Scour and Scour Protection for Windturbine Foundations

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Scour and Scour Protection for Windturbine Foundations

for the London Array

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Scour and Scour Protection for Windturbine Foundations

for the London Array

by

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Contents

Introduction

By request from CORE Ltd. / Energi E2 A/S a test programme has been performed to determine the necessary scour protection around a various types of foundation for an offshore windturbine. Furthermore the unprotected scour depths have 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 if nothing else is mentioned.

Description of Models

The four types of foundation that are being tested are shown underneath in figure 1. In appendix 2 the models are shown in detail.

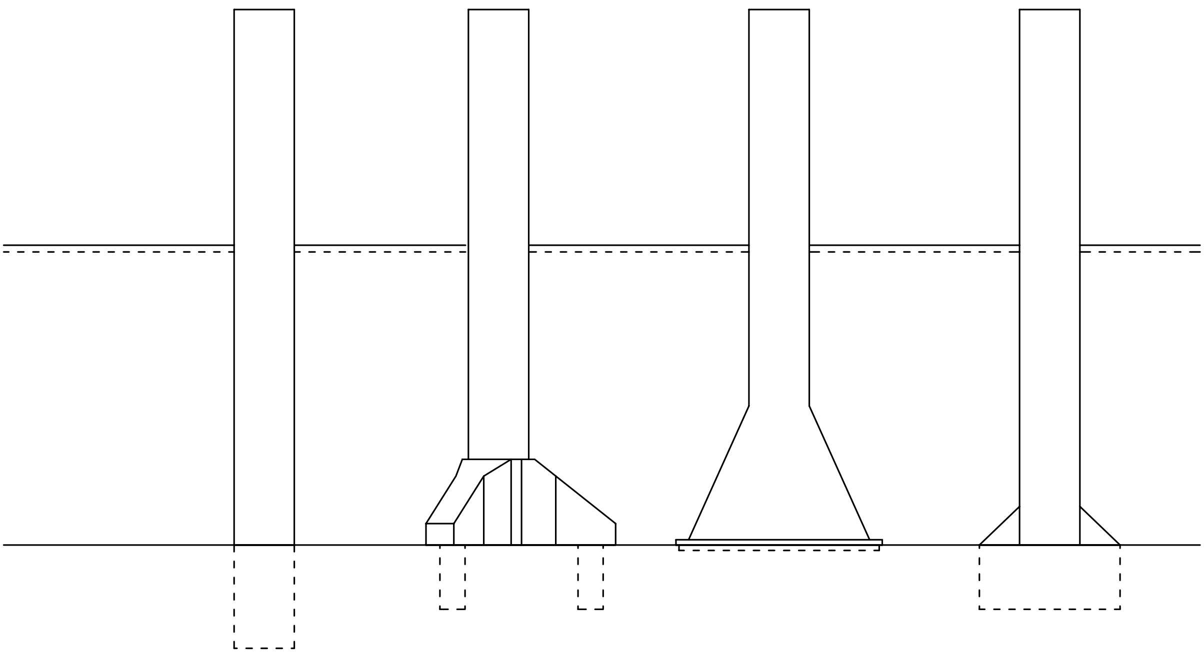


Figure 1. Monopile Concrete tripod Concrete cone Suction bucket

The models are made of various types of plastic. The suction bucket has been added on initiative by Aalborg University in agreement with the client.

Description of Set-up

The tests are conducted in a wave flume that is 945 meters long and 75 meters wide, see figure 2.

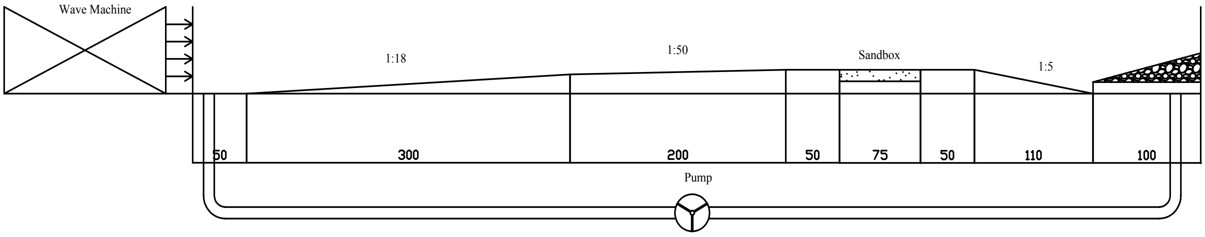


Figure 2. The wave flume. All measures in meters.

Waves

All tests were 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 3½ hours to insure a proper amount of waves to reach a near equilibrium state. For the scour protection tests the test duration were also set at 3½ hours. Current only tests had a duration of 7 hours.

Measurements

The wave elevation signal was measured beside the model by means of three wave gauges. The current velocity has been measured with an ultrasonic flowmeter. In addition to that the scour holes are measured manually.

Bed material

The sand in the sandbox has a D_{50} of 8.4 mm in prototype scale. The critical Shields parameter is approximately 0.055. To simulate global scour after installation the entire seabed around the protected area is lowered two metres in some tests.

