Appendix A. Summary of the SWASH scripts

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A.1. Introduction

In this report I try to summarize the main features of the simulations that I have done with SWASH software. I comment the majority of the scripts I have worked with and their differences and results. At different points of this summary I expose my partial conclusions and the problems I faced that I do (or did) not know how to solve. The real conclusions and analysis of the global results is done in section 3.2 of the thesis report. In fact, this is a kind of laboratory netbook where I was writing notes about ideas and observations rather than a report. The valid explanations are given in chapter 3.

I have disposed all the tests according to blocks and I tried to group all the scripts that are modifications of the same one. However, they may not be performed exactly in this order. For this reason, at the end of this appendix I added a chronological list of the scripts as they were computed.

A.2. Wave propagation trials

Attempt with a deep water flume

First I tried to model the flume with deep water (Deep_Flume01.sws, Deep_Flume02.sws and Deep_Flume03.sws), but I did not succeed. I do not know the reason. At the beginning I received some comments telling me that I did not have enough water (water level below the bottom level), situation that I can not believe and I do not know how can occur in my script; and messages advising me to reduce time steps. After doing that, the scripts do not show me any error message when I order to run them, but no results are given. The software just starts and gets blocked... Or it needs an incredibly high amount of time to start.

After these attempts I decided to try with shallow water, though the bottom will affect the waves.

Shallow water flumes

The following commands are common in all files:

Water Depth of 10 m, computation mesh size of 1 m and initial computation time step of 0.0001 s which is doubled up to 0.0128 s in the majority of the scripts.

FRIC CONST 0, VISC 0.

BOUNDCOND SIDE E CCW BTYPE RADIATION

SPONgelayer RIght 10

INIT ZERO

NONHYDROSTATIC BOX PREC ILU

At the beginning I had to use VERT 10 (10 horizontal layers), because I could not start the computation.

Shallow_Flume02.sws

The main features of this script are that the wave has been defined from a spectrum and that the chosen boundary condition is *Weak reflective*.

Boundary Shape Jonswap 3.3 SIG MEAN DSPR DEGR

Boundcond side W CCW BTYPE WEAK CON SPECTRUM 3.5 10 90 0 5 MIN

The spectrum waves are then characterized by $H_{m0} = 3.5\ m$ and $T_{m01} = 10\ s$.

DISCRET UPW UMOM MOM (type of space discretization about the momentum equations that indicates that momentum is conserved everywhere)

Water level measured as an output near the end of the flume (x = 805m)

The script at least works, but I do not think that I have got the expected results.

I have plotted the results with Matlab and analysed the waves to find the characteristics of the wave as I would do with any wave record.

What has surprised me most is that the majority of the results are below 0 despite the fact that it should be the mean value ($\bar{\eta} = -0.13\ m!$). Since the Matlab script that I have written to identify the waves and compute the mean wave period, the mean and significant wave height splits the waves at zero down-crossing, it may not offer the best analysis, because there are some waves that are not considered. However, there is also another conclusion that can be reached: the wave height have been reduced a lot, from 3.5 m to a range of 0.11 to 0.77 m! The significant wave height is 0.61 m and the mean wave period, 8.44 s. Something is clearly wrong with the spectrum data.

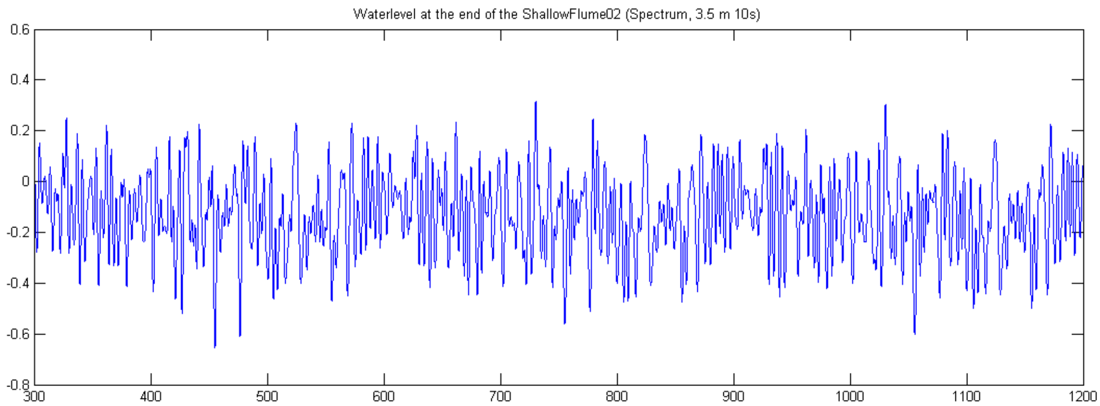

Figure A.1. Recorded water elevation at the end of Shallow_Flume02.sws.

After spectral analysis (see Deep_Flume06.sws for further details and explanations), I obtain unexpected values such as a mean wave period of 9.98 s and a significant wave height of 0.77 m!

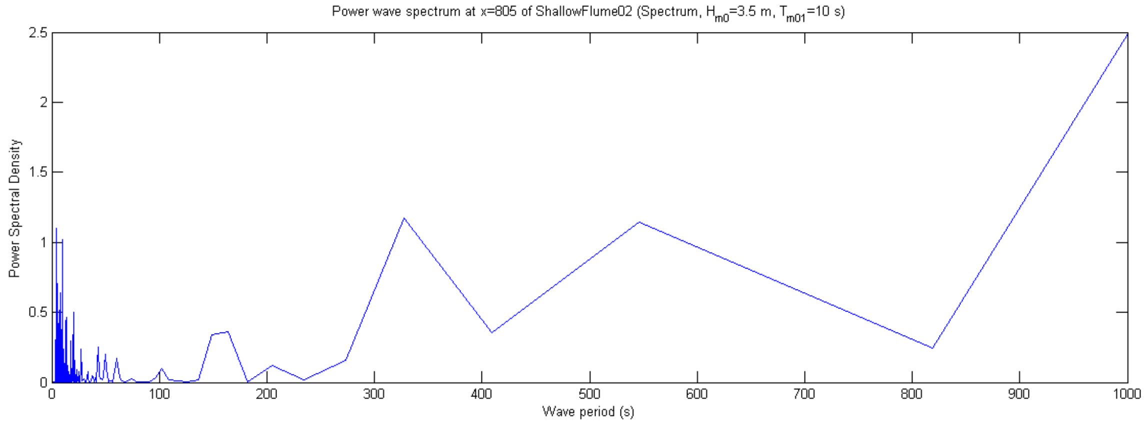

Figure A.2. Power Spectral Density at the end of the flume Shallow_Flume02.sws.

I have modified the script creating Shallow_Flume02_3.sws, which also gets the water levels at a distance of 20 m of the wave generator (x=20m).

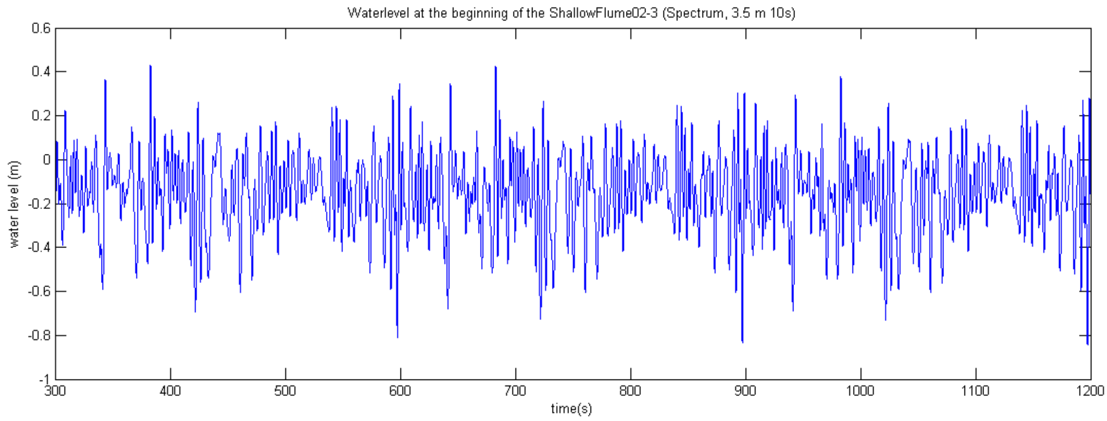

Figure A.3. Water elevation at 20 m from the wave generator in Shallow_Flume02_3.sws.

Higher water levels are reached here, all of them within the range between 0.10 and 1.16 m. The majority of the values continue below 0 (mean value -15 cm). After spectral analysis (see Deep_Flume06.sws at the end for more details and comments about it), the mean period is around 8 s and the significant wave height is 0.88 m, surprisingly low. In both cases, the peak frequency is 0 Hz with an extremely high energy (at least one order of magnitude larger than the others).

One conclusion is clear: the spectrum has not been right defined.

Shallow_Flume01.sws

This script tries to introduce the wave through the boundary condition VEL, but it does not work. The software asks me to put Porosity (POROSITY grid) and Grain size (PSIZE grid) as input values (I guess VEL requires them), but it shows me an error:

Error: Terminating error: INSTABLE: water level is too far below the bottom level!

From this script I conclude that I have to impose WEAKREFLECTIVE as a boundary condition at the wave generator.

Shallow_Flume03.sws

It is a very similar script to Shallow_Flume02.sws. The only changes are referred to the DISCRET commands, as they are written in test case a14prw0X.sws (propagation of a linear wave in a deep water flume).

DISCRET UPW NONE (standard central difference scheme applied for the horizontal advective terms of the momentum equations, momentum is not always conserved)

DISCRET UPW UMOM V NONE (standard central difference scheme applied for the vertical advective terms of the momentum equations, momentum is not always conserved)

DISCRET CORRDEP NONE (standard central difference scheme is applied to the discretization of water depth in velocity points)

Despite that the only commands that change from the test cases scripts to this one is a regular wave (with smoothing at the beginning) to a spectrum wave, the script does not work. Well, it computes around 800 s (it should do 1200 s) and stops, because it says that there is no water.

Error: Terminating error: INSTABLE: water level is too far below the bottom level!

When the computation is stopped, the water level is -0.3328 m at x=805 m, which is not strange (0 is the initial water level with the bottom at -10 m). First I did not know where was the problem, but afterwards I had a look on the wave record at x=0 m and I found that the last 3 values showed large variations in a very small time step of 0.05 m. The first of them was +1.29 m and the last one, -2.3 m. Then, the software could have stopped because the next water level was far below. The mean water level is +0.067 m.

I cannot understand why this happens and why it does not occur when running other similar scripts. I may think that are the DISCRET commands, since they are the only commands that have changed from the last script, but they are probably better than the first used ones. Furthermore, these commands work in some deep flume tests that I have done afterwards (Deep_Flume04.sws, Deep_Flume05.sws and Deep_Flume06.sws).

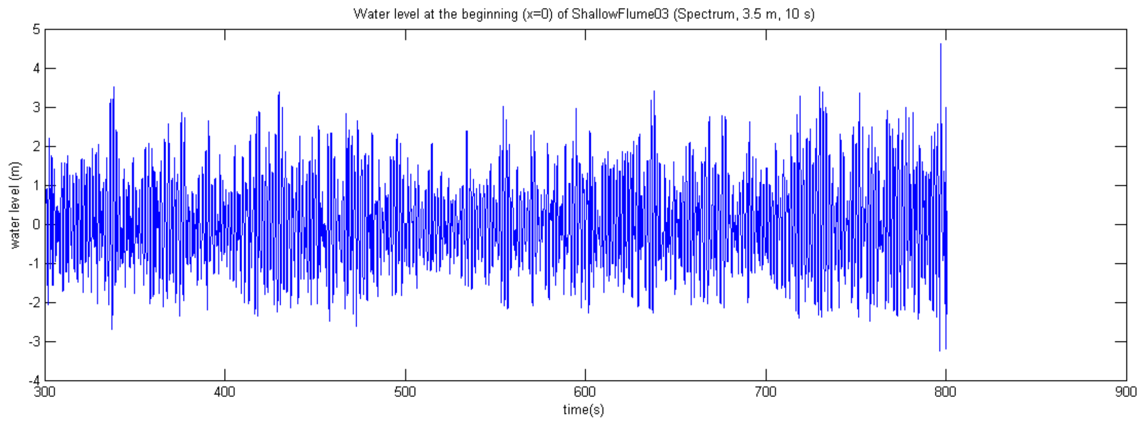

Figure A.4. Water elevation at x=0 m of Shallow_Flume03.sws.

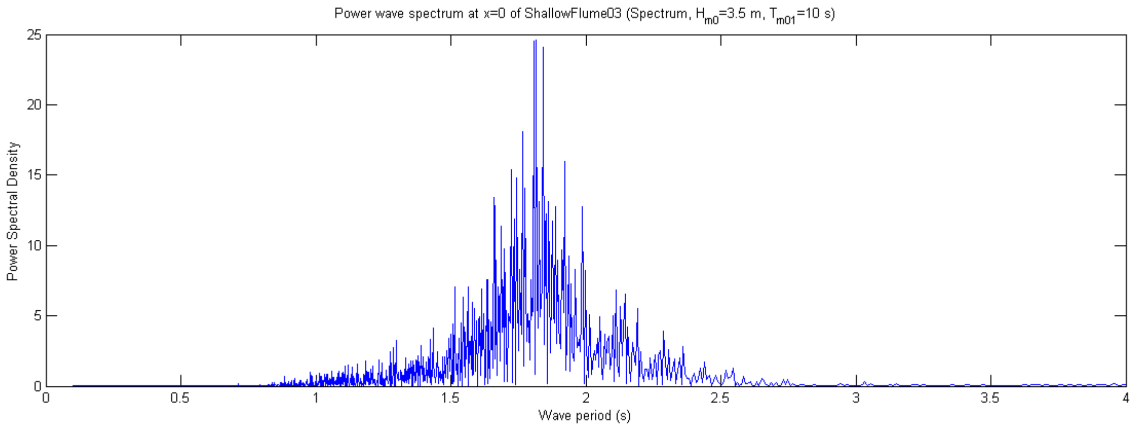

Figure A.5. Power Wave spectrum at x=0 m of the flume Shallow_Flume03.sws.

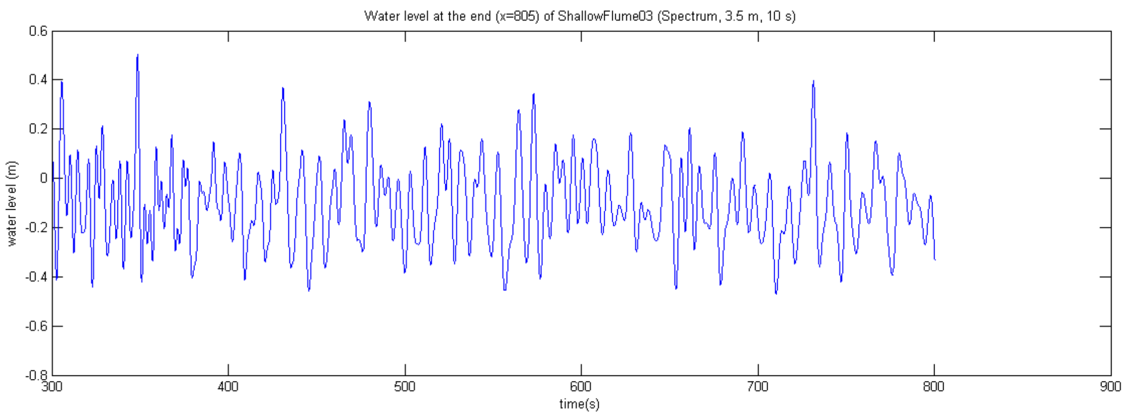

Figure A.6. Water elevation at x=805 m of Shallow_Flume03.sws.

I was really surprised, because the recorded waves at the beginning were too high, with a significant wave height of 4.45m (waves within a range of 0.21 and 7.85 m) and wave period of 1.64 s. After spectral analysis I obtained a significant wave height of 4.68 m and a wave period of 1.66 s.

There is a strong reduction of wave height at the end of the flume (0.026-0.805 m). The significant wave height is 0.60 m and the mean wave period is 8.6 s. The mean water level is -0.1 m. Then we have a similar problem as in Shallow_Flume02.sws.

From spectral analysis I can see that the waves with very large periods have by far the largest energy at the end of the flume. For the short waves, there is a small peak around 10 s.

Shallow_Flume03_2.sws

Only two changes have been done with respect with Shallow_Flume03.sws:

The cyclic period of the Fourier series have been extended up to 60 MIN and I have reduced the number of vertical layers from 10 to 5.

From observation of the graphs I have seen that in the previous script runs, the spectrum repeated after 5 min, which was the value I introduced first. After these changes, the running does not stop at 800 s and continues until the end of the specified computation time.

From the wave per wave analysis at x=0 I get waves with a significant wave height of 3.08 cm and a mean wave period of 1.73 s. The range of wave heights is far lower than the ones recorded in Shallow_Flume03.sws, which were very high. Here the range reduces until a range between 0.07 and 4.68 m. The mean water level is +0.057 m.

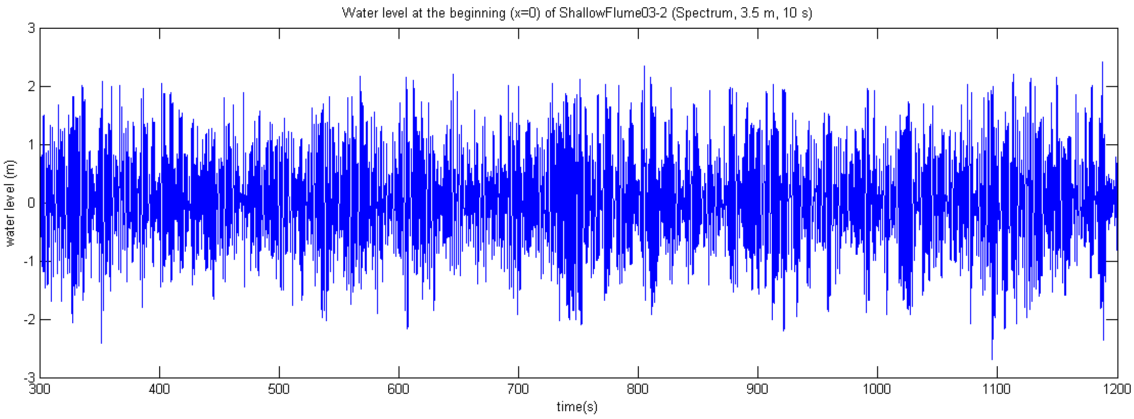

Figure A.7. Water elevation at x=0 m of Shallow_Flume03_2.sws.

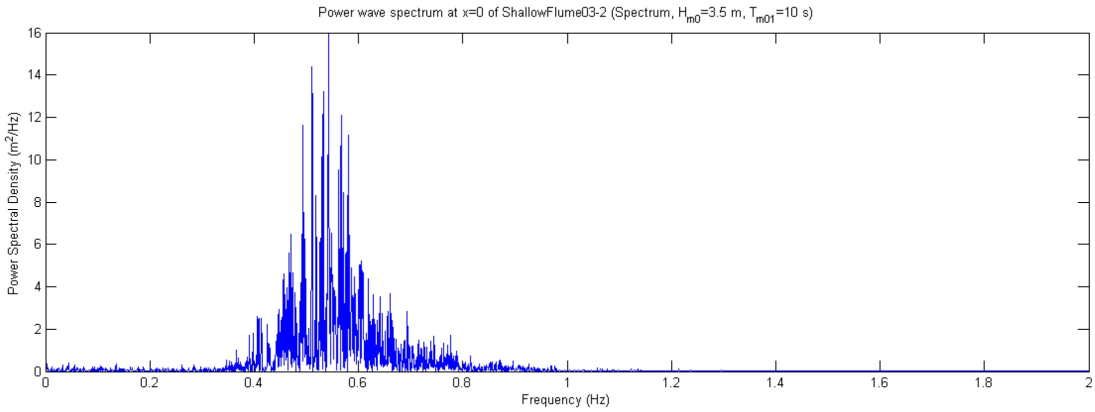

Figure A.8. Power wave spectrum at x=0 m of Shallow_Flume03_2.sws.

The frequency spectrum does not look much different from the previous one. From spectral analysis, the significant wave height is 3.33 m and the mean period is 1.78 s.

At x=805 m, the waves reduce up to a range between 0.029 and 1.031 m, with a significant wave height of 0.63 m and a mean wave period of 7.07 s. The mean water level is -0.089 m. From spectral analysis I get a significant wave height of 0.72 m and a mean period of 8.23 s. As it occurs in other simulations, the largest energy is associated to the largest wave periods.

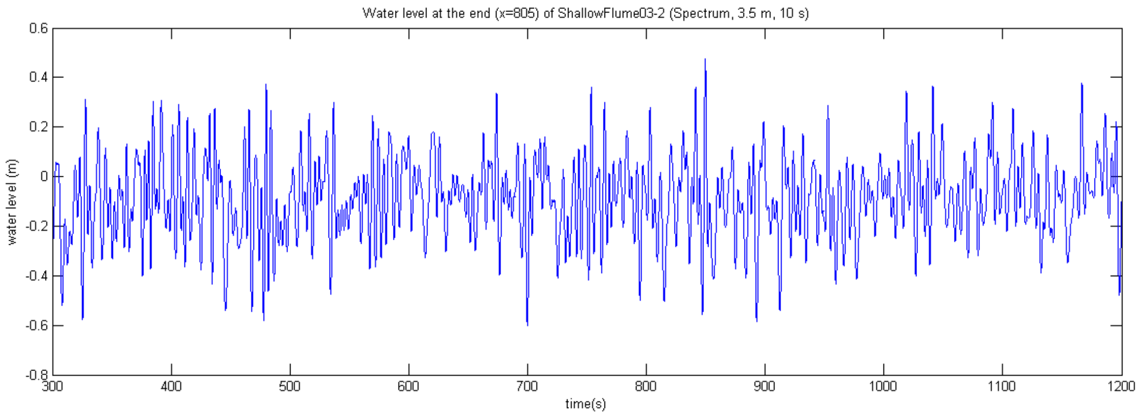

Figure A.9. Water elevation at x=805 m of Shallow_Flume03_2.sws.

After reducing the number of layers I get "better" results. I conclude that the increase of the number of operations have brought more errors than precision.

Shallow_Flume03_3.sws

The water depth has been divided in 2 layers.

At x=0 m, the recorded wave has a mean period of 1.73 s and a significant height of 2.93 m. The mean water level is 0.087 m. After spectral analysis, the significant wave height is 3.15 m and the mean period is 1.80 s.

At x=805 m, the mean wave period is 8.8 s and the significant wave height is 0.57 m. The mean water level is $\bar{\eta} = -0.12\ m$, which is a non-negligible reduction. From spectral analysis a mean wave period of 10.55 s and a significant wave height of 0.71 m are obtained.

Changes can be appreciated in the wave height at the beginning of the flume and wave period at the end.

In Shallow_Flume03_6.sws I run Shallow_Flume03_3.sws without the sponge layer.

At the beginning of the flume, the mean wave period is 1.75 s and the significant wave height is 2.89 m. The mean water level is +0.158 m. After doing the spectral analysis, I get a mean wave period of 1.84 s and a significant wave height of 3.13 m. Despite the wave parameters do not change much, the increase of the mean se level has doubled. In addition to this, the large waves (with very small frequencies) have almost twice as energy as the waves with a two-second wave period, the second peak in the spectrum.

At x=805 m, the mean wave period is 7.82 s and the significant wave is 0.58 m. The mean water level decreases to -0.085 m. From the spectrum I can see very long waves and I get a mean period of 8.58 s and a significant wave height of 0.67 m. Thus, at the end of the flume we get smaller wave periods and a smaller lowering of the mean water level.

Shallow_Flume03_4.sws

It is the same script as Shallow_Flume03_2.sws, but it reduces the time step of the output table from 0.05 s to 0.1 s.

At x=0 m we get waves within a range of 0.074 and 4.678 m, a significant wave height of 3.07 m and a mean wave period of 1.73 s. They are the same values as in Shallow_Flume03_2.sws, as it was expected since the only change is the time resolution of the output water level. From spectral analysis we get also the same values: a significant wave height of 3.33 m and a mean wave period of 1.78 s. The mean water level is 0.057 m.

The larger time step does not reduce the spectrum problems.

At x=805 m the significant wave height is 0.63 m; the mean wave period, 7.07 s and the mean water level, -0.089 m. After spectral analysis no major changes are observed. The significant wave height is 0.72 m and the mean wave period, 8.24 s.

Shallow_Flume03_5.sws

Same script as Shallow03_3.sws using one layer.

At x=0 m there is a reduction of the wave height. From wave per wave analysis I get a significant wave height of 2.16 m, a mean wave period of 1.76 s and a mean water level of $\bar{\eta} = +0.086\ m.$

From spectral analysis I get a significant wave height of 2.26 m and a mean period of 1.89 s. Despite a clear peak period around 2 s, large waves have also large energy.

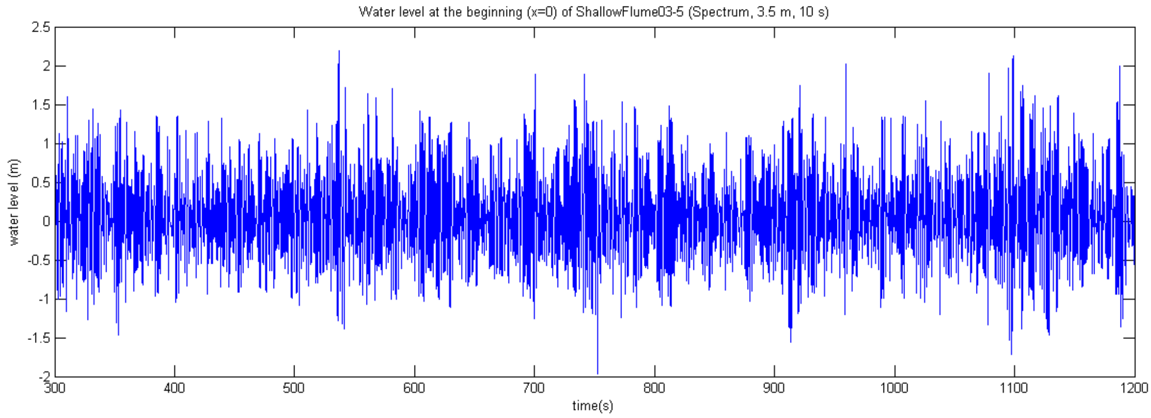

Figure A.10. Water elevation a x=0 m of Shallow_Flume03_5.sws.

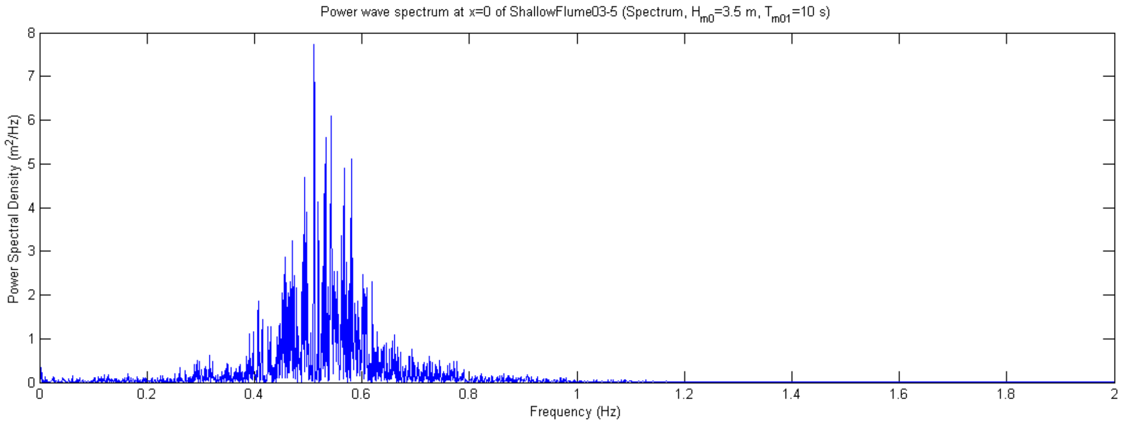

Figure A.11. Power wave spectrum at x=0 m of Shallow_Flume03_5.sws.

At x=805 m the significant wave height is 0.49 m and the mean wave period is 7 s. Thus the wave dissipates. The mean water level is -0.1 m, quite a reduction. From spectrum analysis we can see a large wave. The significant wave height is 0.61 m and the mean wave period 8.5 s.

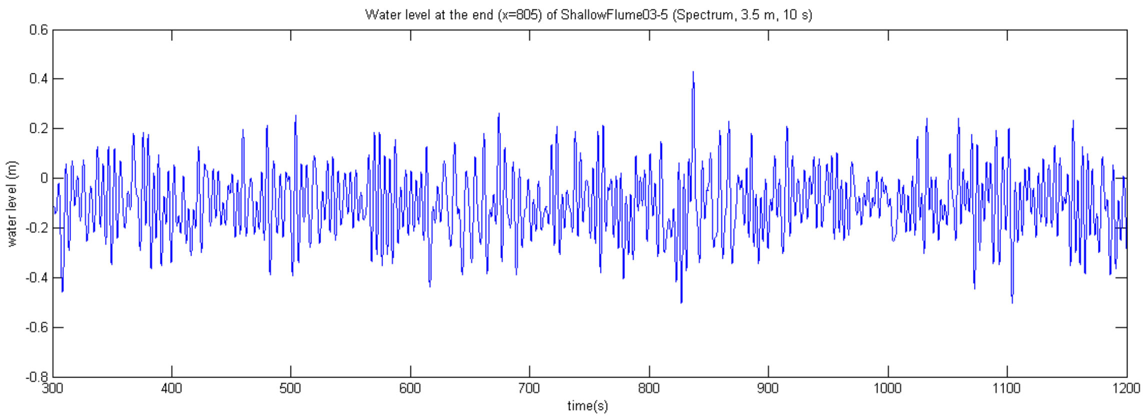

Figure A.12. Water elevation at x=805 m of Shallow_Flume03_5.sws.

With decreasing number of layers with a wave spectrum the wave height reduces.

In comparison with Shallow_Flume03_3.sws (2 layers) I get slightly smaller waves. Periods are larger than before, but a larger increase is observed at x=805 than at the beginning. In contrast with Shallow_Flume03_2.sws (5 layers), at both points the recorded wave heights are quite smaller and the wave periods very close. Also in Shallow_Flume03_2.sws the mean water level is closer to zero than in Shallow_Flume03_5.sws.

There is a clear problem with the wave spectra, because the introduced one does not correspond to the measured one. The reduction of wave period is very large although the wave heights are quite high and close to the input. As a result, the waves are very steep and they break. This explains the strong wave dissipation along the flume.

Despite not having solved the problems with wave spectra, I would consider (at this moment) Shallow_Flume03_2.sws the best simulation with spectrum waves in shallow water.

Shallow_Flume04.sws

This script is very similar to Shallow_Flume02.sws, since it only changes how the wave is defined. It works with a REGULAR wave instead of a wave spectrum.

BOUNDCOND SIDE W CCW BTYPE WEAK CON REGULAR 3.5 10

The wave periods are around 10 s at the beginning and at the end of the flume. The measured wave heights at the wave generator are around 3.5 m although there are little oscillations. Then, I conclude that the wave is well introduced. However, it can be observed that the mean water level decreases with time around one meter! It looks like the water is going out. Something is surely wrong, but I do not know what. At the end of the flume there is a large increase of wave heights (range between 3.76 and 6.49 m).

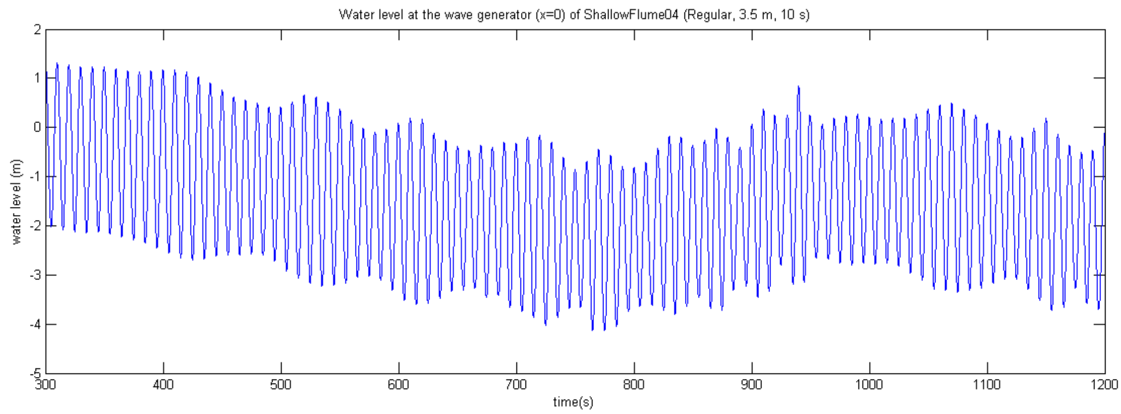

Figure A.13. Water elevation at x=0 m of Shallow_Flume04.sws.

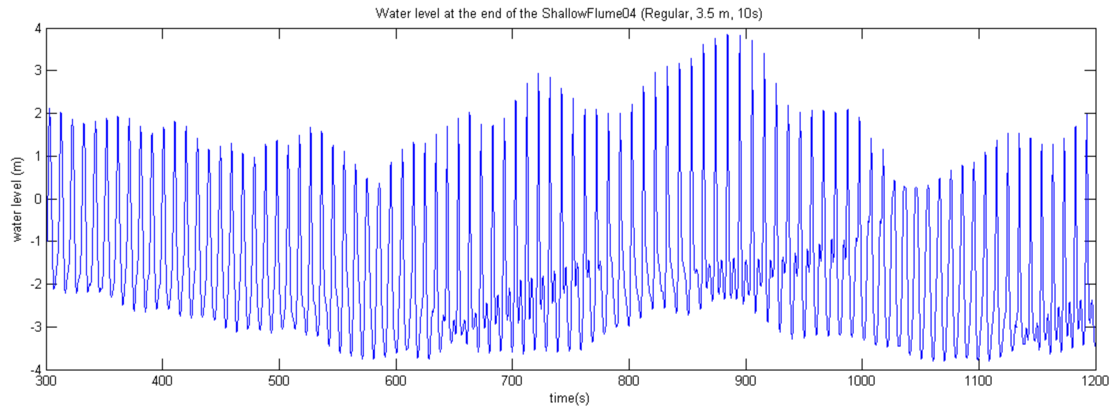

Figure A.14. Water elevation at x=805 m of Shallow_Flume04.sws.

This phenomenon takes place in every simulation I do with Regular waves in shallow water. Or anything else has to be introduced as a boundary condition or a sponge layer on the generator side, or other SWASH commands should be implemented.

Shallow_Flume04_2.sws

This is a modification of the last script using the same DISCRETE commands as in Shallow_Flume03.sws

Analysing the results in x=0 m, we can see a strong reduction of the mean water level, which is now more progressive arriving at one meter! The mean wave height is 3.36 m and the mean period is 9.99 s. The mean water level is -0.74 m.

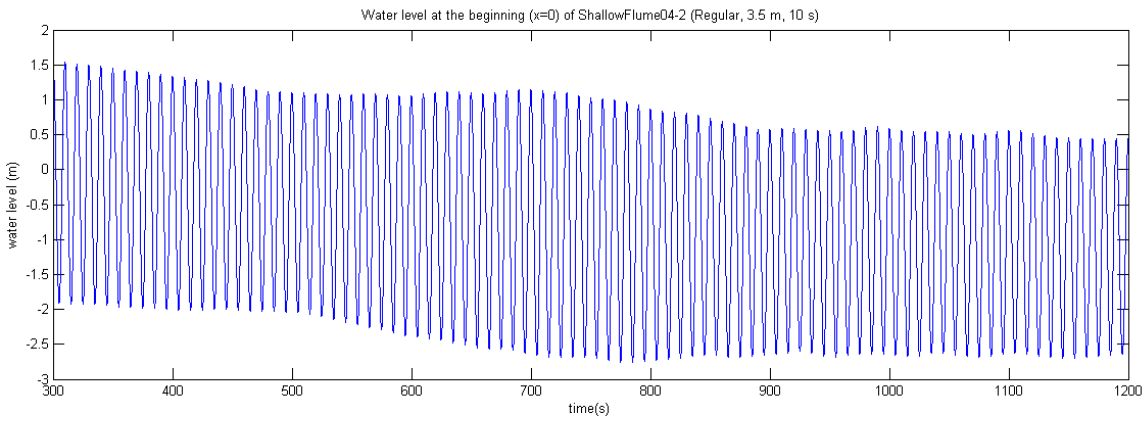

Figure A.15. Water elevation at x=0 m of Shallow_Flume04_2.sws.

At the end of the flume there is an increase of wave height up to a mean value of 4.08 m. The period is 9.93 s. The mean water level reduction is less though the computed mean value is $\bar{\eta} = -0.79\ m$. The cause is that there are a larger number of points in the wave trough than in the wave crest although it is not clearly seen on the plots.

Shallow_Flume04_3.sws

This script reduces the number of vertical layers of Shallow_Flume04_2.sws from 10 to 5. The breaking command BREAK has been activated due to the reduction of the number of layers. However, wave breaking is not expected to occur.

The main change in the results is that in this simulation the water level increases around one meter. The mean water level is +0.95 m. However, the measured wave has a mean wave height of 3.55 m and a mean wave period of 10 s. Thus, the recorded wave corresponds with the introduced one.

