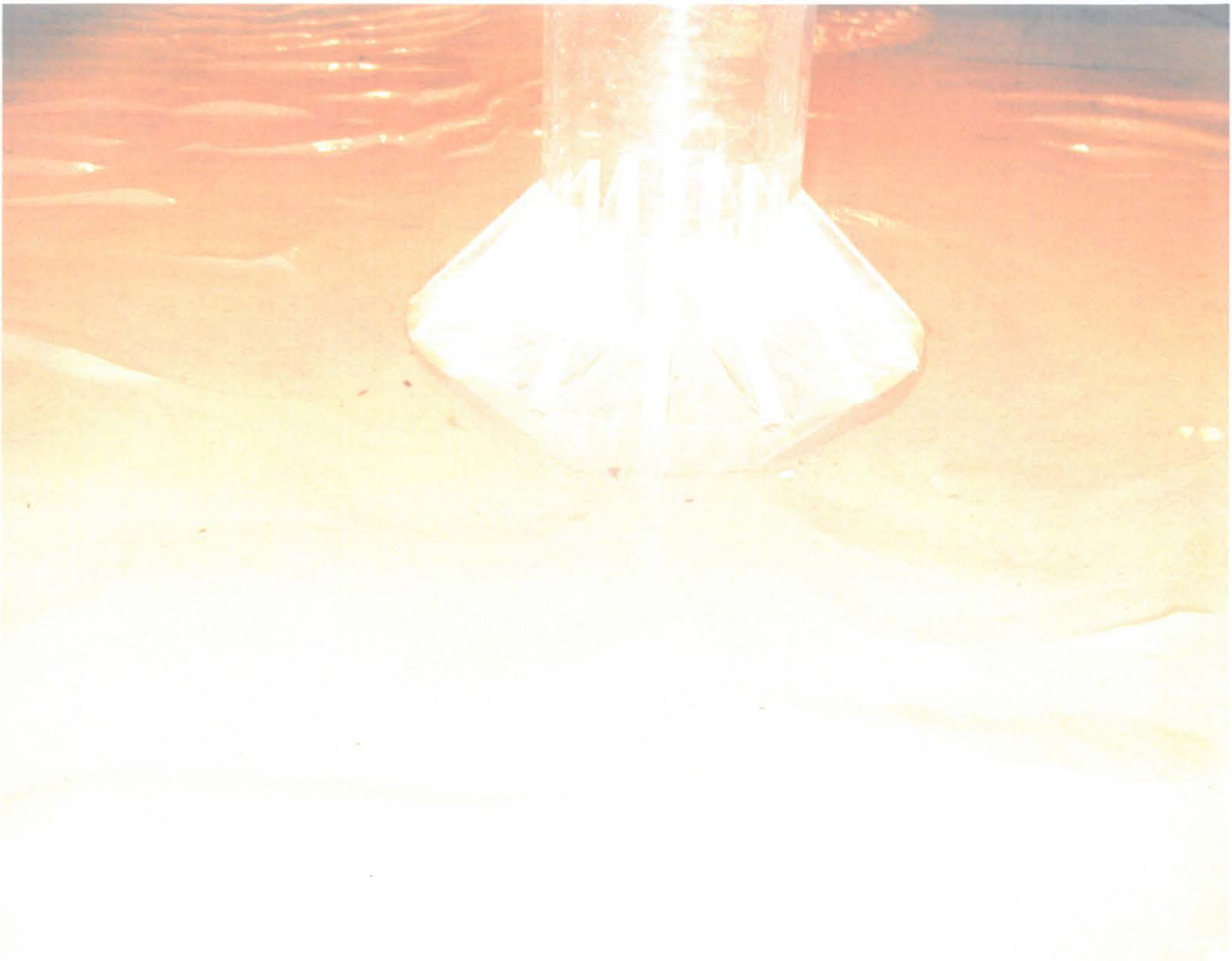

Scour and Scour Protection for Bucket Foundations

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Scour and Scour Protection for Bucket Foundations

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Introduction

By request from MBD Offshore Power A/S a test programme has been performed to determine the scour around a bucket foundation for an offshore windturbine. Furthermore the necessary scour protection has been investigated.

For further information on the conducted test programme contact Brian Juul Larsen (phone: 96 35 72 31, email: i5bjl@civil.aau.dk) or Peter Frigaard (phone: 96 35 84 79, email: peter.frigaard@civil.aau.dk).

Tests

Scaling

The tests are performed with a length scale of 1:50. All values are scaled according to Froudes modellaw:

Length: $\lambda_L = 50$
Time: $\lambda_T = \lambda_L^{1/2} = 7.07$

All measures in the following report will be in prototype values.

Description of Models

The two types of foundation that are being tested are shown underneath in figure 1. In appendix 3 the models are shown in detail.

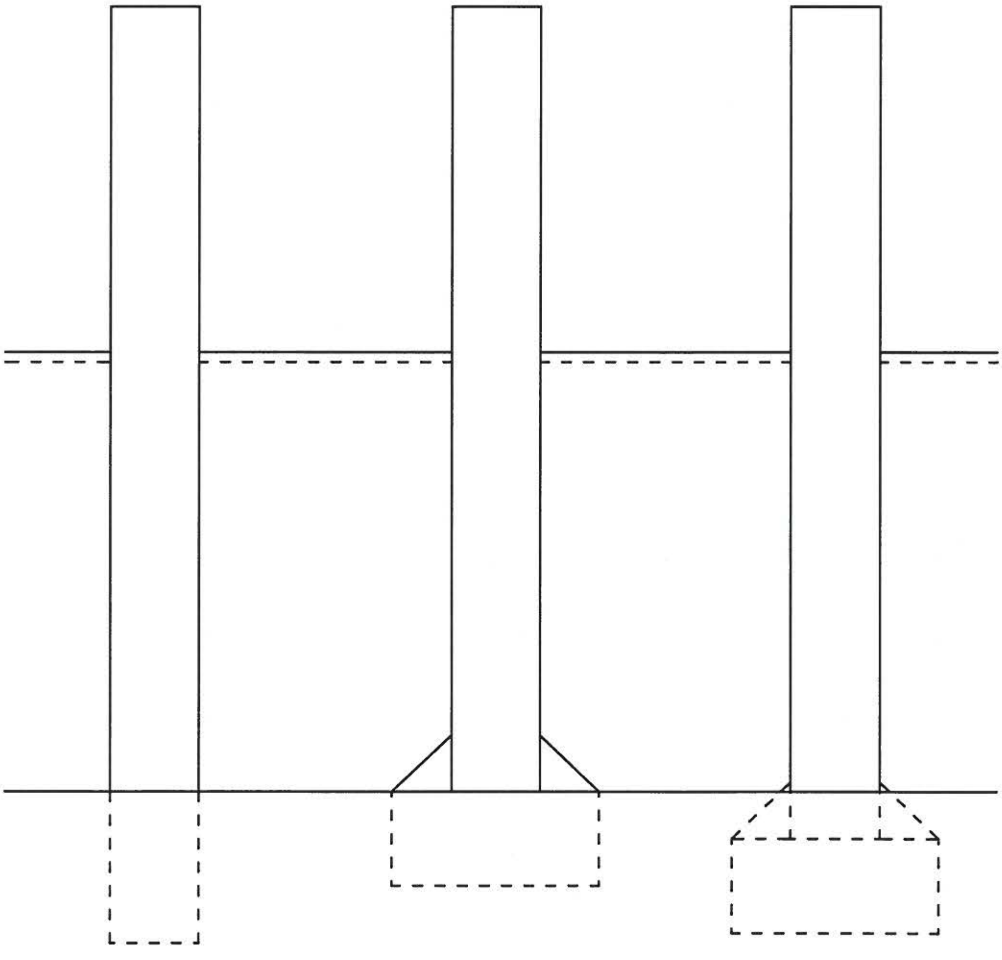


Figure 1. Monopile Bucket Bucket, low position

The models are made of various types of plastic.