Test programme

Test No.	Hs [m]	Tp [m]	U [m/s]	h [m]	Structure	Comments
1.1	0	0	1.5	10	Monopile	Scour Hole Test
1.2	0	0	1.5	10	Concrete tripod	Scour Hole Test
1.3	0	0	1.5	10	Concrete cone	Scour Hole Test
1.4	0	0	1.5	10	Suction bucket	Scour Hole Test
1.5	3.92	10.3	1.5	10	Monopile	Scour Hole Test
1.6	4.29	10.3	1.5	10	Concrete tripod	Scour Hole Test
1.7	4.06	10.3	1.5	10	Concrete cone	Scour Hole Test
1.8	4.05	10.3	1.5	10	Suction bucket	Scour Hole Test
2.1	0	0	1.5	10	Monopile	Protection 1
2.2	4.21	10.3	1.5	10	Monopile	Protection 1
2.3	4.13	10.3	1.5	10	Monopile	Protection 2
2.4	4.01	10.3	1.5	10	Monopile	Protection 3
2.5	3.96	10.3	1.5	10	Monopile	Protection 2, refilled scour hole
2.6	3.96	10.3	1.5	10	Monopile	Protection 3, refilled scour hole
2.7	4.12	10.3	1.5	10	Concrete tripod	Protection 4
2.8	4.24	10.3	1.5	10	Concrete cone	Protection 1
2.9	4.09	10.3	1.5	10	Suction bucket	Protection 4
3.1	4.34	10.3	1.5	10	Monopile	Protection 1, lowering of seabed
3.2	4.00	10.3	1.5	10	Monopile	Protection 2, lowering of seabed
3.3	4.25	10.3	1.5	10	Monopile	Protection 3, lowering of seabed
3.4	4.29	10.3	1.5	10	Monopile	Protection 3, lowering, refilled
3.5	4.13	8.4	1.1	10	Monopile	Pro. 3, lowering, stacked
3.6	4.25	10.3	1.5	10	Monopile	Pro. 3, lowering, stacked
3.7	4.09	8.4	1.1	10	Monopile	Pro. 4, lowering, stacked
3.8	4.54	10.3	1.5	10	Monopile	Pro. 4, lowering, stacked
3.9	4.13	8.4	1.1	10	Monopile	Pro. 2, lowering, thick layer
3.10	4.40	10.3	1.5	10	Monopile	Pro. 2, lowering, thick layer
3.11	4.28	10.3	1.5	10	Concrete cone	Protection 2, lowering of seabed
3.12	4.68	10.3	1.5	10	Concrete cone	Protection 3, lowering of seabed
3.13	4.55	10.3	1.5	10	Concrete cone	Pro. 3, lowering, stacked
3.14	4.93	10.3	1.5	10	Concrete cone	Protection 4, lowering of seabed
3.15	4.37	8.4	1.1	10	Concrete cone	Pro. 4, lowering, stacked
3.16	4.80	10.3	1.5	10	Concrete cone	Pro. 4, lowering, stacked
3.17	4.39	8.4	1.1	10	Concrete cone	Pro. 2, lowering, thick layer
3.18	4.83	10.3	1.5	10	Concrete cone	Pro. 2, lowering, thick layer
3.19	4.86	10.3	1.5	10	Concrete tripod	Pro. 2, lowering, thick layer

Table 1. Test programme.

Results

Scour Hole Tests

In appendix 1 the test results are commented on and there are photos that show the shapes of the scour holes. Appendix 4 attached to the backside of the report contains movie bits from the tests. In table 2 the end result of all scour tests are listed. S is the largest obtained depth of the scour hole and R is the largest obtained stretch of the scour hole from the surface / edge of the structures. The definitions of S and R are shown in figure 3.

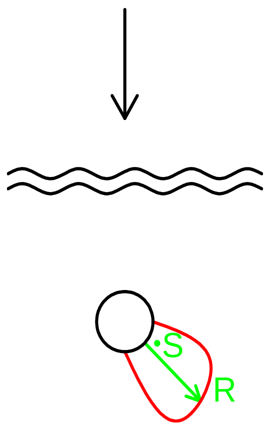


Figure 3. Definitions of S and R.

Test nr.	Hs [m]	Tp [m]	U [m/s]	h [m]	Structure	S [m]	R [m]
1.1	0	0	1.5	10	Monopile	1.00	17.5
1.2	0	0	1.5	10	Concrete tripod	2.50	5.0
1.3	0	0	1.5	10	Concrete cone	0.50	1.5
1.4	0	0	1.5	10	Suction bucket	0.50	5.0
1.5	3.92	10.3	1.5	10	Monopile	2.50	7.5
1.6	4.29	10.3	1.5	10	Concrete tripod	3.00	6.5
1.7	4.06	10.3	1.5	10	Concrete cone	2.00	5.0
1.8	4.05	10.3	1.5	10	Suction bucket	1.50	10.0

Table 2. Test results for the scour tests.

Scour Protection Tests

In appendix 1 there are photos of the damage of the scour protection. Four different types of scour protection have been tested. The tested grain sizes (D_{50}) were 93 mm, 258 mm, 365 mm and 585 mm. (Further information about the grain gradiation in appendix 3). All of the three biggest stone sizes could be used as protection for all four structures but the necessary amount would vary. E.g. for the monopile the necessary volume of scour protection material is as listed in table 3.

Test No.	Hs [m]	Tp [m]	U [m/s]	h [m]	Structure	D_{50} [mm]	Used Vol. [m^3]
2.1	0	0	1.5	10	Monopile	93	678
2.2	4.21	10.3	1.5	10	Monopile	93	Failure
2.3	4.13	10.3	1.5	10	Monopile	258	Failure
2.4	4.01	10.3	1.5	10	Monopile	585	678
2.5	3.96	10.3	1.5	10	Monopile	258	Failure
2.6	3.96	10.3	1.5	10	Monopile	585	126
2.7	4.12	10.3	1.5	10	Concrete tripod	365	250
2.8	4.24	10.3	1.5	10	Concrete cone	93	Failure
2.9	4.09	10.3	1.5	10	Suction bucket	365	275
3.1	4.34	10.3	1.5	10	Monopile	93	Failure
3.2	4.00	10.3	1.5	10	Monopile	258	Failure
3.3	4.25	10.3	1.5	10	Monopile	585	678
3.4	4.29	10.3	1.5	10	Monopile	585	126
3.5	4.13	8.4	1.1	10	Monopile	585	126
3.6	4.25	10.3	1.5	10	Monopile	585	126
3.7	4.09	8.4	1.1	10	Monopile	365	226
3.8	4.54	10.3	1.5	10	Monopile	365	226
3.9	4.13	8.4	1.1	10	Monopile	258	452
3.10	4.40	10.3	1.5	10	Monopile	258	452
3.11	4.28	10.3	1.5	10	Concrete cone	258	Failure
3.12	4.68	10.3	1.5	10	Concrete cone	585	722
3.13	4.55	10.3	1.5	10	Concrete cone	585	Failure
3.14	4.93	10.3	1.5	10	Concrete cone	365	722
3.15	4.37	8.4	1.1	10	Concrete cone	365	1083
3.16	4.80	10.3	1.5	10	Concrete cone	365	1083
3.17	4.39	8.4	1.1	10	Concrete cone	258	1444
3.18	4.83	10.3	1.5	10	Concrete cone	258	1444
3.19	4.86	10.3	1.5	10	Concrete tripod	258	Failure

Table 3. Necessary volume of scour protection material for the monopile.

Appendix 1 - Results

This appendix contains the entire results of the scour tests and pictures of the scour holes as they looked at the end of the tests. On page 17 - 44 there is an overview of the results of the scour protection tests. In addition to this a DVD has been made (appendix 4). The DVD contains video footage of the tests. (Due to technical problems with the camera there are no clips from the tests with the suction bucket).