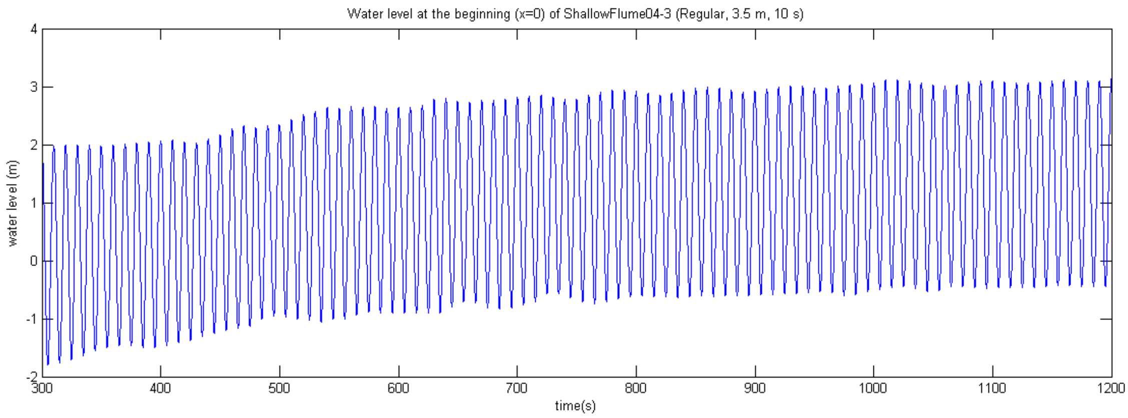

Figure A.16. Water elevation at x=0 m of Shallow_Flume04_3.sws.

At x=805 m the mean water level is +1.04 m. The mean wave period is 12.15 s and the mean wave height is 3.51 m. The plotted record has a strange shape with shows a kind of wave grouping.

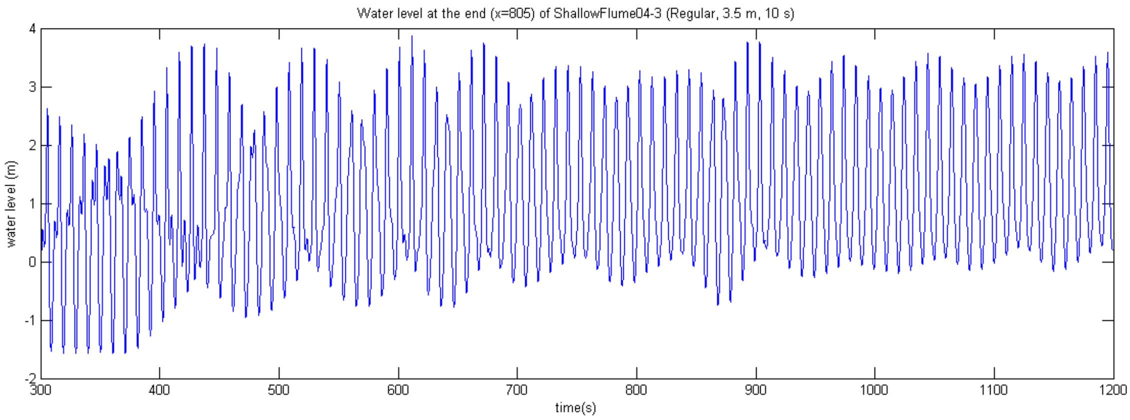

Figure A.17. Water elevation at x=805 m of Shallow_Flume04_3.sws.

Shallow_Flume04_4.sws

It is a new script that uses 1 layer. I do not know why it works with one or five, but not with 2 (computational error).

The wave heights are quite larger at x=0 m, with a mean wave height of 3.79 m and a mean wave period of 10.15 s. The mean water level is +2.29 m! There is a large increase!

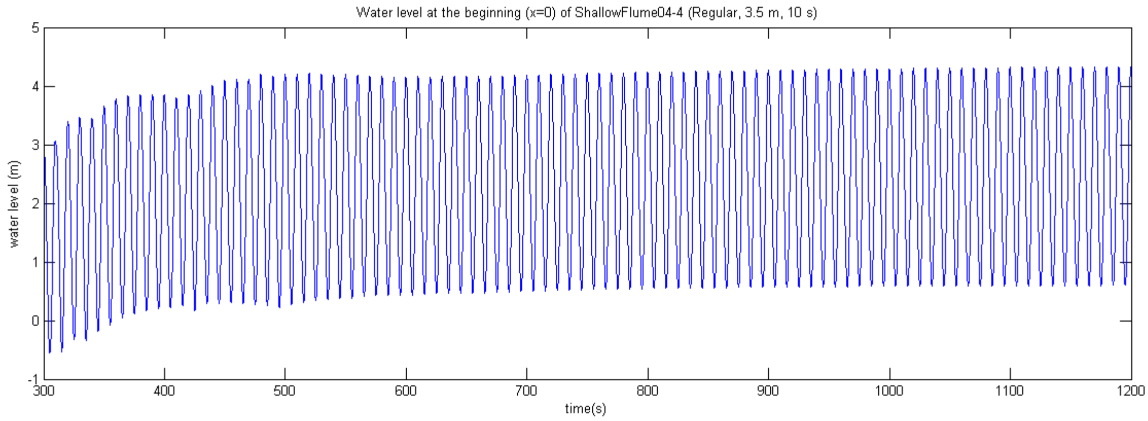

Figure A.18. Water elevation at x=0 m of Shallow_Flume04_4.sws.

At x=805 m I can not compute the wave parameters with my Matlab script because almost all waves are above 0. There is a large increase of water level. The mean water level is + 2.34 m. However, the mean wave period can be estimated around 10 s and the mean wave height of the right side around 3.7-3.8 m.

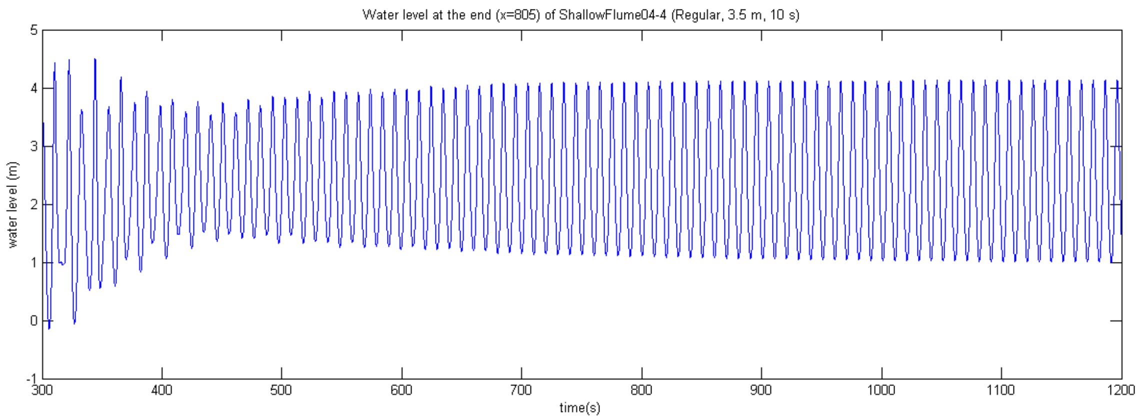

Figure A.19. Water elevation at x=805 m of Shallow_Flume04_4.sws.

Shallow_Flume04_5.sws

3 layers are used this time.

At x=0 m I obtain a similar plot as in Shallow_Flume04_3.sws: $\bar{\eta} = +1.05\ m$, $H_m = 3.60\ m$ and $T_m = 10\ s$.

At x=805 m I obtain a similar pattern as at the beginning: $\bar{\eta} = +1.05\ m$, $H_m = 3.60\ m$ and $T_m = 10\ s$. I have measured the same wave at both sides of the flume for the first time!

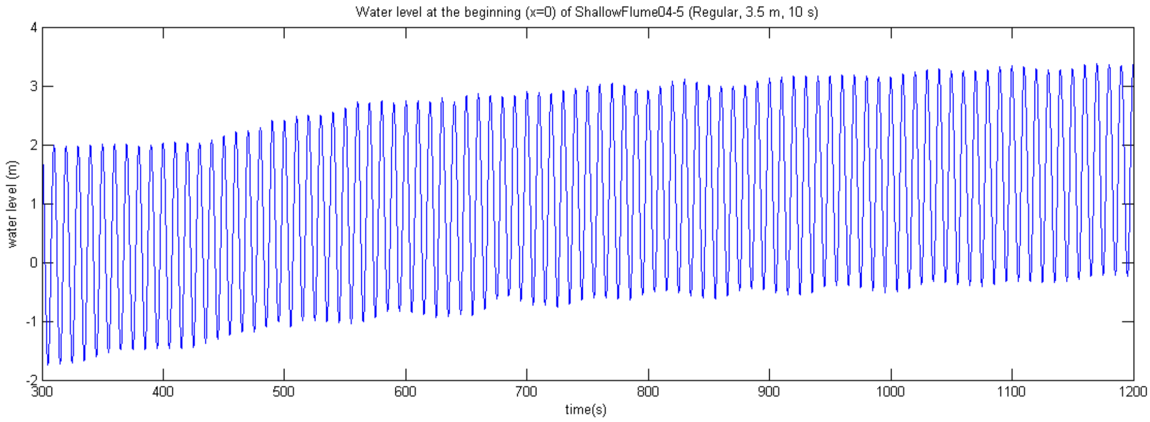

Figure A.20. Water elevation at x=0 m of Shallow_Flume04_5.sws.

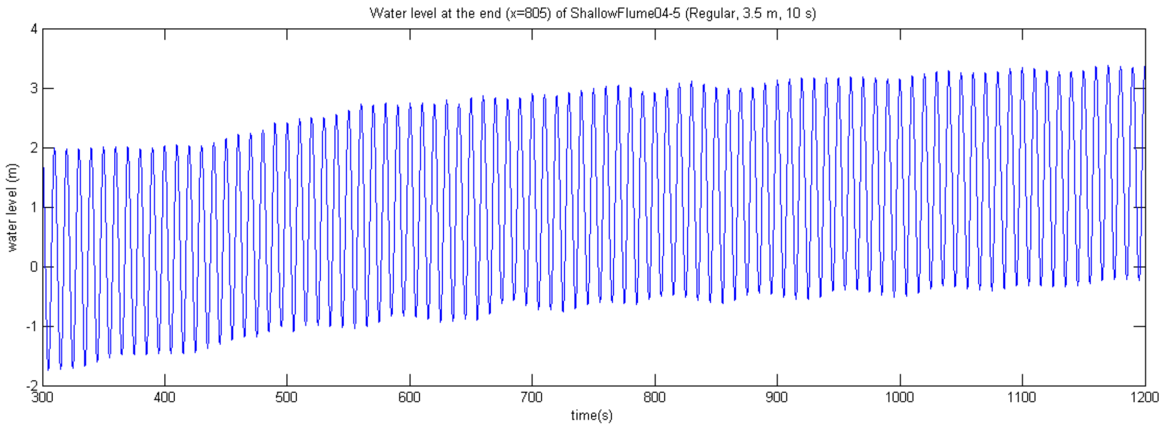

Figure A.21. Water elevation at x=805 m of Shallow_Flume04_5.sws.

If I delete the sponge layer (Shallow_Flume04_6.sws) at the right, the mean water level is +2.25 at x=0 m. The majority of the waves can not be measured, because they are above the zero-meter level. However, a mean period of 10 s and a have height around 3.7-4 m can be estimated. A very strange graph is obtained at x=805 m.

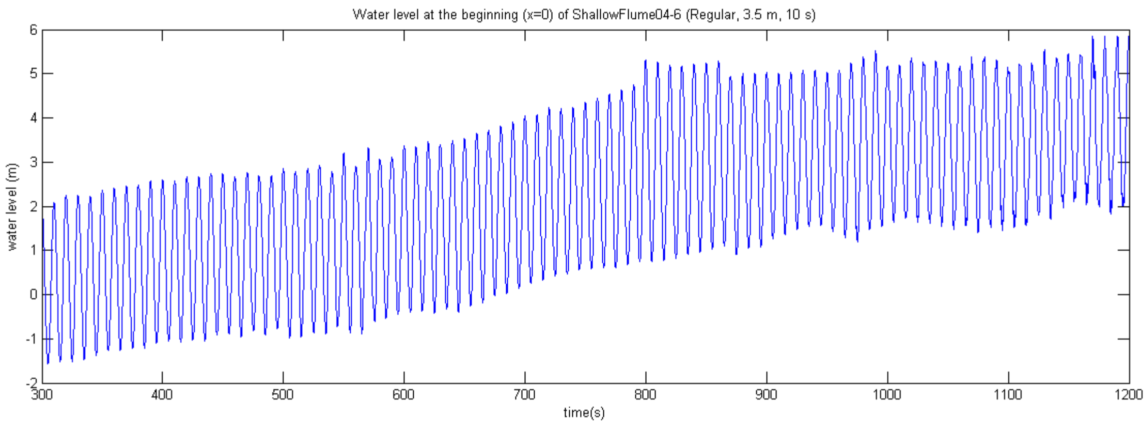

Figure A.22. Water elevation at x=0 m of Shallow_Flume04_6.sws.

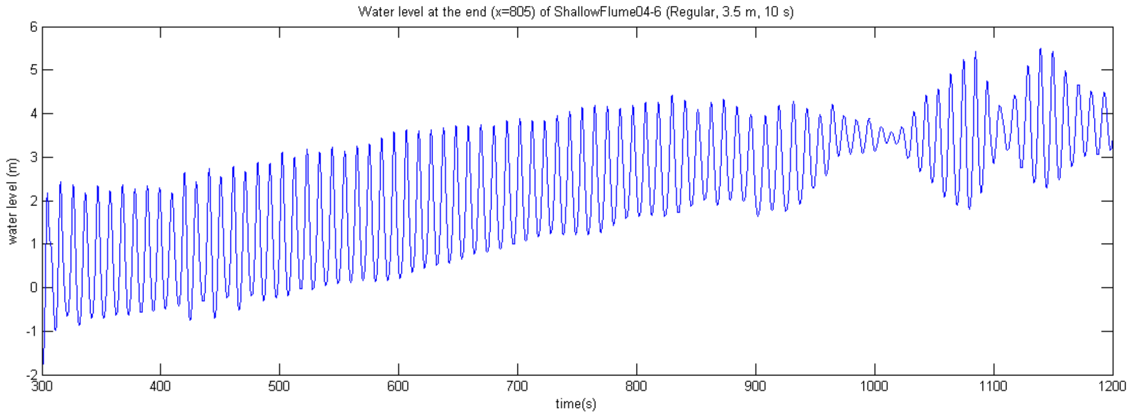

Figure A.23. Water elevation at x=805 m of Shallow_Flume04_6.sws.

Some comments and (partial) conclusions

It is clear that some of the commands given in Shallow_Flume03.sws do not work, that the regular wave has been correctly introduced whereas the wave spectrum has not. Also something is wrong when the majority of the water levels are negative, which must be corrected, especially in the case with regular waves.

As we are not in deep water, the bottom influences wave propagation. Nevertheless, the effects should not be very important due to the fact that we are far from breaking conditions (10/3.5=2.86). Propagating the introduced wave in deep water, I have obtained that the wave height should reduce to 3.1 meters. Then, I think that the bottom effect does not explain the reduction of water level, but wave parameters variations along the flume. However, the output spectrum waves are very steep and they are breaking.

During wave propagation the flux of Energy is conserved. I expect that SWASH considers it. In deep water the water particles do not displace, they just oscillate tracing circles. However in shallow water they move towards the coast. In the SWASH User Manual it is said that (in principle) energy head conservation will be applied only in strong contractions, while elsewhere the momentum conservation is applied. Will the increase of water level be a sort of water piling?

In wave propagation waves behave as an ideal fluid, so considering viscosity equal to 0 is true.

Deep Water Flume

The first attempts with a deep water flume did not succeed as commented above. For this reason, once I had some scripts that worked with shallow water (10 m), I decided to adapt them to deep water. However, it did not work as expected.

After some trials with increasing water depth, I concluded that my mistake was that I increased too much the number of layers (from 10 to 20), which apparently my laptop could not manage or took too much time to start the calculations (more than one hour, sometimes even 4, after what I stop running the program). I succeed in computing the flume for 40 and 60 meter of water depth through the scripts Shallow_Flume06.sws (h=40 m with 10 layers) and

Shallow_Flume07.sws (h=60 m, 10 layers). In Shallow_Flume07_2.sws, I used 15 layers instead of 10, which took much more time than the previous script. It works, though I stopped before finishing the calculations.

Despite being in intermediate water and not in deep water, I can see that the mean water level continues decreasing. The wave period does not change, but the wave height slightly does. These can be seen in the following graphs:

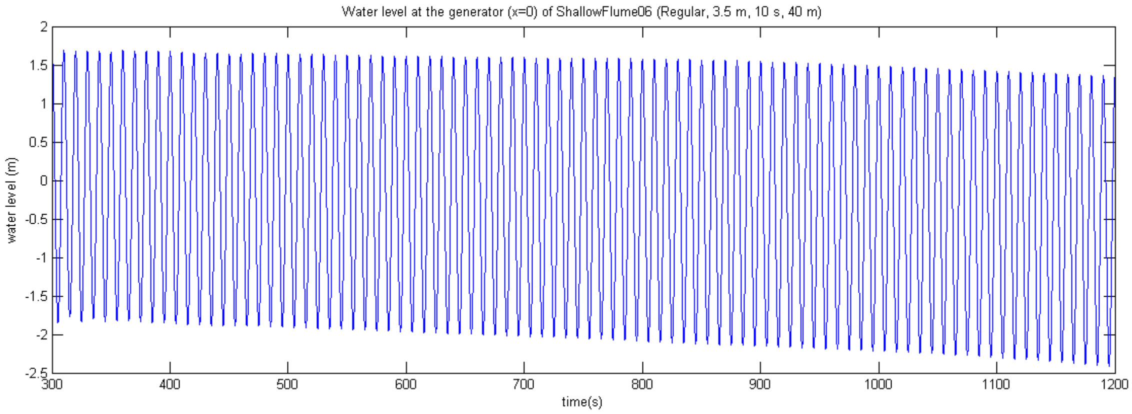

Figure A.24. Water elevation at x=0 m of Shallow_Flume06.sws.

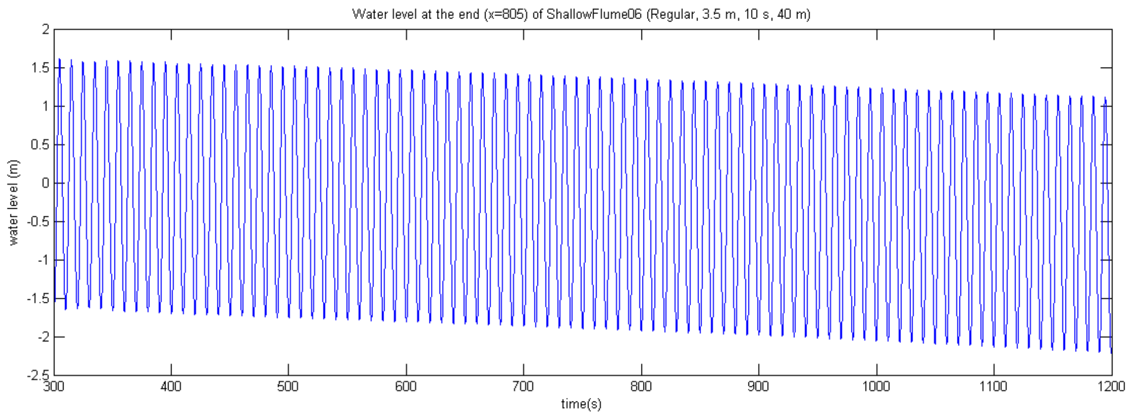

Figure A.25. Water elevation at x=805 m of Shallow_Flume06.sws.

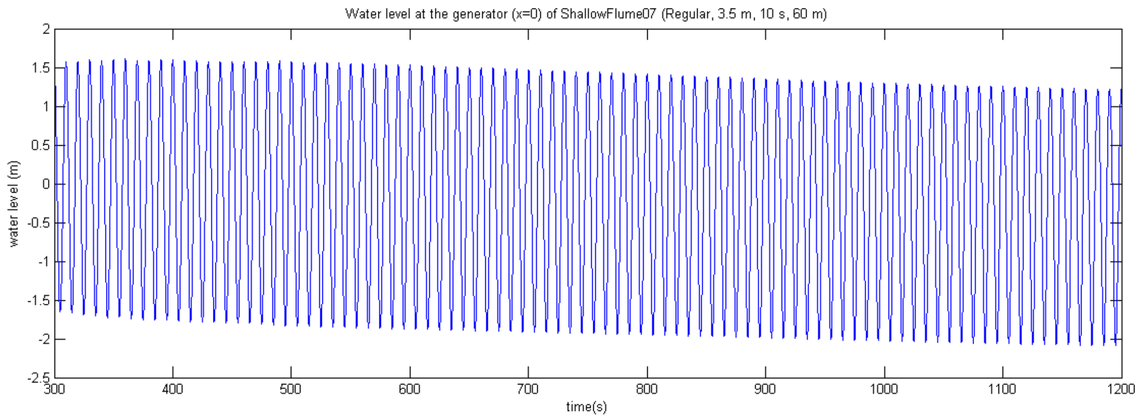

Figure A.26. Water elevation at x=0 m of Shallow_Flume07.sws.

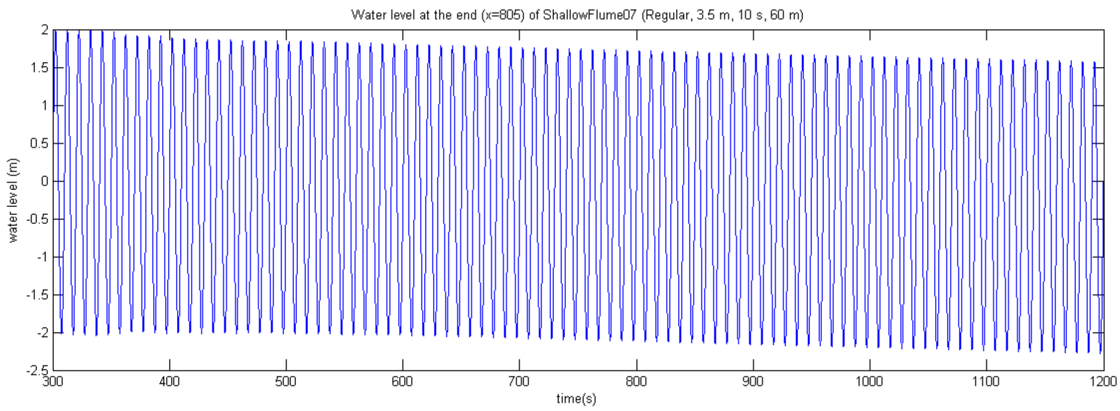

Figure A.27. Water elevation at x=805 m of Shallow_Flume07.sws.

At least, with increasing water depth, the mean water level experiences a lower reduction.

After this, I came back to deep water flumes.

Deep_Flume05.sws

To get deep water conditions I have to increase the ratio h/L_0. Since I had problems with large depths, I decided to reduce the wave dimensions to a wave height of 2 m and a wave period of 7 s.

This script considers a water depth of 50 m, which gives $h/L_0 = 0.65$. I have used 12 layers and it works perfectly. Regular waves are generated.

At the wave generator, waves have a mean period of 7 s (with a 0.05 s tolerance, which is the output table “resolution”) and a mean wave height of 2.01 m. This is by far the closest wave I have got in all my tests until now. The mean water level is -0.067 m, so the reduction of the mean water level does not occur in deep water.

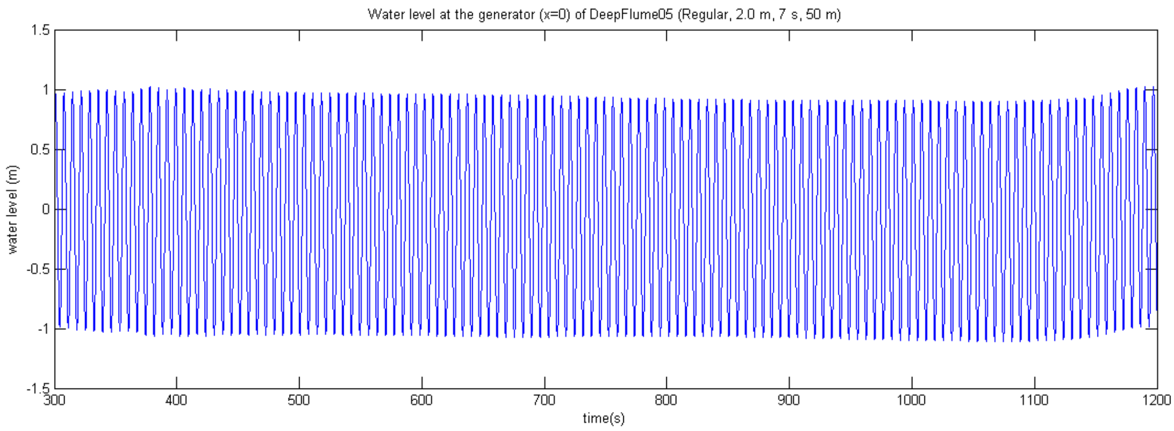

Figure A.28. Water elevation at x=0 m of Deep_Flume05.sws.

At the end of the flume the period does not change, but the wave height reduces to a mean value of 1.66 m. The mean water level is -0.072. An increase of the wave height and water level occurs at the end of the computation. I find it really strange.

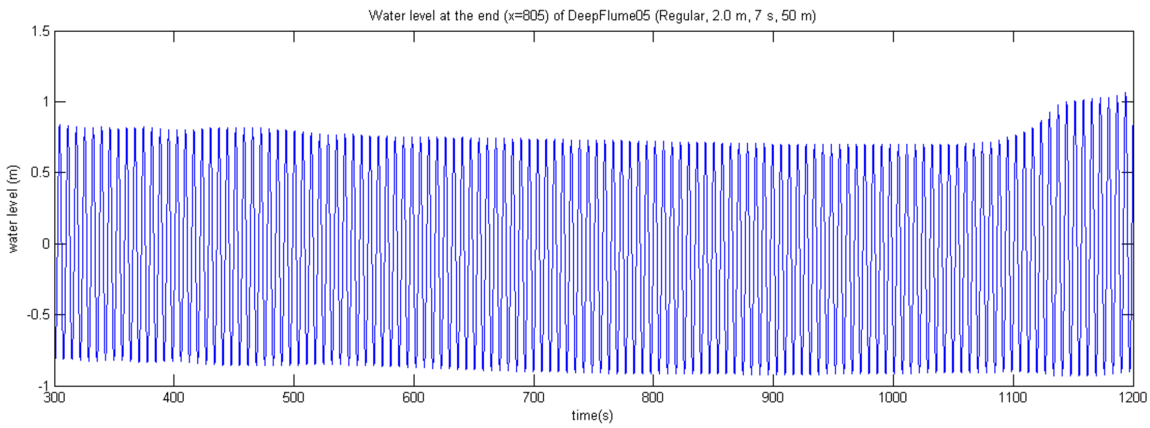

Figure A.29. Water elevation at x=805 m of Deep_Flume05.sws.

From this simulation a conclusion can be drown: the reduction of water level that takes place in shallow water does not occur in deep water. However, during propagation, wave height reduces, which it is not expected to happen in deep water.

The following commands are written in this script, which are taken from the test cases a14prw0X.sws (propagation of a linear wave in a deep water flume). As it is explained above, they are also implemented (and explained) in Shallow_Flume03.sws without success. The only explanation that comes to my mind is that they only work in deep water and not in shallow water, but it does not convince me, since I found it nonsense. Later on I found that reflection at the end of the flume was the cause.

DISCRET UPW NONE

DISCRET UPW UMOM V NONE

DISCRET CORRDEP NONE

Deep_Flume05_2.sws

The only variation that presents this script with respect with the previous one is that it considers 10 layers instead of 12.

I have done both simulations in order to see if there are appreciable differences between both results. After comparing the results, the largest difference between water levels is 0.0903 m. I have computed the relative error (assuming that the result with 12 layers is more precise and the reference solution) and I have found a maximum error of 20.986. However, this can be easily explained because the difference between both values is divided by a very small number. Then, it is non-sense to fix a maximum relative error for all values to fix an adequate number of layers. The mean relative error is 0.0387, so only one figure is enough accurate with this criterion! Thus, we should add more layers to get a better result.

Nevertheless, I think that the final number of layers should be adjusted at the end of the process, once the whole model has been built and tested, in order to increase the accuracy. It will save time and it will be fixed for that concrete situation. Furthermore, I do not think that so many layers are needed.

Deep_Flume05_3.sws

It is the script Deep_Flume05.sws modified with 8 vertical layers.

At the wave generator the recorded waves are equal to the introduced ones, since the mean wave period is 7 s and the mean wave height is 1.98 m. Remember that I introduced a regular wave with a wave height of 2 m and a period of 7 s. The mean water level is +0.085 m and a progressive rise up to approximately 25 cm at the end of the simulation.

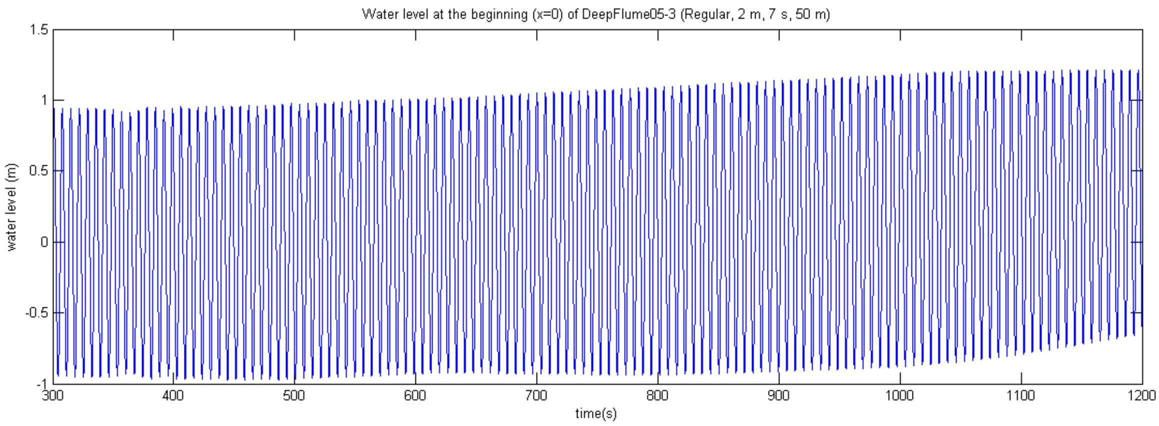

Figure A.30. Water elevation at x=0 m of Deep_Flume05_3.sws.

At the end of the flume (x=805 m), the wave heights decrease. Then the mean wave height is 1.66 m although the wave period remains “constant” (7.01 s). The mean water level is +0.083 m, the same value as at the wave generator. Also, a progressive increase of water level can be observed.

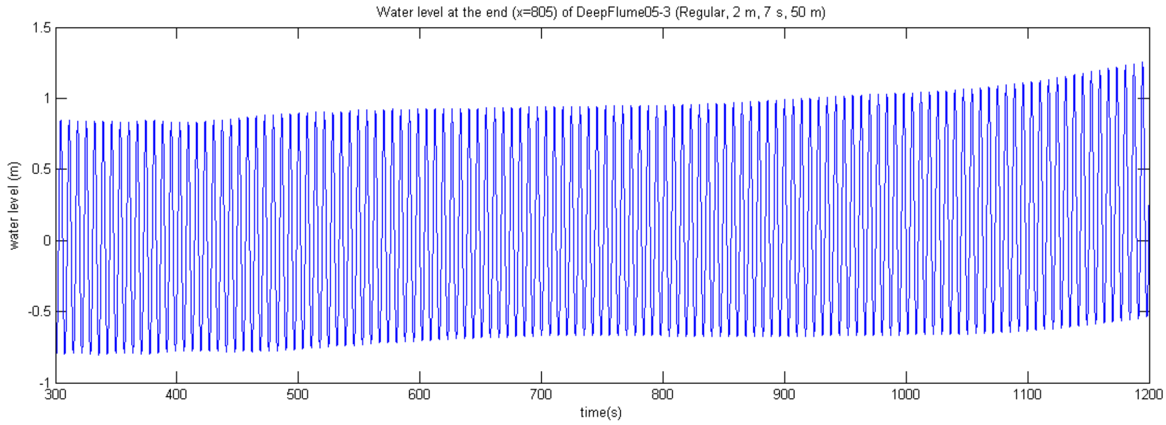

Figure A.31. Water elevation at x=805 m of Deep_Flume05_3.sws.

After comparing these results with the obtained in Deep_Flume05.sws I conclude that a decrease of the number of layers leads to a rise of the water level though the recorded wave heights and periods do not change.

Deep_Flume05_4.sws

Now I have only considered 5 vertical layers.

In this simulation there is hardly any reduction of water level, since the mean value is -0.046 m at the beginning, but there is a progressive reduction of the wave height. The mean wave height is 1.83 m and the mean wave period is 7 s.

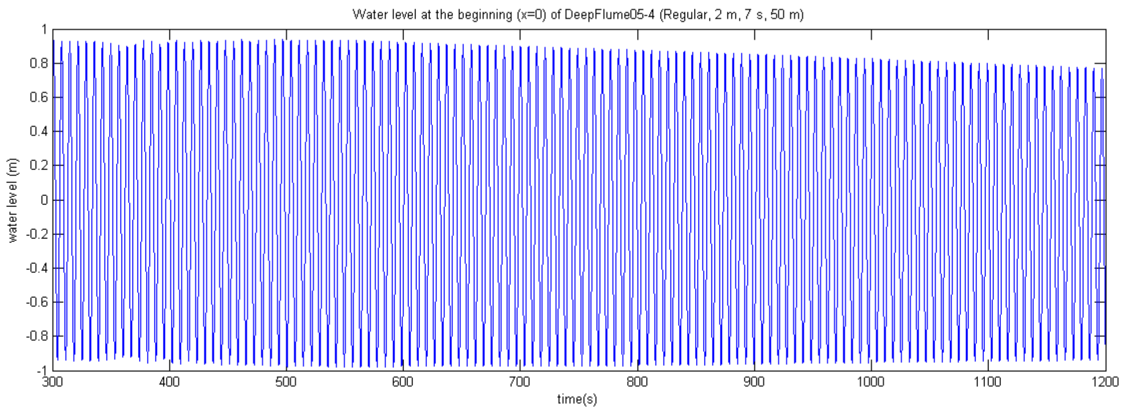

Figure A.32. Water elevation at x=0 m of Deep_Flume05_4.sws.

At x=805 m, the global image is the same although there is a small reduction of the wave height. The mean wave height is then 1.64 m. The mean wave period is still 7 s and the mean water level is -0.061 m.

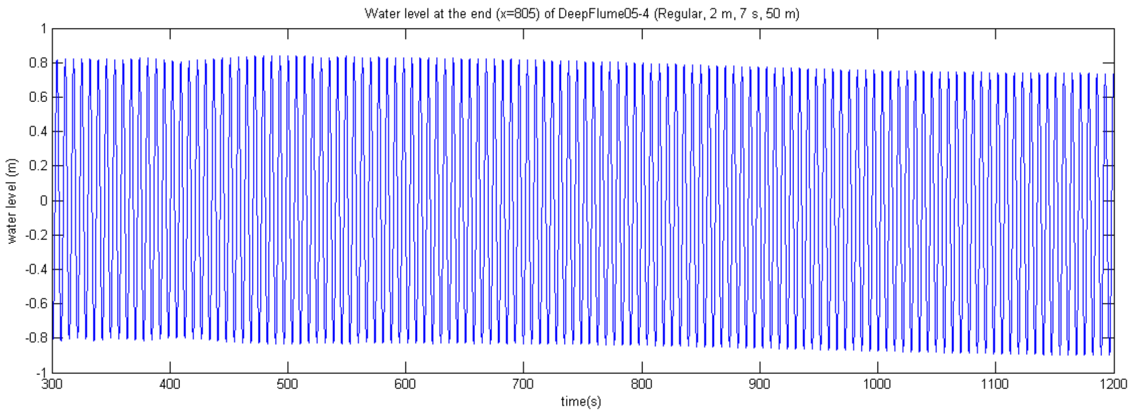

Figure A.33. Water elevation at x=805 m of Deep_Flume05_4.sws.

Deep_Flume06.sws

This script defines the wave through the wave spectrum ($H_{m0} = 2\ m$ and $T_{m01} = 7\ s$). The commands used are the ones used in Shallow_Flume02.sws (also with a spectrum wave). 12 vertical layers are considered.

BOUNd SHAPespec JONswap 3.3 SIG MEAN DSPR DEGR

BOUNdcond SIDE W CCW BTYPE WEAK CON SPECTrum 2.0 7. 90 0 5 MIN

BOUNDCOND SIDE E CCW BTYPE RADIATION

SPONgelayer RIght 10

If we analyse the record at the wave generator wave per wave, we get that the mean sea level is 0.0075 m (so there is no reduction as in Shallow water), the mean wave period is 1.26 s, the mean wave height is 0.41 m and the significant wave height is 0.63 m. The wave does not correspond to the introduced one.

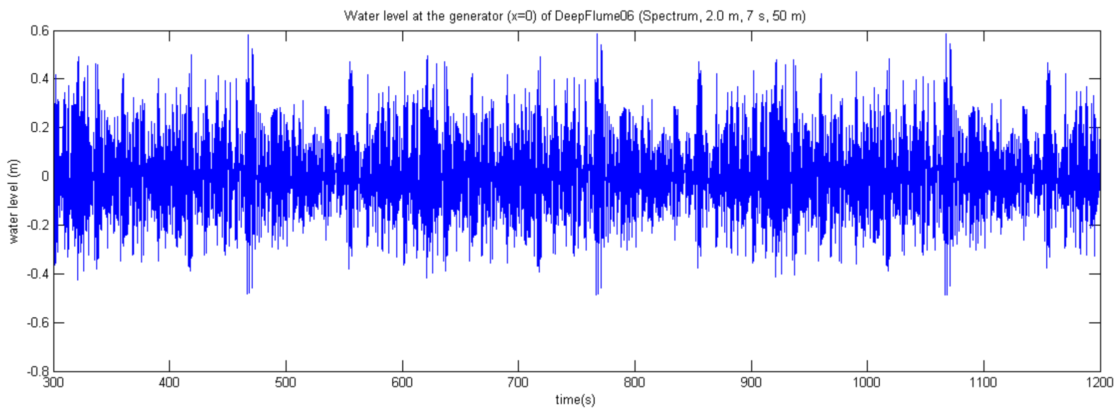

Figure A.34. Water elevation at x=0 m of Deep_Flume06.sws.