Description of Set-up

The tests are conducted in a wave flume that is 995 meters long and 75 meters wide, see figure 2.

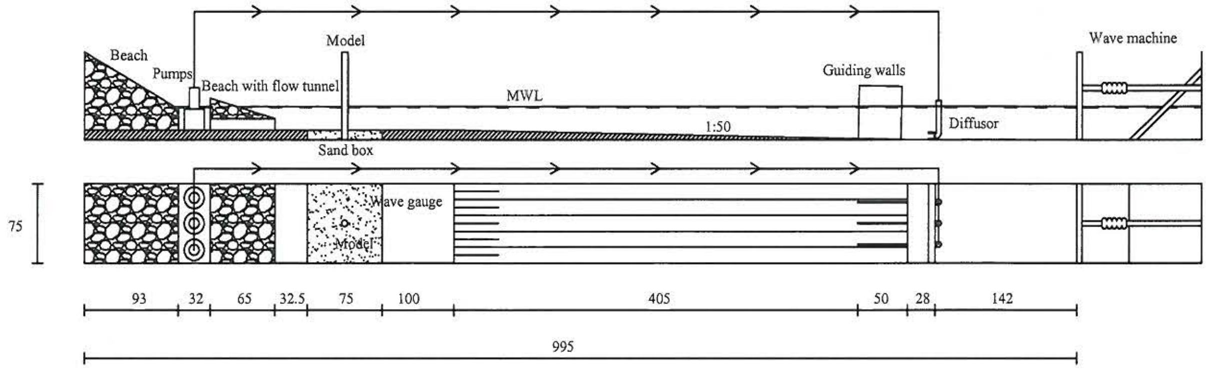


Figure 2. The wave flume. All measures in meters.

The test set-up is also shown on the movie DVD attached on the inside of the backside of this report.

Waves

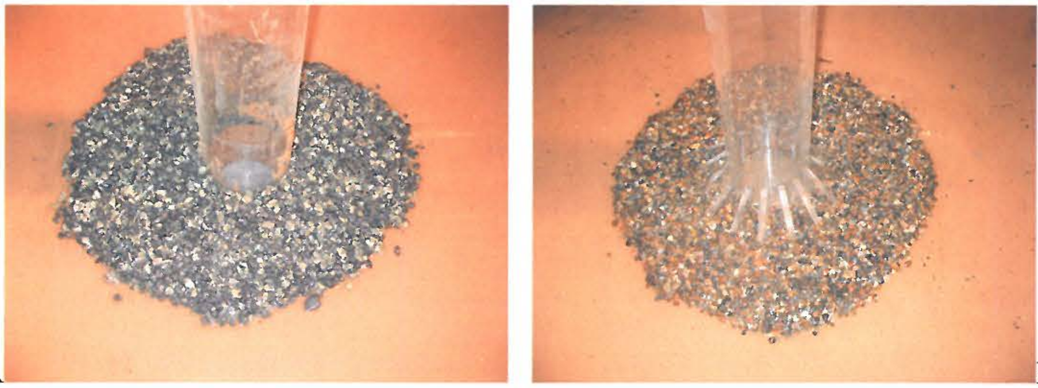
All tests where made with a JONSWAP spectra. The peak enhancement factor, γ, is at all times set at 3.3 and for the scour tests the test durations were generally set at 3000 times T_p to insure a proper amount of waves to reach a near equilibrium state. For the scour protection tests the test duration were set at 1000 times T_p.

Measurements

The wave elevation signal was measured beside the model by means of a single wave gauge. The current velocity has been measured with a propeller. In addition to that the scour holes are measured manually.

Scour Protection

The thickness of the scour protection layer is 1 m in all test cases. For the monopile the layout radius is 12 m from the center of the pile. For the bucket the layout is 5 m beyond the edges of the bucket. The three different types of scour protection that has been used are described in appendix 4. In figure 3 the layout of the scour protection is showed.



A B

Figure 3. Layout of the scour protection material.

A. Monopile: 12 m. B. Bucket: 5 m beyond the edges of the bucket.

Test programme

Test nr.	H_s [m]	T_p [s]	h [m]	U [m/s]	Structure	Comments
A1A	0	0	12.5	1.80	Monopile	
A2A	0	0	25	0.59	Monopile	
A2B	0	0	25	0.87	Monopile	
A3A	6.92	11.6	25	0	Monopile	
A3B	6.50	11.6	25	0.59	Monopile	
A3C	6.57	12.1	25	0.87	Monopile	
A3D	7.51	13.5	25	0.87	Monopile	
B1A	0	0	12.5	1.80	Bucket	
B2A	0	0	25	0.59	Bucket	
B2B	0	0	25	0.87	Bucket	
B3A	6.38	11.6	25	0	Bucket	
B3B	6.69	11.6	25	0.59	Bucket	
B3C	6.74	12.1	25	0.87	Bucket	
B3D	8.40	13.5	25	0.87	Bucket	
C1A	0	0	12.5	1.80	Bucket	Low position
C2A	0	0	25	0.59	Bucket	Low position
C2B	0	0	25	0.87	Bucket	Low position
C3A	8.00	11.4	25	0	Bucket	Low position
C3B	7.26	11.8	25	0.59	Bucket	Low position
C3C	6.12	11.6	25	0.87	Bucket	Low position
C3D	7.74	13.8	25	0.87	Bucket	Low position
D1A	7.54	14.1	25	0.87	Monopile	Protection 1
D2A	7.75	13.2	25	0.87	Monopile	Protection 2
D3A	7.71	13.5	25	0.87	Monopile	Protection 3
D3B	10.52	20.7	25	0.87	Monopile	Protection 3
E1A	8.07	13.8	25	0.87	Bucket	Protection 2
E1B	9.80	16.6	25	0.87	Bucket	Protection 2
F1A	5.99	11.6	25	0.87	Bucket	Protection 1
F1B	7.36	13.8	25	0.87	Bucket	Protection 1
F1C	9.31	16.1	25	0.87	Bucket	Protection 1
G1A	7.78	13.6	25	0.87	Bucket	Pro. 1, refilled
G1B	9.43	16.1	25	0.87	Bucket	Pro. 1, refilled
H1A	7.70	13.5	25	0.87	Bucket	Pro. 1, low pos., refilled
H1B	9.18	16.1	25	0.87	Bucket	Pro. 1, low pos., refilled

Table 1. Test programme.