1.1:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	-	-	25452

Table 1.1. Climate during 1.1.

Figure 1.1. Scour hole at the end of 1.1.

Minutes	S [m]	R [m]
106	0.5	15
212	1.0	17.5
424	1.0	17.5

Table 1.2. Results of 1.1.

1.2:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete tripod	1.5	-	-	25452

Table 1.3. Climate during 1.2.

Figure 1.2. Scour hole at the end of 1.2.
The scour is occurring underneath the structure.

Minutes	S [m]	R [m]
106	1.5	2.5
212	2.0	3.5
424	2.5	5.0

Table 1.4. Results of 1.2.

1.3:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	-	-	25452

Table 1.5. Climate during 1.3.

Figure 1.3. Scour hole at the end of 1.3.

Minutes	S [m]	R [m]
106	0	0
212	0.5	1.5
424	0.5	1.5

Table 1.6. Results of 1.3.

1.4:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Suction bucket	1.5	-	-	25452

Table 1.7. Climate during 1.4.

Figure 1.4. Scour hole at the end of 1.4.

Minutes	S [m]	R [m]
106	0.5	5.0
212	0.5	5.0
424	0.5	5.0

Table 1.8. Results of 1.4.

1.5:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	3.92	10.3	12726

Table 1.9. Climate during 1.5.

Figure 1.5. Scour hole at the end of 1.5.

Minutes	S [m]	R [m]
106	2.0	5.0
212	2.5	7.5

Table 1.10. Results of 1.5.

1.6:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete tripod	1.5	4.29	10.3	12726

Table 1.11. Climate during 1.6.

Figure 1.6. Scour hole at the end of 1.6.
The scour is occurring underneath the structure.

Minutes	S [m]	R [m]
106	2.5	5.0
212	3.0	6.5

Table 1.12. Results of 1.6.

1.7:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.06	10.3	12726

Table 1.13. Climate during 1.7.

Figure 1.7. Scour hole at the end of 1.7.

Minutes	S [m]	R [m]
106	2	5.5
212	2	5.0

Table 1.14. Results of 1.7.

1.8:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Suction bucket	1.5	4.05	10.3	12726

Table 1.15. Climate during 1.8.

Figure 1.8. Scour hole at the end of 1.8.

Minutes	S [m]	R [m]
106	1.0	10.0
212	1.5	10.0

Table 1.16. Results of 1.8.

2.1:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	-	-	12726

Table 1.17. Climate during 2.1.

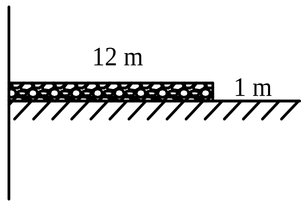


Figure 1.9. Protection arrangement. In this test protection type number one was used. It has a D_{50} of 93 mm. No damage occurred.

2.2:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.21	10.3	12726

Table 1.18. Climate during 2.2.

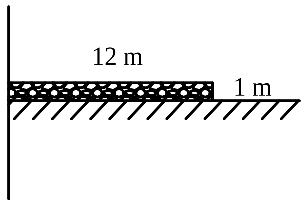


Figure 1.10. Protection arrangement.
In this test protection type number one was used. It has a D_{50} of 93 mm.

Figure 1.11. Shape of scour protection at the end of 2.2. Complete damage. 2.5 m scour depth.

2.3:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.13	10.3	12726

Table 1.19. Climate during 2.3.

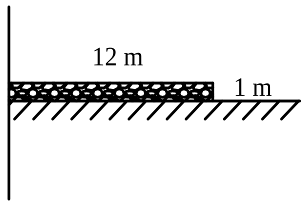


Figure 1.12. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.13. Shape of scour protection at the end of 2.3.
Severe damage. 1.5 m scour depth.

2.4:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.01	10.3	12726

Table 1.20. Climate during 2.4.

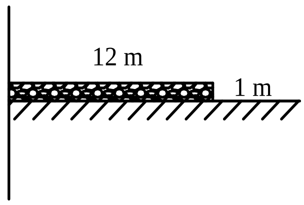


Figure 1.14. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.15. Shape of scour protection at the end of 2.4.
No damage occurred.

2.5:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	3.96	10.3	12726

Table 1.21. Climate during 2.5.

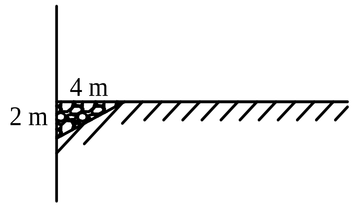


Figure 1.16. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm

Figure 1.17. Shape of scour protection at the end of 2.5.
Severe damage. 1.5 m scour depth.

.

2.6:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	3.96	10.3	12726

Table 1.22. Climate during 2.6.

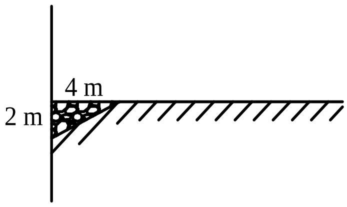


Figure 1.18. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.19. Shape of scour protection at the end of 2.6.
No damage occurred.

2.7:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete tripod	1.5	4.12	10.3	12726

Table 1.23. Climate during 2.7.

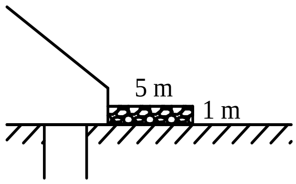


Figure 1.20. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.21. Shape of scour protection at the end of 2.7.
No severe damage.

2.8:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.24	10.3	12726

Table 1.24. Climate during 2.8.

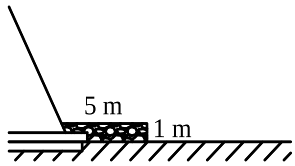


Figure 1.22. Protection arrangement.
In this test protection type number one was used. It has a D_{50} of 93 mm.

Figure 1.23. Shape of scour protection at the end of 2.8.
Complete damage. 1.0 m scour depth.

2.9:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Suction bucket	1.5	4.09	10.3	12726

Table 1.25. Climate during 2.9.

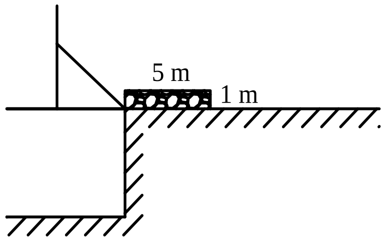


Figure 1.24. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.25. Shape of scour protection at the end of 2.9.
No severe damage.