After building the wave spectrum I confirm that the spectrum does not correspond to the introduced one (or something was wrong introduced). The peak wave period is 1.38 s.

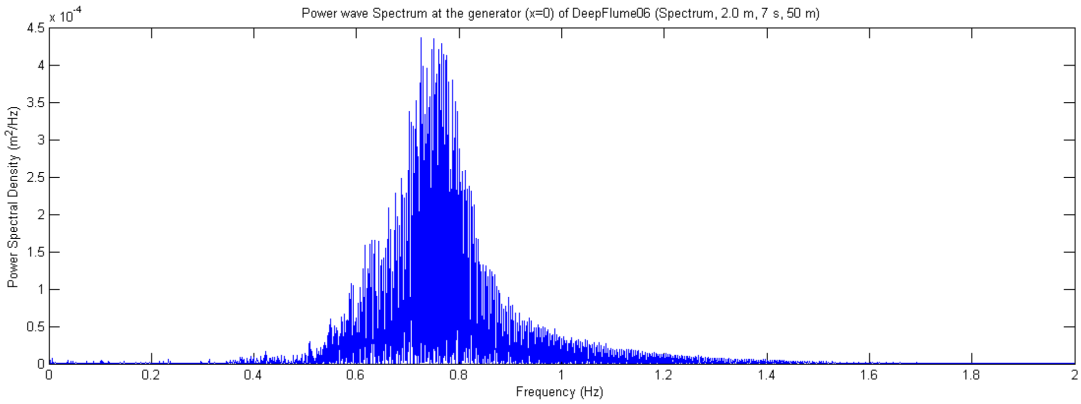

Figure A.35. Wave spectrum at x=0 m of Deep_Flume06.sws.

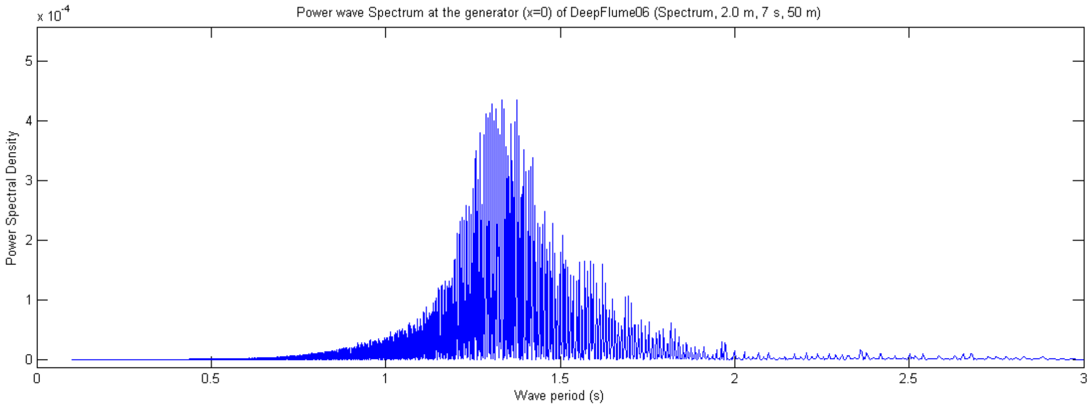

Figure A.36. Wave spectrum at x=0 m of Deep_Flume06.sws.

Using numerical integration (Composite trapezoidal rule), I get the mean wave period (1.28 s, close the measured wave per wave) and the significant wave height (0.65 m). The spectral wave height is close to the recorded significant wave height. Afterwards, the spectrum script must be improved to reduce the noise.

Close to the end of the flume I get a wave with a mean period of 5.53 s and a significant wave height of 0.0567 m, which is very low. The wave has almost dissipated. The mean water level is one centimetre below 0, so I can assume there is no variation.

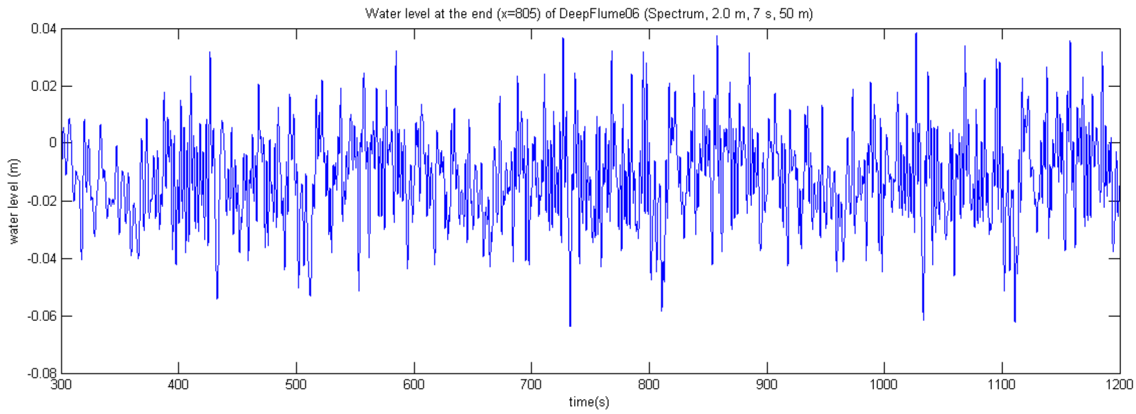

Figure A.37. Water elevation at x=805 m of Deep_Flume06.sws.

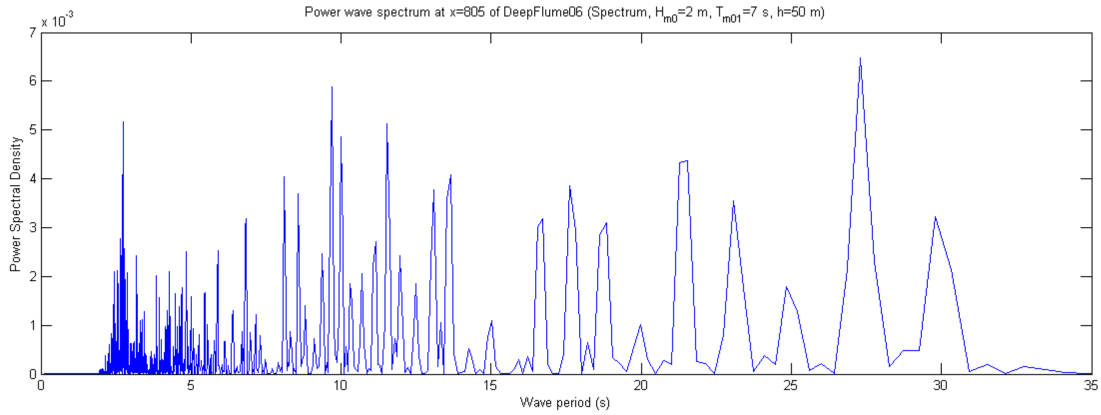

Figure A.38. Wave spectrum at x=805 m of Deep_Flume06.sws.

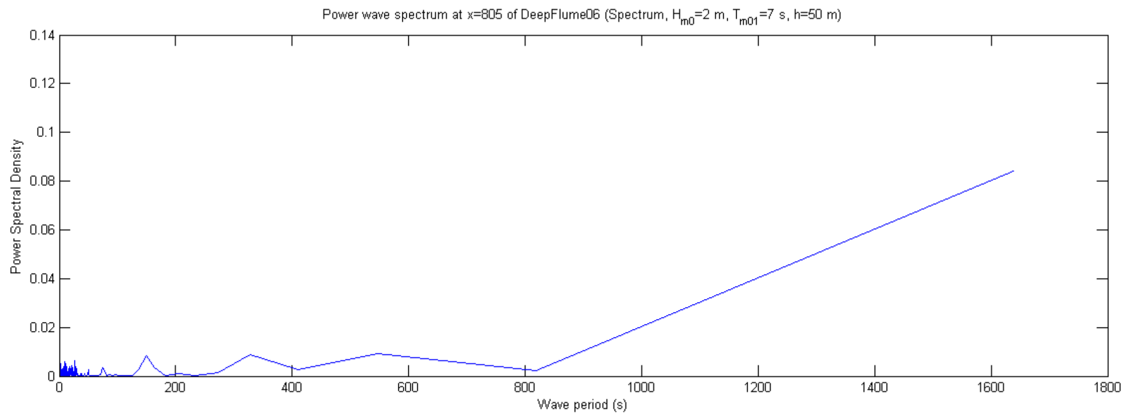

Figure A.39. Wave spectrum at x=805 m of Deep_Flume06.sws.

From spectral analysis I get that the significant wave height is 73.3 mm and the mean wave period is 7.86 s. The wave "has absolutely dissipated" and this may also be related to the introduced commands in SWASH such as the cyclic period of the Fourier series or some problem of the software.

This cyclic period of the Fourier series is defined in the SWASH User Manual as "the time period over which surface elevation is outputted after steady-state condition has been established". I have initially set 5 minutes, because I start recording the results after 5 minutes of computation. Later I realized that SWASH begins the same spectrum every five minutes, so it is repeated. To avoid it I set a longer time though this should not affect much the results.

Deep_Flume04.sws

This script considers a water depth of 80 m and a regular wave of $H = 3.5\, m$ and $T = 10\, s$. We are in the limit of deep water ($h/L_0 = 0.51$). The water depth is divided in 10 layers.

The 3 previously commented DISCRET commands are used in this script.

Analysing the wave record at x=20 m, an increase of wave height can be appreciated, since it increases from 3.5 m to 3.62 m. The wave period stands at 10 s. The mean water level reduces to -0.18 m. It is similar to what happens in shallow water tests.

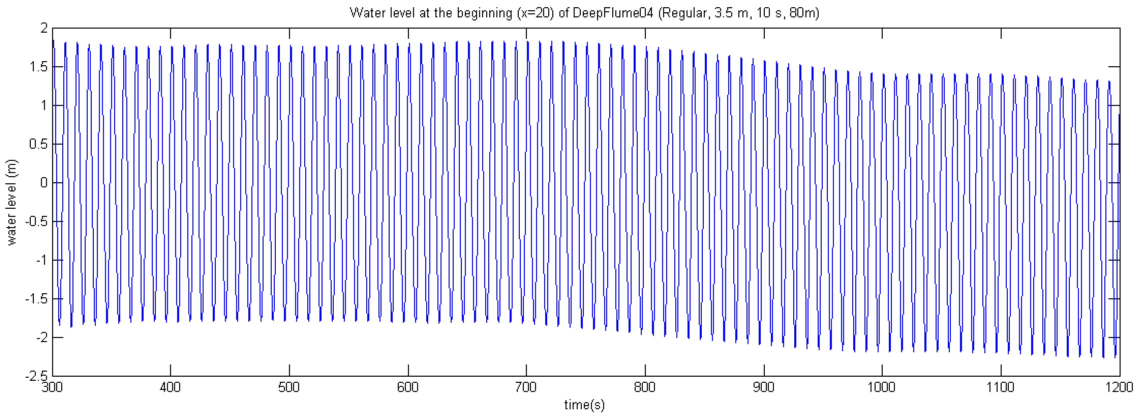

Figure A.40. Water elevation at x=20 m of Deep_Flume04.sws.

At x=805 m, near the end of the flume, the mean water level decreases up to -0.24 m, but the mean wave height slightly reduces to 3.55 m (range 3.42-3.60 m). The wave period does not change at all.

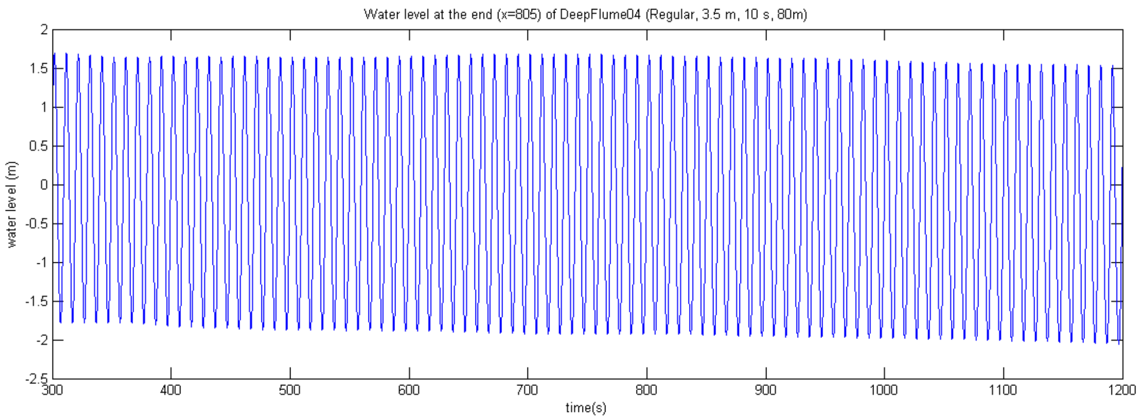

Figure A.41. Water elevation at x=805 m of Deep_Flume04.sws.

Deep_Flume07.sws

This script is based on Deep_Flume06.sws considering the discretization used in Deep_Flume04.sws and Deep_Flume05.sws. Therefore, the script considers a water depth of 50 m and a wave defined by a spectrum ($H_{m0} = 2\ m$ and $T_{m01} = 7\ s$).

Analysing the wave at the generator, we get no mean water level variation (7.6 mm) and a smaller wave (as usual with spectrum waves), with a mean period of 1.27 s and significant wave height of 0.673 m (results from wave per wave analysis).

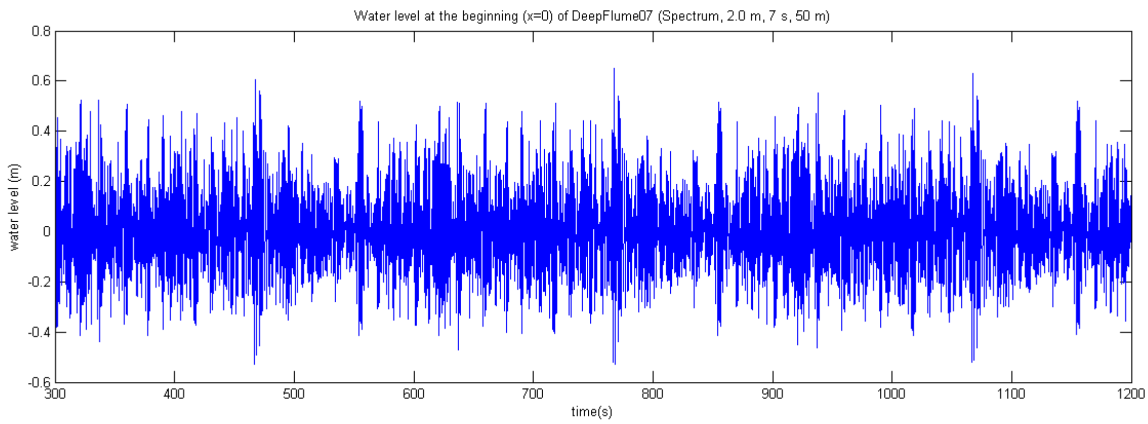

Figure A.42. Water elevation at x=0 m of Deep_Flume07.sws.

From spectral analysis I get a mean period of 1.3 s, a peak of 1.38 s, and a significant wave height of 0.7 m.

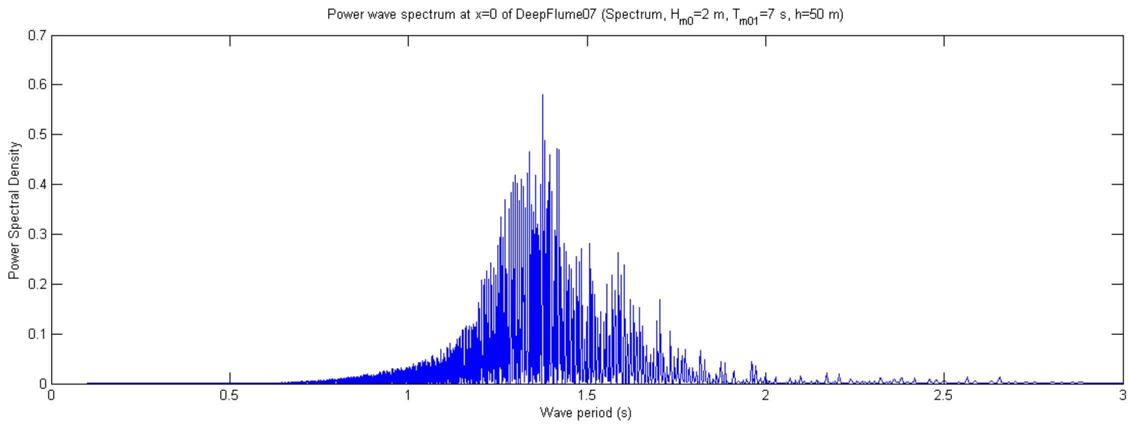

Figure A.43. Wave spectrum at x=0 m of Deep_Flume07.sws.

At the end of the flume (x=805 m), the wave has almost dissipated. From wave per wave analysis I get a mean wave period of 4 s and a significant wave height of 0.077 m. The mean sea level is at -1.2 cm, so it can be assumed there is no reduction.

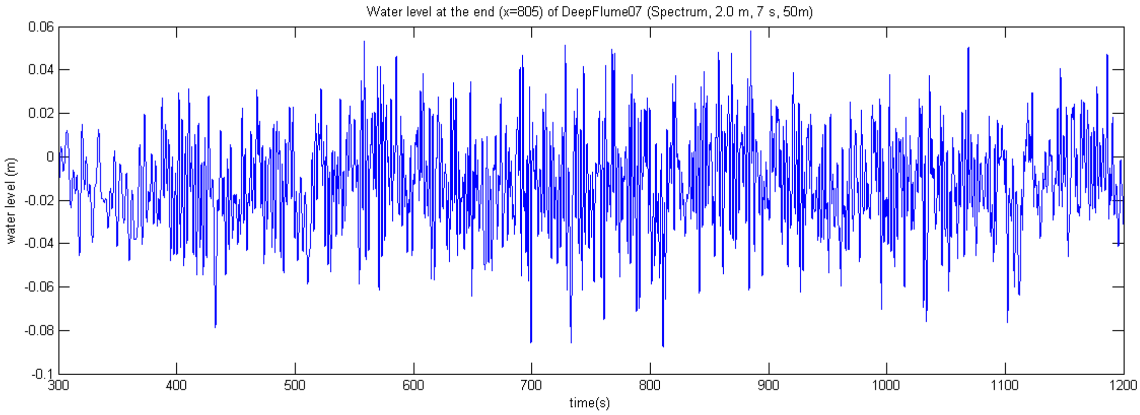

Figure A.44. Water elevation at x=805 m of Deep_Flume07.sws.

From spectral analysis I get a mean period of 4.86 sand a significant wave height of 0.095 m. From the graph, I can see that the energy is concentrated in waves with long periods.

Comparing the results from Deep_Flume07.sws with Deep_Flume06.sws no bigger differences can be appreciated. In Deep_Flume07.sws, slightly larger waves are recorded though they could be within the same range of vales once the possible error is considered. In Deep_Flume07.sws, however, quite smaller mean wave periods are obtained at the end of the flume (4 s to 5.53 s). After spectral analysis, the wave periods reduce even more from 7.86 to 4.86 s.

Deep_Flume07_2.sws

This script is a modification of Deep_Flume07_2.sws. The cyclic time of the Fourier series is increased form 5 minutes to 60 minutes and the number of layers has been reduced from 12 to 8.

At the beginning of the flume (x=0 m), the significant wave height is 0.67 m, the wave mean period is 1.25 s and the mean water level is +0.012 m. Once analysed the wave spectrum, I get a mean wave height of 1.29 s and a significant wave height of 0.69 m. Then I get almost the same results as with 12 layers in Deep_Flume07.sws.

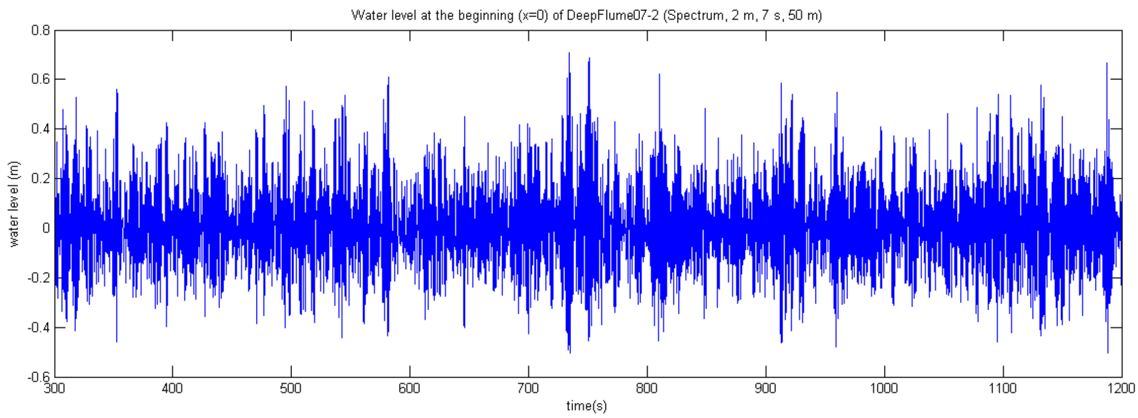

Figure A.45. Water level at x=0 m of Deep_Flume07_2.sws.

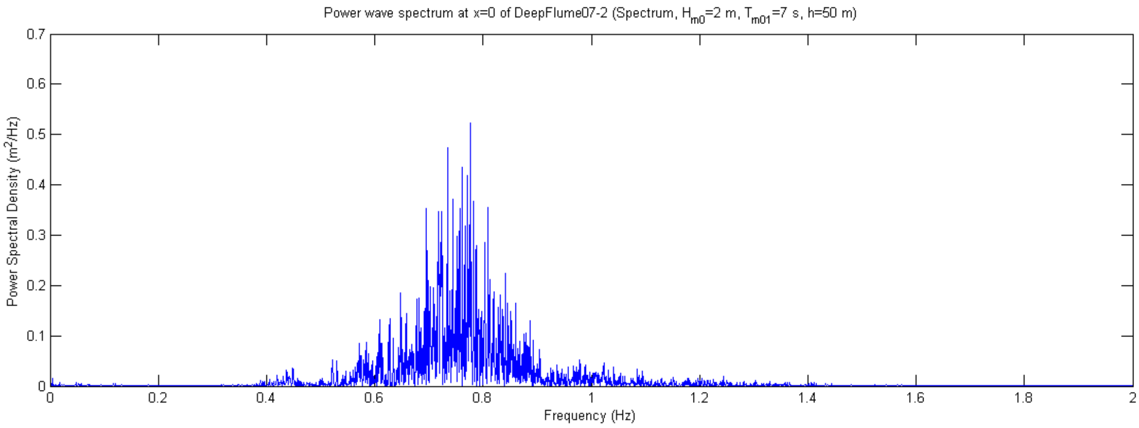

Figure A.46. Wave spectrum at x=0 m of Deep_Flume07_2.sws.

Close to the end of the flume at x=805 m, again the waves dissipate increasing their wave period and reducing their height. The significant wave height is then 0.085 m and the mean wave period is 5.73 s. The mean water level is -0.019 m. From spectral analysis I can observe long waves and a mean wave period of 7.33 s and a significant wave height of 0.11 m. Therefore, I have longer and slightly larger waves than in Deep_Flume07.sws.

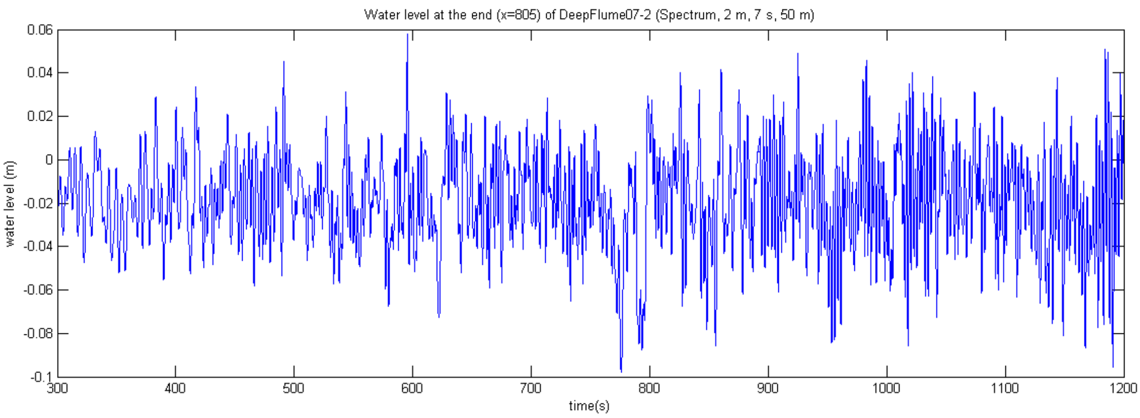

Figure A.47. Water elevation at x=805 m of Deep_Flume07_2.sws.

Deep_Flume07_3.sws

In this script I have considered 5 vertical layers.

At the wave generator the mean water level is + 0.011 m, the significant wave height is 0.65 m and the mean wave period is 1.26 s. After spectrum analysis I get a mean wave period of 1.31 s and a significant wave height of 0.66 m. From the spectrum a small second peak can be seen.

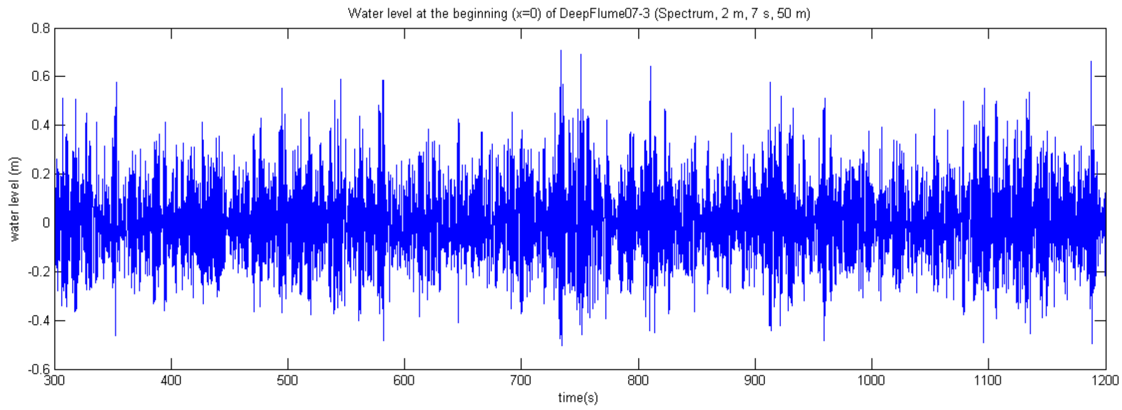

Figure A.48. Water elevation at x=0 of Deep_Flume07_3.sws.

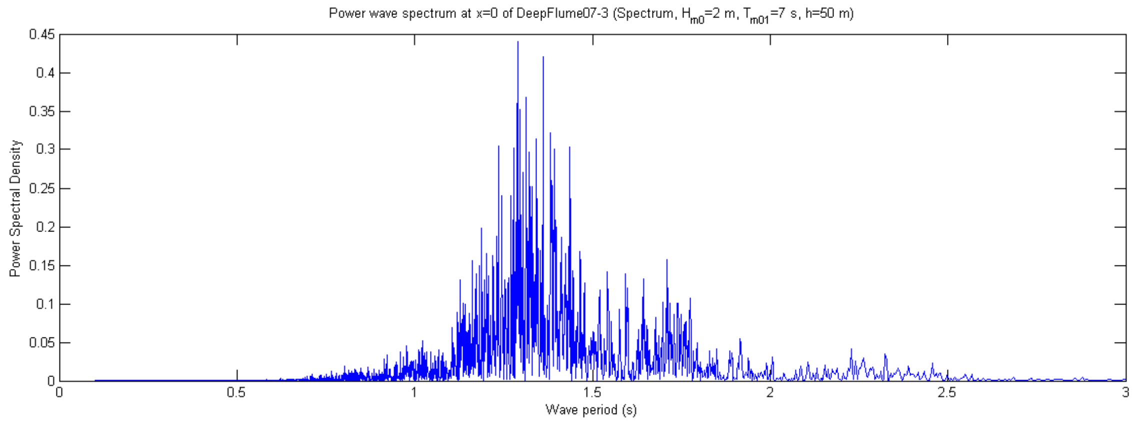

Figure A.49. Wave spectrum at x=0 of Deep_Flume07_3.sws.

At x=805 m the significant wave height has reduced to 0.090 m and the mean wave period is 4.88 s. It can be seen that at the end of the simulation larger waves appear, which is quite strange. The mean water level is – 0.017 m. From spectral analysis I obtain long waves again, with a mean period of 5.72 s and a significant height of 0.11 m.

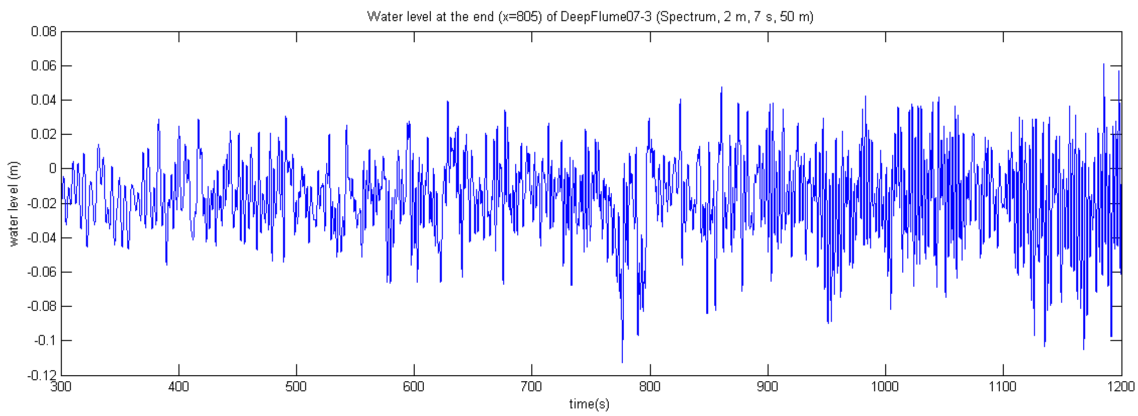

Figure A.50. Water elevation at x=805 m of Deep_Flume07_3.sws.

Compared with Deep_Flume07_2.sws, I obtain the same waves at the origin and quite shorter waves at the end of the flume. The wave heights and the water level variations do not change. However, the waves are longer than in Deep_Flume07.sws.

Conclusions and Questions to be solved

The wave spectrum is not well defined. Which cyclic period of the Fourier Series should I introduce when defining the wave spectrum? I have noticed that when I have introduced 5 minutes the same wave pattern is repeated 3 times (in 15-minute record) and can be observed in the graphs. Then, I conclude that this parameter indicates the duration of the spectrum and once this period of time is over, it starts again with the same spectrum. This makes sense as an input parameter. Therefore, I am quite sure that this input parameter does not have any influence on the spectrum results. Afterwards I tried with longer durations.

The regular waves are well introduced both in deep and shallow water.

In shallow water a non-depreciable reduction of the mean water level takes place. It looks like water is going out of the flume. This phenomenon affects all the results in shallow water and the results of Deep_Flume04.sws (at the limit of deep water) if I consider 10 layers or so, but only one record in very deep water (just at the end of the flume). The rest of the records in deep water do not show any reduction. Why? Is it related to the smaller water depth and to any bottom effect? I do not think so, but it seems to be one reason. Is it due to the presence or absence of any SWASH command such as boundary condition, sponge layer or discretization? I would say so. Since waves are not breaking, it is not due to a kind of set down effect and must be corrected.

Nevertheless, I reduced afterwards the number of layers, because I thought it was very large, and I got the complete opposite effect. Reducing the number of layers from 10 to 5 or fewer I observe a large increase of the mean water level. It mainly takes place for regular waves rather than for spectrum waves. Thus, the used number of layers plays a role in the mean water level variation either by increase it or hide it. Besides, they also have an influence on the wave period and wave height.

Why do I get an error message telling me that I have not enough water in some simulations in shallow water? The cause of the error message could be the same or related to the cause of the reduction of water level. Did I put the right conditions in TIMEI command?

Apparently there are not big differences between the results from different scripts that consider different discretization (or at least at this stage), except at the end of the flume for spectral analysis. However, one script did not work with these commands.

The larger dissipation in deep water is explained by the dissipative character of the waves in deep water conditions. This enhances wave dissipation after the generated spectrum waves, which are very steep, break.

Other comments and notes

The mean water level is computed as the mean value of all the recorded water levels. If the waves are drawn with more points at the trough than at the crest, a lower value than the expected one after looking at the wave graph will be given, and vice versa. Sometimes, however, this can not be easily seen from the graphs.

Comments of Marcel Zijlema (22/02/2013)

I must use a larger sponge layer, which should be around 3 times the introduced wave length. To do this, I will have to enlarge the initial flume length around 250 m or so.

The number of layers should be fixed according to the ratio h/L. In shallow water one layer will be enough although I can use more (with an increase of computation time).

Due to the very short sponge layer that I first introduced, it is likely that the flume reflects the waves, which can explain the large increase or decrease of the water level with regular waves. These variations could be a part of (one mode of) the reflected wave. With the recommended sponge layer length it should be solved.

Shallow_Flume08.sws

I have enlarged the flume up to 1200 m to give enough room to the sponge layer, whose length is 280 m, and I have used a single vertical layer in this simulation. For the other commands of the script, look at Shallow_Flume04_5.sws. Regular waves are performed. Break command is not activated.

At the beginning of the flume I obtain a mean water level of $\bar{\eta} = +0.04\ m$, which can be neglected, a mean wave period of 10 s and a mean wave height of 3.53 m. Then, the recorded waves are the same than the introduced ones.

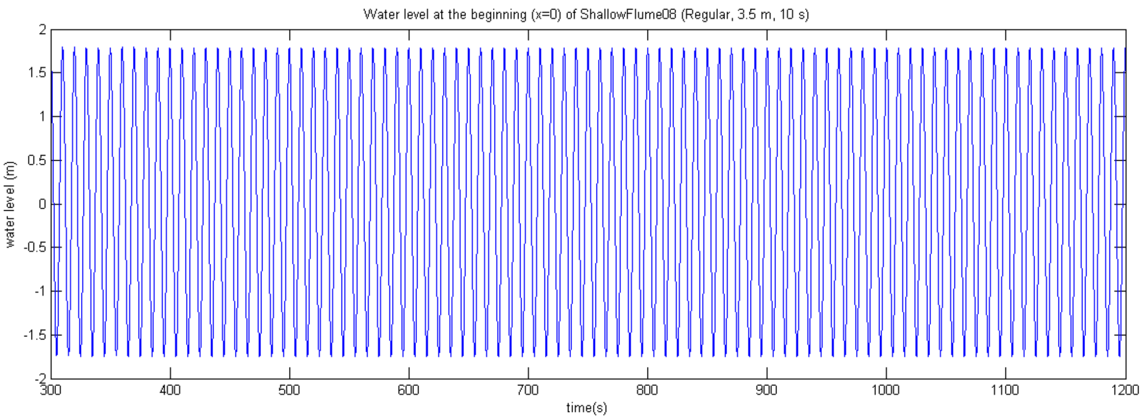

Figure A.51. Water elevation at x=0 m of Shallow_Flume08.sws.

At x=805 m, the waves slightly reduce their wave height reaching a mean wave height of 3.288 m and a mean wave period of 10 s. The man water level is $\bar{\eta} = +0.035\ m$.

If I consider that the waves come from deep water with a wave height of 3.5, I get that at this water depth the waves should reduce to 3.1 m through some hand calculations. This could be the wave height reduction before shoaling plus some dissipation along the flume, because we are in intermediate water conditions and not in shallow water indeed.

Shallow_Flume08_2.sws

With 2 layers the mean water level reduces at x=0 to + 0.0368, and the wave heights reduce to a mean value of 3.46 m. The mean wave period remains in 10 s.

However, at x=805 m the wave height increases. The mean wave height is then 3.55 m. The wave period is 10 s and the mean water level is +0.05 m.

Shallow_Flume09.sws

I introduced the improvements of Shallow_Flume08.sws, but I will try now with spectrum waves. I consider one single vertical layer, which should be enough. I have not reduced the introduced waves (mean period of 10 s and significant wave height of 3.5 m). Break command is activated.

At the beginning of the flume the recorded mean wave period is $T_m = 1.77\ s$ and the significant wave height is $H_s = 2.16\ m$. The waves are within a range of 0.0057 and 3.9322 m, which is larger than in previous scripts. The mean water level is $\bar{\eta} = +0.019\ m$.

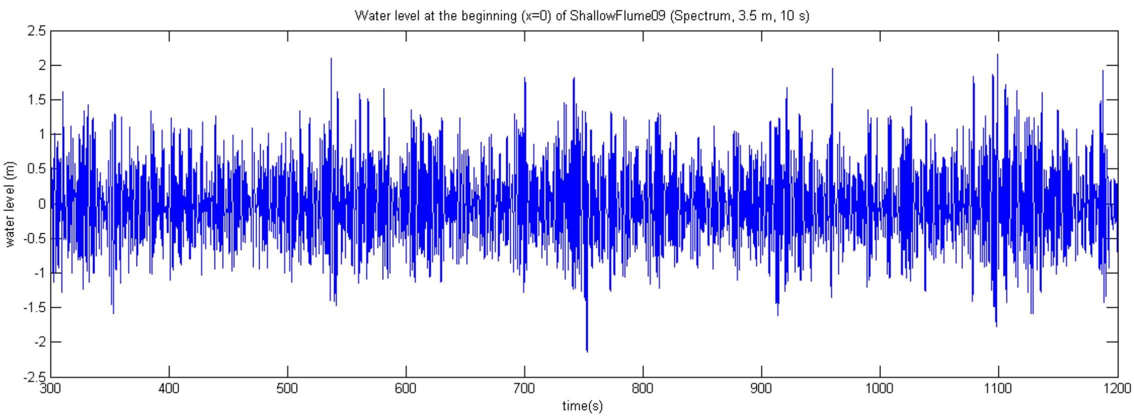

Figure A.52. Water elevation at x=0 m of Shallow_Flume09.sws.