Low position means that the bucket lit is placed 3 m underneath the bed. Refilled means that the scour protection was arranged in an imitated scour hole around the bucket. The "hole" had a stretch of 4 meters and a depth of 2.5 meters.

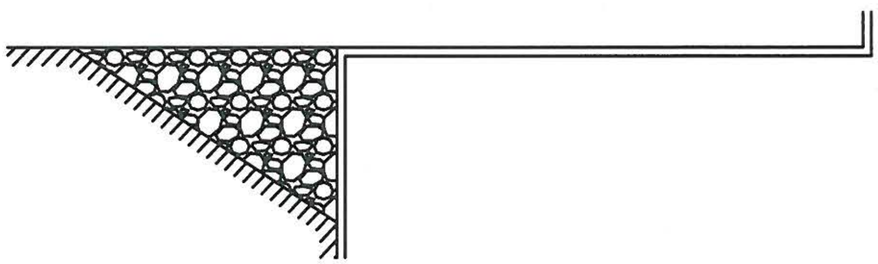


Figure 4. Scour protection filled in to a scour hole as in part G of the test programme.

Results

Scour Tests

In appendix 2 the test results are commented on and there are illustrations that show the shapes of the scour holes. In table 3 the end result of all scour tests are listed. The definitions of S, R and Θ are shown in figure 5.

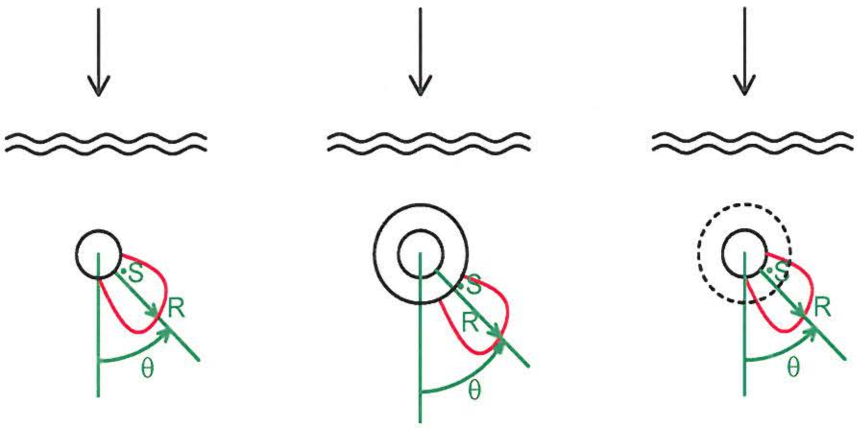


Figure 5. S is the deepness of the scour hole. R is the largest stretch of the scour hole and Θ describes the direction of R. For the bucket R is measured from the edge of the bucket in part B of the tests. In part C where the bucket is not visible, R is measured from the main pile.

Test nr.	S [m]	R [m]	Θ [°]	S/D	R/D
A1A	4.75	11.0	15	0.79	1.83
A2A	-	-	-	-	-
A2B	1.00	7.5	15	0.17	1.25
A3A	1.00	4.0	90	0.17	0.67
A3B	1.00	4.0	90	0.17	0.67
A3C	1.25	4.0	90	0.21	0.67
A3D	1.25	4.5	90	0.21	0.75
B1A	2.00	9.5	30	0.33	1.58
B2A	-	-	-	-	-
B2B	-	-	-	-	-
B3A	-	-	-	-	-
B3B	-	-	-	-	-
B3C	0.75	2.5	30	0.13	0.42
B3D	1.00	3.5	180	0.17	0.58
C1A	3.00	15.0	0	0.50	2.50
C2A	-	-	-	-	-
C2B	1.50	4.0	60	0.25	0.67
C3A	0.75	2.5	90	0.13	0.42
C3B	2.50	4.0	90	0.42	0.67
C3C	2.75	4.0	90	0.46	0.67
C3D	3.00	6.0	90	0.50	1.00

Table 2. Test results for the scour tests on both structures. D is set at 6 m in all cases.

The literature normally suggests a scour depth relative to structure diameter S/D equal to 1.3. It is generally accepted, that currents results in much more scour than waves.

Scour Protection Tests

Three different types of scour protection have been tested. All cases constructed of a 1 m thick one layer of gravel. For the monopile the layout radius is 12 m. For the bucket the layout is 5 m beyond the edges of the bucket in part E and F. In part G and H the stretch of the refilled circular holes is 4 m. The tested grain sizes (D_{50}) were 89 mm, 258 mm and 290 mm.

For the monopile it was found that scour protection type number three (D_{50} = 290 mm) was stable for a case of significant wave heights of approximately 7.5 meters, peak periods of approximately 13.5 seconds and current velocities of 0.87 meters per second. For the bucket in the same climate it was found that scour protection type number one (D_{50} = 89 mm) was stable.

In appendix 1 there are photos of the damage of the scour protection and in appendix 2 the test results are commented on and there are illustrations that show the shapes of the holes in the scour protection after the tests. Below test E1 (where D_{50} were 258 mm) is shown as an example.

Figure 6. Before After

Summary

In wave-current conditions comparable to design situations and slightly worse situations at Borkum Riffgrund the bucket foundation (Ø = 12.5 m / Ø = 6 m) resulted in a 1 meter deep scour hole (test case B). When the bucket was lowered 3 meters (test case C) the deepest scour hole was 3 meters. In this situation the scour development is stopped by the lit of the bucket. Notice, that in the first case the scour occurred at the edge of the bucket, whereas in the latter case the scour occurred on top of the bucket.

The necessary scour protection for design situations at Borkum Riffgrund would according to these tests be protection type number one (D_{50} = 89 mm) in both cases. A rough guess of necessary amounts of scour protection material is 1150 m^3.

The findings from the tests are assumed to be valid also for buckets with slightly larger and smaller diameters. In such situations the scour depths and the stretch of the scour holes should be scaled with the diameter of the tower structure.

Appendix 1 - Photos

Set-up:

Figure 1.1. A: The paddle. B: Diffuser and guiding walls. C: Model in front of stone beach with a flow tunnel to increase the flow at the bottom. D: Side view with ruler to the left and a video camera in the front. The video footage on the movie DVD is shot through the glass. E: Pump. There are three pumps in all - standing next to each other. F: Propeller for measuring current velocity.

The test set-up is also shown on the movie DVD attached on the inside of the front page of this report.

Models:

Figure 1.2. The models.

The following pictures show some of the results of the tests. In some cases there is still water left in the scour holes and the depth and the general contour of the bed around the structure can seem more smooth then it actually is.