3.1:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.34	10.3	12726

Table 1.26. Climate during 3.1.

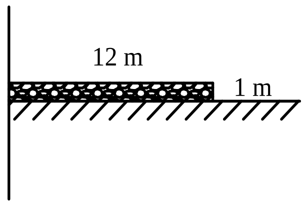


Figure 1.26. Protection arrangement.
In this test protection type number one was used. It has a D_{50} of 93 mm.

Figure 1.27. Shape of scour protection at the end of 3.1.
Complete damage. 2.5 m scour depth.

3.2:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.00	10.3	12726

Table 1.27. Climate during 3.2.

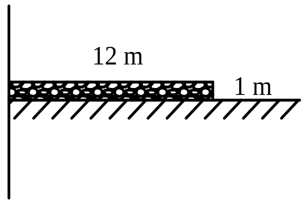


Figure 1.28. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.29. Shape of scour protection at the end of 3.2.
Some damage. 1.5 m scour depth.

3.3:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.25	10.3	12726

Table 1.28. Climate during 3.3.

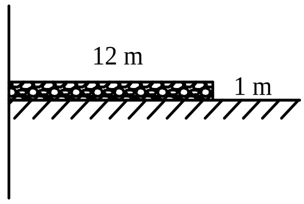


Figure 1.30. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.31. Shape of scour protection at the end of 3.3.
No damage occurred.

3.4:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.29	10.3	12726

Table 1.29. Climate during 3.4.

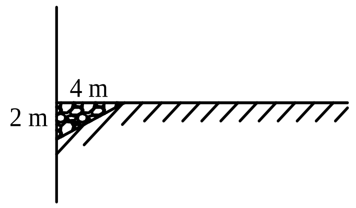


Figure 1.32. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.33. Shape of scour protection at the end of 3.4.
No severe damage.

3.5:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.1	4.13	8.4	12726

Table 1.30. Climate during 3.5.

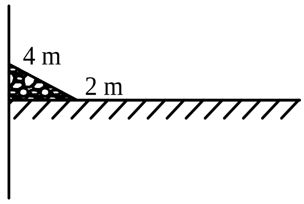


Figure 1.34. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.35. Shape of scour protection at the end of 3.5.
No severe damage.

3.6:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.25	10.3	12726

Table 1.31. Climate during 3.6.

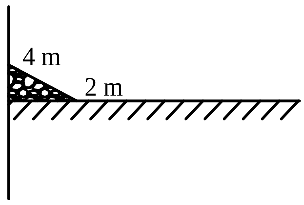


Figure 1.36. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.37. Shape of scour protection at the end of 3.6.
No severe damage.

3.7:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.1	4.09	8.4	12726

Table 1.32. Climate during 3.7.

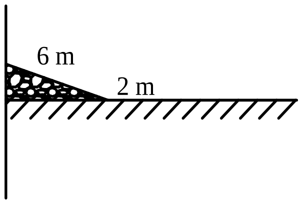


Figure 1.38. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.39. Shape of scour protection at the end of 3.7.
No damage occurred.

3.8:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.54	10.3	12726

Table 1.33. Climate during 3.8.

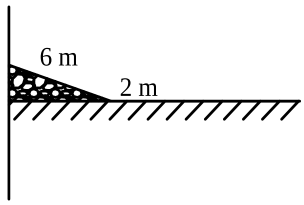


Figure 1.40. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.41. Shape of scour protection at the end of 3.8.
No severe damage.

3.9:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.1	4.13	8.4	12726

Table 1.34. Climate during 3.9.

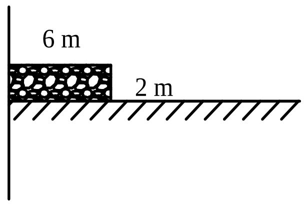


Figure 1.42. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.43. Shape of scour protection at the end of 3.9.
No damage occurred.

3.10:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Monopile	1.5	4.40	10.3	12726

Table 1.35. Climate during 3.10.

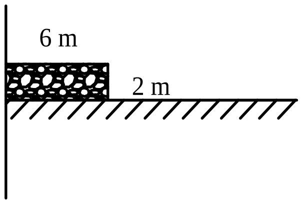


Figure 1.44. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.45. Shape of scour protection at the end of 3.10.
No severe damage.

3.11:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.28	10.3	12726

Table 1.36. Climate during 3.11.

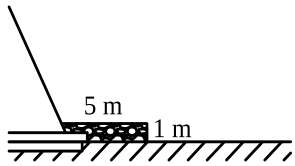


Figure 1.46. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.47. Shape of scour protection at the end of 3.11.
Complete damage. 1.0 m scour depth.

3.12:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.68	10.3	12726

Table 1.37. Climate during 3.12.

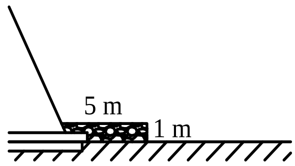


Figure 1.48. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.49. Shape of scour protection at the end of 3.12.
No damage occurred.

3.13:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.55	10.3	12726

Table 1.38. Climate during 3.13.

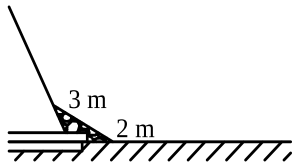


Figure 1.50. Protection arrangement.
In this test protection type number three was used. It has a D_{50} of 585 mm.

Figure 1.51. Shape of scour protection at the end of 3.13.
Some damage. 1.0 m scour depth.

3.14:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.93	10.3	12726

Table 1.39. Climate during 3.14.

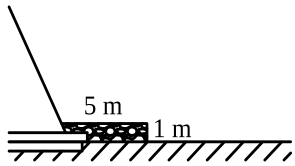


Figure 1.52. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.53. Shape of scour protection at the end of 3.14.
No damage occurred.

3.15:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.1	4.37	8.4	12726

Table 1.40. Climate during 3.15.

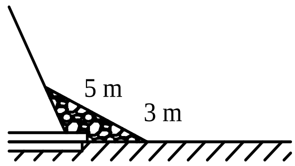


Figure 1.54. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.55. Shape of scour protection at the end of 3.15.
No damage occurred.

3.16:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.80	10.3	12726

Table 1.41. Climate during 3.16.

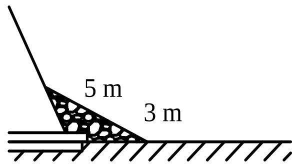


Figure 1.56. Protection arrangement.
In this test protection type number four was used. It has a D_{50} of 365 mm.