No long waves are found in the spectral analysis. A mean wave period of $T_{m01} = 1.86\ s$ and a significant wave height $H_{m0} = 2.25\ m$ are found.

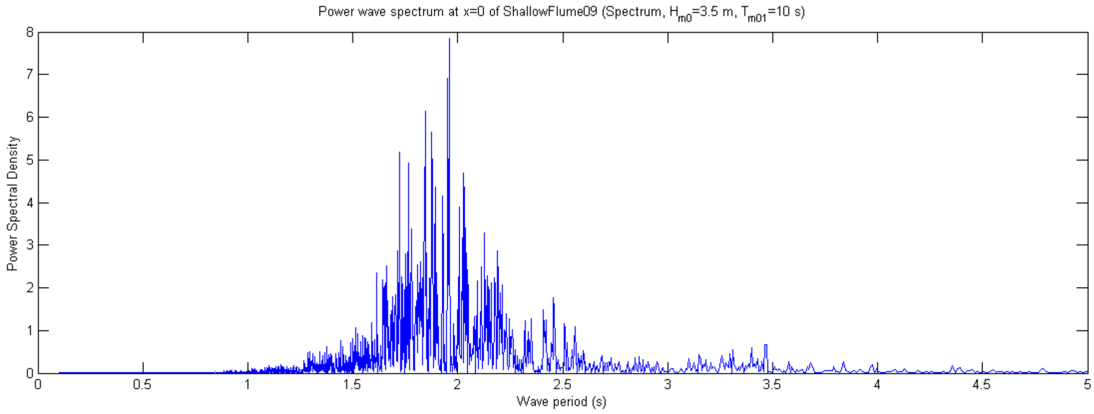

Figure A.53. Wave spectrum at x=0 m of Shallow_Flume09.sws.

At x=805 m the water level drops to $\bar{\eta} = -0.162\ m$. The wave parameters are $H_s = 0.58\ m$ and $T_m = 10.60\ s$. From spectral analysis I can see very long waves. The mean wave period is $T_{m01} = 11.63\ s$ and the spectral wave height is $H_{m0} = 0.77\ m$.

Shallow_Flume09_2.sws

In this script I have introduced a wave spectrum with a significant wave height of 1.5 m. The results that I obtain are not better than before.

At the wave generator the significant wave height is $H_s = 0.96\ m$, the mean wave period is $T_m = 1.77\ s$ and the mean water level is $\bar{\eta} = +0.005\ m$. From spectral analysis I get a significant wave height of $H_{m0} = 0.99\ m$ and a mean wave period of $T_{m01} = 1.81\ s$.

At x=805 m the significant wave height is $H_s = 0.1\ m$, the mean wave period, $T_m = 18.17\ s$, and the mean water level, $\bar{\eta} = -0.035\ m$. The waves have dissipated (the maximum wave height is 0.14 m) and longer waves are observed. From spectral analysis, the significant wave height is $H_{m0} = 0.16\ m$ and the mean wave period is $T_{m01} = 17.12\ s$.

Something is clearly wrong with the introduced wave spectrum.

Shallow_Flume09_3.sws

The introduced wave height is now 0.5 m.

At the beginning of the flume it is measured $H_s = 0.33\ m$, $T_m = 1.76\ s$ and $\bar{\eta} = +0.005\ m$. At the end of the flume the wave dissappears again. There it is recorded $H_s = 0.014\ m$, $T_m = 18.55\ s$ and $\bar{\eta} = -0.004\ m$.

Definitevely there is something wrong with the spectrum input command.

Deep_Flume08.sws

The main commands of this script are written in Deep_Flume08_4.sws. This script considers 5 vertical layers. The flume length has been enlarged until 1200 m to give enough room to the sponge layer at the end of the flume, whose length is 280 m. Regular waves with a wave height of 2 m and a wave period of 7 s are generated.

At the beginning of the flume the mean wave height is 2.01 m, the mean wave period is 7 s and the mean water level is -0.0002 m. Then, the recorded wave matches the introduced one although the wave period is smaller

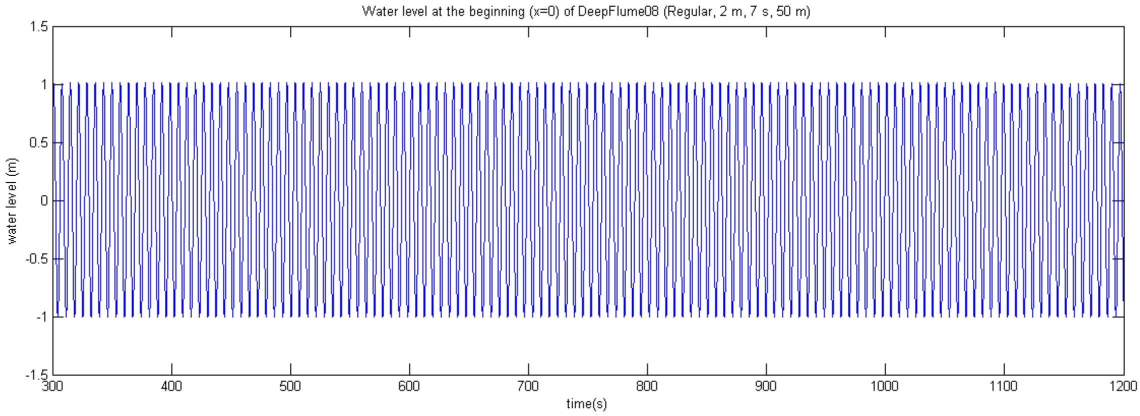

Figure A.54. Water elevation at x=0 m of Deep_Flume08.sws.

At the point x=805 m the recorded wave has a mean wave height of 1.92 m and a mean wave period of 7 s. The mean water level is -0.006 m. Then, I can consider that the wave has propagated right in deep water although there is a slight reduction of the wave height.

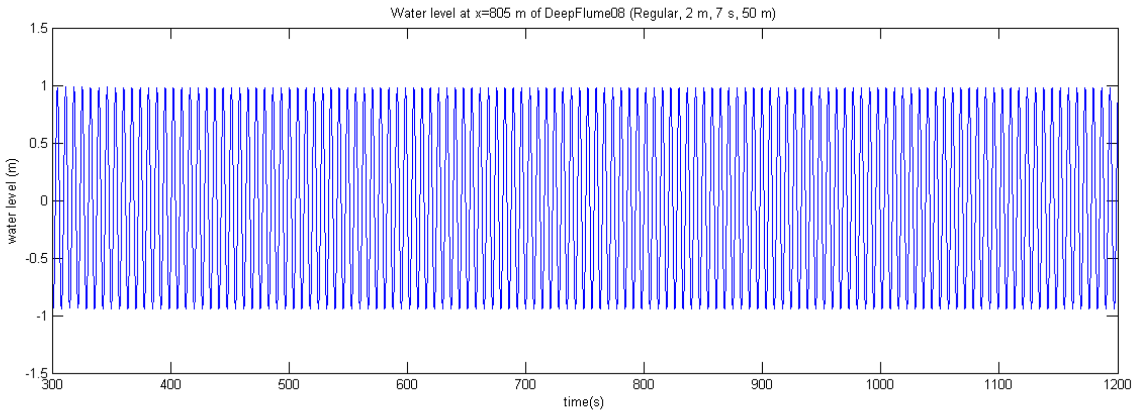

Figure A.55. Water elevation at x=805 m of Deep_Flume08.sws.

Deep_Flume09.sws

I have adapted this script from Deep_Flume07_3.sws. I have kept the 5 vertical layers and I have enlarged the flume and the sponge layer to 1200 and 280 m respectively. Waves are generated from a wave spectrum with a significant wave height of 2 m and a mean wave period of 7 s.

At x=0 the significant wave height is $H_s = 0.67\ m$, the mean wave period is $T_m = 1.29\ s$ and the mean water level is $\overline{\eta} = +0.005\ m$. From spectral analysis I get a significant wave height of $H_{m0} = 0.69\ m$ and a mean wave period of $T_{m01} = 1.31\ s$. The peak period is 1.29 s.

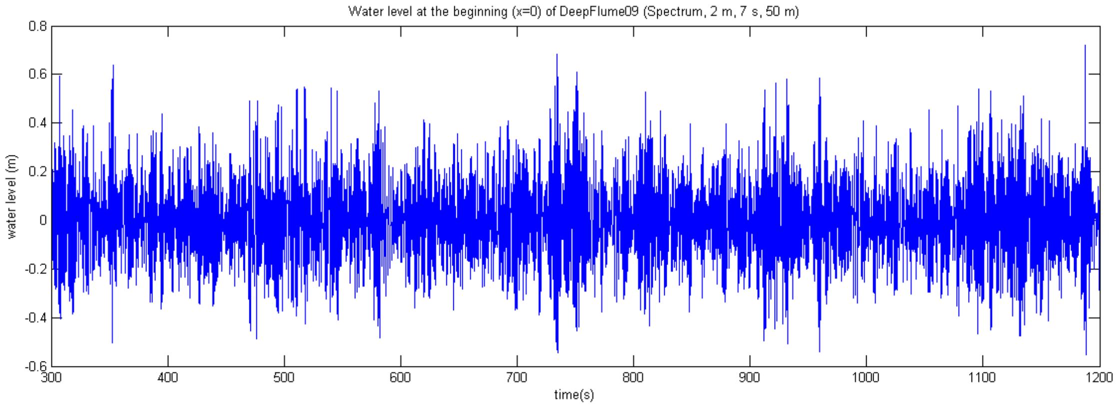

Figure A.56. Water elevation at x=0 m of Deep_Flume09.sws.

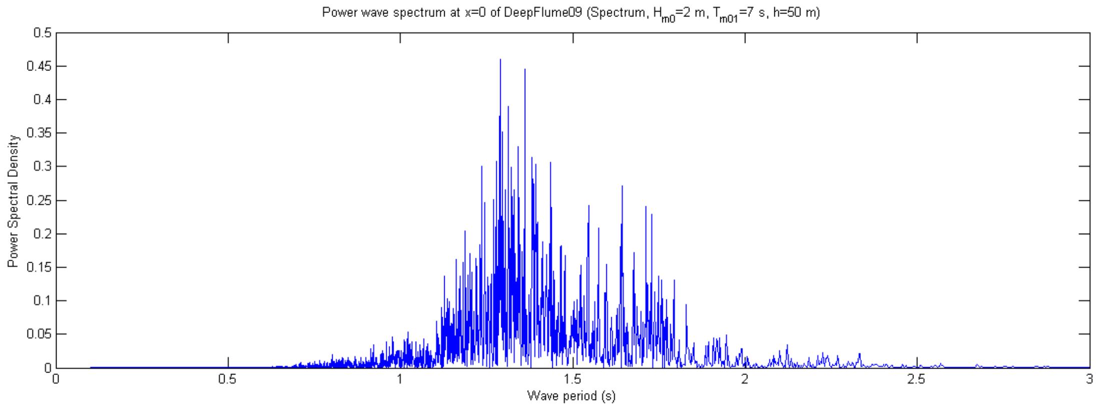

Figure A.57. Wave spectrum at x=0 m of Deep_Flume09.sws.

At x=805 m, $H_s = 0.0719\, m$, $T_m = 6.56\, s$ and $\overline{\eta} = -0.02\, m$ are recorded. The wave dissipates in smaller and much longer waves. There is a severe problem with spectrum waves.

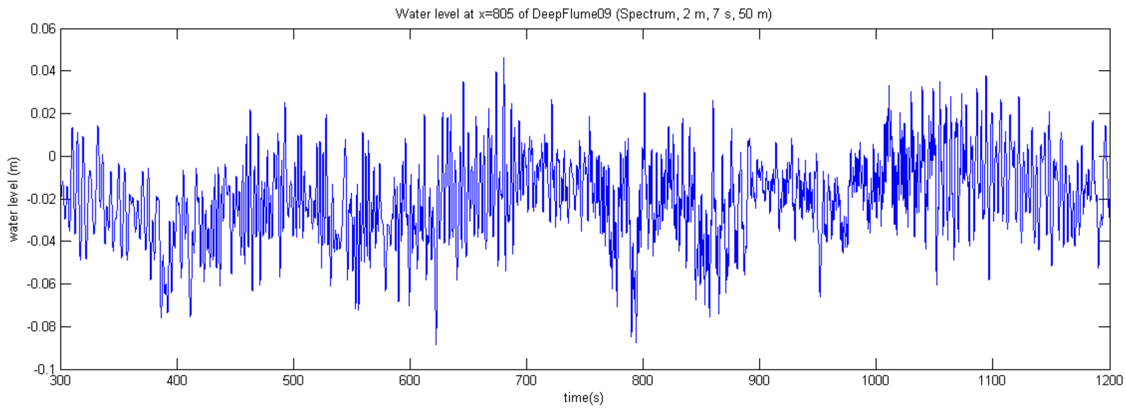

Figure A.58. Water elevation at x=805 m of Deep_Flume09.sws.

Comments of Marcel Zijlema (04/03/2013). Second discussion

SWASH computes the spectrum with the peak wave period. Thus, when the mean wave period is introduced (T_{m01}), it computes the peak period first (T_p). If a mean wave period of 10 s is introduced, the peak period (computed by SWASH) is about 1.86 s. It is very low ($kh = 12$), which means that one layer is not enough and this will result in wave dissipation. This explains what I have observed. However, this computation was wrong introduced in the SWASH code!

Shallow_Flume10.sws

It is the same script as Shallow_Flume09.sws, but I have changed the mean wave period. If I introduce the mean period I want (10 s) multiplied by 2π (62.83 s) I get waves with a mean period close to 10 s. The reason why I tried this is because in the Appendix A of the SWASH User Manual, the mean wave period is defined multiplying the ratio m_0/m_1 by 2π, which is a wrong expression.

At the beginning of the flume, the significant wave height is $H_s = 3.72\ m$, the mean wave period is $T_m = 9.86\ s$, and the mean water level is $\overline{\eta} = +0.019\ m$. The range of wave heights is 0.134-5.519 m, far larger than before. The recorded wave is close to the wave I wanted to introduce although the wave height is larger.

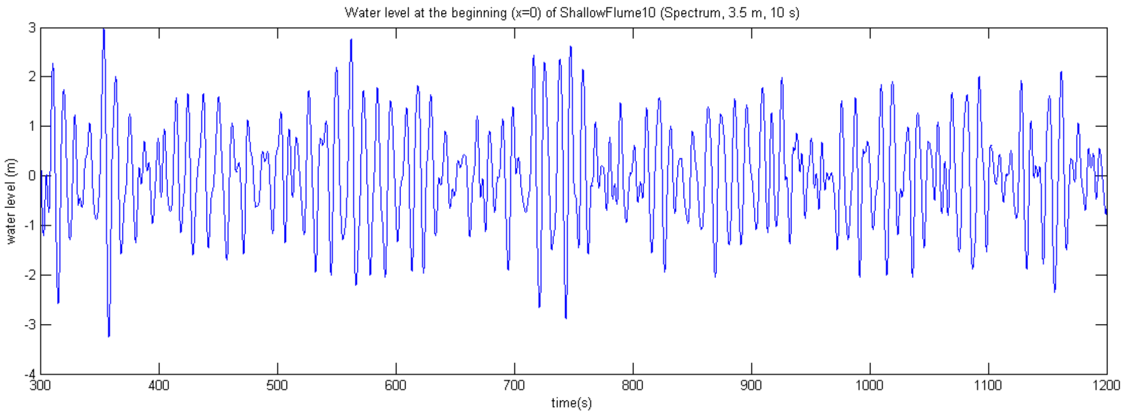

Figure A.59. Water elevation at x=0 m of Shallow_Flume10.sws.

From spectral analysis I get a significant wave height of $H_{m0} = 3.94\ m$, a mean wave period of $T_{m01} = 9.94\ s$ and a peak wave period of $T_p = 11.54\ s$.

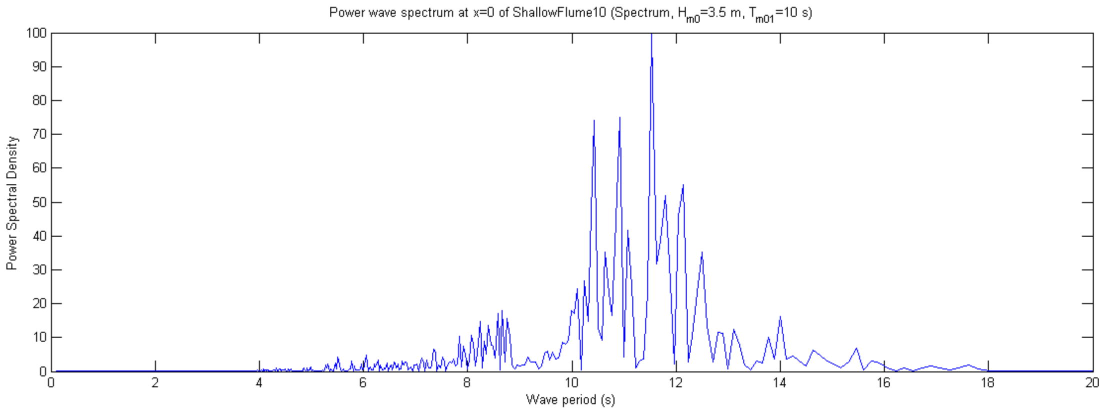

Figure A.60. Wave spectrum at x=0 m of Shallow_Flume10.sws.

At x=805 m, the measured wave parameters are $H_s = 3.44\,m$ and $T_m = 9.70\,s$. The mean water level is $\overline{\eta} = +0.009\,m$. The recorded wave is very close to the introduced one. From spectral analysis I get $H_{m0} = 3.57\,m$, $T_{m01} = 8.99\,s$ and $T_p = 12.9\,s$. A few long waves are observed.

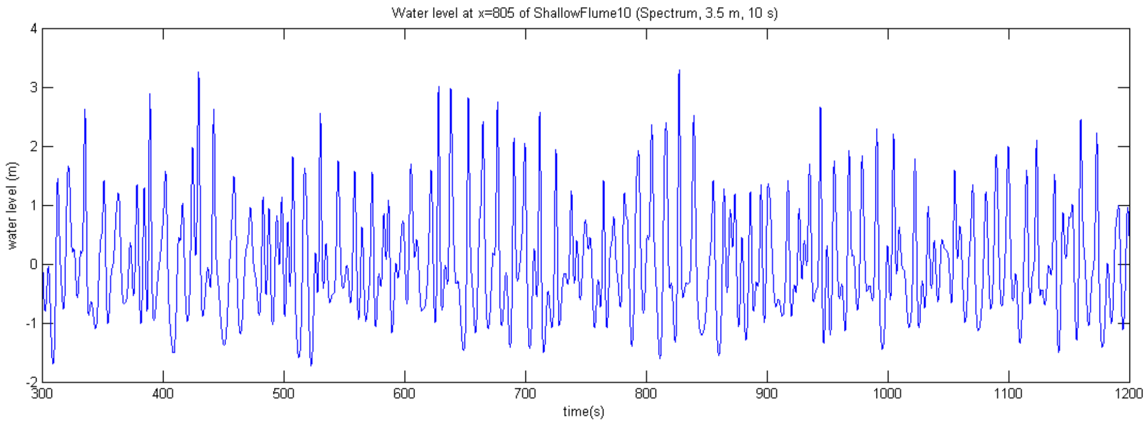

Figure A.61. Water elevation at x=805 m of Shallow_Flume10.sws.

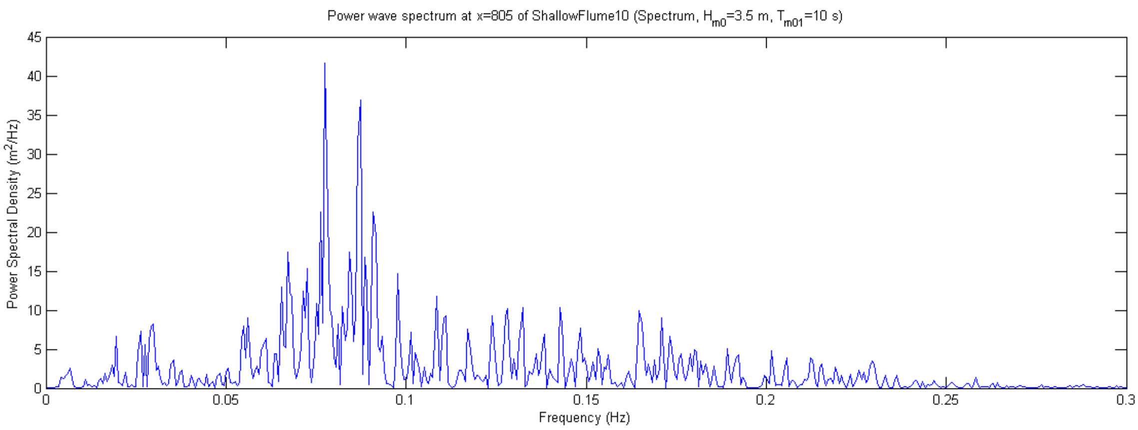

Figure A.62. Wave spectrum at x=805 m of Shallow_Flume10.sws.

Shallow_Flume10_2.sws

The only change of this script with respect to the previous one is the wave height. Here a significant wave height of 1.5 m has been introduced in the spectrum.

At x=0 the recorded significant wave height is 1.62 m, the mean wave period is 10.1 s and the mean water level is +0.003 m. From spectral analysis I get a mean wave period of 9.93 s and a significant wave height of 1.67 m. The peak period is 11.54 s.

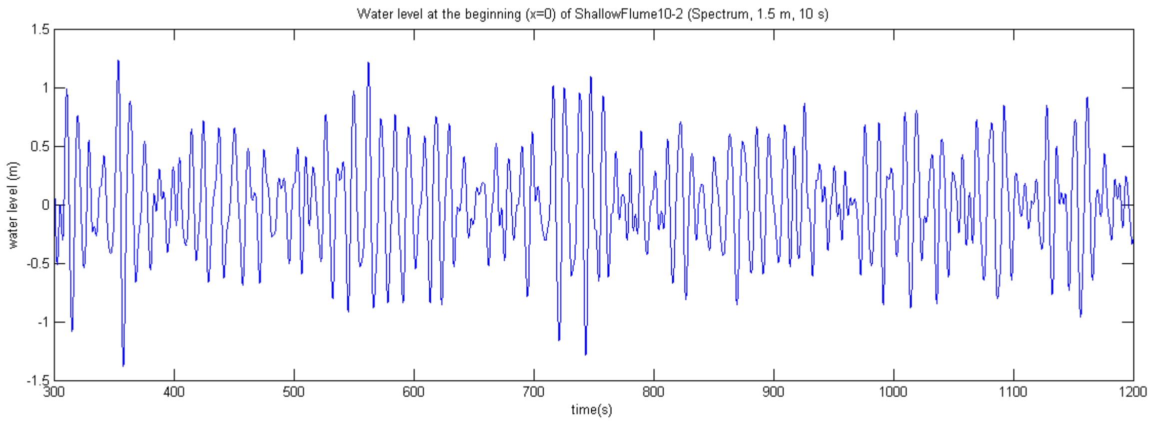

Figure A.63. Water elevation at x=0 of Shallow_Flume10_2.sws.

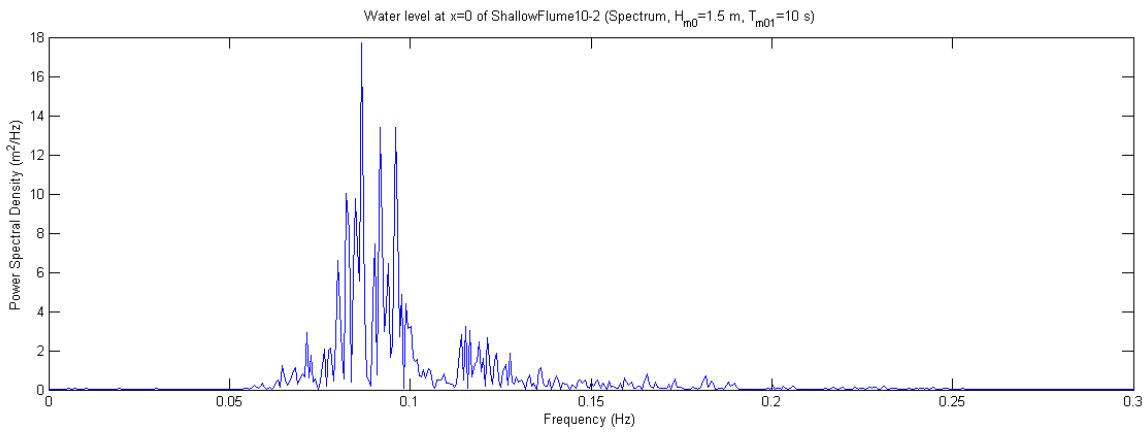

Figure A.64. Wave spectrum at x=0 m of Shallow_Flume10_2.sws.

At x=805 m the significant wave height is 1.53 m and the mean wave period is 10.07 s. The mean water level is +0.002 m. After spectral analysis I get a significant wave height of 1.62 m, a mean wave period of 9.94 s and a peak period of 12.4 s. Hardly any long waves are observed.

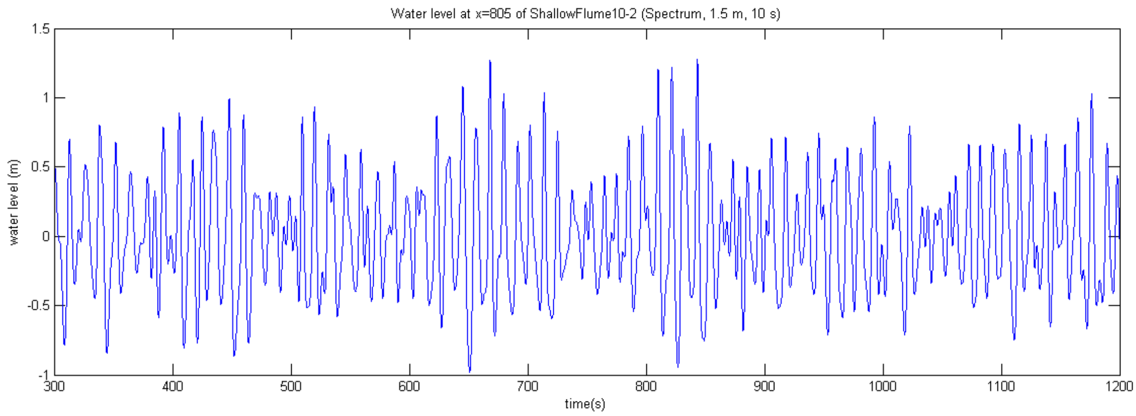

Figure A.65. Water elevation at x=805 m of Shallow_Flume10_2.sws.

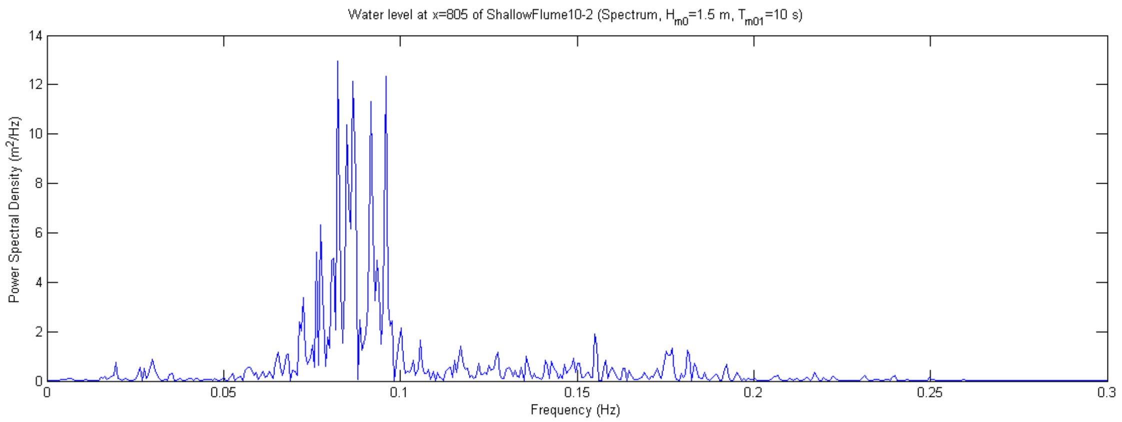

Figure A.66. Wave spectrum at x=805 m of Shallow_Flume10_2.sws.

Shallow_Flume11.sws

This script is similar to Shallow_Flume10.sws. I have introduced $H_{m0} = 3.5\ m$ and a peak wave period of $T_p = 11\ s$. I have used the approximate relation $T_p = 1.1 \cdot T_{m01}$.

At the beginning of the flume I have recorded a significant wave height of 3.92 m and a mean wave period of 9.05 s. The mean water level is +0.025 m, larger than before. After spectral analysis I obtain a mean wave period of 9.50 s and a significant wave height of 4.01 m. The peak wave period is around 10.2 s.

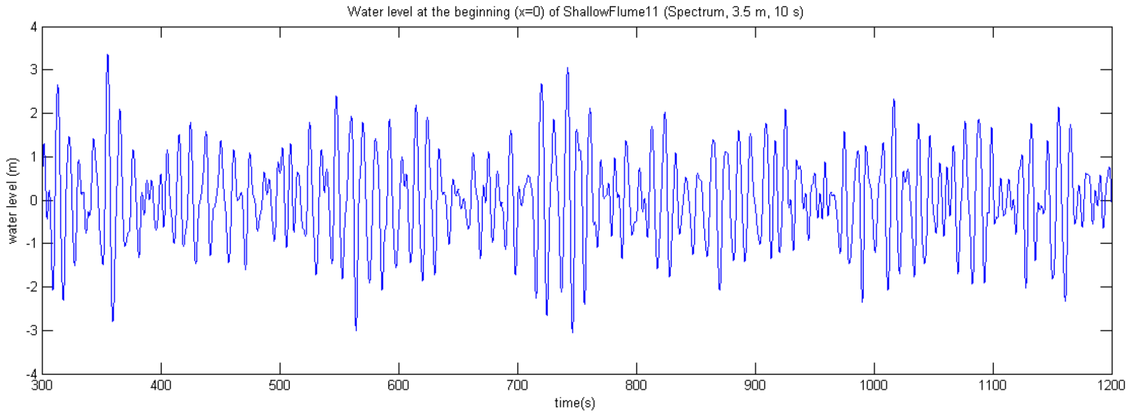

Figure A.67. Water elevation at x=0 m of Shallow_Flume11.sws.

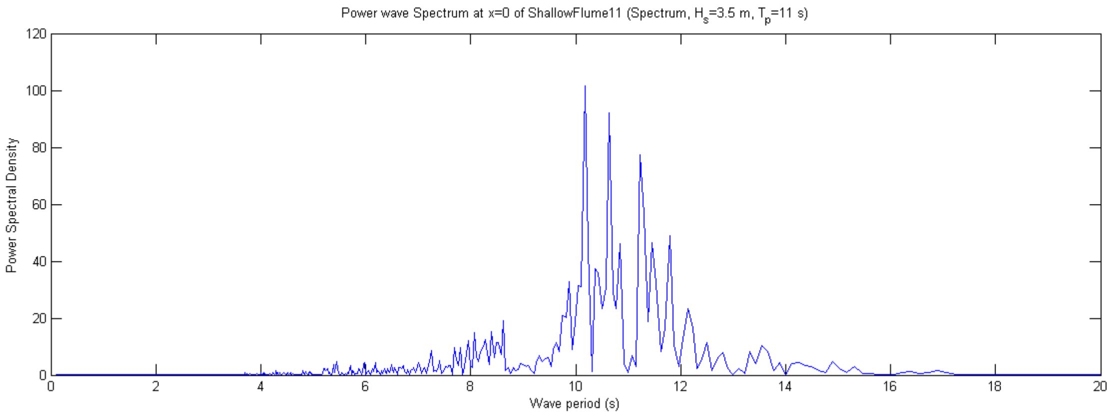

Figure A.68. Wave spectrum at x=0 m of Shallow_Flume11.sws.

At x=805 m the significant wave height is 3.04 m, the mean wave period is 9.06 s and the mean water level is +0.01 m. A more irregular shape is observed. From spectral analysis I obtain a significant wave height of 3.59 m, a mean wave period of 9.02 and a peak wave period around 12.5 s. Long waves are observed on the spectrum, which would explain the irregular shape.

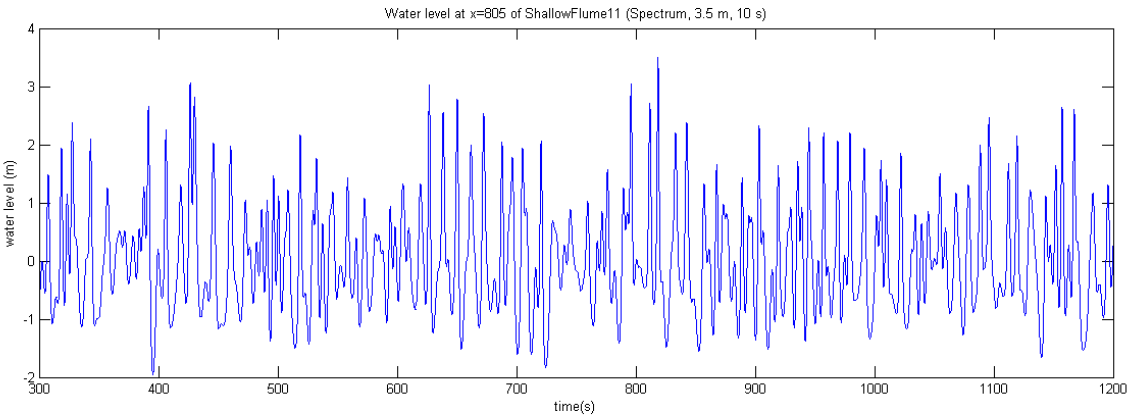

Figure A.69. Water elevation at x=805 m of Shallow_Flume11.sws.

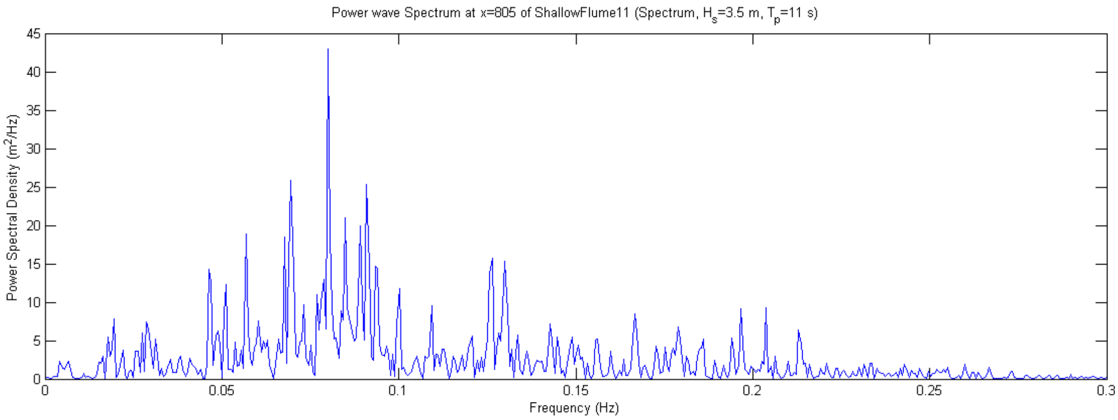

Figure A.70. Wave spectrum at x=805 m of Shallow_Flume11.sws.

Shallow_Flume11_2.sws

The only modification with respect to Shallow_Flume.11.sws is considering a significant wave height of 1.5 m instead of 3.5 m.

At x=0 the significant wave height is 1.68 m, the mean wave period is 9.33 s and the mean water level is +0.005 m. From spectral analysis I get a significant wave height of 1.69 m, a mean wave period of 9.48 s and a peak wave period of 10.18 s.

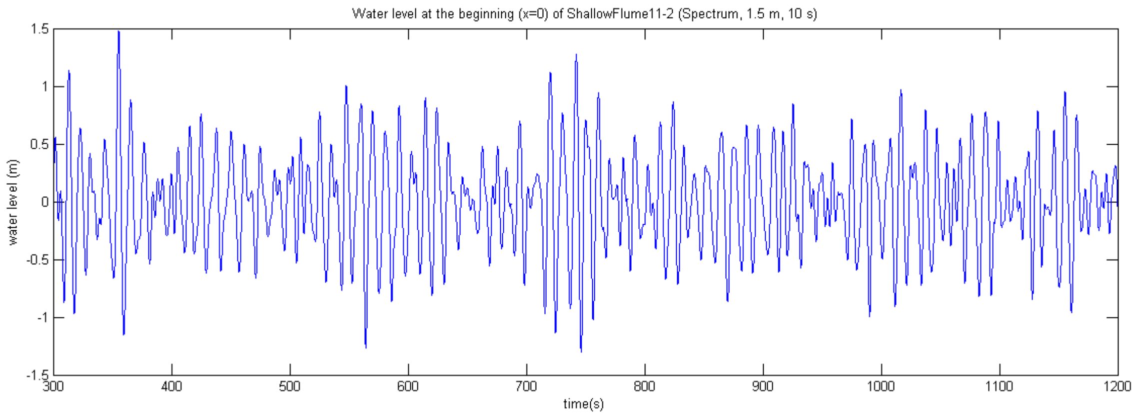

Figure A.71. Water elevation at x=0 m of Shallow_Flume11_2.sws.