A1:

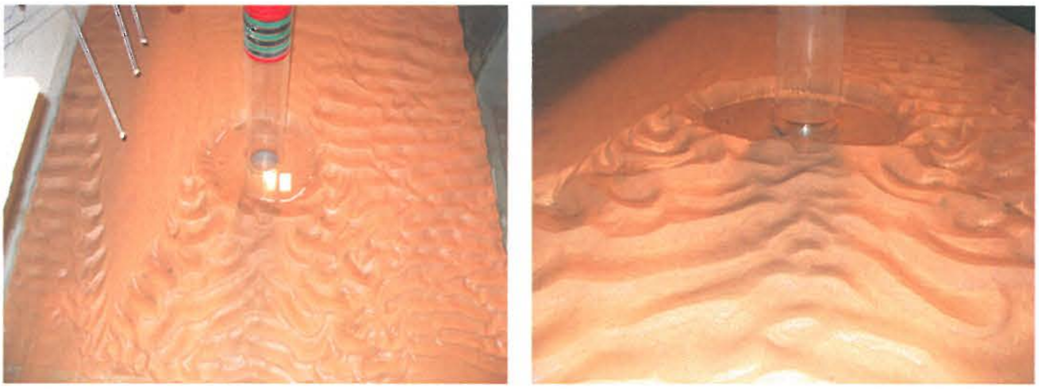


Figure 1.3.

A2:

Figure 1.4.

A3:

Figure 1.5.

B1:

Figure 1.6.

B2:

In B2 no scour occurred.

B3:

Figure 1.7.

C1:

Figure 1.8.

C2:

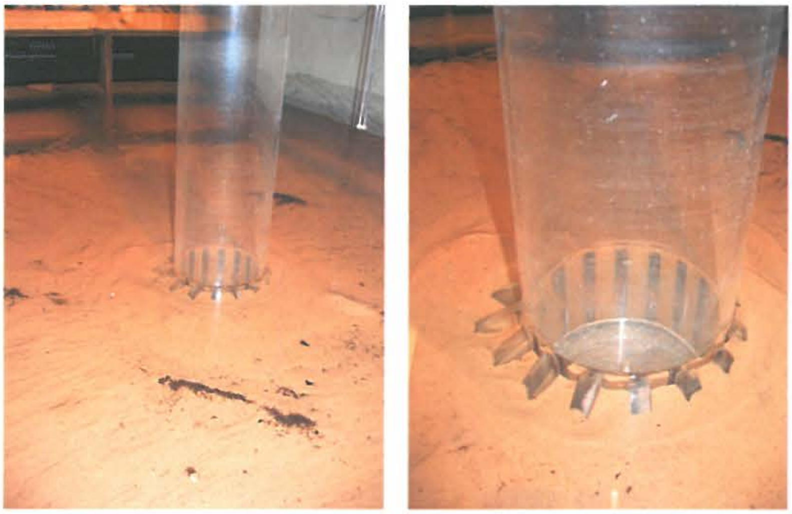


Figure 1.9.

C3:

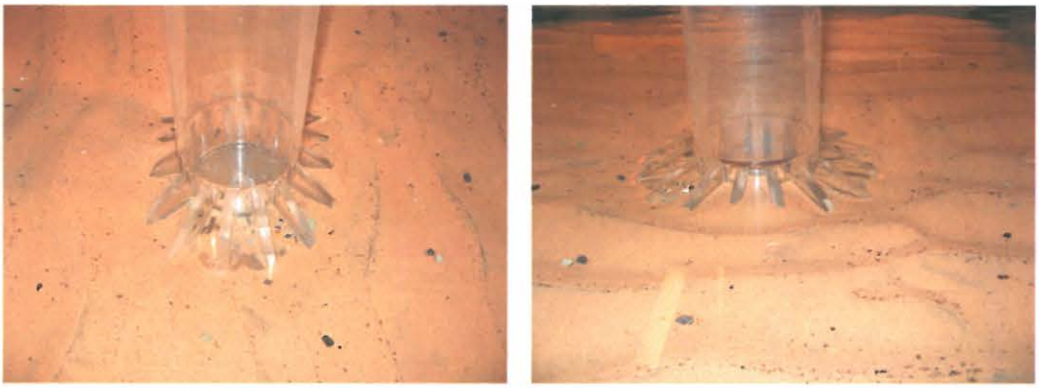


Figure 1.10.

In the following pictures of scour protection the "after" pictures may appear more damaged then they are due to bed material covering the protection material. In appendix 2 it is sketched which level of damage actually occurred.

D1:

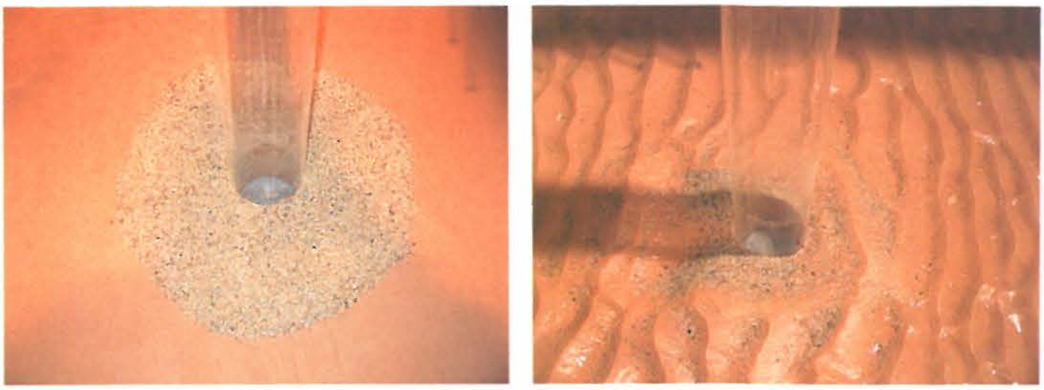


Figure 1.11. Before After

D2:

Figure 1.12. Before After

D3:

Figure 1.13. Before

E1:


Figure 1.14. Before After

F1:

No picture available

Figure 1.15. Before After

G1:


Figure 1.16. Before After

H1:

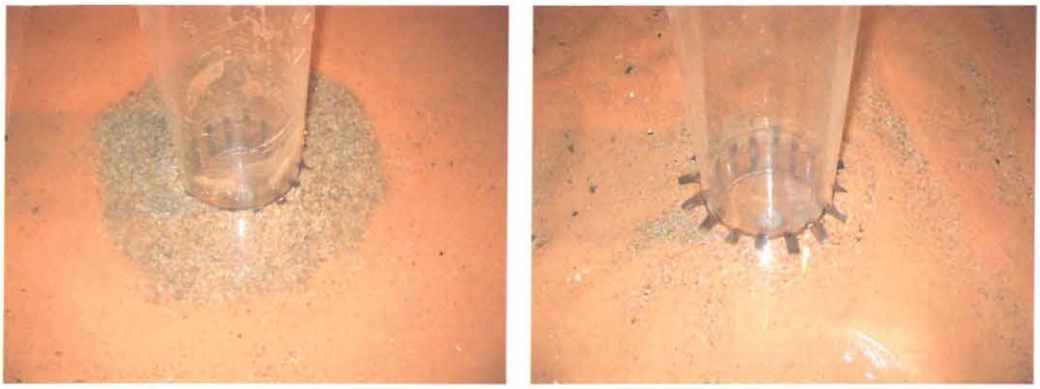


Figure 1.17. Before After

Appendix 2 - Results

This appendix contains the entire results of the scour tests and rough sketches of the shapes of the scour holes as they looked at the end of the tests. On page 28 - 33 there is an overview of the results of the scour protection tests.