Figure 1.57. Shape of scour protection at the end of 3.16.
No damage occurred.

3.17:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.1	4.39	8.4	12726

Table 1.42. Climate during 3.17.

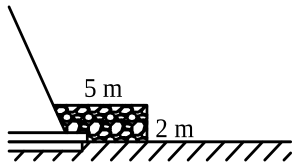


Figure 1.58. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.59. Shape of scour protection at the end of 3.17.
No damage occurred.

3.18:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete cone	1.5	4.83	10.3	12726

Table 1.43. Climate during 3.18.

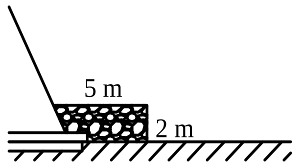


Figure 1.60. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.61. Shape of scour protection at the end of 3.18.
No damage occurred.

3.19:

Structure	U [m/s]	Hs [m]	Tp [m]	Duration [s]
Concrete tripod	1.5	4.86	10.3	12726

Table 1.44. Climate during 3.19.

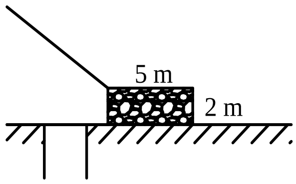


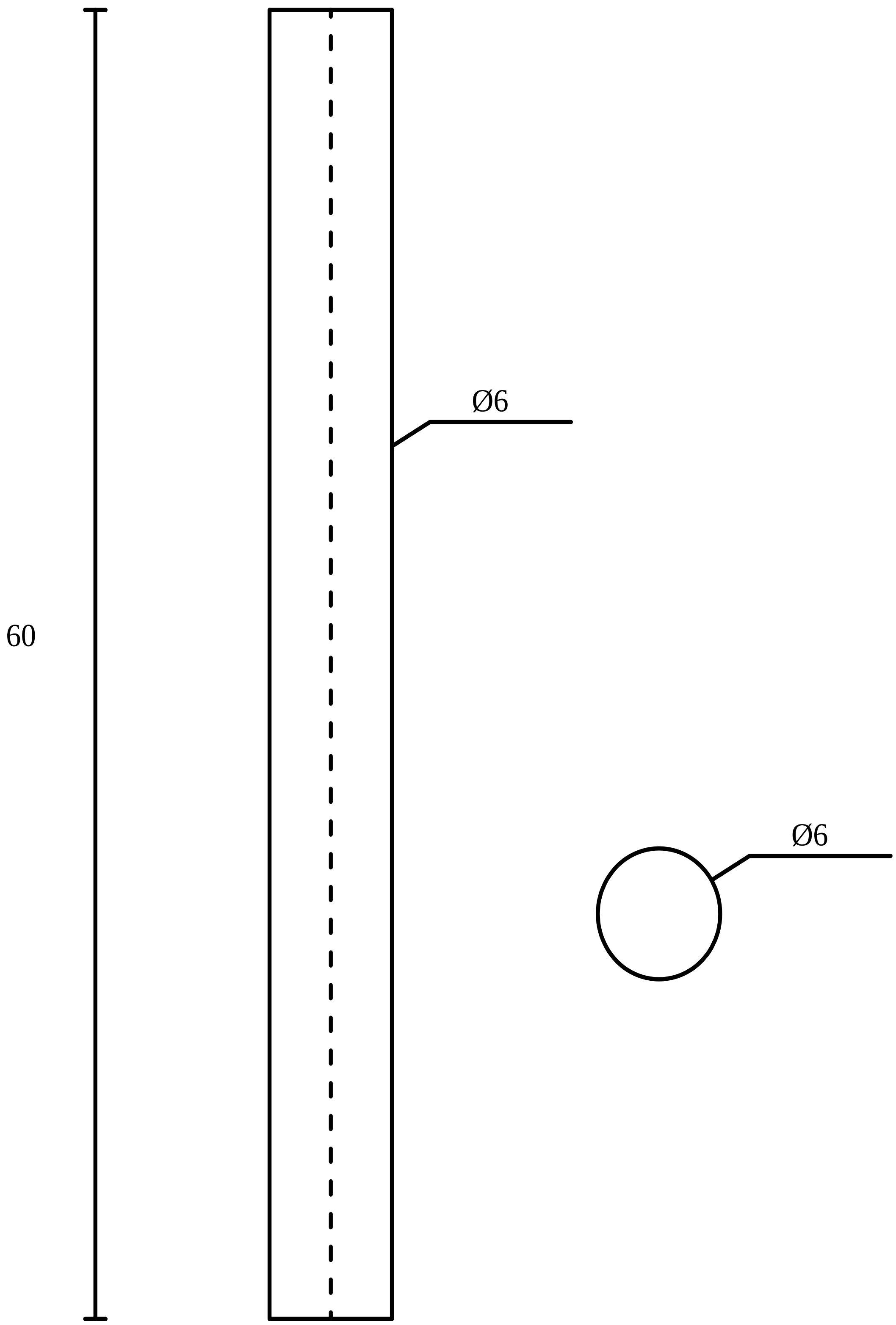
Figure 1.62. Protection arrangement.
In this test protection type number two was used. It has a D_{50} of 258 mm.

Figure 1.63. Shape of scour protection at the end of 3.19.
Some damage occurred.