At x=805 the significant wave height is 1.57; the mean wave period, 9.64 s; and the mean water level can be assumed 0. From spectral analysis the significant wave height is 1.62 m, the mean wave period is 9.58 s and the peak wave period is 10.6 s.

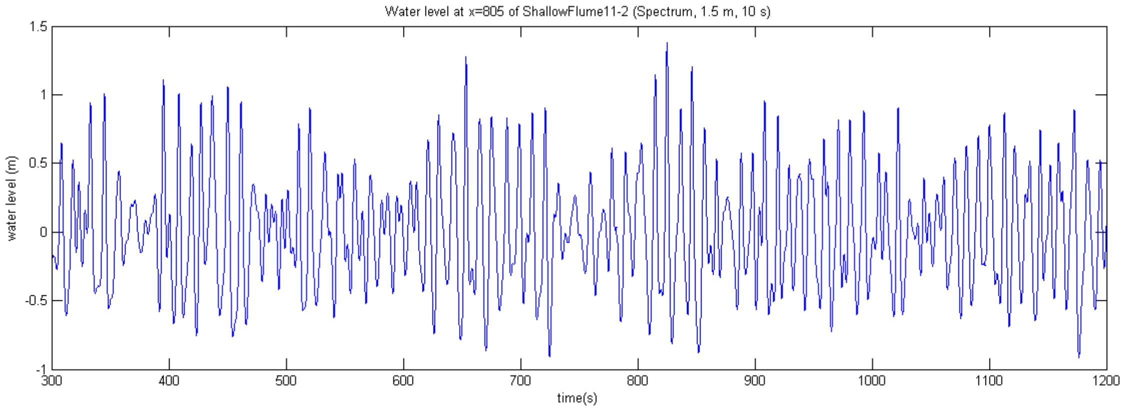

Figure A.72. Water elevation at x=805 m of Shallow_Flume11_2.sws.

The results of the spectrum analysis are not very accurate, because I have to smooth the spectrum and I need a longer time record, but they are a first approximation.

Error found in the definition of the mean wave period in SWASH (06/03/2013)

After some tests (Shallow_Flume10.sws, Shallow_Flume10_2.sws, Shallow_Flume11.sws and Shallow_Flume11_2.sws) I found what was wrong with the spectrum waves. The problem was that SWASH had not defined correctly the mean wave period by a factor of 2π. Therefore, if I introduce the peak wave period, the spectrum generates the desired waves (because the spectrum is built from the peak wave period), but if I do it with the mean wave period, the software computes a wrong peak period from the mean and, thus, a wrong wave spectrum. However, if I introduce a mean wave period 2π times larger than the desired one, I get the desired mean wave period from the record.

When I introduced a peak wave period of 11 s in the scripts Shallow_Flume11.sws and Shallow_Flume11_2.sws, I obtained a mean wave period between 9 and 9.5 s and a peak wave period between 10 and 10.5 s. This was the wave that I wanted to introduce. Then, the problem was solved, but I was still not sure about what was wrong. This peak period is said to be about 1.1 and 1.3 times the mean period and this was the reason I chose 11 s.

As a conclusion, the SWASH code computed wrong the peak wave period from the mean period. To prove that, in Shallow_Flume10.sws and Shallow_Flume10_2.sws I multiplied the mean wave period by 2π and I introduced the value $10 \cdot 2 \cdot \pi = 62.83\ s$. After analysing the wave record, I got a mean wave period of 10 s and a peak wave period around 12 s. These results are close to the ones I obtain when I introduce a peak period of 11 s. As a result, a factor of 2π was wrong.

Also when I consulted the Appendix A of the SWASH User Manual (version 1.10A), I saw that the definition of the mean wave period was not right. The factor m_0/m_1 which defines T_{m01} had an extra factor 2π, which should only be used if the spectrum function is defined through the angular wave frequency ω and not the wave frequency f (as it was). In fact, I decided to multiply the mean wave period by this factor after seeing that. I reported this error to Marcel

Zijlema and he fixed the bug. The new versions 1.20 of SWASH and User Manual overcome this problem. However, I have continued working with version 1.10 and the peak period.

I could physically explain why the waves slightly dissipate along the flume. In fact, the shallow flume tests are in intermediate water (water depth of 10 m and mean wave period of 10 s), so the waves still have a dissipative character and they “notice” the bottom. It could represent the situation when the waves, before reaching the shoaling zone, reduce a little bit their wave height, before shoaling and breaking afterwards. These are the reasons that come to my mind to explain the changes between x=0 m and x=805 m. From spectral analysis a slightly wider spectrum is observed, which would explain some wave dissipation.

However, I do not know yet why the recorded waves at the beginning of the flume are slightly larger than the introduced ones. The reason may be that I have not recorded a large part of the input wave spectrum and I have measured the largest waves of the cycle.

Deep_Flume10.sws

The mean wave period introduced in Deep_Flume09.sws has been enlarged by a factor 2π from 7 s to 44 s.

Next table summarizes the most important parameters recorded at x=0. Besides it, the mean water level is 0 and the maximum wave height is 3.55 m. From spectral analysis I obtain a 2-peak wave spectrum with peaks at $T_p = 7.5$ and $T_p = 8.8\,s$. The second one is the largest peak.

Measured data at x=0 m (Deep_Flume10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.07\,m$	$T_m = 6.85\,s$	$H_{m0} = 2.12\,m$	$T_p = 8.81\,s$
$4 \cdot \sigma = 2.12\,m$	$3.8 \cdot \sigma = 2.02\,m$	$T_{m01} = 7.16\,s$	$T_{m-1,0} = 7.61\,s$

Table A.1. Wave parameters at x=0 m of Deep_Flume10.sws.

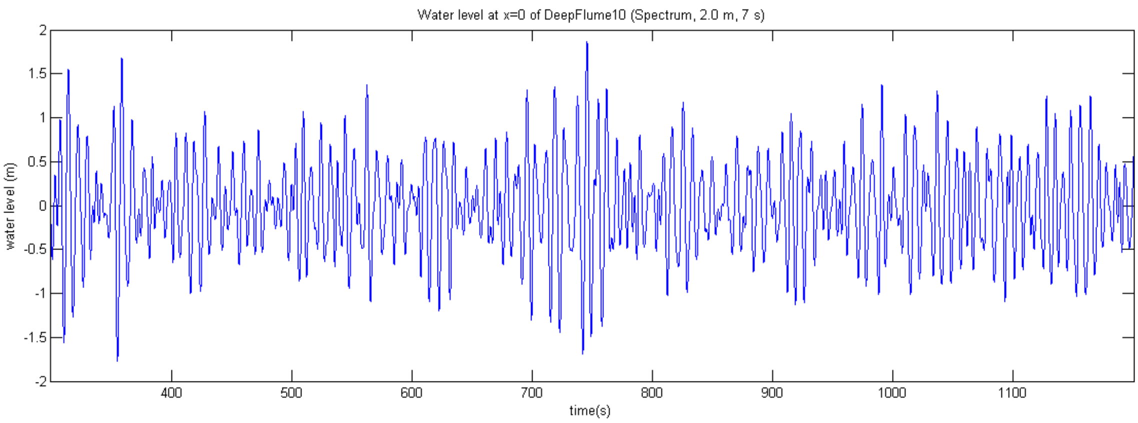

Figure A.73. Water elevation at x=0 m of Deep_Flume10.sws.

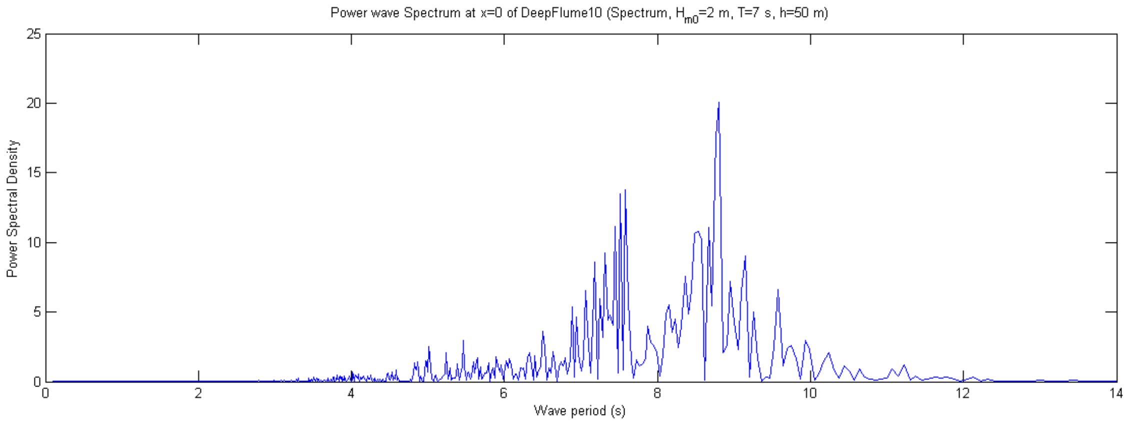

Figure A.74. Wave spectrum at x=0 m of Deep_Flume10.sws.

At x=805 m we do not have a bimodal spectrum any more. The first peak has disappeared. The following table shows the recorded wave parameters.

Measured data at x=805 m (Deep_Flume10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.98\ m$	$T_m = 7.16\ s$	$H_{m0} = 1.99\ m$	$T_p = 8.81\ s$
$4 \cdot \sigma = 1.99\ m$	$3.8 \cdot \sigma = 1.89\ m$	$T_{m01} = 7.48\ s$	$T_{m-1,0} = 7.84\ s$

Table A.2. Wave parameters at x=805 m of Deep_Flume10.sws.

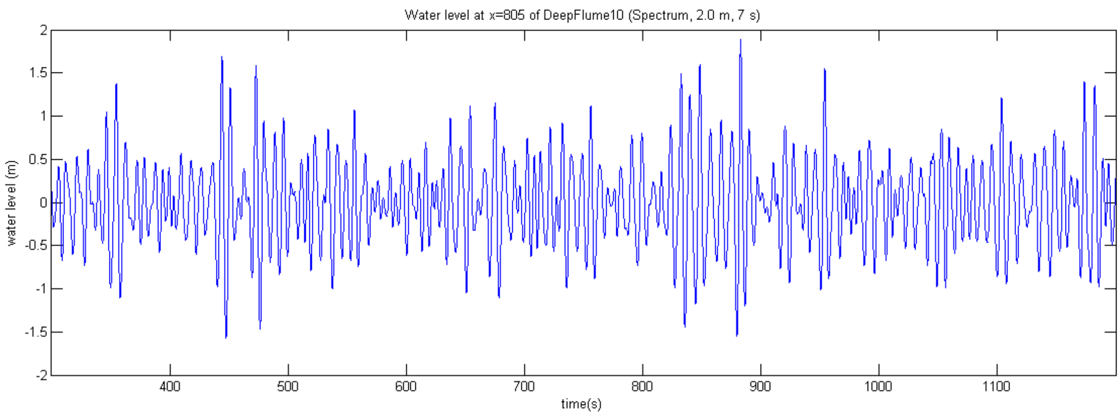

Figure A.75. Water elevation at x=805 m of Deep_Flume10.sws.

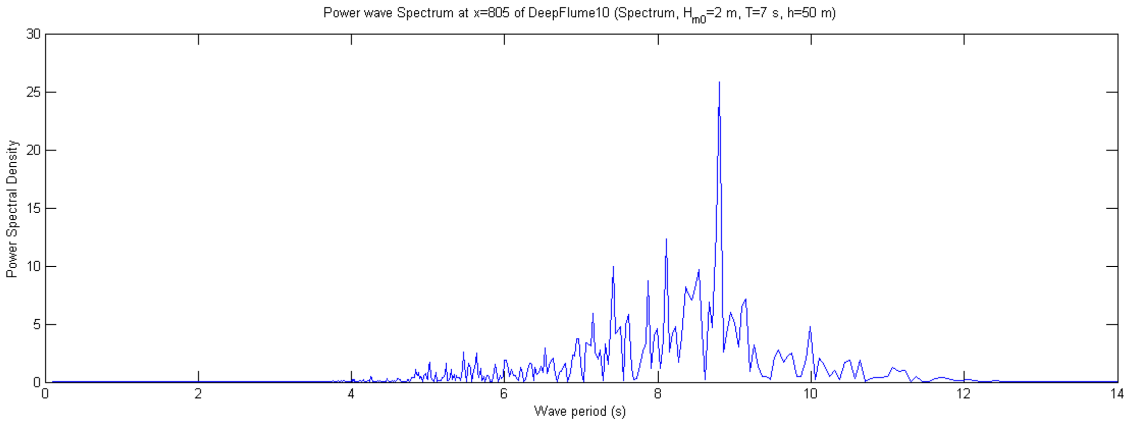

Figure A.76. Wave spectrum at x=805 m of Deep_Flume10.sws.

Deep_Flume11.sws

This script has the same code as Deep_Flume09.sws, but the wave spectrum is built with a peak wave period of 7.5 s instead of a mean wave period.

The recorded values at x=0 m are shown at the next table. The largest wave height is 3.51 m. From spectral analysis I get a bi-modal spectrum, with the largest peak at 7.28 s and a second one around 8.3 s.

Measured data at x=0 m (Deep_Flume11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.06\ m$	$T_m = 6.16\ s$	$H_{m0} = 2.12\ m$	$T_p = 7.28\ s$
$4 \cdot \sigma = 2.12\ m$	$3.8 \cdot \sigma = 2.01\ m$	$T_{m01} = 6.52\ s$	$T_{m-1,0} = 6.92\ s$

Table A.3. Wave parameters at x=0 m of Deep_Flume11.sws.

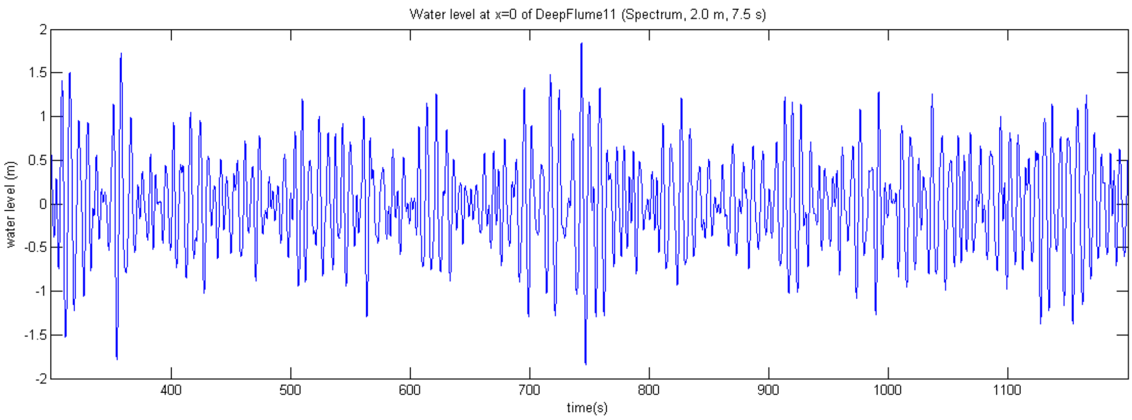

Figure A.77. Water elevation at x=0 m of Deep_Flume11.sws.

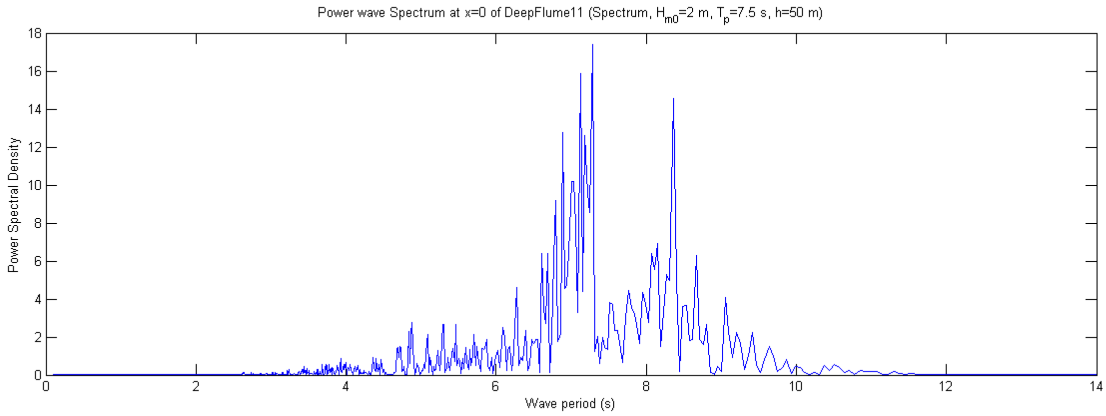

Figure A.78. Wave spectrum at x=0 m of Deep_Flume11.sws.

At x=805 m the wave slightly dissipates. The most important parameters are shown in the next table. The maximum wave height is 3.19 m. We obtain again a bi-modal spectrum with peaks at $T = 7.3\ s$ and $T = 8.3\ s$. However, this time the largest peak is 8.34 s.

Measured data at x=805 m (Deep_Flume11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.92\ m$	$T_m = 6.79\ s$	$H_{m0} = 1.92\ m$	$T_p = 8.34\ s$
$4 \cdot \sigma = 1.92\ m$	$3.8 \cdot \sigma = 1.82\ m$	$T_{m01} = 6.87\ s$	$T_{m-1,0} = 7.19\ s$

Table A.4. Wave parameters at x=805 m of Deep_Flume11.sws.

I can consider now that the recorded wave corresponds to the introduced one.

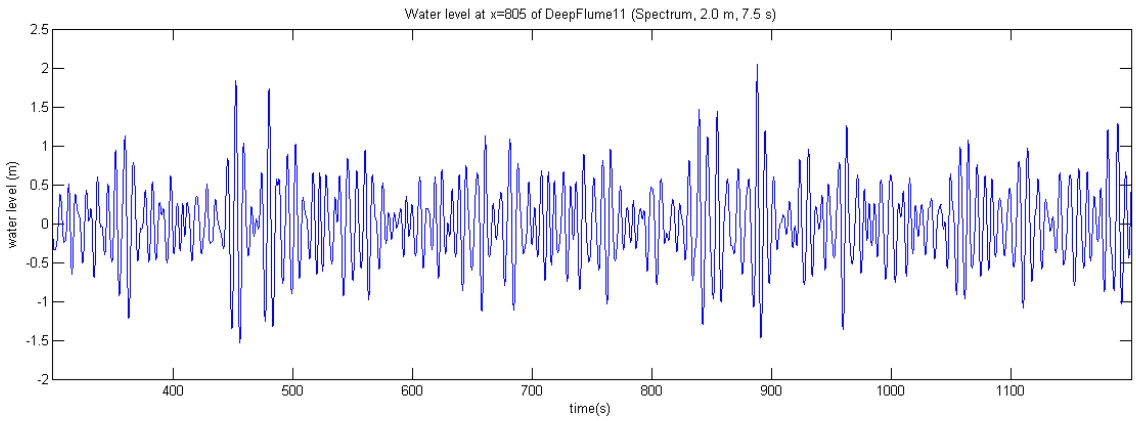

Figure A.79. Water elevation at x=805 m of Deep_Flume11.sws.

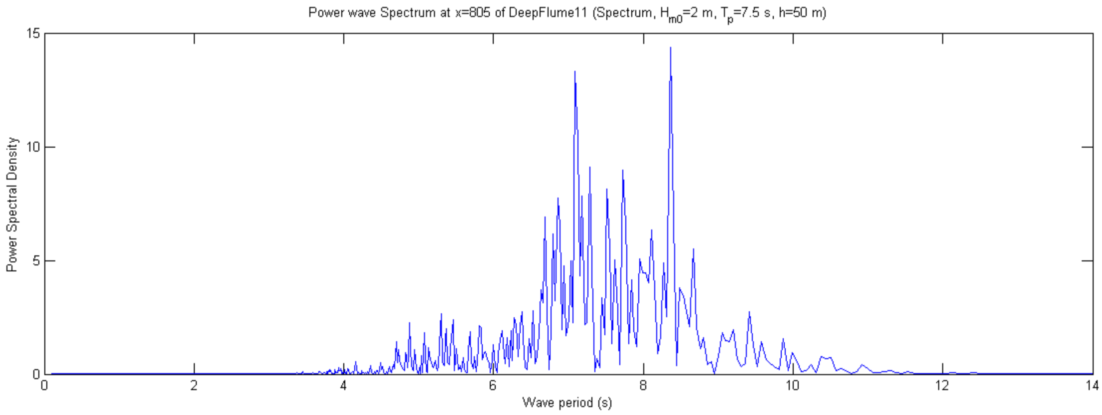

Figure A.80. Wave spectrum at x=805 m of Deep_Flume11.sws.

Shallow_Flume11_4.sws

To produce a nice spectrum graph and delete "the noise" I had to enlarge the simulation time in order to obtain more data. Then, with a longer water level record, I can divide it in different periodograms and average them. I built a new Matlab script called Spectral.m, later converted into a function spectral_analysis.m where the numbers of periodograms was also an output.

In this script, I have used a computation time of 50 min and I have taken measures during the last 45 min. Then, I had enough data to build and average 5 periodograms. As a result, I obtained a better spectrum and predictions for the data obtained from it.

At x=0 the mean water level is $\overline{\eta} = +0.0195\ m$, which can be considered negligible. The wave range goes from 0.058 m to 5.19 m. The wave parameters are shown on the next table.

Measured data at x=0 m (Shallow_Flume11_4.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.49\ m$	$T_m = 8.86\ s$	$H_{m0} = 3.64\ m$	$T_p = 10.77\ s$
$4 \cdot \sigma = 3.64\ m$	$3.8 \cdot \sigma = 3.46\ m$	$T_{m01} = 9.40\ s$	$T_{m-1,0} = 10.90\ s$

Table A.5. Wave parameters at x=0 m of Shallow_Flume11_4.sws.

The results are very close to the introduced wave, and the spectral wave height coincides with 4 times the variance of the water elevation. In this case, the significant wave height obtained from the wave per wave analysis is closer to $3.8 \cdot \sigma$ than $4 \cdot \sigma$. The mean wave period measured through the wave per wave analysis is pretty close to the period between crests obtained from spectral analysis, which is 8.61 s (not in table A.5).

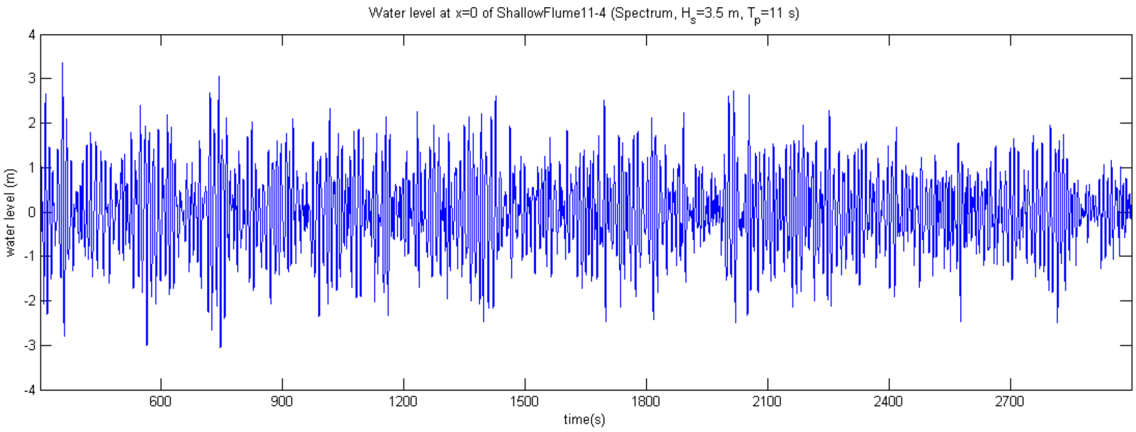

Figure A.81. Water elevation at x=0 m of Shallow_Flume11_4.sws.

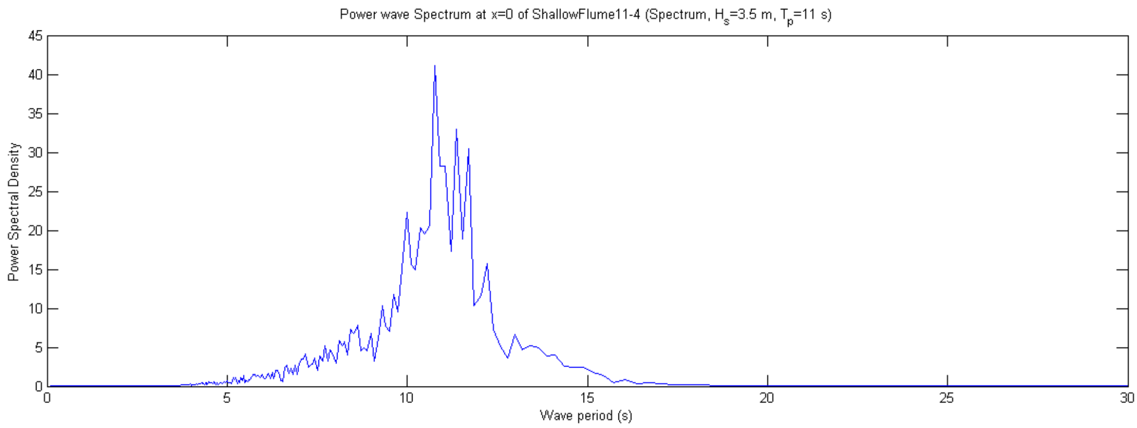

Figure A.82. Wave spectrum at x=0 m of Shallow_Flume11_4.sws.

At x=805 m the mean water level is $\overline{\eta} = +0.0059\ m$ and the wave height reduce to a range between 0.11 and 4.46 m. Wave parameters are shown on the table below. Through spectral analysis I get a “bimodal” spectrum with the largest peak at 14.6 s and a second peak very close to the first one around 11 s. There are 3 peaks between the range 11-12 s that could be considered as one due to the remaining noise.

Measured data at x=805 m (Shallow_Flume11_4.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.16\ m$	$T_m = 9.01\ s$	$H_{m0} = 3.35\ m$	$T_p = 14.62\ s$
$4 \cdot \sigma = 3.35\ m$	$3.8 \cdot \sigma = 3.18\ m$	$T_{m01} = 9.10\ s$	$T_{m-1,0} = 14.25\ s$

Table A.6. Wave parameters at x=805 m of Shallow_Flume11_4.sws.

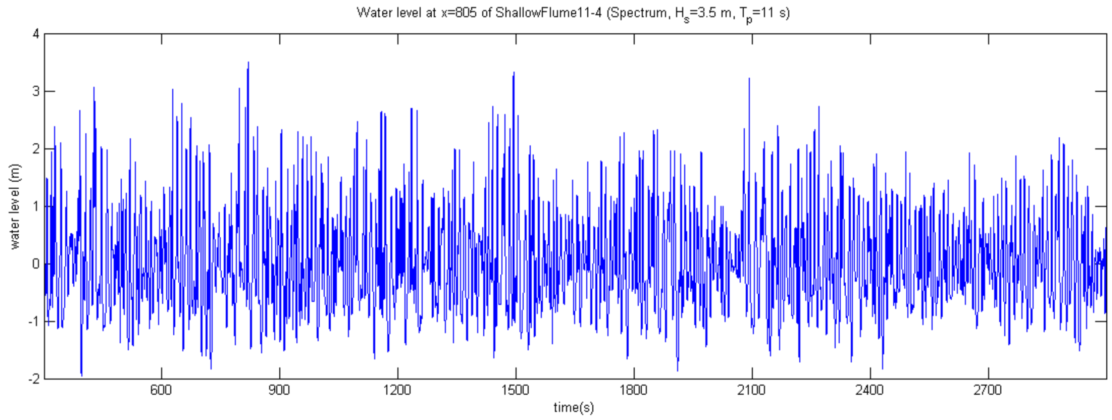

Figure A.83. Water elevation at x=805 m of Shallow_Flume11_4.sws.

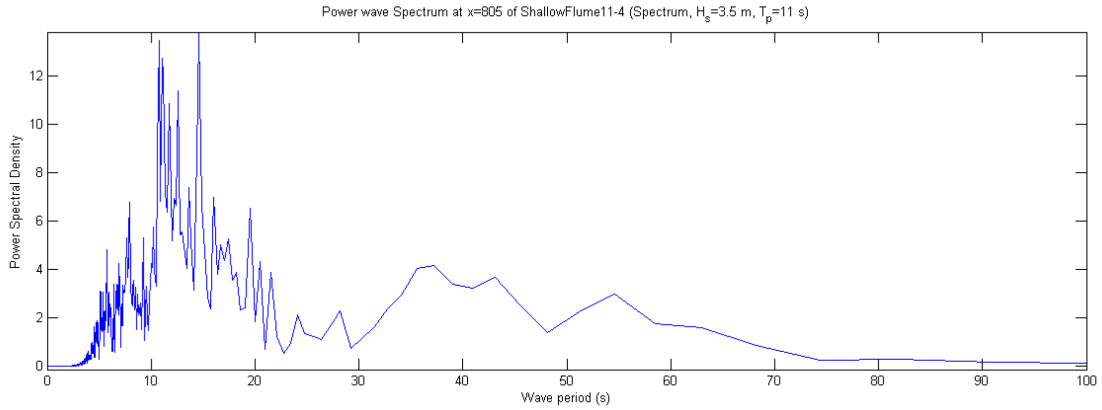

Figure A.84. Wave spectrum at x=805 m of Shallow_Flume11_4.sws.

The wider spectrum band and the reduction of wave height indicate that there is some dissipation along the flume.

Shallow_Flume11_5.sws

In this script I have enlarged the duration of the wave spectrum signal to 120 min and I have recorded 90 min. As a result, I am able to build the spectrum with 10 periodograms.

The table below summarizes the wave parameters at x=0. These results are almost identical to the ones obtained in Shallow_Flume11_4.sws. The mean water level is $\overline{\eta} = +0.017\ m$.

Measured data at x=0 m (Shallow_Flume11_5.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.49\ m$	$T_m = 8.84\ s$	$H_{m0} = 3.66\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.66\ m$	$3.8 \cdot \sigma = 3.48\ m$	$T_{m01} = 9.40\ s$	$T_{m-1,0} = 11.08\ s$

Table A.7. Wave parameters at x=0 m of Shallow_Flume11_5.sws.

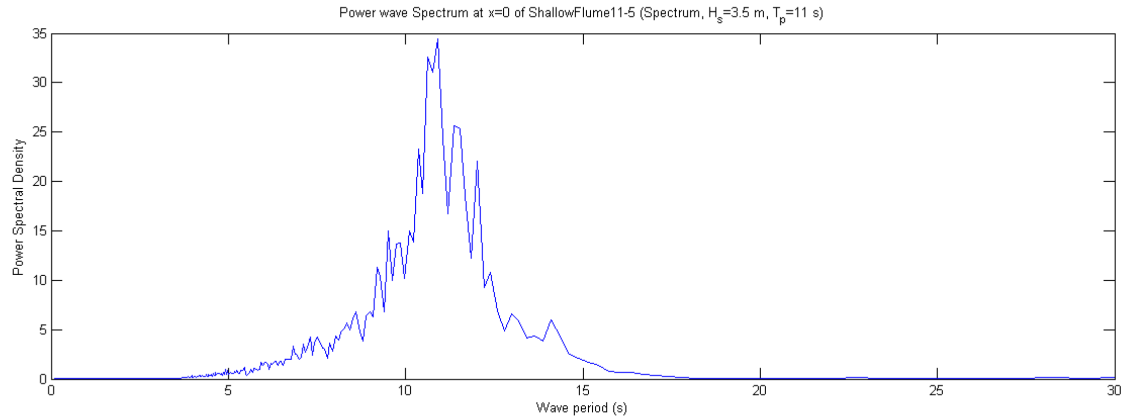

Figure A.85. Wave spectrum at x=0 m of Shallow_Flume11_5.sws.

Measured data at x=805 m (Shallow_Flume11_5.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.14\,m$	$T_m = 9.02\,s$	$H_{m0} = 3.30\,m$	$T_p = 11.52\,s$
$4 \cdot \sigma = 3.30\,m$	$3.8 \cdot \sigma = 3.13\,m$	$T_{m01} = 9.15\,s$	$T_{m-1,0} = 14.90\,s$

Table A.8. Wave parameters at x=805 m of Shallow_Flume11_5.sws.

At x=805 m the mean water level is $\bar{\eta} = +0.008\,m$. The results are quite closer to Shallow_Flume11_4.sws. A bimodal spectrum with a second high peak around 14 s is obtained. However, long waves with periods around 30 s and 60 s appear, forming a third and much lower peak on the spectrum. As it occurs in Shallow_Flume11_4.sws, the significant wave height obtained from the wave per wave analysis is closer to $3.8 \cdot \sigma$ than to $4 \cdot \sigma$.

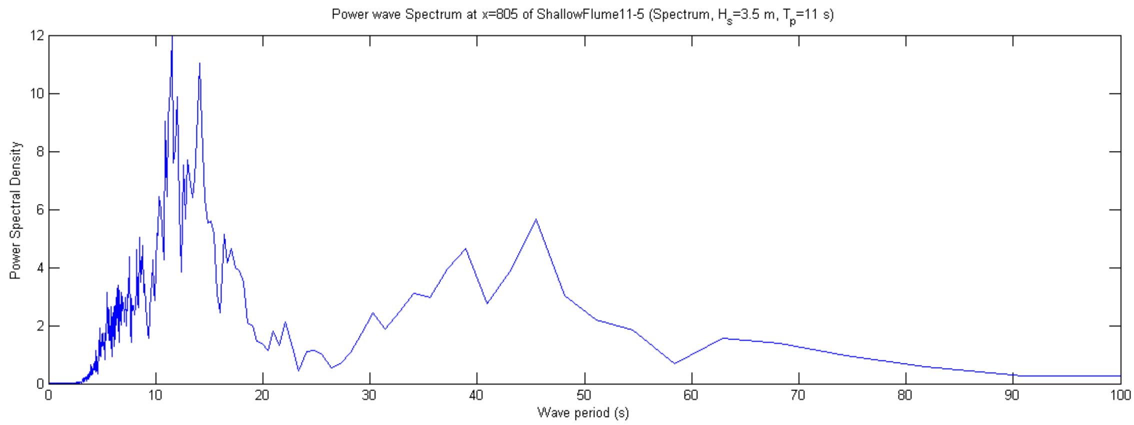

Figure A.86. Wave spectrum at x=805 m of Shallow_Flume11_5.sws.

Shallow_Flume11_7.sws

In this script regular waves are performed during 90 minutes. The introduced wave height is 3.5 m and the mean wave period, 10 s. Also, the dissipation along the wave flume can be easily analysed.

At x=0 m, the mean water level is +0.038 m, the mean wave height are 3.53 m and the mean wave period is 10.00 s. From the graph a perfect pattern along all simulation time can be seen.

From spectral analysis, the mean wave period is 9.90 s and the peak period, 9.98 s. The spectrum shape has a very large and narrow peak, as it should be with a sinusoidal wave.

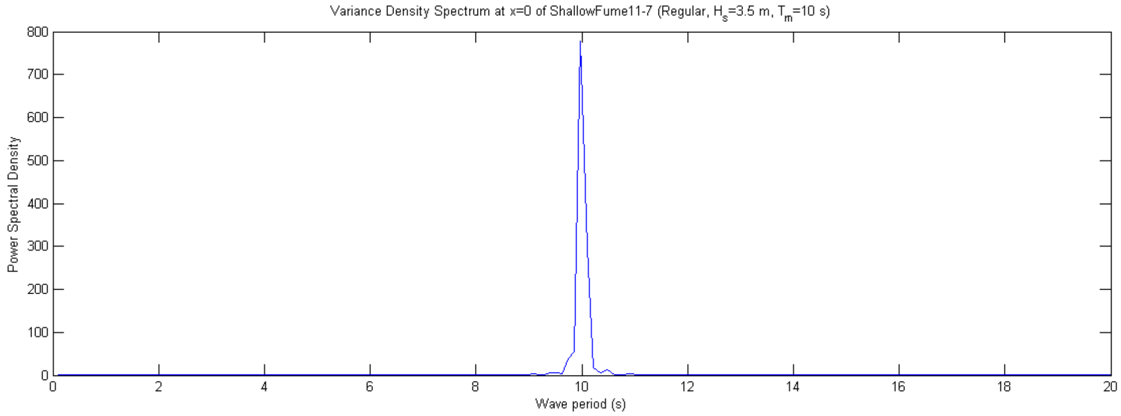

Figure A.87. Wave spectrum at x=0 of Shallow_Flume11_7.sws.

At x=805 m, the mean water level is +0.033 m, the mean wave period, 10.00 s, and the mean wave height 3.27 m. The wave period does not change, but some wave dissipation can be observed along the flume although zero friction and viscosity has been considered. From spectral analysis I get a mean wave period of 9.92 s and a peak wave period of 9.98 s. Then, the wave obtained 800 far away from the wave generation shows a small dissipation of around 25 cm.

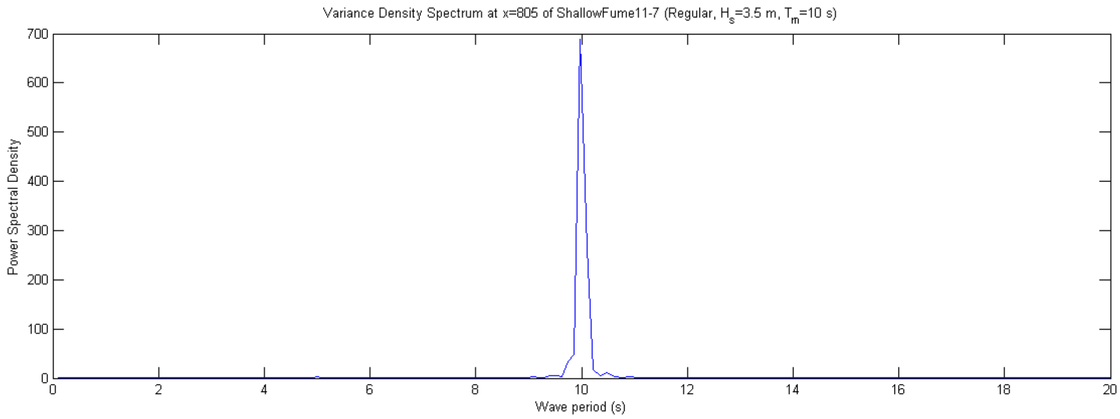

Figure A.88. Wave spectrum at x=805 of Shallow_Flume11_7.sws.