A1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
1.80	-	-	42420	None

Table 2.1. Climate during A1A.

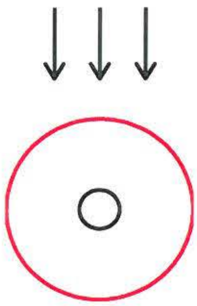


Figure 2.1. Scour hole at the end of A1A.

Minutes	S [m]	R [m]	Θ [°]
177	2.00	6.5	55
354	3.00	7.0	15
530	4.00	9.0	15
707	4.75	11.0	15

Table 2.2. Results of A1A.

A2A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.59	-	-	31815	None

Table 2.3. Climate during A2A.

The sediment did not move.

A2B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	-	-	42420	None

Table 2.4. Climate during A2B.

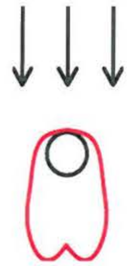


Figure 2.2. Scour hole at the end of A2B.

Minutes	S [m]	R [m]	Θ [°]
177	0.50	2.5	50
354	0.75	6.0	25
530	1.00	7.5	15
707	1.00	7.5	15

Table 2.5. Results of A2B.

A3A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0	6.92	11.6	33936	3414

Table 2.6. Climate during A3A.

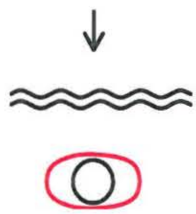


Figure 2.3. Scour hole at the end of A3A.

Waves	S [m]	R [m]	Θ [°]
1138	1.00	3.5	120
2276	1.00	4.0	90
3414	1.00	4.0	90

Table 2.7. Results of A3A.

Throughout A3 the distance between the ripples settled at 4 meters.

A3B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.59	6.50	11.6	33936	3009

Table 2.8. Climate during A3B.

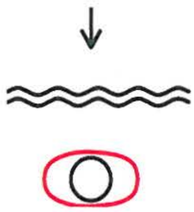


Figure 2.4. Scour hole at the end of A3B.

Waves	S [m]	R [m]	Θ [°]
1003	1.25	4.0	90
2006	1.00	4.0	80
3009	1.00	4.0	90

Table 2.9. Results of A3B.

A3C:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	6.57	12.1	33936	2973

Table 2.10. Climate during A3C.

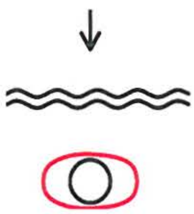


Figure 2.5. Scour hole at the end of A3C.

Waves	S [m]	R [m]	Θ [°]
991	1.25	4.5	80
1982	1.25	4.0	90
2973	1.25	4.0	90

Table 2.11. Results of A3C.

A3D:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.51	13.5	39239	3132

Table 2.12. Climate during A3D.

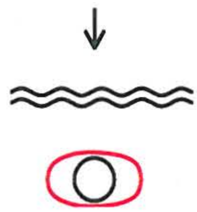


Figure 2.6. Scour hole at the end of A3D.

Waves	S [m]	R [m]	Θ [°]
1044	1.25	4.5	80
2088	1.25	4.0	90
3132	1.25	4.5	90

Table 2.13. Results of A3D.

During A3D there was a tendency for a pulsating "dust cloud" at the bottom suggesting a 'live bed' situation.

B1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
1.80	-	-	42420	None

Table 2.14. Climate during B1A.

Figure 2.7. Scour hole at the end of B1A.

Minutes	S [m]	R [m]	Θ [°]
177	0.75	6.0	30
354	1.50	8.5	30
530	1.75	9.5	30
707	2.00	9.5	30

Table 2.15. Results of B1A.

B2A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.59	-	-	10605	None

Table 2.16. Climate during B2A.

The sediment did not move.

B2B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	-	-	10605	None

Table 2.17. Climate during B2B.

The sediment did not move.

B3A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0	6.38	11.6	11312	1108

Table 2.18. Climate during B3A.

The sediment did not move.

B3B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.59	6.69	11.6	22624	2038

Table 2.19. Climate during B3B.

The sediment did not move.

B3C:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	6.74	12.1	22624	1938

Table 2.20. Climate during B3C.

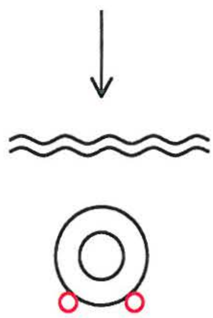


Figure 2.8. Scour hole at the end of B3C.

Waves	S [m]	R [m]	Θ [°]
969	0.75	2.5	30
1938	0.75	2.5	30

Table 2.21. Results of B3C.

During B3C there was a live bed tendency. The small scour holes that occurred during the test were mainly caused by rippling of the bed.

B3D:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	8.40	13.5	26159	2054

Table 2.22. Climate during B3D.

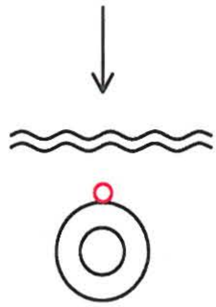


Figure 2.9. Scour hole at the end of B3D.

Waves	S [m]	R [m]	Θ [°]
1027	1.00	3.5	180
2054	1.00	3.5	180

Table 2.23. Results of B3D.

During B3D there was a live bed tendency. The small scour hole that occurred during the test were mainly caused by rippling of the bed.

C1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
1.80	-	-	42420	None

Table 2.24. Climate during C1A.

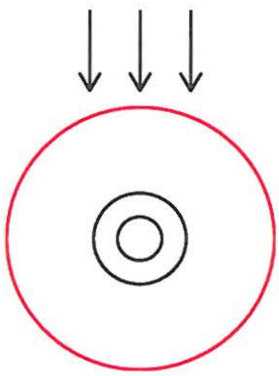


Figure 2.10. Scour hole at the end of C1A.

Minutes	S [m]	R [m]	Θ [°]
177	3.00	11.5	0
354	3.00	13.5	15
530	3.00	14.5	0
707	3.00	15	0

Table 2.25. Results of C1A.

C2A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.59	-	-	10605	None

Table 2.26. Climate during C2A.

The sediment did not move.

C2B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	-	-	31815	None

Table 2.27. Climate during C2B.

Figure 2.11. Scour hole at the end of C2B.

Minutes	S [m]	R [m]	Θ [°]
177	0.75	2.5	90
354	1.25	3.5	75
530	1.50	4.0	60

Table 2.28. Results of C2B.