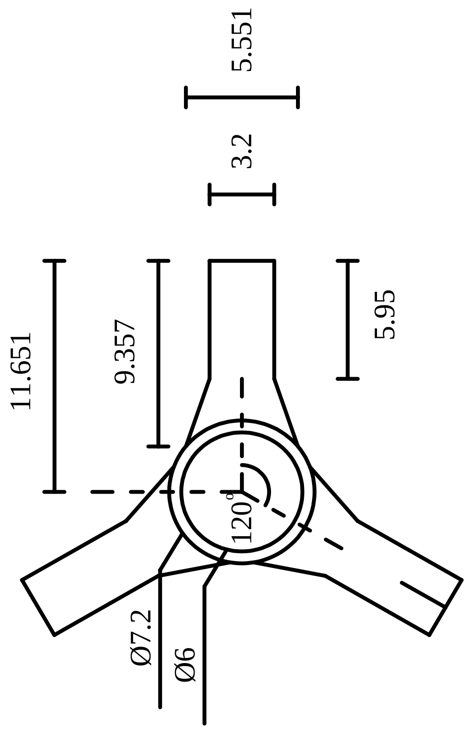
Appendix 2 - Models

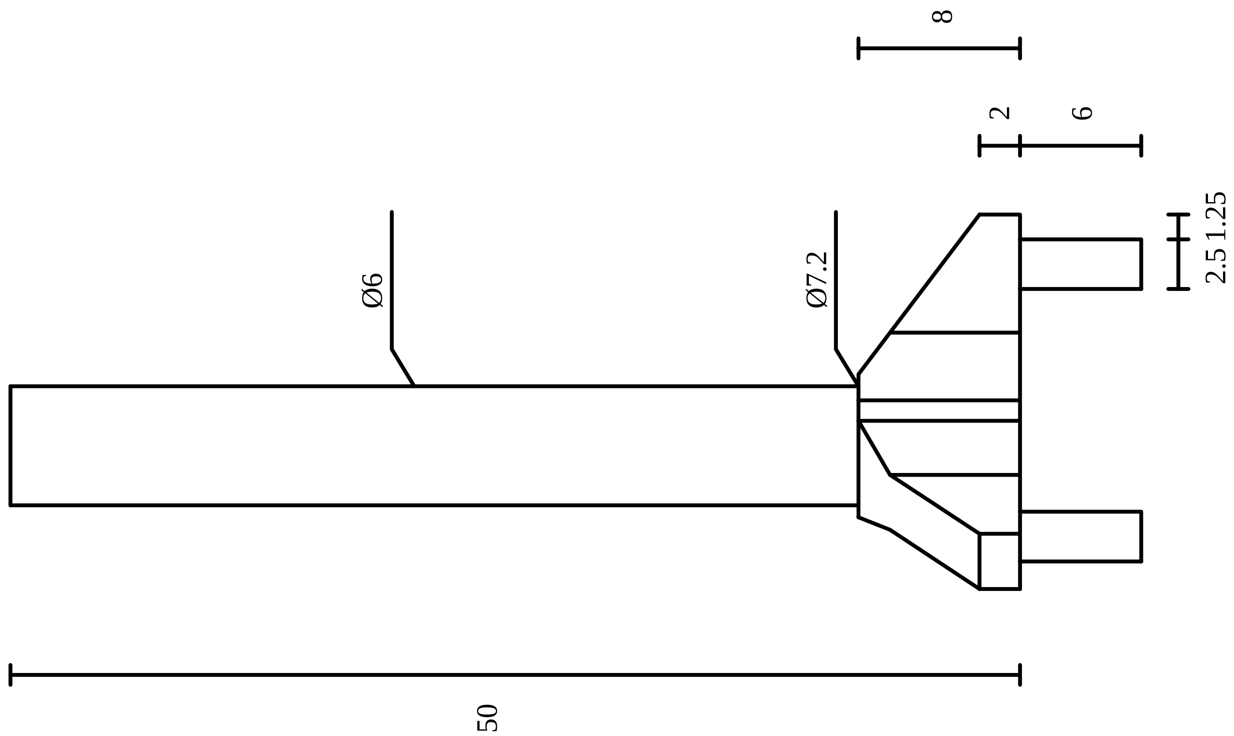
All measures in meters – prototype values.

Monopile:

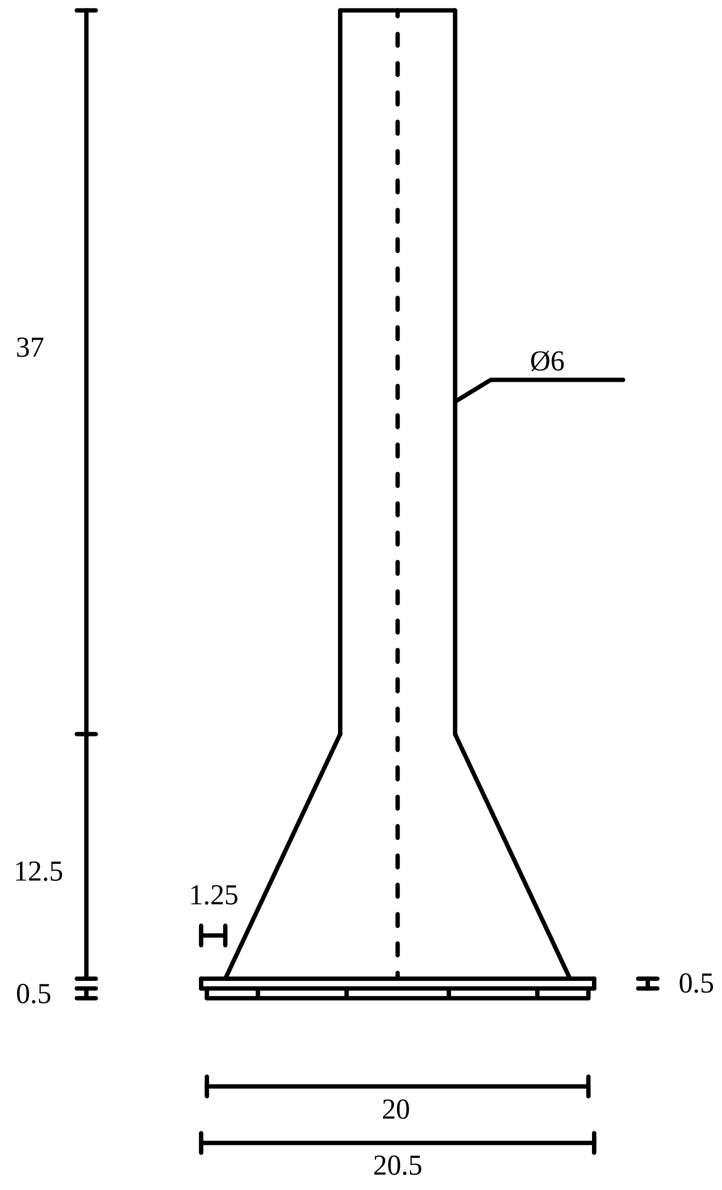


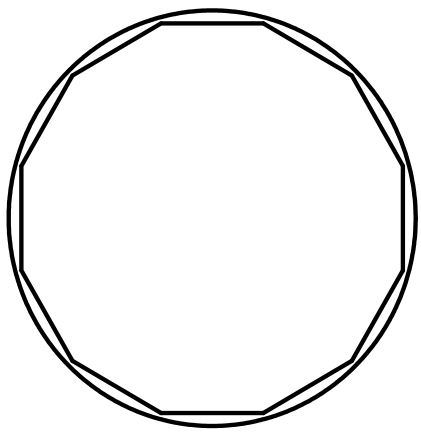
Concrete tripod:



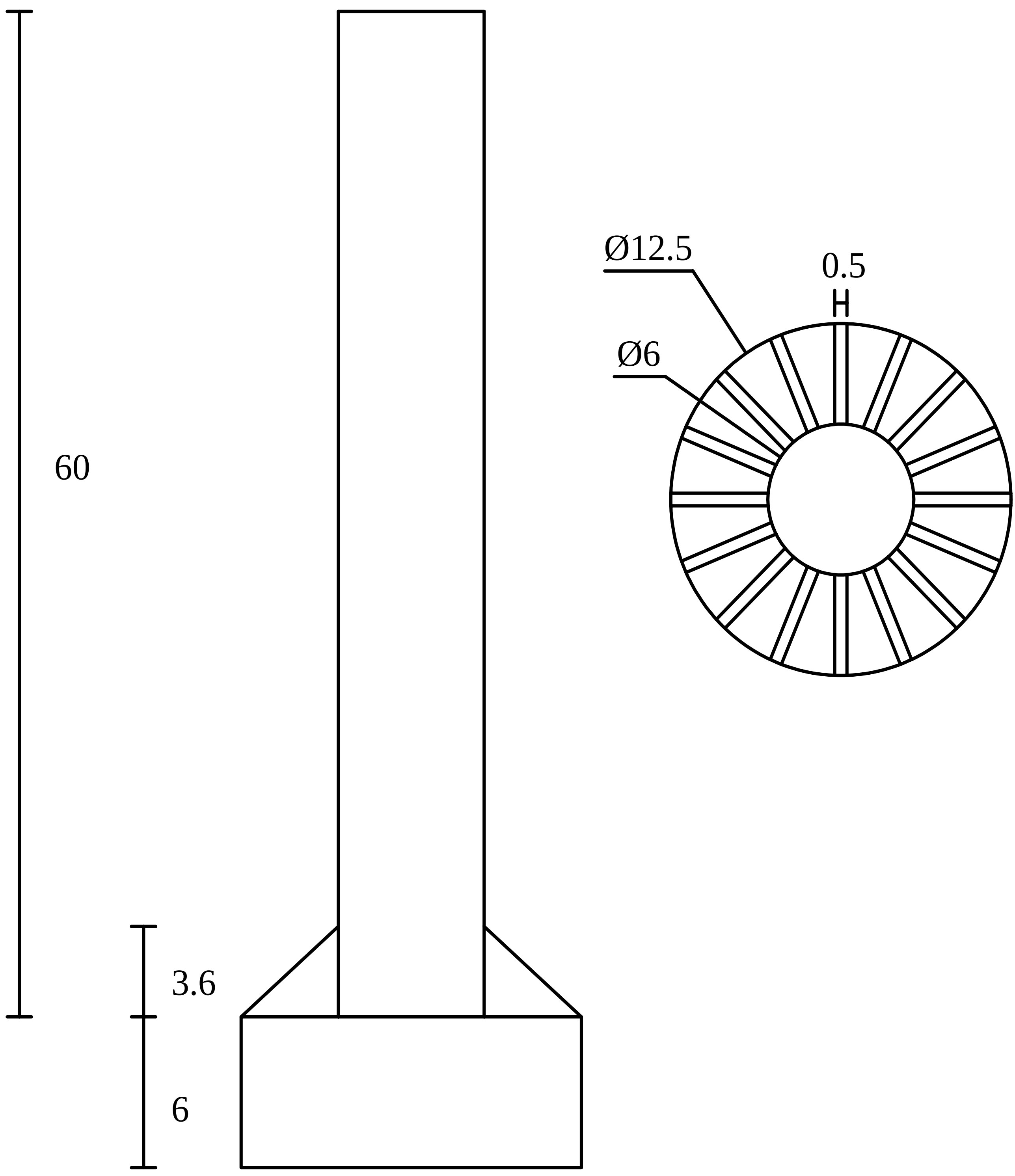


Concrete cone:





Suction bucket:



Appendix 3 – 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 3.1. Grain size distribution. D_{50} is 0.17 mm.
In prototype scale D_{50} is 8.4 mm.

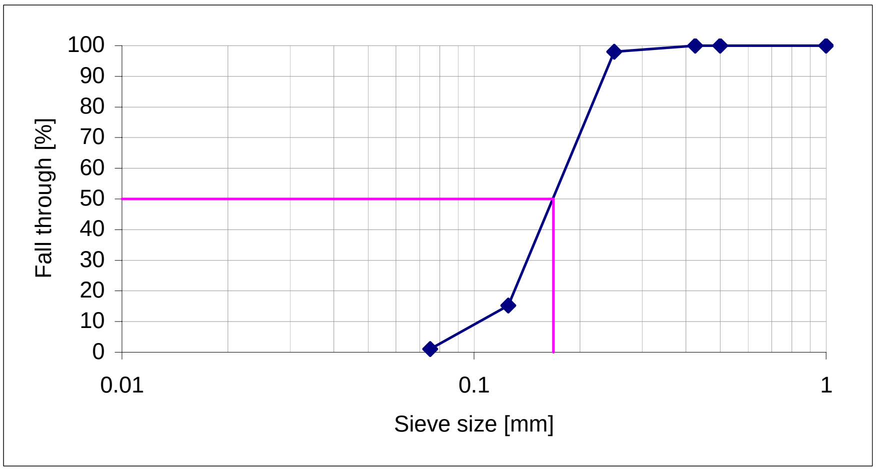


Figure 3.1. Grain size distribution curve.

Protection 1

The material that is being used for scour protection number one is some small pearl-like stones. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
4	0	323.33	100.000
2	142.61	180.72	55.893
1	179.58	1.14	0.353
0.5	0.88	0.26	0.080
0.25	0.11	0.15	0.046
Bottom	0.15	0	0

Table 3.2. Grain size distribution. D_{50} is 1.85 mm.
In prototype scale D_{50} is 93 mm and W_{50} is 1.21 kg.