Shallow_Flume12.sws

It is the same script as Shallow_Flume05.sws but reducing the Courant number accepted range from between 0.1 s and 0.5 s to between 0.01 s and 0.25. I did it, because this time step was not stable although I did not have any problem.

At the wave generator (x=0 m) I get the same result, but at x=805 m wave height slightly reduces and the wave periods increase.

Measured data at x=0 m (Shallow_Flume12.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.50\, m$	$T_m = 8.84\, s$	$H_{m0} = 3.66\, m$	$T_p = 10.91\, s$
$4 \cdot \sigma = 3.66\, m$	$3.8 \cdot \sigma = 3.48\, m$	$T_{m01} = 9.40\, s$	$T_{m-1,0} = 11.05\, s$

Table A.9. Wave parameters at x=0 of Shallow_Flume12.sws.

Measured data at x=805 m (Shallow_Flume12.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.07\, m$	$T_m = 9.21\, s$	$H_{m0} = 3.23\, m$	$T_p = 11.52\, s$
$4 \cdot \sigma = 3.23\, m$	$3.8 \cdot \sigma = 3.07\, m$	$T_{m01} = 9.30\, s$	$T_{m-1,0} = 15.03\, s$

Table A.10. Wave parameters at x=805 m of Shallow_Flume12.sws.

A.3. Wave propagation without the influence of the structure

Now that the problems with wave propagation have been solved and good results are obtained, we can move to dikes.

The next simulations give the wave parameters at the toe of the dikes and breakwaters, so this data can be used as the measured incoming wave without the effect of the structure. Besides, the recorded waves in this flume can be compared to the waves affected by the structure to estimate wave reflection.

Since the first simulations with dikes were unstable, the DISCRET commands were changed with the advice of Pieter Smit.

DISCRET UPW UMOM H BDF (second order backward upwind scheme applied for the horizontal advective terms of the horizontal components of the momentum equations, momentum is not always conserved)

DISCRET UPW WMOM H BDF (second order backward upwind scheme applied for the horizontal advective terms of the vertical component of the momentum equations, momentum is not always conserved)

The discretizations used for vertical advective terms or the water depth are not needed anymore, because only one horizontal layer is used.

The computations are done with a grid size of 1 m and a time steep of 0.001 s (between the input Courant number range of 0.1-0.25).

With these changes, all simulations are very stable now.

Propagation01.sws

The input wave spectrum has a duration of 2 h and it is defined by $H_{m0} = 3.5\ m$, $T_p = 11\ s$. 50 minutes are simulated and the last 45 are recorded.

Measured data at x=0 m (Propagation01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.59\ m$	$T_m = 8.72\ s$	$H_{m0} = 3.71\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.71\ m$	$3.8 \cdot \sigma = 3.52\ m$	$T_{m01} = 9.30\ s$	$T_{m-1,0} = 11.02\ s$

Table A.11. Wave parameters at x=0 m of Propagation01.sws.

Measured data at x=780 m (Propagation01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.00\ m$	$T_m = 9.18\ s$	$H_{m0} = 3.23\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 3.23\ m$	$3.8 \cdot \sigma = 3.06\ m$	$T_{m01} = 9.36\ s$	$T_{m-1,0} = 15.42\ s$

Table A.12. Wave parameters at x=780 m of Propagation01.sws.

At x=780 m, a second peak around 11 s and long waves can be observed. This would be the result from some wave dissipation during the wave propagation.

Propagation02.sws

The input wave spectrum has a duration of 50 min and it is defined by $H_{m0} = 3.5\ m$, $T_p = 11\ s$. 50 minutes are simulated and the last 45 recorded.

Measured data at x=0 m (Propagation02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.35\ m$	$T_m = 8.98\ s$	$H_{m0} = 3.50\ m$	$T_p = 11.37\ s$
$4 \cdot \sigma = 3.50\ m$	$3.8 \cdot \sigma = 3.33\ m$	$T_{m01} = 9.29\ s$	$T_{m-1,0} = 10.86\ s$

Table A.13. Wave parameters at x=0 m of Propagation02.sws.

Measured data at x=780 m (Propagation02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.03\ m$	$T_m = 9.48\ s$	$H_{m0} = 3.16\ m$	$T_p = 11.06\ s$
$4 \cdot \sigma = 3.16\ m$	$3.8 \cdot \sigma = 3.00\ m$	$T_{m01} = 9.02\ s$	$T_{m-1,0} = 13.78\ s$

Table A.14. Wave parameters at x=780 m of Propagation02.sws.

At x=780 m there are long waves and a second peak around 14 s.

Propagation03.sws

The input wave spectrum has a duration of 2 h and it is defined by $H_{m0} = 3.5\ m$, $T_p = 11\ s$. 95 minutes are simulated and the last 90 are recorded.

Measured data at x=0 m (Propagation03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.40\ m$	$T_m = 8.88\ s$	$H_{m0} = 3.58\ m$	$T_p = 11.05\ s$
$4 \cdot \sigma = 3.58\ m$	$3.8 \cdot \sigma = 3.40\ m$	$T_{m01} = 9.37\ s$	$T_{m-1,0} = 11.03\ s$

Table A.15. Wave parameters at x=0 m of Propagation03.sws.

Measured data at x=780 m (Propagation03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.07\ m$	$T_m = 9.22\ s$	$H_{m0} = 3.19\ m$	$T_p = 12.78\ s$
$4 \cdot \sigma = 3.19\ m$	$3.8 \cdot \sigma = 3.03\ m$	$T_{m01} = 9.02\ s$	$T_{m-1,0} = 14.35\ s$

Table A.16. Wave parameters at x=780 m of Propagation03.sws.

There is a second peak at 14.5 s and a third one at 45 s. Long waves are also observed.

Propagation04.sws

The input wave spectrum has a duration of 90 min and it is defined by $H_{m0} = 3.5\ m$, $T_p = 11\ s$. 95 minutes are simulated and the last 90 are recorded.

Measured data at x=0 m (Propagation04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.40\ m$	$T_m = 8.82\ s$	$H_{m0} = 3.58\ m$	$T_p = 10.98\ s$
$4 \cdot \sigma = 3.58\ m$	$3.8 \cdot \sigma = 3.40\ m$	$T_{m01} = 9.30\ s$	$T_{m-1,0} = 10.95\ s$

Table A.17. Wave parameters at x=0 m of Propagation04.sws.

Measured data at x=780 m (Propagation04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.07\ m$	$T_m = 9.18\ s$	$H_{m0} = 3.19\ m$	$T_p = 12.70\ s$
$4 \cdot \sigma = 3.19\ m$	$3.8 \cdot \sigma = 3.03\ m$	$T_{m01} = 8.97\ s$	$T_{m-1,0} = 14.26\ s$

Table A.18. Wave parameters at x=780 m of Porpagation04.sws.

Very long waves are measured at the second gauge. The recorded values are practically the same as in Propagation03.sws.

Propagation09.sws

The input wave spectrum has a duration of 2 h and it is defined by $H_{m0} = 2\ m$, $T_p = 7\ s$. 50 minutes are simulated and the last 45 are recorded. No long waves are recorded.

Measured data at x=0 m (Propagation09.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.07\ m$	$T_m = 5.77\ s$	$H_{m0} = 2.15\ m$	$T_p = 7.06\ s$
$4 \cdot \sigma = 2.15\ m$	$3.8 \cdot \sigma = 2.04\ m$	$T_{m01} = 5.93\ s$	$T_{m-1,0} = 6.68\ s$

Table A.19. Wave parameters at x=0 of Propagation09.sws.

Measured data at x=780 m (Propagation09.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.80\ m$	$T_m = 6.56\ s$	$H_{m0} = 1.87\ m$	$T_p = 7.12\ s$
$4 \cdot \sigma = 1.89\ m$	$3.8 \cdot \sigma = 1.78\ m$	$T_{m01} = 6.69\ s$	$T_{m-1,0} = 8.20\ s$

Table A.20. Wave parameters at x=780 m of Propagation09.sws.

Propagation10.sws

The input wave spectrum has a duration of 2 h and it is defined by $H_{m0} = 2\ m$, $T_p = 7\ s$. 95 minutes are simulated and the last 90 are recorded. No long waves are recorded.

Measured data at x=0 m (Propagation10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.00\ m$	$T_m = 5.69\ s$	$H_{m0} = 2.08\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 2.08\ m$	$3.8 \cdot \sigma = 1.98\ m$	$T_{m01} = 5.91\ s$	$T_{m-1,0} = 6.59\ s$

Table A.21. Wave parameters at x=0 m of Propagation10.sws.

Measured data at x=780 m (Propagation10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.75\ m$	$T_m = 6.59\ s$	$H_{m0} = 1.82\ m$	$T_p = 7.11\ s$
$4 \cdot \sigma = 1.82\ m$	$3.8 \cdot \sigma = 1.73\ m$	$T_{m01} = 6.62\ s$	$T_{m-1,0} = 8.00\ s$

Table A.22. Wave parameters at x=780 m of Propagation10.sws.

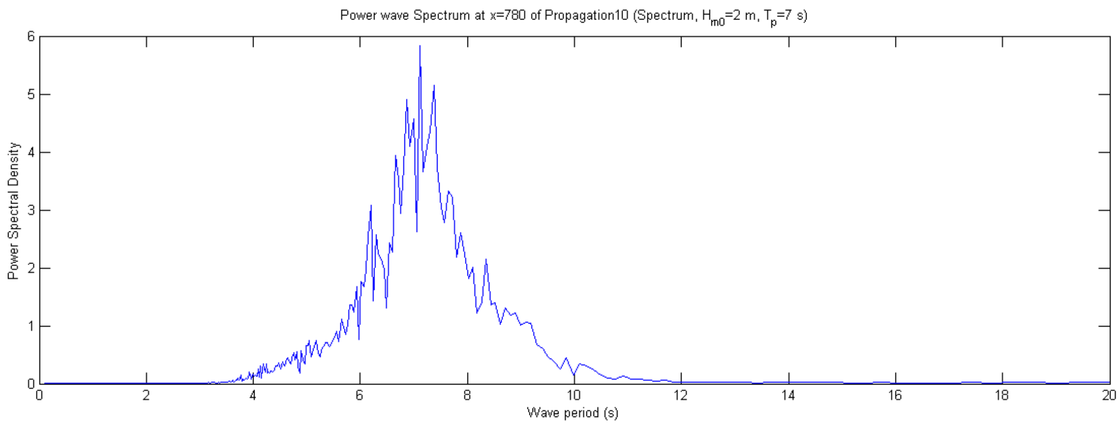

Figure A.89. Wave spectrum at x=780 m of Propagation10.sws.

Propagation11.sws

The input wave spectrum has a duration of 2 h and it is defined by $H_{m0} = 1.5\ m$, $T_p = 7\ s$. 95 minutes are simulated and the last 90 are recorded. No long waves are recorded.

Measured data at x=0 m (Propagation11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.50\ m$	$T_m = 5.68\ s$	$H_{m0} = 1.55\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 1.55\ m$	$3.8 \cdot \sigma = 1.48\ m$	$T_{m01} = 5.90\ s$	$T_{m-1,0} = 6.49\ s$

Table A.23. Wave parameters at x=0 m of Propagation11.sws.

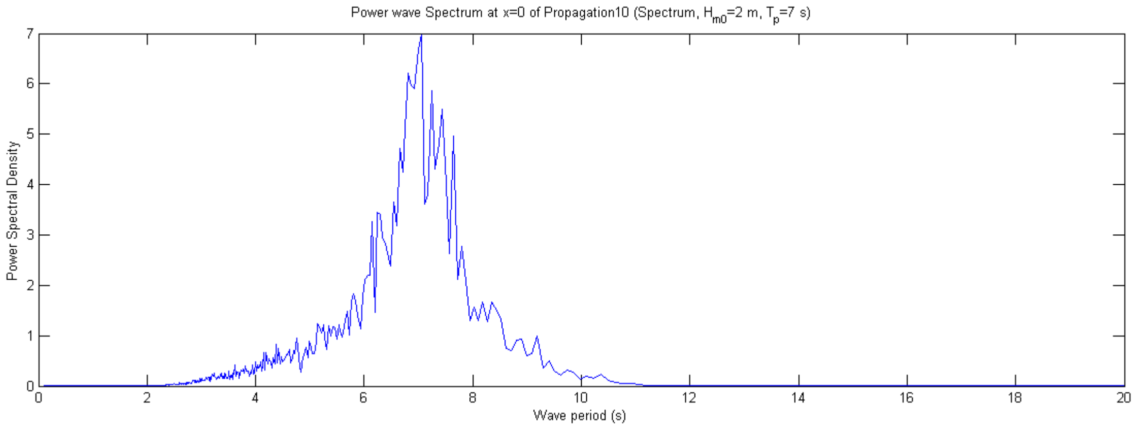

Figure A.90. Wave spectrum at x=0 m of Propagation10.sws.

Measured data at x=780 m (Propagation11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.35\ m$	$T_m = 6.48\ s$	$H_{m0} = 1.40\ m$	$T_p = 6.87\ s$
$4 \cdot \sigma = 1.40\ m$	$3.8 \cdot \sigma = 1.33\ m$	$T_{m01} = 6.53\ s$	$T_{m-1,0} = 7.46\ s$

Table A.24. Wave parameters at x=780 m of Propagation10.sws.

A very wide and flat peak is observed around 7 s on the wave spectrum plot at the location of the structure toe.

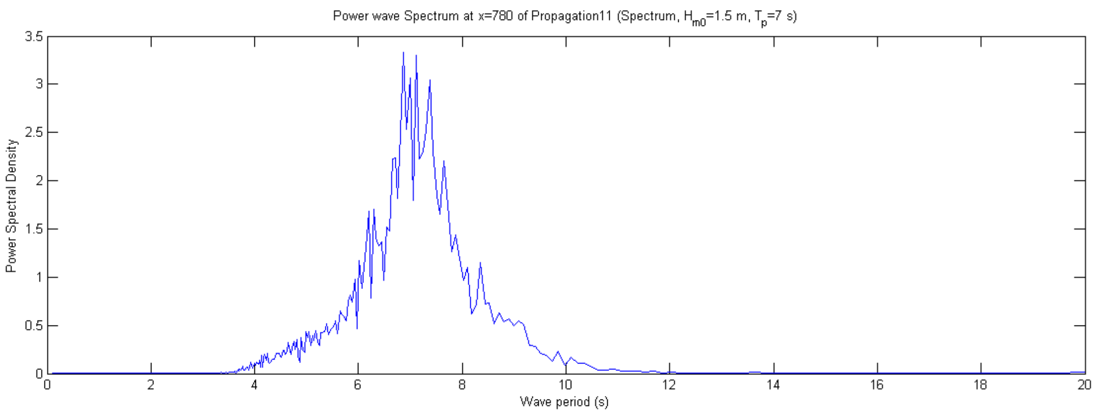

Figure A.91. Wave spectrum at x=780 m of Propagation11.sws.

A.4. Impermeable smooth dike

As a first step to introduce a breakwater, I want to introduce a smooth impermeable dike. The reason is to measure easily if SWASH can compute right wave overtopping before dealing with a porous structure.

In order to introduce a hydraulic structure, its porosity, grain size and structure height have to be defined. To do that, one input file for each property is needed.

First of all I tried to introduce a very impermeable dike with a porosity value of 0 and a grain size of 0.000000001 m. However, I could not measure absolutely anything beyond the toe of the structure. It looks like that the computation stops there. There are two reasons that can explain why this happens. The first one is that SWASH can not work with very low porosity values, because it is dividing some terms of the used momentum equations. The second one is that the model is not stable enough and I must reduce the time step (see previous section A.3.).

This last adjustment let me simulate an impermeable smooth dike as a bottom variation with the dike profile. This was what I tried first, but the script did not run then.

Dike01.sws

In this script I perform waves in the flume with a bottom variation with the desired dike profile. Since the bottom is impermeable, this is the simplest way to simulate a smooth and impervious dike.

The dike profile is introduced in the bottom file Dike01.bot. The features of the dike are a crest level 2.5 m above water level, a crest width of 5 m and slopes of 1:2. The bottom is horizontal and it is located at 10 m water depth. This is quite a "strange" dike, with a very low crest and steep slope, but I should remember that the purpose was to test overtopping and I wanted a significant value to start with.

I have computed first the expected overtopping in this dike with the formulas given in the Wave Overtopping Manual. With the following input parameters: $R_C = 2.5\ m,\ h = 10\ m$, $\tan\alpha = 0.5$, $H_{m0} = 3.5\ m,\ T_{m-1,0} = 10\ s$, normal incident waves and a very smooth dike ($\gamma_f = 1.0$), I expect to have a run-up $R_{u2\%} = 11.13\ m$ and a mean overtopping discharge of $q = 0.640\ \ m^3/sm = 640\ \ l/sm$. Then, constant overtopping is expected.

At the wave generator there is some reflection due to the smooth, impermeable and quite steep smooth dike although many waves overtop. Figures can be seen on the table A.25.

Measured data at x=0 m (Dike01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.88\ m$	$T_m = 8.87\ s$	$H_{m0} = 4.16\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.16\ m$	$3.8 \cdot \sigma = 3.95\ m$	$T_{m01} = 9.40\ s$	$T_{m-1,0} = 12.85\ s$

Table A.25. Wave parameters at x=0 m of Dike01.sws.

At the toe of the dike (x=780 m) the waves reduce, and I can observe a large number of peaks on the spectrum plot and the presence of long waves. The reflection produced by the smooth dike and the waves running up and down explains it.

Measured data at x=780 m (Dike01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.24\ m$	$T_m = 8.22\ s$	$H_{m0} = 3.75\ m$	$T_p = 38.98\ s$
$4 \cdot \sigma = 3.75\ m$	$3.8 \cdot \sigma = 3.56\ m$	$T_{m01} = 10.37\ s$	$T_{m-1,0} = 23.53\ s$

Table A.26. Wave parameters at x=780 m of Dike01.sws.

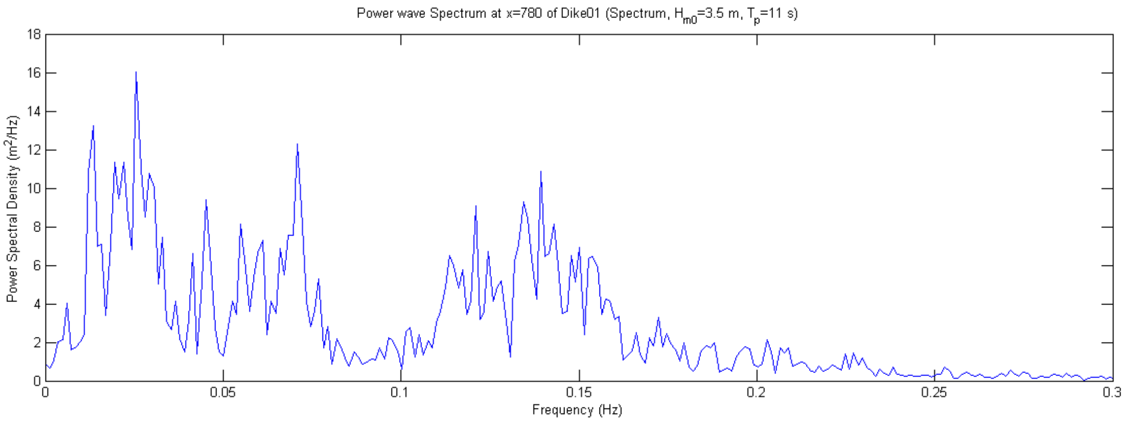

Figure A.92. Wave spectrum at x=780 m of Dike01.sws.

From the recorded values at the toe of the structure, the overtopping discharge would be $q = 0.715\ m^3/sm$. It is bigger due to the larger $T_{m-1,0}$. If I compute the overtopping discharge from the values of the incoming wave, which was recorded in Propagation01.sws, the expected value is $q = 0.4781\ \ m^3/sm$.

I have recorded the wave overtopping with a time series time-discharge and analyse the results. Discharge is directly measured by SWASH.

When I measure the wave overtopping at the beginning of the crest (x=805 m), just at the top of the seaward slope, I get a smaller value of $q = 0.313\ \ m^3/sm$. This is a smaller value, but has the same order of magnitude.

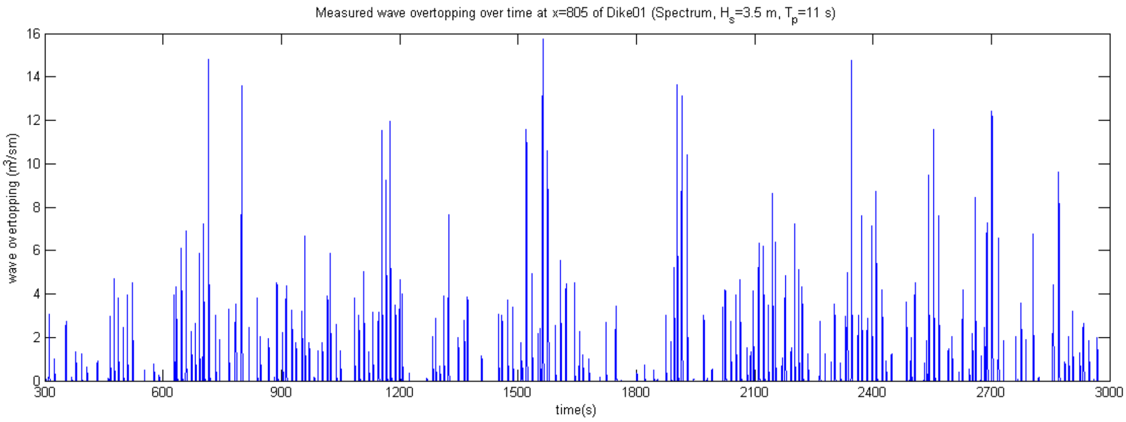

Figure A.93. Overtopping discharge at the top of the seaward slope of Dike01.sws.

At the end of the crest (x=810 m), just at the top of the inner slope and where wave overtopping is defined, I get a smaller value of $q = 0.267\ m^3/sm$. This is around the 37% of the expected one using the recorded values at the toe of the dike, and approximately the 56% of the expected one considering only the incoming wave, so the results are close, but there is an important relative difference. From the Neural Network available at Deltares website, the 90% confidence interval is limited between $q = 0.2078\ m^3/sm$ and $q = 1.106\ m^3/sm$. The mean value is $q = 0.4876\ m^3/sm$, which is practically the same value given by the empirical formulas. However, I do not know how many tests close to this situation are in the Neural Network database.

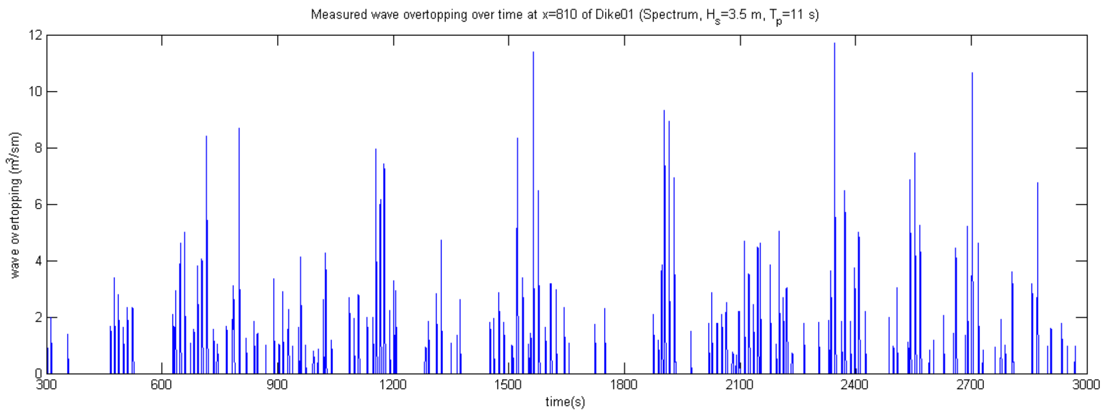

Figure A.94. Overtopping discharge at the top of the inner slope of Dike01.sws.

With some zoom I can see that approximately half of the waves reach the top of the front slope, and fewer, the inner slope.

The result from SWASH is close to the empirical value although not very precise. Nevertheless, in the Wave Overtopping Manual it is stated that the empirical formulas usually overestimate wave overtopping, because the discharge is measured behind the crest and we compute the number of waves that reach the crest (not the back slope). Then, it would be reasonable that the discharge computed by SWASH by solving the momentum equations would be smaller than the value predicted by the empirical formulas. SWASH gives a value with the same order of magnitude of the empirical formulas, but smaller and on the safe side, which is what matters. I mean the safe side, because if the values are much bigger than the Eurotop guidelines, the code should be revised.

In summary, I think that in case of dikes, SWASH may also overcome the overestimations that the empirical formulae do and give a value closer to the real overtopping. As a conclusion, it looks that SWASH computes correctly wave overtopping in smooth dikes with the same reliability of the empirical formulas, although more tests with different profiles should be performed.

I will not perform tests for all kind of dikes. This would take a lot of time and would be a enough work for a proper MSc Thesis. However, at least I will test with a higher and a gentler dike.

To be sure if the predictions of SWASH are reliable or not, it would be a good idea to check if the results are within the confident bandwidth of the Neural Network developed in the CLASH program. It would be a good verification in case of large differences, because an extremely large amount of tests with dikes were included in the database.

Dike02.sws

In this script I increased the dike height up to a level of 5 m above water level. Dike02.bot describes the new dike. There are no other changes with respect to Dike01.sws and both dikes have the toe located at the same point.

The wave parameters observed in at the wave generator can be seen in the following table A.27. There are higher waves due to the higher freeboard, which reduces overtopping and enhances wave reflection along the wave flume.

Measured data at x=0 m (Dike02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.92\ m$	$T_m = 8.87\ s$	$H_{m0} = 4.24\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.24\ m$	$3.8 \cdot \sigma = 4.03\ m$	$T_{m01} = 9.40\ s$	$T_{m-1,0} = 13.26\ s$

Table A.27. Wave parameters at x=0 m of Dike02.sws.

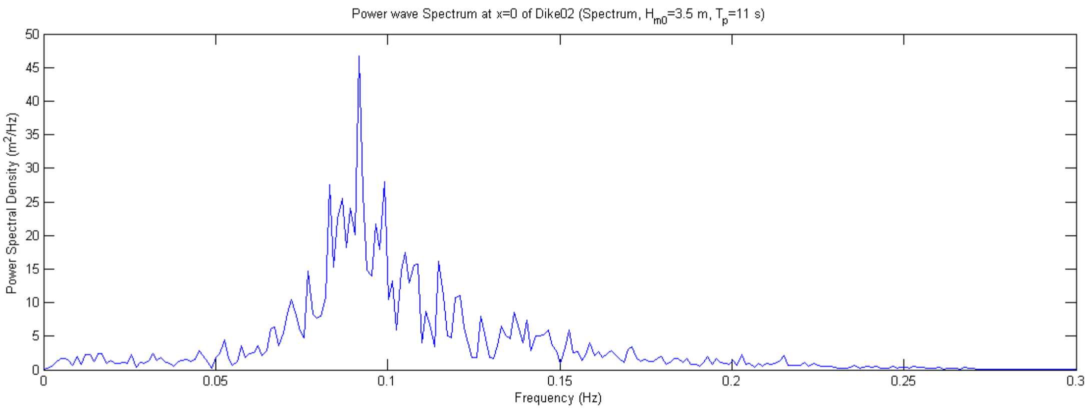

Figure A.95. Wave spectrum at x=0 m of Dike02.sws.

At x=780 m many peaks and long waves can be observed on the spectrum plot (figure A.96). The most important parameters are shown in table A.29.

Measured data at x=780 m (Dike02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.36\,m$	$T_m = 8.22\,s$	$H_{m0} = 3.84\,m$	$T_p = 38.98\,s$
$4 \cdot \sigma = 3.84\,m$	$3.8 \cdot \sigma = 3.65\,m$	$T_{m01} = 10.04\,s$	$T_{m-1,0} = 22.79\,s$

Table A.28. Wave parameters at x=780 m of Dike02.sws.

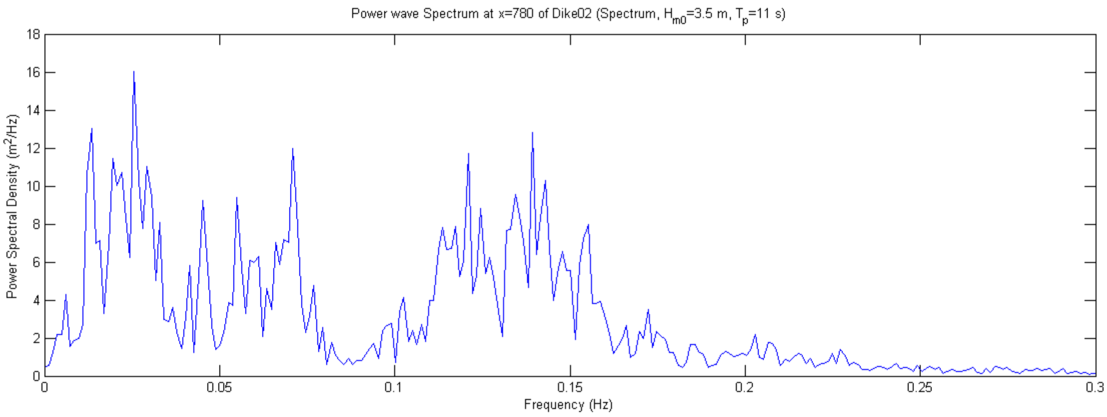

Figure A.96. Wave spectrum at x=780 of Dike02.sws.

From the wave parameters at the toe of the dike the mean wave overtopping can be estimated. The input parameters are then: $R_C = 5\,m$, $h = 10\,m$, $\tan\alpha = 0.5$, $H_{m0} = 3.84\,m$, $T_{m-1,0} = 22.79\,s$, normal incident waves and a very smooth dike ($\gamma_f = 1.0$). The expected run-up is $R_{u2\%} = 13.22\,m$ and the mean overtopping is $q = 0.1986\ m^3/sm = 198.6\ l/sm$. There is a considerable reduction due to the higher crest. As I did in Dike01.sws, if I only consider the incoming wave, the mean wave discharge is $q = 0.0693\ m^3/sm = 69.3\,l/sm$. The Irribarren number and the run-up are the same as before, because the slope and the incoming wave have not changed.

At the beginning of the crest (x=810 m), the mean overtopping is $q = 31.4\ l/sm$, and at the end (x=815 m), $q = 22.8\ l/sm$. The computed value with SWASH is much smaller (33% or 11% including the reflected wave), but it makes sense, since there is a larger bandwidth with smaller overtopping values. We can consider than it is almost one order of magnitude smaller.

As it can be seen in the next figures, fewer waves reach the crest and are able to cross it.

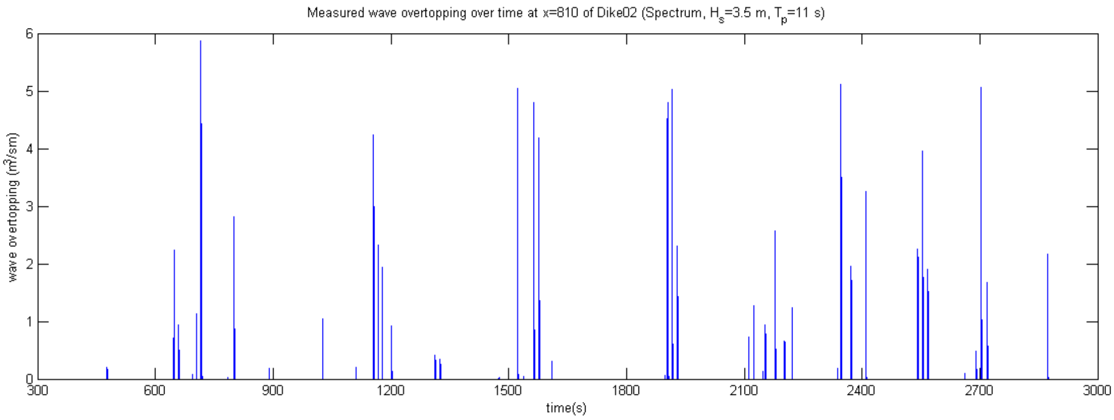

Figure A.97. Overtopping discharge at the top of the outer slope of Dike02.sws.

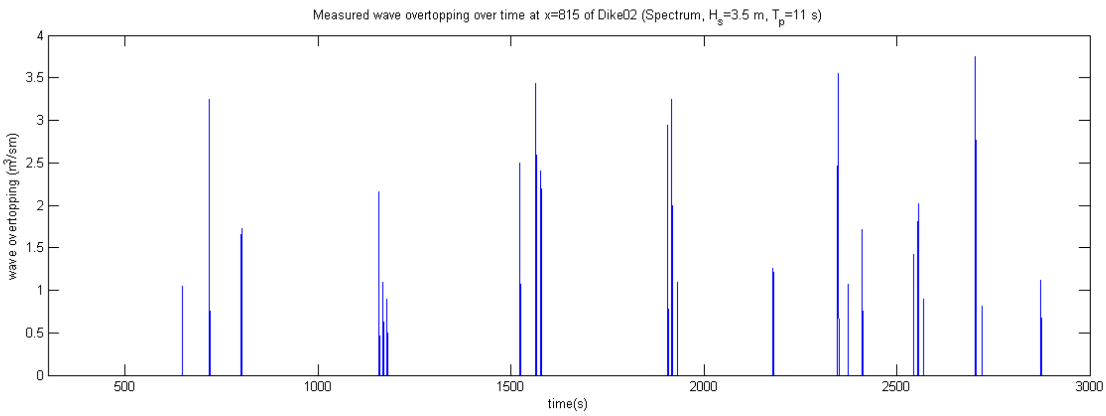

Figure A.98. Overtopping discharge at the top of the inner slope of Dike02.sws.

Dike03.sws

In this script I test a gentler dike. The dike freeboard is 5 m above Mean Sea Level and the slopes are 1:3. The crest width is the same (5 m) and the toe is located at x=780 m. The dike profile is described in Dike03.bot.

The sea state at the wave generator (x=0 m) is summarized in the table A.29. A bimodal wave spectrum with a second and smaller peak at 14 s is observed (figure A.99).

Measured data at x=0 m (Dike03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 4.18\ m$	$T_m = 9.35\ s$	$H_{m0} = 4.28\ m$	$T_p = 11.37\ s$
$4 \cdot \sigma = 4.27\ m$	$3.8 \cdot \sigma = 4.06\ m$	$T_{m01} = 9.59\ s$	$T_{m-1,0} = 12.46\ s$

Table A.29. Wave parameters at x=0 m of Dike03.sws.

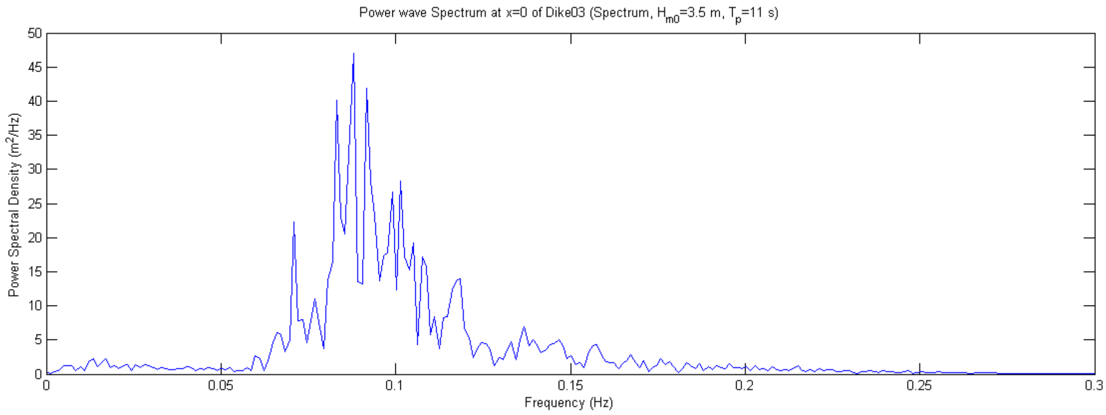

Figure A.99. Wave spectrum at x=0 m of Dike03.sws.

At the toe of the dike (x=780 m) very long waves are observed. They could be either reflected waves or an effect of the waves running up and down the slope.

Measured data at x=780 m (Dike03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.64\ m$	$T_m = 10.03\ s$	$H_{m0} = 3.98\ m$	$T_p = 11.37\ s$
$4 \cdot \sigma = 3.98\ m$	$3.8 \cdot \sigma = 3.78\ m$	$T_{m01} = 10.52\ s$	$T_{m-1,0} = 20.02\ s$

Table A.30. Wave parameters recorded at x=780 m of Dike03.sws.