Waves	S [m]	R [m]	Θ [°]
1001	1.50	3.5	90
2002	2.50	4.0	90
3003	2.50	4.0	90

Table 2.32. Results of C3B.

C3C:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	6.12	11.6	11312	973

Table 2.33. Climate during C3C.

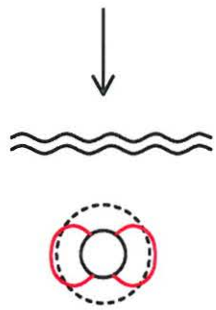


Figure 2.14. Scour hole at the end of C3C.

Waves	S [m]	R [m]	Θ [°]
973	2.75	4.0	90

Table 2.34. Results of C3C.

C3D:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.74	13.8	39239	2024

Table 2.35. Climate during C3D.

D2A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.75	13.2	13080	1018

Table 2.38. Climate during D2A.

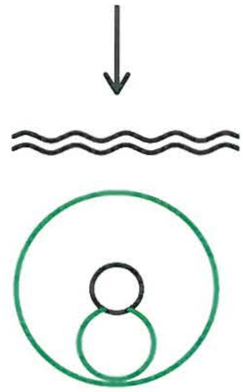


Figure 2.17. Shape of scour protection at the end of D2A.

In this test protection type number two was used. It has a D_{50} of 258 mm.

D3A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.71	13.5	13080	1032

Table 2.39. Climate during D3A.

In D3A there was no significant damage to the scour protection. Protection type number three was used. It has a D_{50} of 290 mm.

D3B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	10.52	20.7	20008	1120

Table 2.40. Climate during D3B.

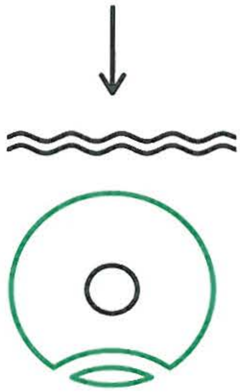


Figure 2.18. Shape of scour protection at the end of D3B.

In this test protection type number three was used. It has a D_{50} of 290 mm.

E1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	8.07	13.8	13080	1022

Table 2.41. Climate during E1A.

In E1A there was no significant damage to the scour protection. Protection type number two was used. It has a D_{50} of 258 mm.

E1B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	9.80	16.6	15554	1056

Table 2.42. Climate during E1B.

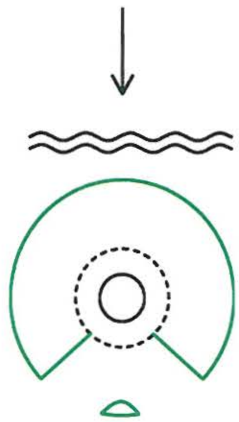


Figure 2.19. Shape of scour protection at the end of E1B.

In test E1B protection type number two was used. It has a D_{50} of 258 mm.

F1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	5.99	11.6	11312	974

Table 2.43. Climate during F1A.

In F1A there was no significant damage to the scour protection. Protection type number one was used. It has a D_{50} of 89 mm.

F1B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.36	13.8	13080	1018

Table 2.44. Climate during F1B.

In F1B there was no significant damage to the scour protection. Protection type number one was used. It has a D_{50} of 89 mm.

F1C:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	9.31	16.1	15554	1045

Table 2.45. Climate during F1C.

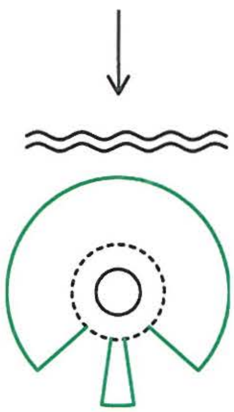


Figure 2.20. Shape of scour protection at the end of F1C.

In this test protection type number one was used. It has a D_{50} of 89 mm.

G1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.78	13.6	13080	1018

Table 2.46. Climate during G1A.

In G1A there was no significant damage to the scour protection. Protection type number one was used. It has a D_{50} of 89 mm. In this test the scour protection was arranged in an imitated scour hole around the bucket. The "hole" had a stretch of 4 meters and a depth of 2.5 meters.

G1B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	9.43	16.1	15554	1058

Table 2.47. Climate during G1B.

In G1B there was no significant damage to the scour protection. Protection type number one was used. It has a D_{50} of 89 mm. The layout of the scour protection was the same as in G1A.

H1A:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	7.70	13.5	13080	1019

Table 2.48. Climate during H1A.

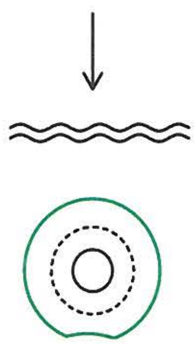


Figure 2.21. Shape of scour protection at the end of H1A.

In this test protection type number one was used. It has a D_{50} of 89 mm. As in G1A and G1B the scour protection was arranged in an imitated scour hole with a stretch of 4 meters and a depth of 2.5 meters.

H1B:

U [m/s]	Hs [m]	Tp [m]	Duration [s]	Waves
0.87	9.18	16.1	15554	1072

Table 2.49. Climate during H1B.