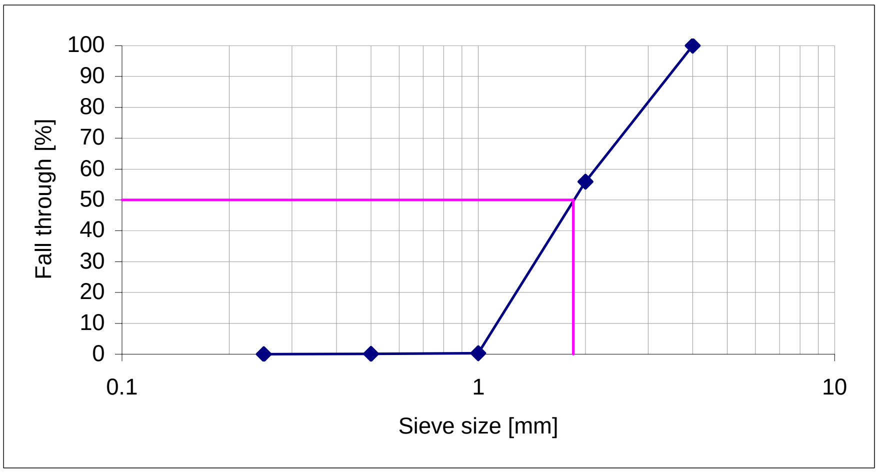


Figure 3.2. Grain size distribution curve.

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

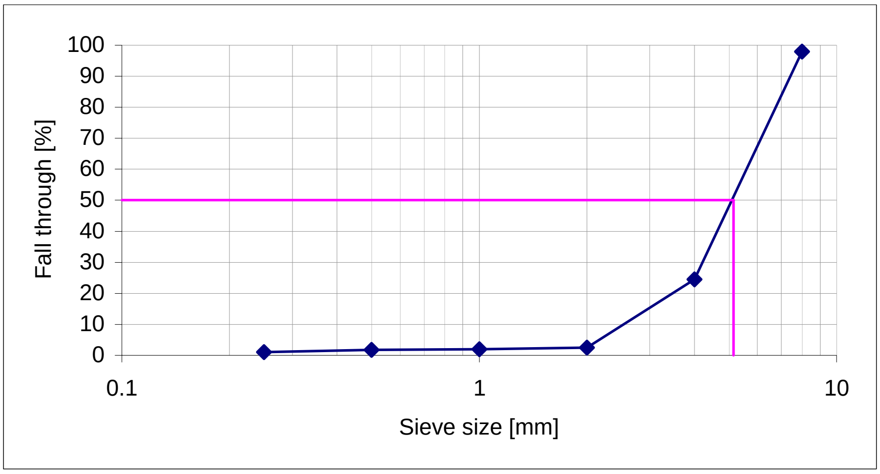


Figure 3.3. Grain size distribution curve.

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 [%]
19	0	2294.73	100.000
12.5	1014.15	1280.58	55.805
8	1147.32	133.26	5.807
4	99.02	34.24	1.492
1	24.41	9.83	0.428
0.5	0.09	9.74	0.424
0.25	0.27	9.47	0.413
Bottom	9.47	0	0

Table 3.4. Grain size distribution. D_{50} is 11.7 mm.
In prototype scale D_{50} is 585 mm and W_{50} is 307 kg.

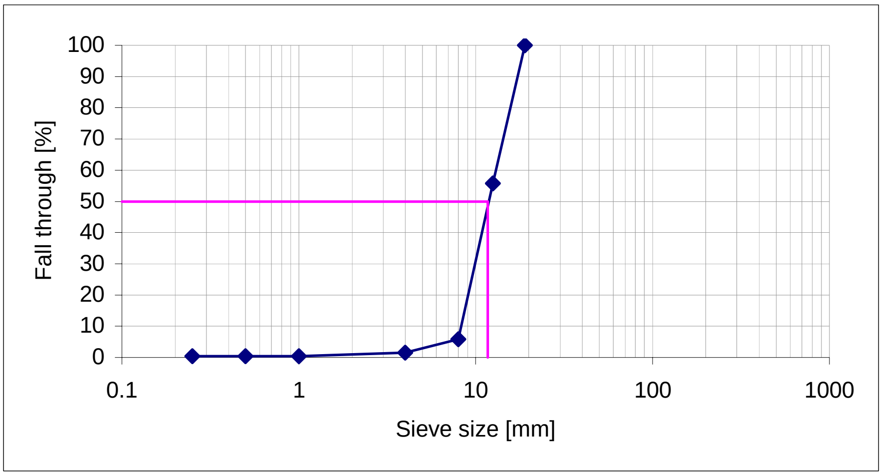


Figure 3.4. Grain size distribution curve.

Protection 4

The material that is being used for scour protection number four is a mixture of the materials used for protection two and three. A small sample has been tested to have the following characteristics:

Sieve [mm]	On sieve [g]	Fall through [g]	Fall through [%]
19	0	1191.04	100.000
12.5	254.17	936.87	78.660
8	289.56	647.31	54.348
4	471.34	175.97	14.774
1	154.68	21.29	1.788
0.5	1.67	19.62	1.647
0.25	4.53	15.09	1.267
Bottom	15.09	0	0

Table 3.5. Grain size distribution. D_{50} is 7.3 mm.
In prototype scale D_{50} is 365 mm and W_{50} is 74.6 kg.

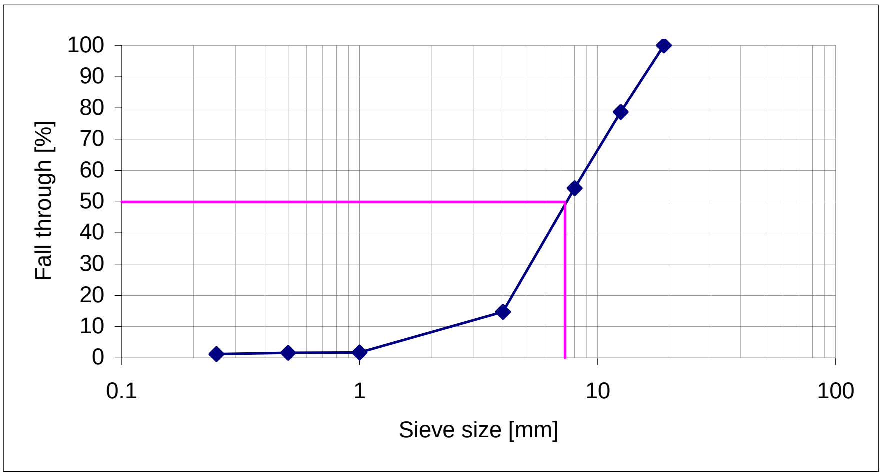


Figure 3.5. Grain size distribution curve.