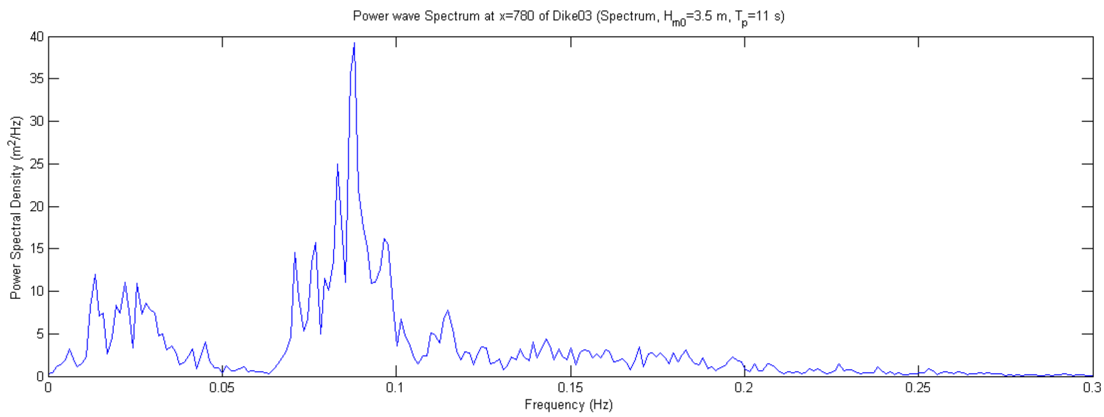

Figure A.100. Wave spectrum at x=780 m of Dike03.sws.

Then the input values to compute overtopping are: $R_C = 5\ m$, $h = 10\ m$, $\tan\alpha = 1/3$, $H_{m0} = 3.98\ m$, $T_{m-1,0} = 20.02\ s$, $\gamma_\beta = 1.0$ and $\gamma_f = 1.0$. The expected run-up is $R_{u2\%} = 13\ m$ and the mean overtopping is $q = 0.1897\ \ m^3/sm = 189.7\ \ l/sm$.

Considering only the incoming wave ($H_{m0} = 3.23\ m$ and $T_{m-1,0} = 15.42\ s$), the run-up is expected to be $R_{u2\%} = 10.36\ m$ and the mean overtopping discharge, $q = 65.0\ \ l/sm$.

The expected overtopping is similar as the expected in Dike02.sws, because it is limited by the part of the formula that does not depend on the slope. The difference between these two cases is due to the different wave parameters, which in deed depend on the interaction between waves and slope. Then the slope influence is limited to the incoming waves at the toe in our case. However, the expected value is slightly smaller than in Dike02.sws due to the gentler slope. If we just not consider the effect of the structure on the waves, so we only take into account the incoming wave, the difference is explained by the interpolation between two formulas needed in Dike02.sws to compute wave overtopping with $5 < \xi_{m-1,0} < 7$.

At the seaward edge of the crest (x=825 m) the mean discharge is $q = 26.3\ l/sm$. At the landward edge (x=830 m) the mean wave overtopping is $q = 21.1\ l/sm$. The results from SWASH are much lower if we consider the reflected wave (11% and around one order of magnitude) than the predicted values with the empirical formulas. Considering only the incoming wave, the measured discharge at the back edge of the crest is around 34% of the expected one. Both of them are lower, but surprisingly close to the measured discharge in Dike02.sws, so the freeboard is much more important than the slope (or at least for the tested cases). Looking at the formulas, the slope angle only appears for low and very high Iribarren numbers.

According to the Neural Network available at Deltares website, the expected mean overtopping is $q = 262\ l/sm$, much higher than the one predicted by the Eurotop formula. The measured value in SWASH is not within the 90% and the 95% confidence interval.

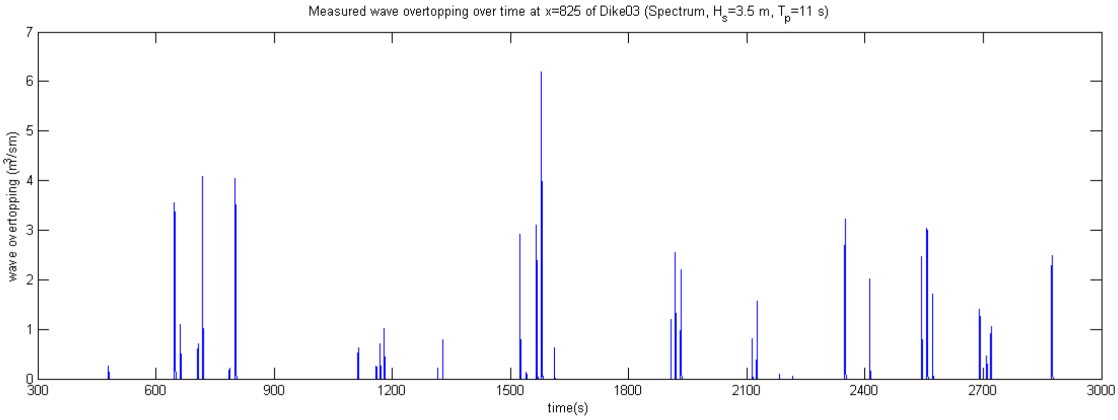

Figure A.101. Overtopping discharge at the top of the outer slope of Dike03.sws.

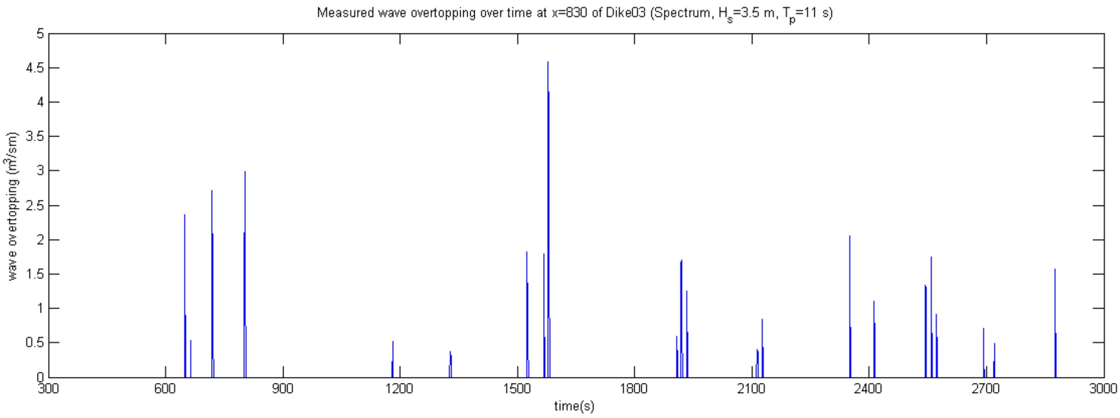

Figure A.102. Overtopping discharge at the top of the inner slope of Dike03.sws.

Dike04.sws

I performed another test with a gentler and lower dike. In Dike04.bot a dike with a 1:4 slope and 2.5 m freeboard is described. This milder slope allows me to fix a lower crest level keeping a grid size of 5 m. This mesh size is very handy to define the bottom levels.

Nothing especial is observed at the wave generator (a part from some reflection of the dike).

Measured data at x=0 m (Dike04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.80\ m$	$T_m = 9.20\ s$	$H_{m0} = 3.99\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.99\ m$	$3.8 \cdot \sigma = 3.79\ m$	$T_{m01} = 9.61\ s$	$T_{m-1,0} = 12.63\ s$

Table A.31. Wave parameters at x=0 m of Dike04.sws.

Longer waves with wave periods between 30 and 90 s are observed in the spectrum at the toe of the dike (x=780 m).

Measured data at x=780 m (Dike04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.49\ m$	$T_m = 9.64\ s$	$H_{m0} = 3.88\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 3.88\ m$	$3.8 \cdot \sigma = 3.68\ m$	$T_{m01} = 10.54\ s$	$T_{m-1,0} = 19.60\ s$

Table A.32. Wave parameters at x=780 m of Dike04.sws.

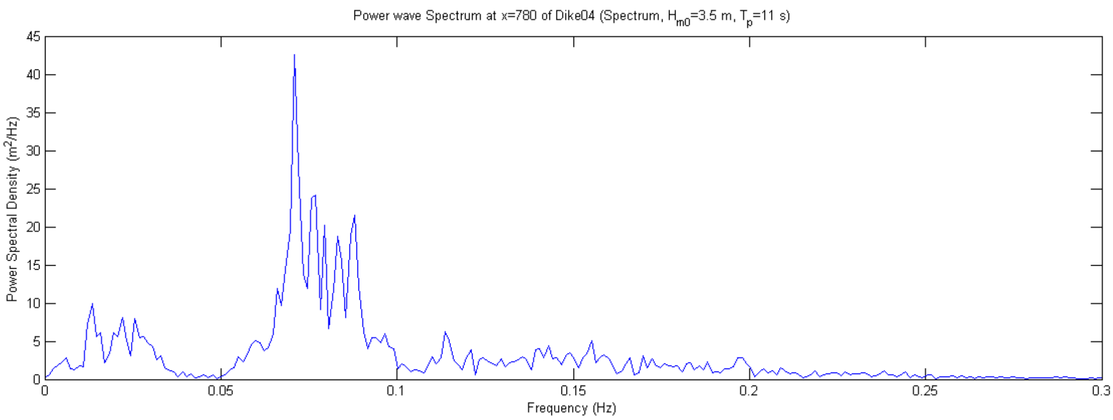

Figure A.103. Wave spectrum at x=780 m of Dike04.sws.

The input parameters (including the reflected wave) are $R_C = 2.5\ m$, $h = 10\ m$, $\tan\alpha = 0.25$, $H_{m0} = 3.88\ m$, $T_{m-1,0} = 19.60\ s$, $\gamma_\beta = 1.0$ and $\gamma_f = 1.0$. Then, the expected run-up is $R_{u2\%} = 12.22\ m$ and the mean overtopping, $q = 0.8965\ m^3/sm = 896.5\ l/sm$. Without the dike and reflection, $R_{u2\%} = 9.96\ m$ and $q = 486.1\ l/sm$.

The expected overtopping is close to the predicted in Dike01.sws, but larger even though the milder slope. The reason is that in Dike04.sws, the wave steepness increases, because H_{m0} increases and $T_{m-1,0}$ decreases, and the slope decreases (milder), which reduces the surf parameter from $\xi_{m-1,0} = 7.59$ in Dike01.sws to $\xi_{m-1,0} = 3.11$ in Dike04.sws. Then the waves behave as surging breaking waves and are reflected by the dike. Without reflexion, we have $\xi_{m-1,0} = 2.68$ due to the gentler slope.

At the top of the seaward slope (x=830 m) the recorded mean overtopping is $q = 291.8\ l/sm$, while at the backward edge of the crest (x=835 m) the recorded discharge is $q = 269.3\ l/sm$. This result is about the 30% of the estimated value through the empirical formulas if we include the reflected wave, and about the 55% if we only consider the incoming wave.

The output values of the Neural Network from Deltares are a mean wave overtopping of $q = 577.3\ l/sm$, and a 90% confidence interval limited by $258.9\ l/sm$ and $1318\ l/sm$.

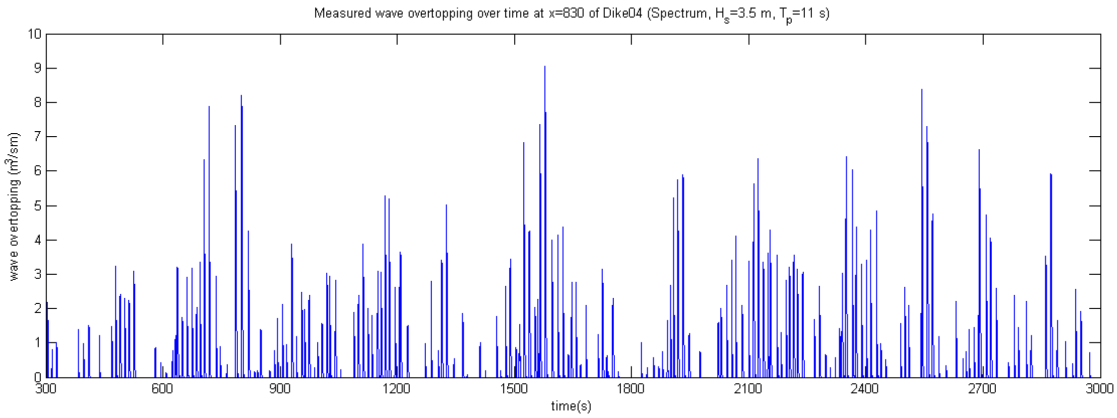

Figure A.104. Overtopping discharge at the top of the outer slope of Dike04.sws.

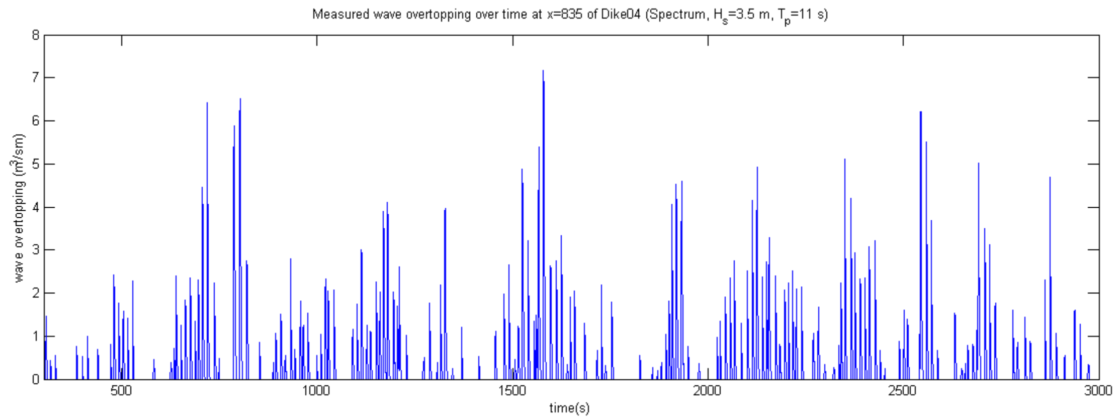

Figure A.105. Overtopping discharge at the top of the inner slope of Dike04.sws.

From these 4 tests in impermeable smooth dikes I drew the following conclusions.

Partial conclusions about Dikes

Long waves are found at the toe of the dike in Dike03.sws and Dike04.sws, but they are not very much different than the recorded ones at Propagation01.sws. Nevertheless, large energy is concentrated in these long waves in Dike01.sws and Dike02.sws. The reason would be the reflexion generated by these steep dikes with a 1:2 slope. See next figures.

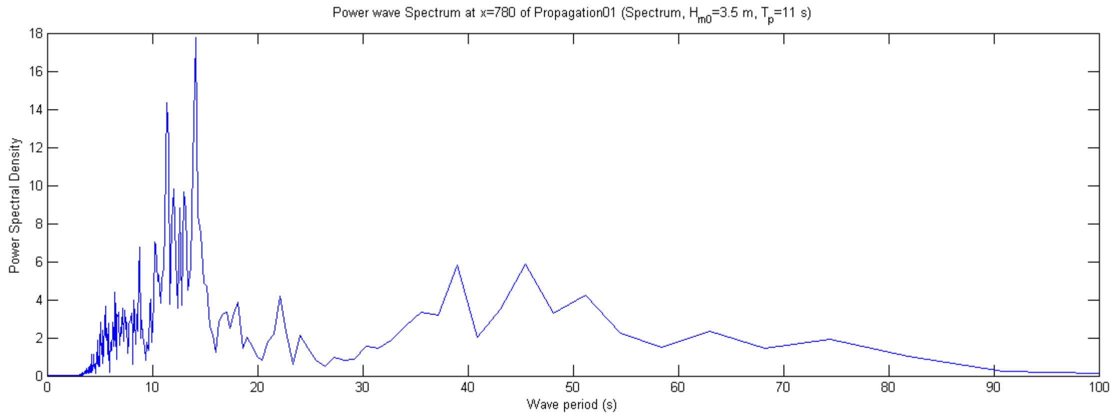

Figure A.106. Wave spectrum at the toe location of Propagation01.sws.

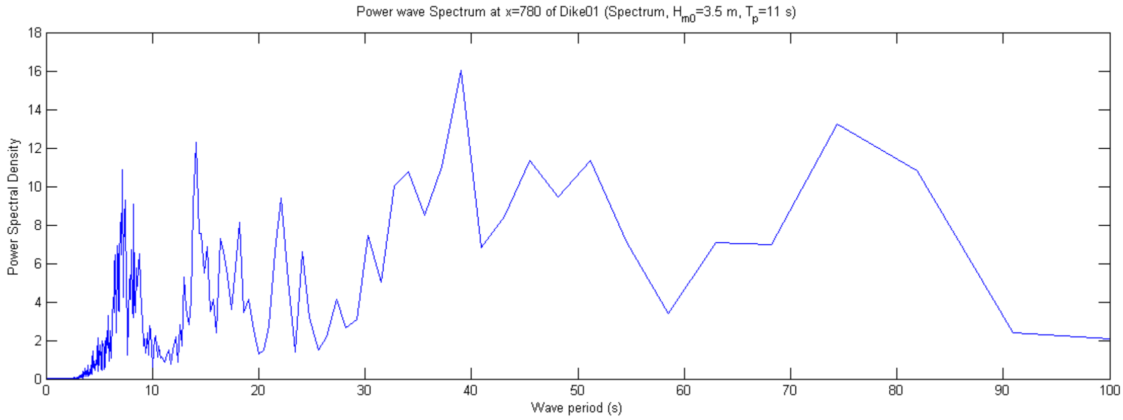

Figure A.107. Wave spectrum the toe location of Dike01.sws.

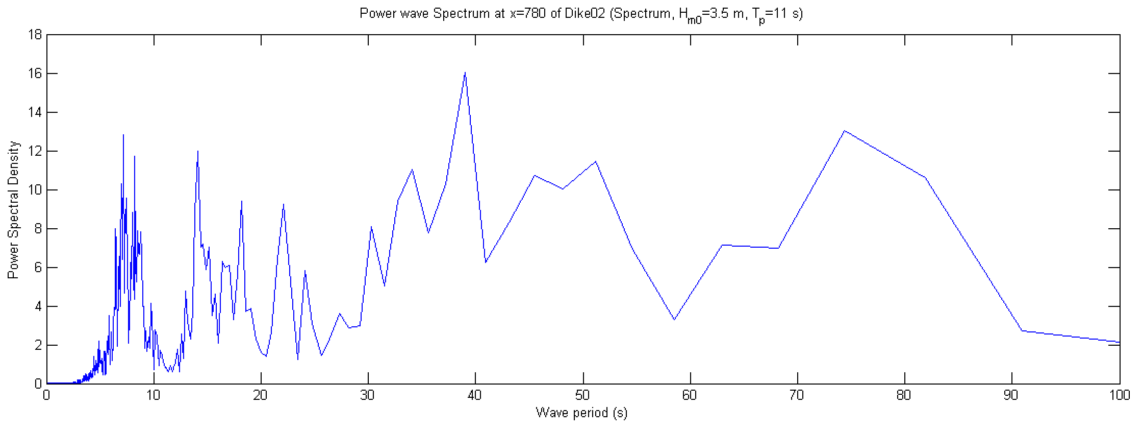

Figure A.108. Wave spectrum at the toe location m of Dike02.sws.

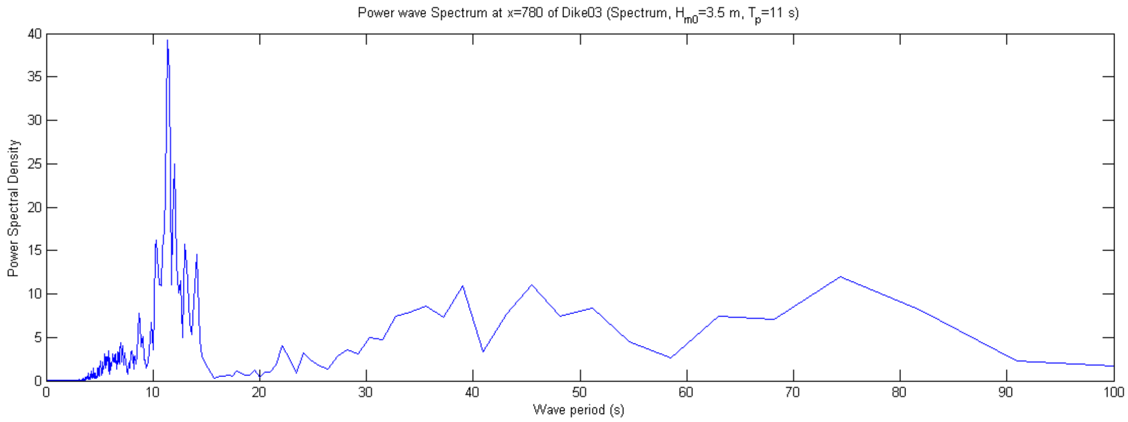

Figure A.109. Wave spectrum at the toe location of Dike03.sws.

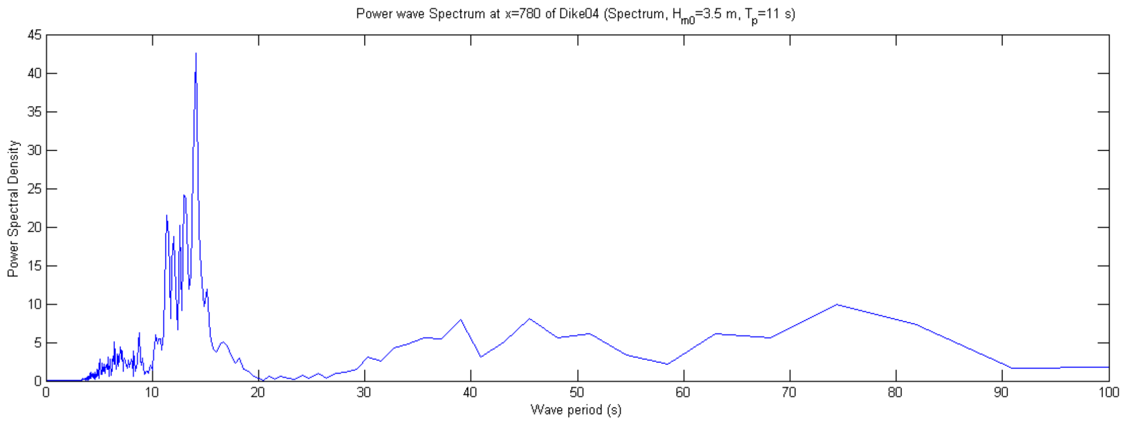

Figure A.110. Wave spectrum at the toe location of Dike04.sws.

Apparently, SWASH computes quite accurate wave overtopping giving results smaller than the estimated values from the formulas of the Wave Overtopping Manual. These empirical formulas tend to overestimate the discharge, so a smaller value predicted by SWASH will be on the safe side. If I consider only the incoming wave (whose data was recorded in Propagation01.sws), I predict a lower mean discharge through the empirical formulas of the Eurotop Manual than if I consider the measured wave at the toe of the breakwater with the structure itself, because of the wave reflection, which gives larger and longer waves.

Model	$R_c\ (m)$	Slope $(\tan \alpha)$	$\xi_{m-1,0}$	$q_{Eurotop}\ (l/sm)$	$q_{SWASH}\ (l/sm)$
Dike01.sws	2.5	1:2 (0.5)	7.59	715.1	267.0
Dike02.sws	5	1:2 (0.5)	7.27	198.6	22.8
Dike03.sws	5	1:3 (0.3333)	4.18	189.7	21.1
Dike04.sws	2.5	1:4 (0.25)	3.11	896.5	269.3

Table A.33. Overtopping discharges taking into account the reflected wave.

Model	$R_c\ (m)$	Slope	$\xi_{m-1,0}$	$q_{Eurotop}\ (l/sm)$	$q_{SWASH}\ (l/sm)$	$q_{NN}\ (l/sm)$
Dike01.sws	2.5	1:2	5.36	478.1	267.0	487.6
Dike02.sws	5	1:2	5.36	69.3	22.8	190.7
Dike03.sws	5	1:3	3.57	65.0	21.1	262.0
Dike04.sws	2.5	1:4	2.68	486.1	269.3	577.3

Table A.34. Overtopping discharges taking into account only the incoming wave.

Since I should use the wave values at the location of the toe of the structure without any interaction with it to compute wave overtopping, from now on, I will only comment the predictions given using this approach, i.e. the incoming wave without reflection.

Eq. 5.8 Eurotop Manual $\xi_{m-1,0} < 5$

$$\frac{q}{\sqrt{g \cdot H_{m0}{}^3}} = \frac{0.067}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left(\frac{-4.75 \cdot R_C}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)$$

$$= 0.067 \cdot T_{m-1,0} \cdot \sqrt{\frac{g \cdot \tan\alpha}{2\pi \cdot H_{m0}}} \cdot \gamma_b$$

$$\cdot \exp\left(\frac{-4.75 \cdot R_C}{H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v \cdot \tan\alpha \cdot T_{m-1,0}} \cdot \sqrt{\frac{2\pi}{g \cdot H_{m0}}}\right) \le 0.2 \cdot \exp\left(\frac{-R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

Eq. 5.11 Eurotop Manual $\xi_{m-1,0} > 7$

$$\frac{q}{\sqrt{g \cdot H_{m0}{}^3}} \le 10^{-0.92} \cdot \exp\left(\frac{-R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \left(0.33 + 0.022 \cdot \xi_{m-1,0}\right)}\right)$$

$$= 10^{-0.92} \cdot \exp\left(\frac{-R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \left(0.33 + 0.022 \cdot \tan\alpha \cdot T_{m-1,0} \cdot \sqrt{\frac{g}{2\pi \cdot H_{m0}}}\right)}\right)$$

After comparing the results from Dike01.sws and Dike02.sws, I can see that the influence of the crest level on wave overtopping is very important. In these two situations $5 < \xi_{m-1,0} < 7$, so I must use the formulas 5.8 and 5.11 of the Eurotop Manual and interpolate the results to compute wave overtopping. This last formula depends directly on the relative crest freeboard and $\xi_{m-1,0}$ although the influence of the second one is smaller.

The other dikes have a relatively large $\xi_{m-1,0}$ and wave overtopping should be computed through the second branch of the equation 5.8, which is an upper bound that does not depend on $\xi_{m-1,0}$ and only on the relative freeboard and the influence factors of slope roughness and wave obliqueness (this is also used for Dike01.sws and Dike02.sws). As a result, no comparisons strictly related to the slope can be made between these two tests. The slope does not affect much the waves at the toe (there is not a significant difference, only 0.1 m). In addition to this, and as it was expected, much larger overtopping is measured with a lower crest.

When we want to compare the results from the Dike01.sws and Dike02.sws with Dike03.sws and Dike04.sws, we must be aware that we are comparing 2 different formulas, or different stretches.

A small and ridiculous reduction of the overtopping discharge is found with milder slopes when there is a high crest, but the “same” one with low freeboards. However, these differences are very small, the numbers are very close and they have the same order of magnitude. It seems that there is no influence of the slope though and only on the freeboard. This could explain why the second stretch of equation 5.8 does not depend on the slope, and why in 5.11 the coefficient that multiplies $\xi_{m-1,0}$ or $(\tan\alpha)$ is 15 times smaller than the other, reducing the influence of the slope. Then, in this brief sensitivity analysis, the results measured in SWASH and the differences between the different cases are satisfactory and agree with the predictions given by the Eurotop formulas.

It would be interesting to test SWASH for even smaller Iribarren numbers. I think that the most interesting option would be decreasing the wave period instead of increasing the wave height or decreasing the slope.

Remember that I have used the values of the spectral analysis at the toe of the dike to compute the expected wave overtopping using the empirical formulations of Eurotop. The values recorded from the dike simulations include the reflected wave (which can not be dissipated in the flume). The data from only the incoming wave is obtained from Propagation01.sws, a simulation that propagates the same wave spectrum and measures the waves at the same point without the structure.

Note: All these 4 simulations have a duration time of 50 minutes and recorded the last 45 minutes.

Dike05.sws

In this script I have repeated Dike01.sws with a larger duration, since I have simulated 95 min and recorded the last 90 min. The results are expected to be very close to Dike01.sws and I will use the wave parameters recorded in Propagation03.sws to compute the expected overtopping with the Eurotop formulas.

The following tables summarize the wave parameters recorded at the wave generator and at the toe of the dike.

Measured data at x=0 m (Dike05.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 4.02\ m$	$T_m = 9.05\ s$	$H_{m0} = 4.24\ m$	$T_p = 10.62\ s$
$4 \cdot \sigma = 4.24\ m$	$3.8 \cdot \sigma = 4.03\ m$	$T_{m01} = 9.55\ s$	$T_{m-1,0} = 12.48\ s$

Table A.35. Wave parameters at x=0 m of Dike05.sws.

At the toe of the dike (x=780 m) the waves reduce, and I can observe a large number of peaks on the spectrum plot (figure A.111) and the presence of very long waves.

Measured data at x=780 m (Dike05.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.20\ m$	$T_m = 8.30\ s$	$H_{m0} = 3.65\ m$	$T_p = 45.44\ s$
$4 \cdot \sigma = 3.64\ m$	$3.8 \cdot \sigma = 3.46\ m$	$T_{m01} = 9.94\ s$	$T_{m-1,0} = 22.20\ s$

Table A.36. Wave parameters at x=780 m of Dike05.sws.

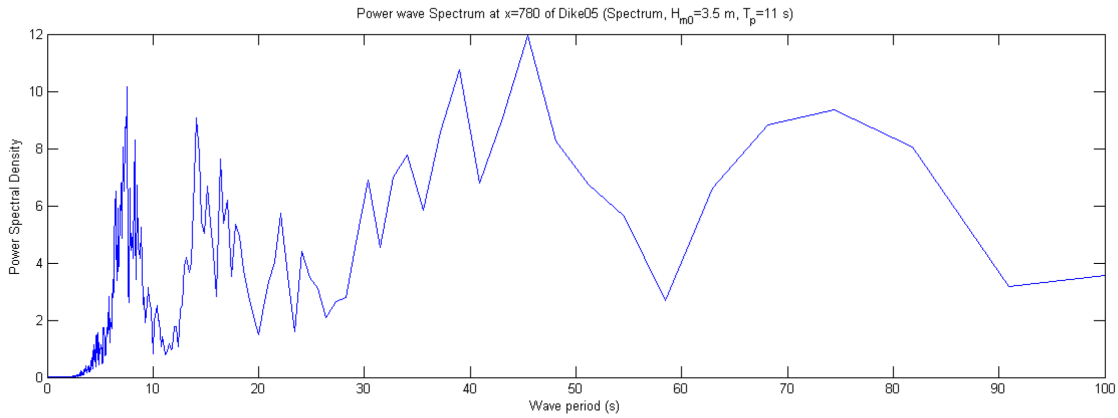

Figure A.111. Wave spectrum at x=780 of Dike05.sws.

With the following input parameters: $R_C = 2.5\ m$, $h = 10\ m$, $\tan\alpha = 0.5$, $H_{m0} = 3.19\ m$, $T_{m-1,0} = 14.35\ s$, and $\gamma_f = 1.0$, I expect to have a run-up of $R_{u2\%} = 10.62\ m$ and a mean overtopping discharge of $q = 464.8\ l/sm$. The mean discharge at the back of the crest is $q = 261.5\ l/sm$, so no significant changes are found with respect to Dike01.sws.

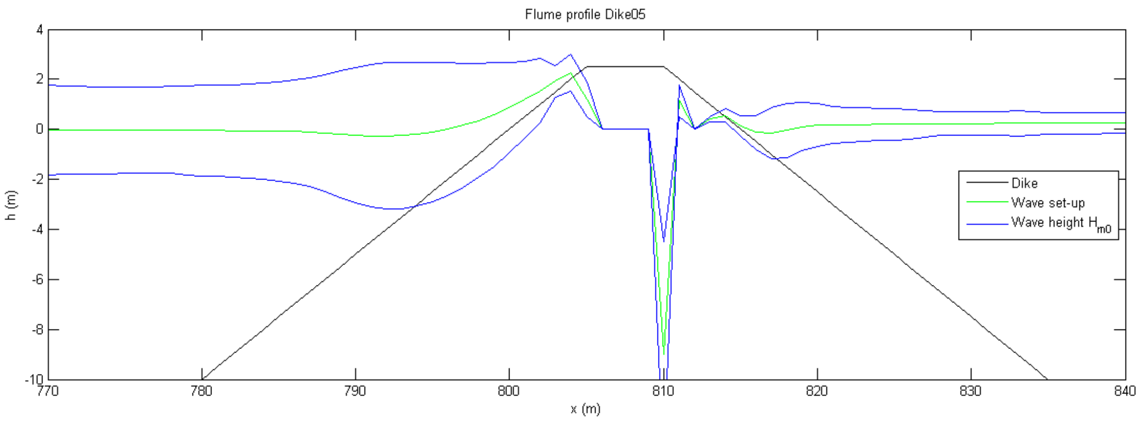

Figure A.112. Dike cross-section of Dike05.sws.

Dike06.sws

As in Dike05.sws, in this script I have repeated Dike02.sws with a larger duration time, since I have simulated 95 min and recorded the last 90 min. The wave parameters recorded in Propagation03.sws are used to compute the expected overtopping according to the Eurotop formulas. The freeboard has increased up to 5 m.

Measured data at x=0 m (Dike06.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 4.09\ m$	$T_m = 8.96\ s$	$H_{m0} = 4.33\ m$	$T_p = 10.76\ s$
$4 \cdot \sigma = 4.33\ m$	$3.8 \cdot \sigma = 4.11\ m$	$T_{m01} = 9.54\ s$	$T_{m-1,0} = 12.75\ s$

Table A.37. Wave parameters at x=0 m of Dike06.sws.

Measured data at x=780 m (Dike06.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.29\ m$	$T_m = 8.09\ s$	$H_{m0} = 3.76\ m$	$T_p = 7{,}57\ s$
$4 \cdot \sigma = 3.76\ m$	$3.8 \cdot \sigma = 3.57\ m$	$T_{m01} = 9.73\ s$	$T_{m-1,0} = 21.35\ s$

Table A.38. Wave parameters at x=780 m of Dike06.sws.

Also very much energy is concentrated in long waves at x=780 m. At this point there are many peaks too.

The expected wave overtopping using the Eurotop formulas is $q = 60.9\ l/sm$, while the measured discharge at the back of the crest in SWASH is $q = 20.9\ \ l/sm$.

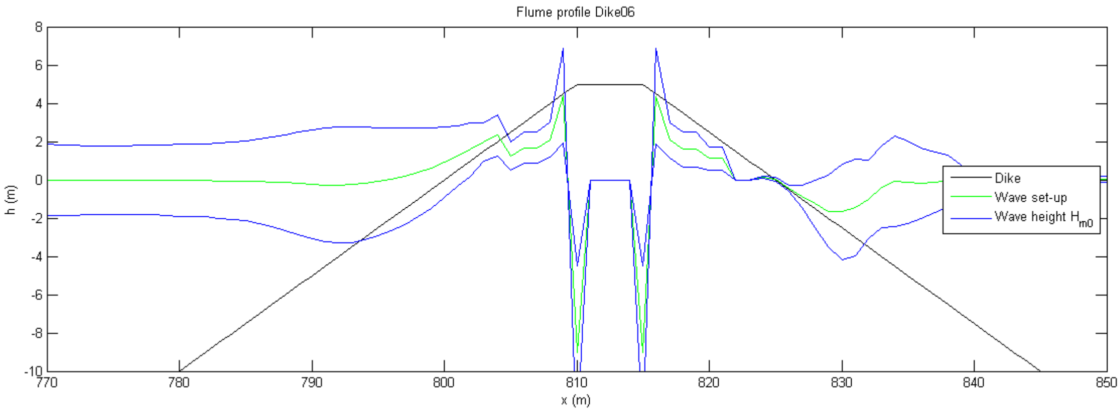

Figure A.113. Dike cross-section of Dike06.sws.

Dike07.sws

I have repeated the simulation Dike03.sws increasing the recorded duration to 90 min. The data from the incoming wave without reflection is given in Propagation03.sws. The dike profile is described now in Dike03.bot (1:3 slope, 5 m freeboard).

Measured data at x=0 m (Dike07.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.95\ m$	$T_m = 9.31\ s$	$H_{m0} = 4.14\ m$	$T_p = 11.36\ s$
$4 \cdot \sigma = 4.14\ m$	$3.8 \cdot \sigma = 3.94\ m$	$T_{m01} = 9.70\ s$	$T_{m-1,0} = 12.49\ s$

Table A.39. Wave parameters at x=0 m of Dike07.sws.

Measured data at x=780 m (Dike07.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.67\ m$	$T_m = 9.90\ s$	$H_{m0} = 3.96\ m$	$T_p = 11.52\ s$
$4 \cdot \sigma = 3.96\ m$	$3.8 \cdot \sigma = 3.76\ m$	$T_{m01} = 10.30\ s$	$T_{m-1,0} = 19.05\ s$

Table A.40. Wave parameters at x=780 m of Dike07.sws.

The expected wave overtopping using the Eurotop formulas is $q = 60.6\ l/sm$, while the measured discharge at the back of the crest in SWASH is $q = 18.3\ \ l/sm$.

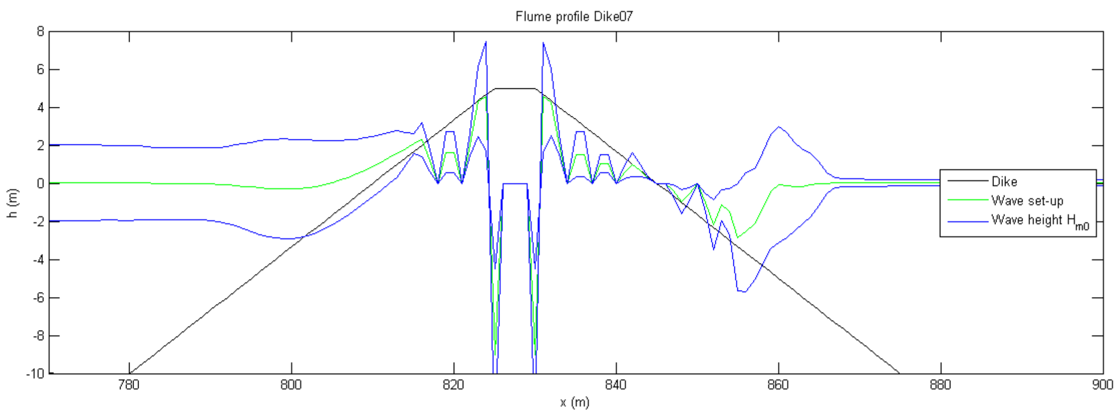

Figure A.114. Dike cross-section of Dike07.sws.