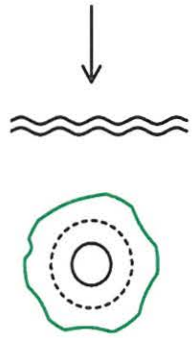


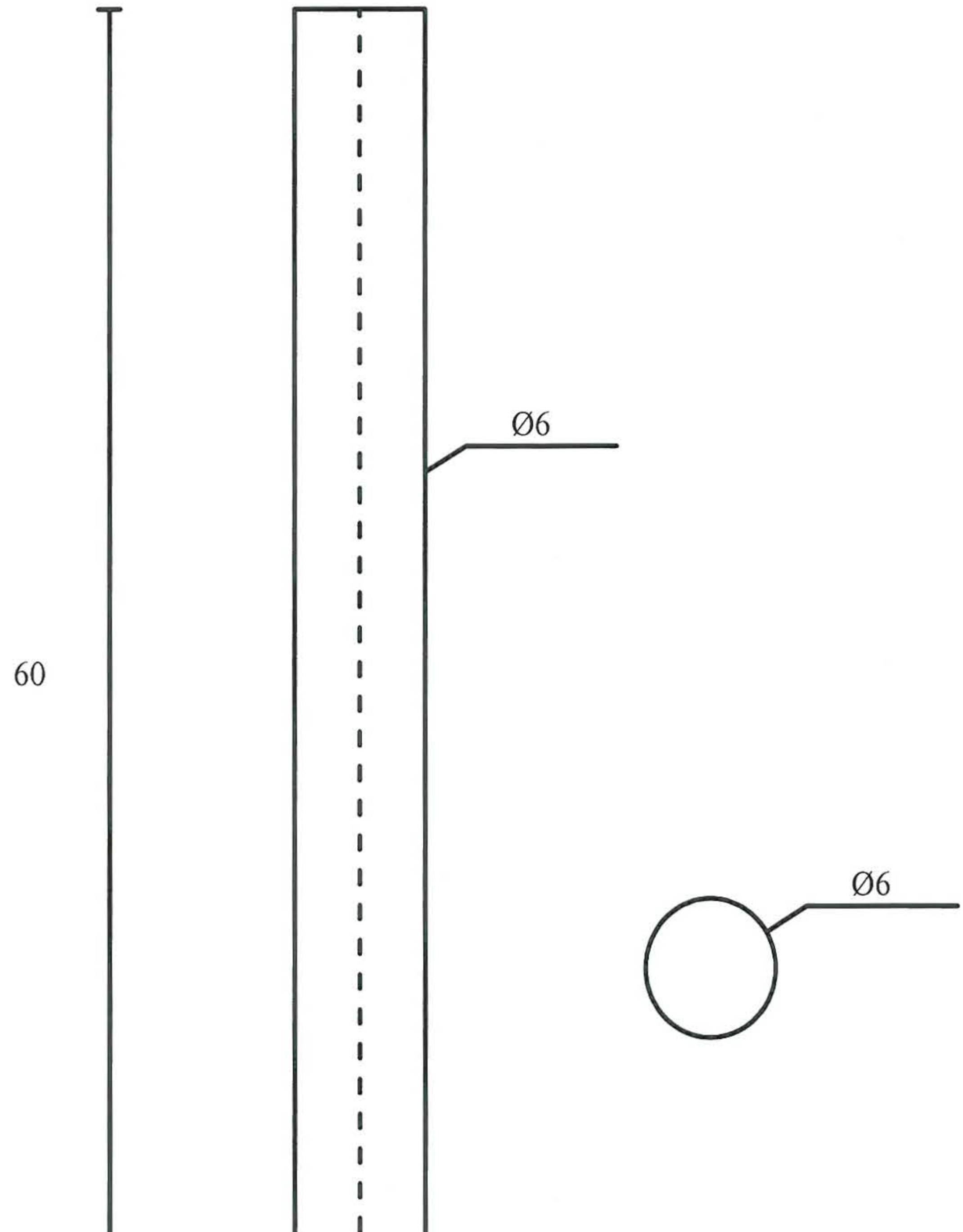
Figure 2.22. Shape of scour protection at the end of H1B.

In this test protection type number one was used. It has a D_{50} of 89 mm. The layout of the scour protection was the same as in H1A.

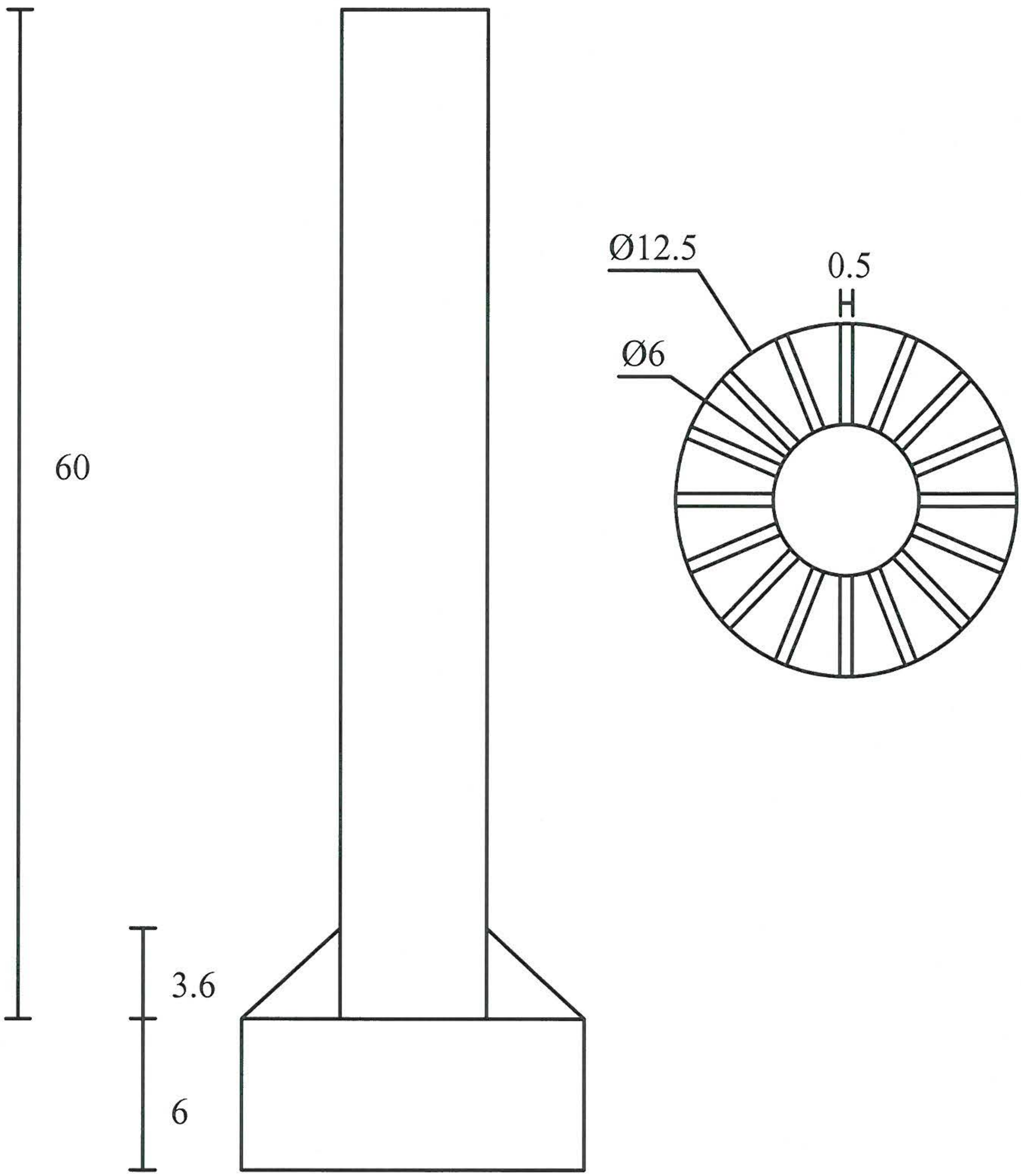
Appendix 3 - Models

All measures in meters – prototype values.

Monopile:



Bucket:



Appendix 4 – Sand and Scour Protection

Sand

The sand that is being used in these scour tests is an industrial product called Baskarp B15. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
1	0	802.68	100.000
0.5	0.04	802.64	99.995
0.425	0.13	802.51	99.979
0.25	15.83	786.68	98.007
0.125	664.14	122.54	15.266
0.075	113.92	8.62	1.074
Bottom	8.62	0	0

Table 4.1. Grain size distribution. D_{50} is 0.17 mm.
In prototype scale D_{50} is 8.4 mm.

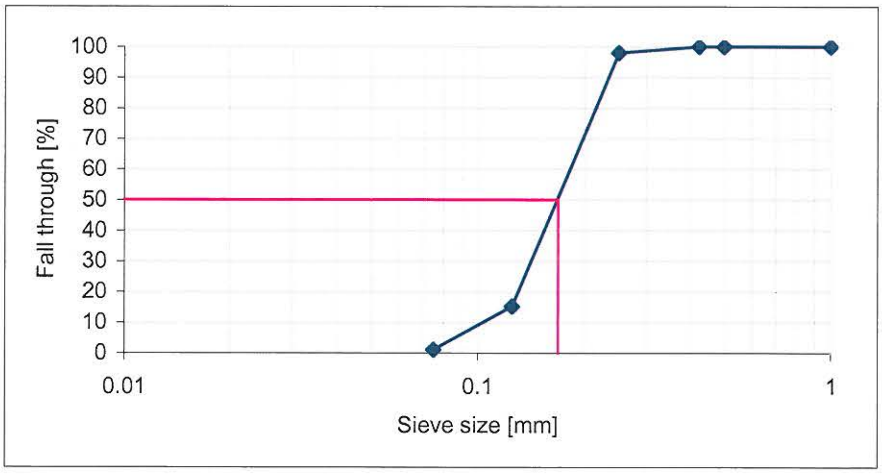


Figure 4.1. Grain size distribution curve.

Protection 1

The material that is being used for scour protection number one is a mixture of sand especially made for these tests. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
8	0	343.82	100.000
4	0.18	343.64	99.948
2	142.61	201.03	58.470
1	179.58	21.45	6.239
0.5	10.01	11.44	3.327
0.25	8.06	3.38	0.983
Bottom	3.38	0	0

Table 4.2. Grain size distribution. D_{50} is 1.77 mm.
In prototype scale D_{50} is 89 mm and W_{50} is 1.06 kg.

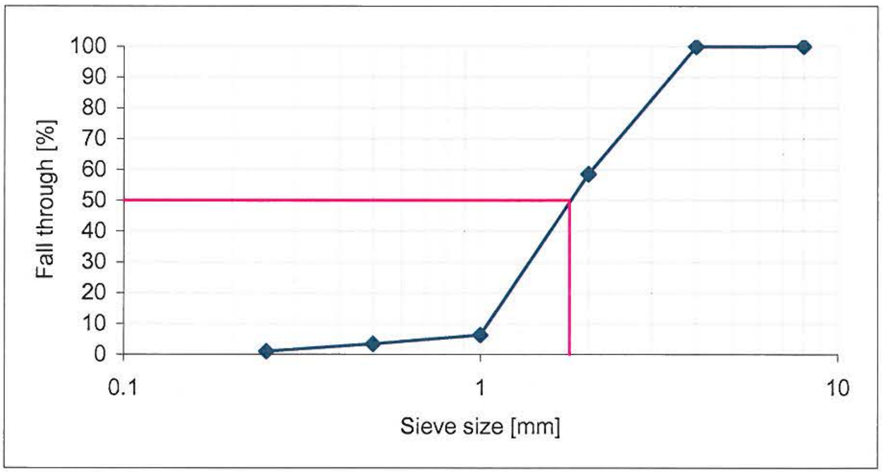


Figure 4.2. Grain size distribution curve.

Protection 2

The material that is being used for scour protection number two is gravel consisting of rounded stones. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
8	12.71	591.5	97.896
4	443.48	148.02	24.498
2	132.86	15.16	2.509
1	3.18	11.98	1.983
0.5	1.58	10.4	1.721
0.25	4.28	6.12	1.013
Bottom	6.12	0	0

Table 4.3. Grain size distribution. D_{50} is 5.15 mm.
In prototype scale D_{50} is 258 mm and W_{50} is 26.2 kg.

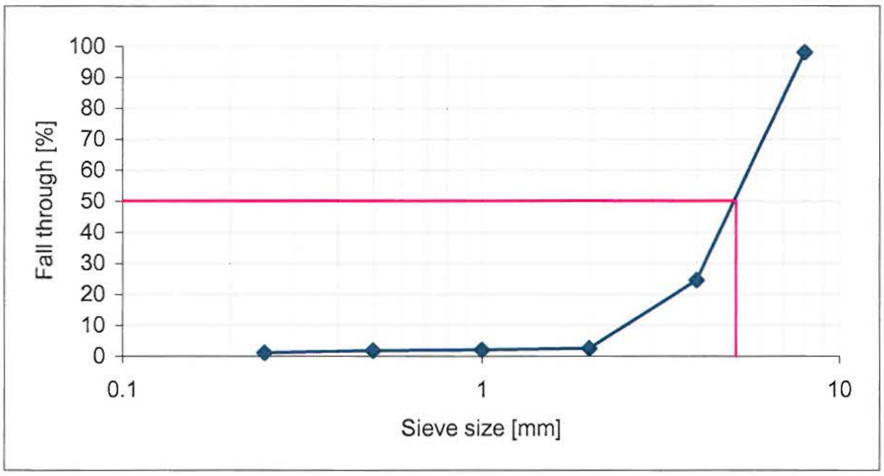


Figure 4.3. Grain size distribution curve.

Protection 3

The material that is being used for scour protection number three is gravel consisting of sharp edged stones. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
8	54.44	482.38	89.859
4	456.93	25.45	4.741
2	16.41	9.04	1.684
1	1.67	7.37	1.373
0.5	0.74	6.63	1.235
0.25	1.04	5.59	1.041
Bottom	5.59	0	0

Table 4.4. Grain size distribution. D_{50} is 5.8 mm.
In prototype scale D_{50} is 290 mm and W_{50} is 37.4 kg.

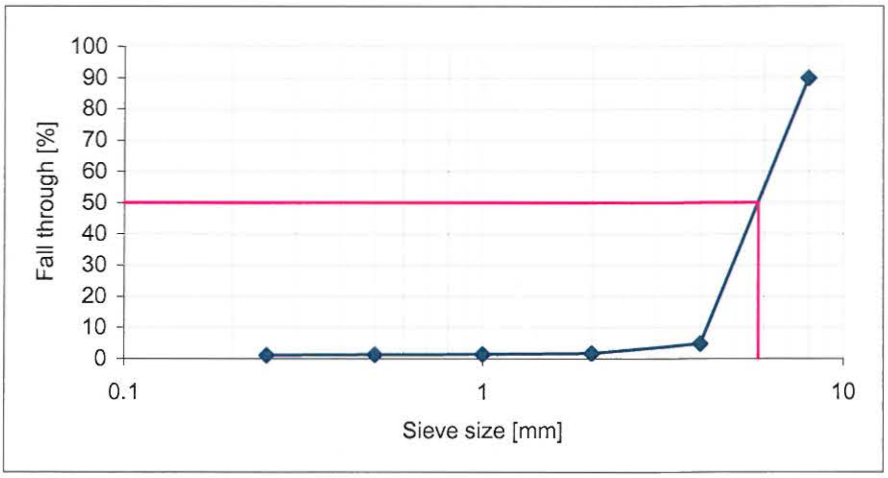


Figure 4.4. Grain size distribution curve.