Dike08.sws

I have repeated the simulation Dike04.sws increasing the recorded duration to 90 min. As in the previous cases, overtopping is computed from the incoming wave without reflection recorded in Propagation03.sws. The dike profile is described now in Dike04.bot (1:4 slope, 2.5 m freeboard).

Measured data at x=0 m (Dike08.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.68\ m$	$T_m = 9.12\ s$	$H_{m0} = 3.90\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.90\ m$	$3.8 \cdot \sigma = 3.70\ m$	$T_{m01} = 9.67 s$	$T_{m-1,0} = 12.54\ s$

Table A.41. Wave parameters recorded at x=0 m of Dike08.sws.

Measured data at x=780 m (Dike08.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.57\ m$	$T_m = 9.59\ s$	$H_{m0} = 3.85\ m$	$T_p = 14.10\ s$
$4 \cdot \sigma = 3.85\ m$	$3.8 \cdot \sigma = 3.65\ m$	$T_{m01} = 10.38\ s$	$T_{m-1,0} = 18.66\ s$

Table A.42. Wave parameters recorded at x=780 m of Dike08.sws.

The expected wave overtopping using the Eurotop formulas is $q = 465.2\ l/sm$, while the measured discharge at the back of the crest in SWASH is $q = 260.4\ \ l/sm$.

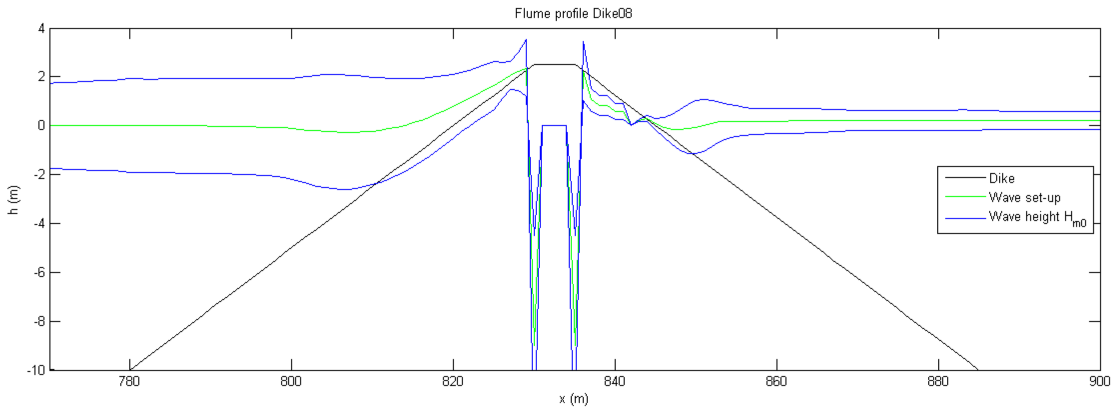

Figure A.115. Dike cross-section of Dike09.sws.

Dike09.sws

In this script I have tested a dike with a freeboard of 2.5 m and a slope of 1:2 (Dike01.bot), but now with lower waves ($H_{m0} = 2\ m$ and $T_p = 7\ s$). These waves were propagated without any structure in Propagation10.sws to measure the incoming wave needed for the overtopping calculations.

Measured data at x=0 m (Dike09.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.27\ m$	$T_m = 5.85\ s$	$H_{m0} = 2.34\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 2.34\ m$	$3.8 \cdot \sigma = 2.20\ m$	$T_{m01} = 6.14\ s$	$T_{m-1,0} = 7.21\ s$

Table A.43. Wave parameters at x=0 m of Dike09.sws.

Measured data at x=780 m (Dike09.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.54\ m$	$T_m = 6.81\ s$	$H_{m0} = 2.64\ m$	$T_p = 7.11\ s$
$4 \cdot \sigma = 2.64\ m$	$3.8 \cdot \sigma = 2.51\ m$	$T_{m01} = 6.91\ s$	$T_{m-1,0} = 8.86\ s$

Table A.44. Wave parameters at x=780 m of Dike09.sws.

The long waves recorded at the toe of the dike are negligible. Some reflection and slightly longer periods are found compared with the data recorded in Propagation10.sws.

According to the Eurotop formulas, the expected run-up is $R_{u2\%} = 5.86\ m$ and the overtopping $q = 43.2\ l/sm$. However, the measured overtopping at the back of the crest is much lower: $q = 3.8\ l/sm$. The measured overtopping at the seaward edge of the crest is $q = 12.0\ l/sm$.

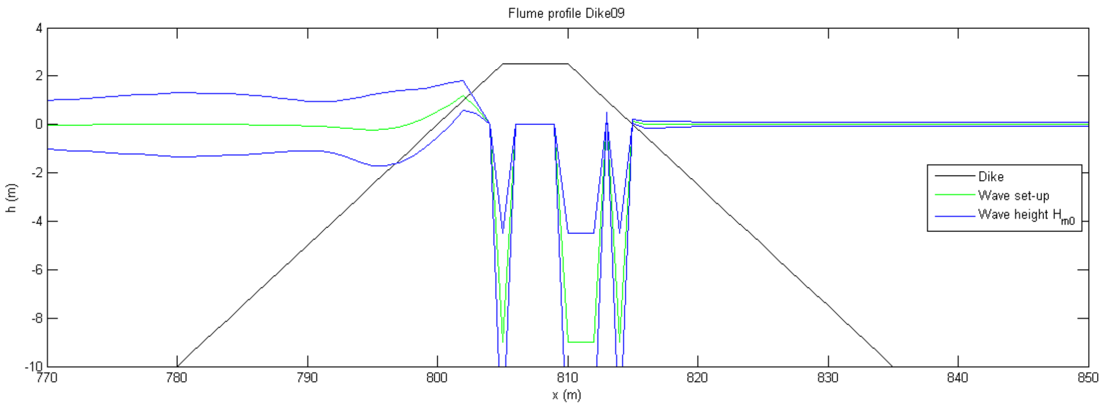

Figure A.116. Dike cross-section of Dike09.sws.

Dike10.sws

I tested the same dike as in Dike05.sws and Dike09.sws with even a lower wave ($H_{m0} = 1.5\ m$ and $T_p = 7\ s$). The incoming wave without structure reflection was recorded in Propagation11.sws.

Measured data at x=0 m (Dike10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.72\ m$	$T_m = 5.84\ s$	$H_{m0} = 1.78\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 1.78\ m$	$3.8 \cdot \sigma = 1.69\ m$	$T_{m01} = 6.14\ s$	$T_{m-1,0} = 6.95\ s$

Table A.45. Wave parameters at x=0 m of Dike10.sws.

Measured data at x=780 m (Dike10.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.00\ m$	$T_m = 6.72\ s$	$H_{m0} = 2.06\ m$	$T_p = 7.11\ s$
$4 \cdot \sigma = 2.06\ m$	$3.8 \cdot \sigma = 1.96\ m$	$T_{m01} = 6.80\ s$	$T_{m-1,0} = 8.00\ s$

Table A.46. Wave parameters at x=780 m of Dike10.sws.

According to the Eurotop formulas, the expected run-up is $R_{u2\%} = 4.54\ m$ and the overtopping $q = 10.0\ l/sm$. The measured overtopping at the seaward edge of the crest is $q = 1.5\ l/sm$, and only 2 single waves reach the back slope, which makes that the measured discharge there is $q = 0.43\ l/sm$. This value is very much lower than the predicted one, but the discharge is very low and there is a low reliability in this range of very low overtopping.

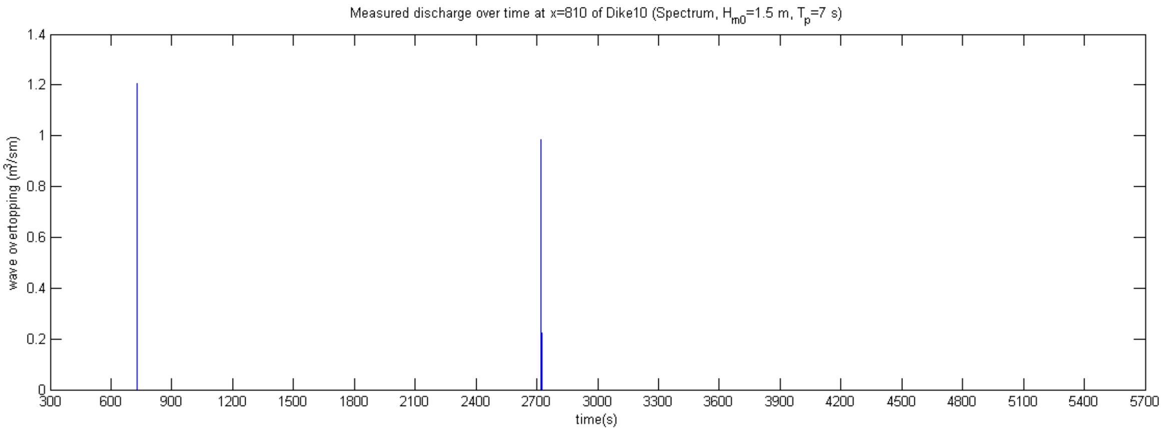

Figure A.117. Overtopping discharge at the top of the inner slope of Dike10.sws

Dike11.sws

In this script I have tested a dike with a freeboard of 5 m and a slope of 1:2 (Dike02.bot). The input wave parameters are $H_{m0} = 2\ m$ and $T_p = 7\ s$. Wave overtopping is computed using the recorded values in Propagation10.sws

Measured data at x=0 m (Dike11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.28\ m$	$T_m = 5.85\ s$	$H_{m0} = 2.34\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 2.34\ m$	$3.8 \cdot \sigma = 2.23\ m$	$T_{m01} = 6.15\ s$	$T_{m-1,0} = 7.20\ s$

Table A.47. Wave parameters at x=0 m of Dike11.sws.

Measured data at x=780 m (Dike11.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.56\ m$	$T_m = 6.85\ s$	$H_{m0} = 2.66\ m$	$T_p = 7.11\ s$
$4 \cdot \sigma = 2.66\ m$	$3.8 \cdot \sigma = 2.52\ m$	$T_{m01} = 6.91\ s$	$T_{m-1,0} = 8.79\ s$

Table A.48. Wave parameters at x=780 m of Dike11.sws.

The expected overtopping is very low: $q = 1.22\ l/sm$. SWASH has not measured any discharge above the crest. In fact, no waves have reached the crest.

Dike12.sws

In this script I have tested a dike with a freeboard of 5 m and a slope of 1:3 (Dike03.bot). The input wave parameters are $H_{m0} = 2\ m$ and $T_p = 7\ s$. Wave overtopping is computed using the recorded values in Propagation10.sws.

Small reflection is found in this flume due to the gentle slope of the dike, but long waves are observed, probably because of slow run-up and run-down along the mild slope.

Measured data at x=0 m (Dike12.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.09\ m$	$T_m = 5.82\ s$	$H_{m0} = 2.17\ m$	$T_p = 6.99\ s$
$4 \cdot \sigma = 2.17\ m$	$3.8 \cdot \sigma = 2.06\ m$	$T_{m01} = 6.05\ s$	$T_{m-1,0} = 7.11\ s$

Table A.49. Wave parameters at x=0 m of Dike12.sws.

Measured data at x=780 m (Dike12.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.77\ m$	$T_m = 6.49\ s$	$H_{m0} = 1.88\ m$	$T_p = 6.87\ s$
$4 \cdot \sigma = 1.88\ m$	$3.8 \cdot \sigma = 1.79\ m$	$T_{m01} = 6.76\ s$	$T_{m-1,0} = 10.72\ s$

Table A.50. Wave parameters at x=780 m of Dike12.sws.

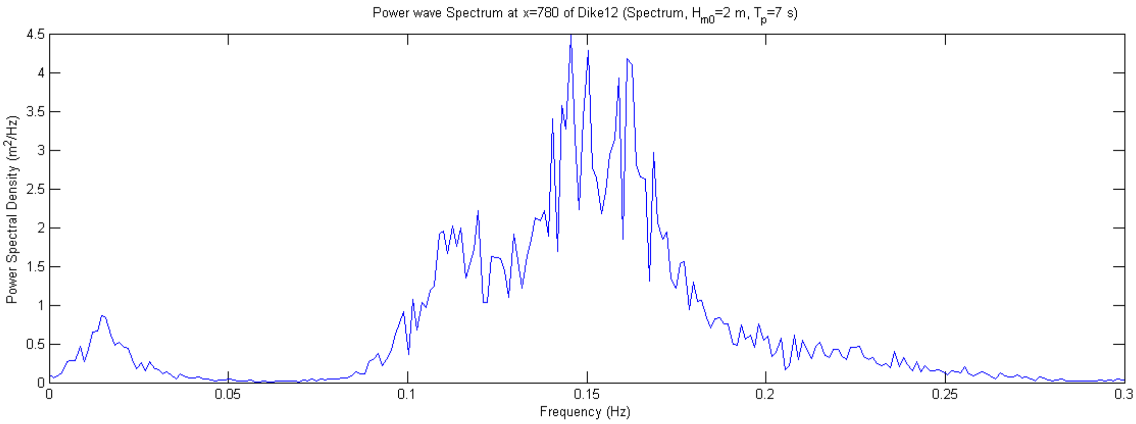

Figure A.118. Wave spectrum at x=780 of Dike12.sws.

According to the Eurotop formulas, the expected run-up is $R_{u2\%} = 5.54\ m$ and the overtopping, $q = 1.22\ l/sm$. As in the last script, there are no waves reaching the crest level and thus, there is no overtopping.

Dike13.sws

In this script I have tested a dike with a freeboard of 2.5 m and a slope of 1:4 (Dike04.bot). The input wave parameters are $H_{m0} = 2\ m$ and $T_p = 7\ s$. Wave overtopping is computed using the recorded values in Propagation10.sws

Measured data at x=0 m (Dike13.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.02\ m$	$T_m = 5.73\ s$	$H_{m0} = 2.11\ m$	$T_p = 7.05\ s$
$4 \cdot \sigma = 2.11\ m$	$3.8 \cdot \sigma = 2.01\ m$	$T_{m01} = 5.99\ s$	$T_{m-1,0} = 7.11\ s$

Table A.51. Wave parameters at x=0 m of Dike13.sws.

Measured data at x=780 m (Dike13.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.82\ m$	$T_m = 6.56\ s$	$H_{m0} = 1.95\ m$	$T_p = 7.11\ s$
$4 \cdot \sigma = 1.95\ m$	$3.8 \cdot \sigma = 1.85\ m$	$T_{m01} = 6.77\ s$	$T_{m-1,0} = 9.90\ s$

Table A.52. Wave parameters at x=780 m of Dike13.sws.

Using the Eurotop formulas with the wave values recorded in Propagation10.sws without the dike, the expected run-up is $R_{u2\%} = 5.27\ m$ and the overtopping is $q = 43.2\ l/sm$, as in Dike09.sws with the same freeboard. No overtopping is measured at the back of the crest.

A.5. First trials with a porous structure

The height of the structure is defined through Dike01.hst. It has the same dimensions as the dike defined in the last section through Dike01.bot although in that case there was a reduction of the bottom depth and not a structure over the bottom.

Smooth01.sws

This was my first attempt trying to model an impermeable smooth dike using the 3 grids (HSTRUCTURE, POROSITY, PSIZE). Dike01.n defined zero porosity and Dike01.psz a very small grain size (10^{-8} m).

Spectrum waves were introduced and the command break activated.

Quite reflection was observed at the beginning of the flume and long waves at the toe. Nothing was recorded beyond the toe of the dike. It looked like there was a wall and no water elevation was recorded there. I concluded that there was something wrong with the porosity and grain size definition.

Smooth02.sws

The code is the same of Smooth02.sws. The purpose of this script was to see what happens if the command BREAK is not activated. The problem was not solved.

Smooth03.sws

I test the same situation with regular waves (H=3.5 m and T=10 s) to confirm if there is reflection. Here also nothing was registered beyond the toe of the dike.

I needed 3 vertical layers to run the script. Otherwise I had negative water depths.

At x=0 m the waves surprisingly reduced. No regular waves were obtained although some wave grouping showed a kind of standing pattern. The significant wave height is 1.92 m and the mean period is 8.30 s. From spectral analysis, a spectral wave height of 2.16 m, a mean wave period of 8.43 s and a peak period of 9.98 s are obtained. The spectrum plot also shows a smaller peak at 5 s and an even smaller third at 3.3 s. These 3 peaks seem to show the 3 first harmonics.

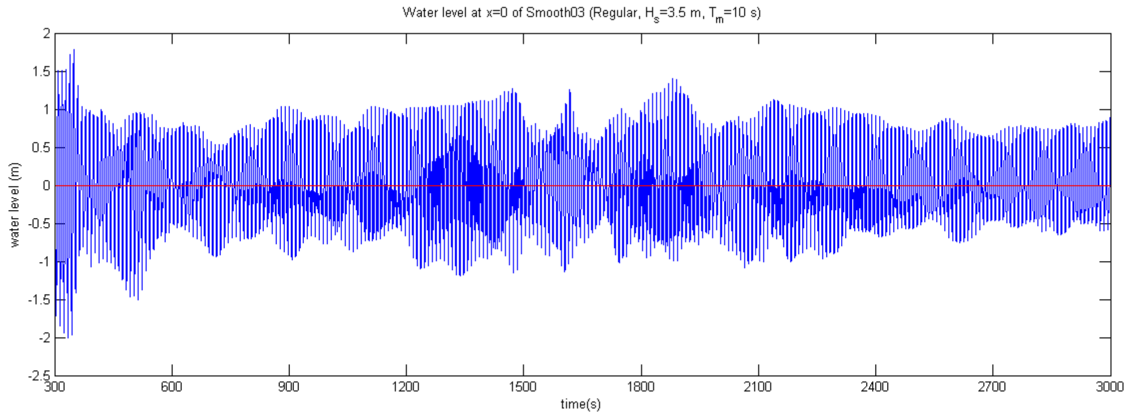

Figure A.119. Water elevation at x=0 of Smooth03.sws.

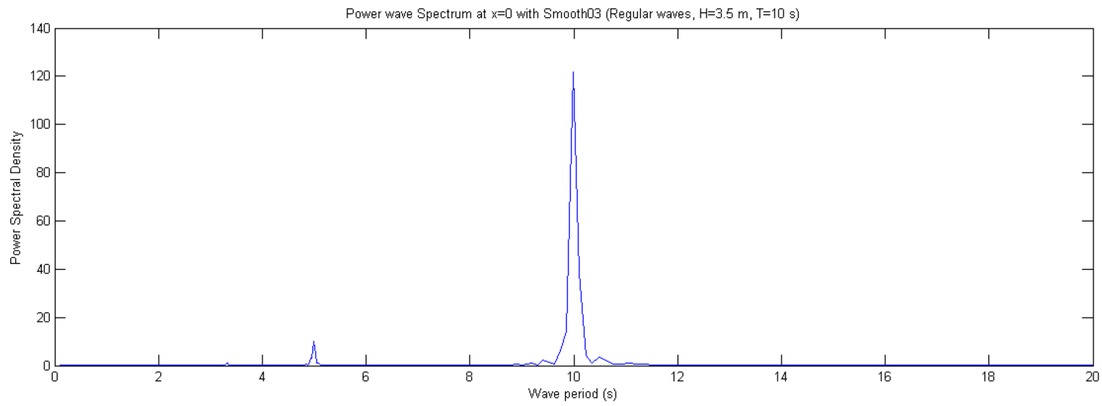

Figure A.120. Wave spectrum at x=0 of Smooth03.sws.

At x=780 m the waves are larger ($H_s = 3.12\ m, T_m = 8.97\ s$). There is a chaotic pattern with a mean water variations that looks like a standing long wave reflected by the dike. From spectral analysis a single and clear peak results at $T_p = 9.98\ s$. The spectral significant wave height is $H_{m0} = 3.77\ m$ and the mean wave period is $T_{m01} = 8.56\ s$.

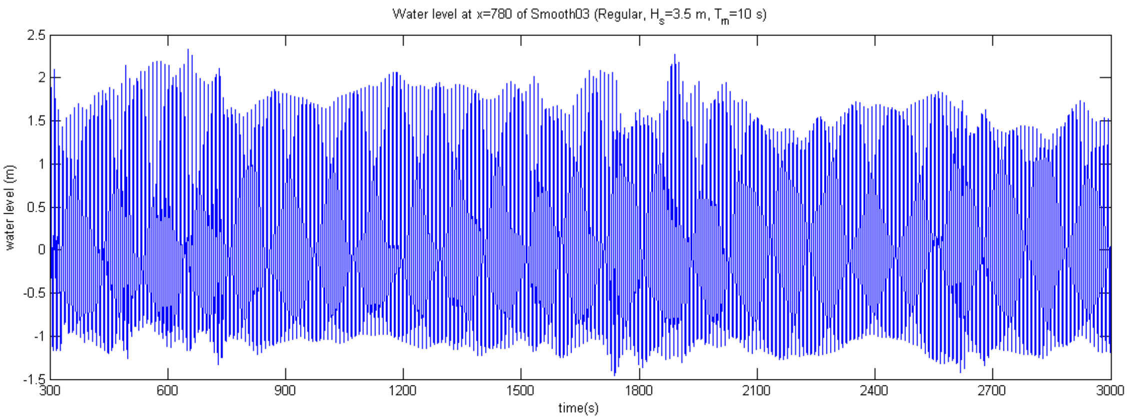

Figure A.121 Water elevation at x=780 m of Smooth03.sws.

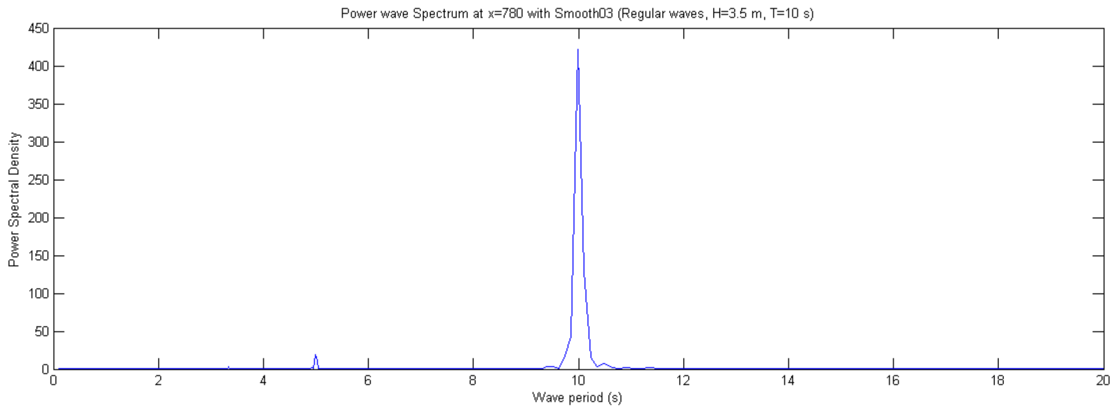

Figure A.122. Wave spectrum at x=780 m of Smooth03.sws.

I performed the tests Smooth04.sws, Smooth04_2.sws and Smooth04_3.sws with a porosity that was a weighted value between the water height and the structure height, but they were just trials to see if the computation worked. They are not interesting and hence, not commented here.

Smooth05.sws

After some unsuccessful attempts and after the experience of Dike01.sws I tried with a more porous structure with porosity equal to 0.2 (Dike03.n) and a larger grain size of 0.1 m (Mound01.psz) and it worked. As a result, I have measured overtopping over the dike and values along the flume.

I have no longer a smooth dike, but a quite impervious rubble mound, but I keep the name since it was an improvement of the last scripts to see if it worked.

I have introduced the usual spectrum waves ($H_{m0} = 3.5\ m$ and $T_p = 11\ s$).

At x=0 m, I measure $H_s = 4.11\ m$ and $T_m = 9.10\ s$. From spectral analysis I get $H_{m0} = 4.33\ m$, $T_{m01} = 9.73\ s$, $T_p = 10.91\ s$ and $T_{m-1,0} = 13.14\ s$. The wave spectrum presents some peaks, but probably it will be a bi-modal spectrum with a large peak at 11 s and a second one at 14 s. There is some wave reflection although it is not easily seen here. In Smooth06.sws where regular waves are performed it is clearer.

At the toe of the dike (x=780 m), the significant wave height is $H_s = 2.10\ m$ and the mean wave period, $T_m = 10.98\ s$. From spectral analysis: $H_{m0} = 2.42\ m$, $T_{m01} = 12.84\ s$, $T_p = 14.11\ s$ and $T_{m-1,0} = 25.54\ s$. Long waves are observed, probably by the influence of the structure.

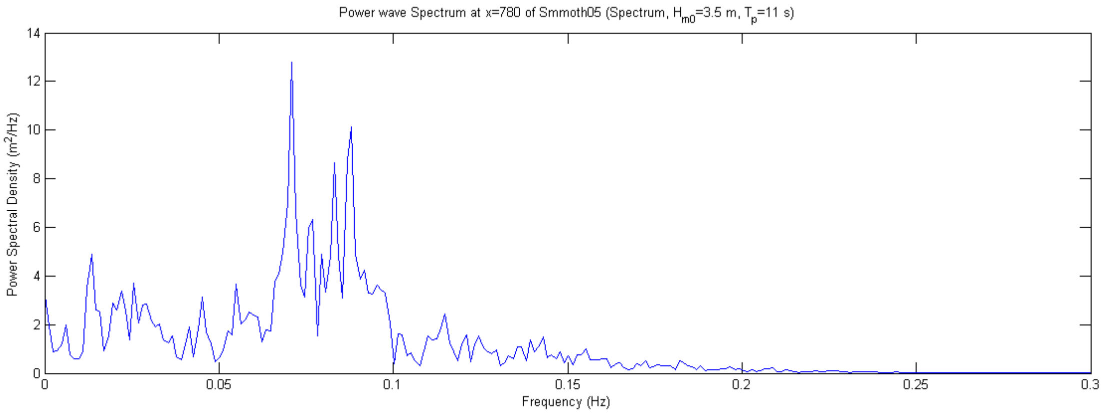

Figure A.123. Wave spectrum at x=780 m of Smooth05.sws.

I have measured overtopping at the top of the front slope as a time-discharge series. From the graph and with some zoom, it can be seen that (almost) each wave overtops. The mean discharge is $q = 4.14 \cdot 10^{-2}\ m^3/sm = 41.4\ l/sm$. It is far lower than the smooth and impermeable dike (see Dike01.sws) with the same freeboard. At the end of the crest (edge with the back slope), the mean overtopping is $q = 3.43 \cdot 10^{-2}\ m^3/sm = 34.3\ l/sm$. However, they were the absolute discharge values. If I consider the discharge vector (with direction), the net discharge is $q = 6.0\ l/sm$. It is important to realize when looking at the discharge plots that each wave has to peaks, which correspond to the “orbital velocities” of crest and trough.

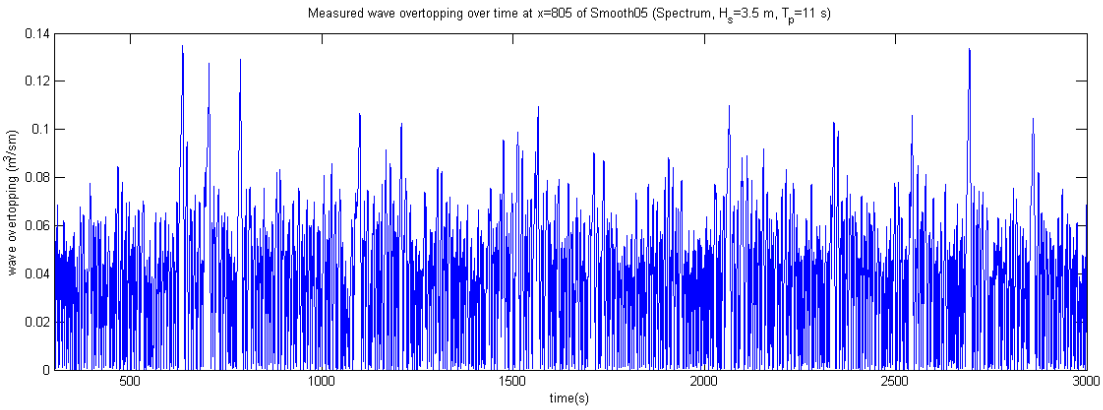

Figure A.124. Overtopping discharge at the top of the outer slope of Smooth05.sws.

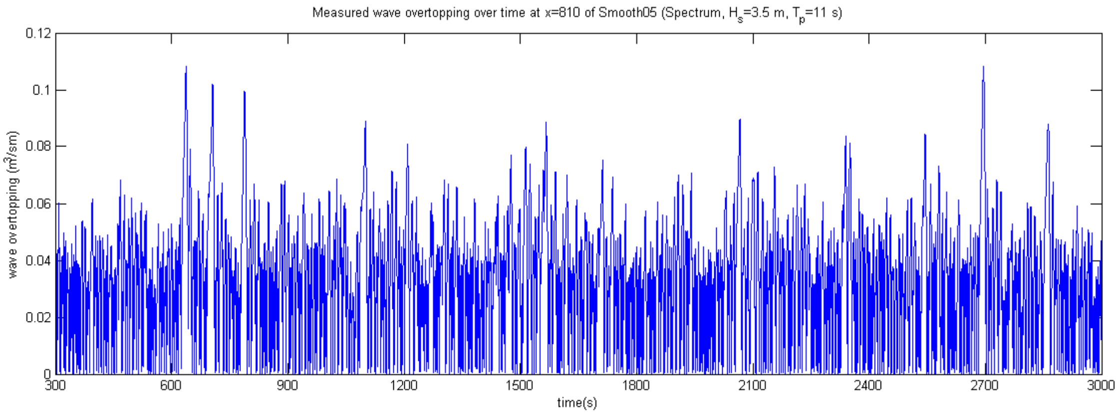

Figure A.125. Overtopping discharges at the top of the outer slope of Smooth05.sws.

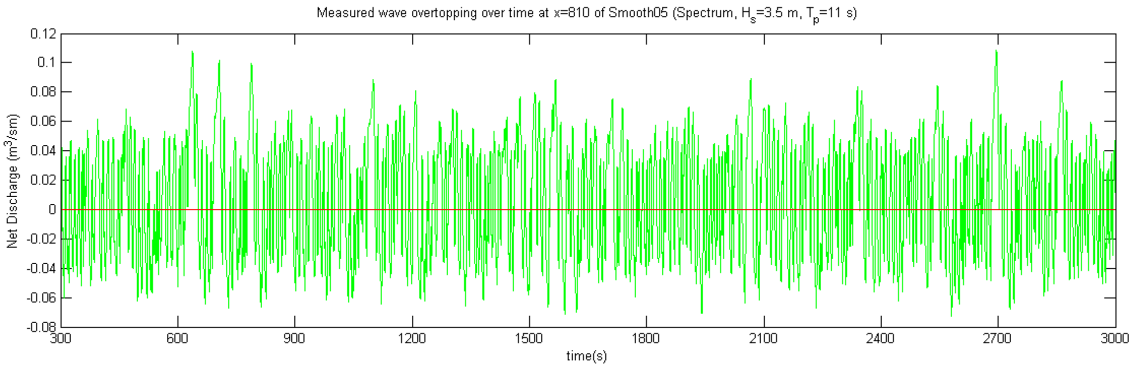

Figure A.126. Net discharges at the cross-section of the top of the outer slope of Smooth05.sws.

Using the formulas and coefficients given in the Eurotop Manual for rubble mound breakwaters I can predict run-up and overtopping discharge. The input parameters are: $R_C = 2.5\,m$, $h = 10\,m$, $\tan\alpha = 0.5$, $H_{m0} = 3.5\,m$, $T_{m-1,0} = 10\,s$ and $\beta = 0°$. For the slope roughness I have considered a single rock layer over an impermeable core ($\gamma_f = 0.6$) although this structure is strange and unrealistic. This results in a wave run-up of $R_{u2\%} = 7.512\,m$ (although there is a second upper boundary for 2.11 times the wave height, which gives 7.385 m) and a mean overtopping discharge of $q = 6.665 \cdot 10^{-2}\ m^3/sm = 66.65\ l/sm$.

If I compute it with the measured values at the toe of the structure I get $q = 3.7\ l/sm$ (if I do not consider the crest width reduction $q = 26.8\ l/sm$). This is much smaller than the measured one! If I try with $\gamma_f = 0.8$, I get $q = 11.3\ l/sm$ (without crest width reduction $q = 82.1\ l/sm$). The measured net discharge is between these two values. No clear conclusions can be drown, because of the results and due to the fact that the structure is very strange and I do not know if I have used the right empirical formula and factors. Therefore, it would be better to directly test a rubble mound breakwater with larger stones that we can better model.

Smooth06.sws

It is the same script as Smooth05.sws, but changing spectrum waves for regular waves (wave height of 3.5 m and period of 10 s). Wave reflection is then observed at the wave generator.

At x=0 m, the mean wave height is 5.13 m and the mean period 10.00 s. Since regular waves do not give me any problem, around an increase of 1.60 m of wave height due to reflexion is clear.

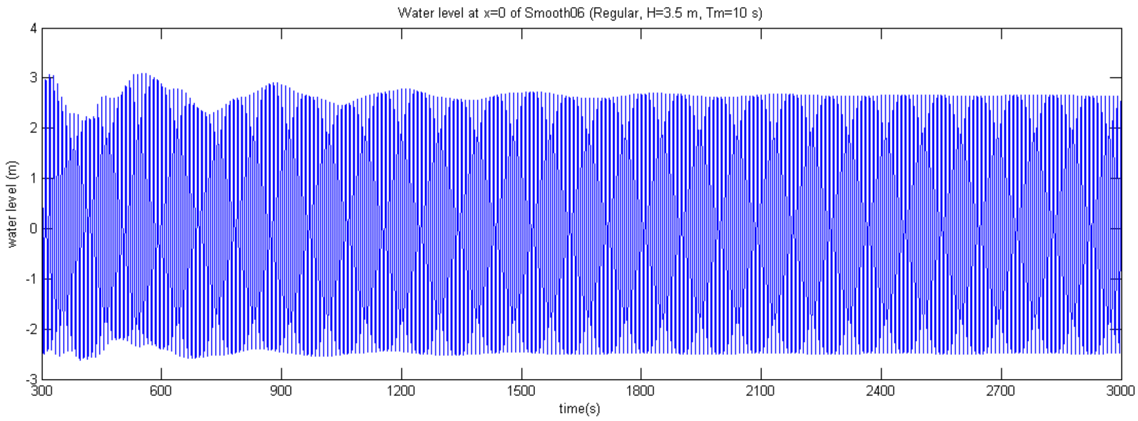

Figure A.127. Water elevation at x=0 m of Smooth06.sws.

At x=780 m the mean wave height is 2.03 m and the mean wave period 10 s. The waves are smaller, but regular although they start tilting.

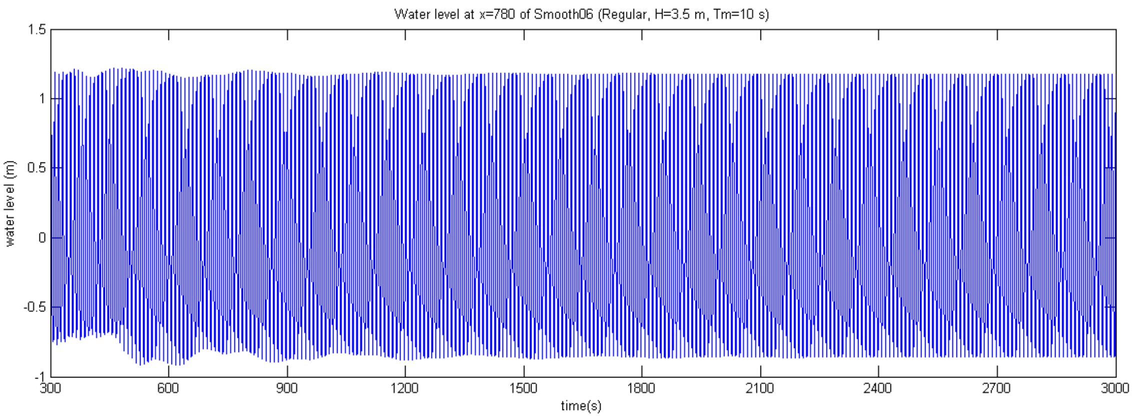

Figure A.128. Water elevation at x=780 m of Smooth06.sws.

As it can be expected, wave overtopping measured at the beginning of the crest is also very regular with a mean value of $q = 3.94 \cdot 10^{-2}\ m^3/sm = 39.4\ l/sm$. The value is very close to the one obtained with irregular (spectrum) waves with the same representative parameters. The mean overtopping at the back of the crest is $q = 28\ l/sm$. The net discharge is $q = -7.3\ l/sm$, which does not make any sense!

If I compute the wave overtopping with the data at the toe, the discharge decreases from $q = 6.665 \cdot 10^{-2}\ m^3/sm = 66.65\ l/sm$ until $q = 6.632 \cdot 10^{-4}\ m^3/sm = 0.6632\ l/sm$ (including crest width reduction). There is a large reduction. However, these formulas may not be applicable for regular waves. I do not know the reason of the negative net discharge.

A.6. Rubble mound breakwater with an impermeable core

First I will verify if SWASH gives good predictions of wave overtopping discharge in rubble mound breakwaters with an impermeable core. The results will be compared with the empirical formulas of the Eurotop Manual for rubble mound breakwaters. The formulas consider a reduction due to the armour crest width.

I have considered in all cases a breakwater with a "grain" size of 1 m. The roughness factor is $\gamma_f = 0.6$ (one rock layer over an impermeable core) and the porosity is $n = 0.35$. Remember that I can only define a global porosity value for the whole breakwater.

Imp_Mound01.sws

In this script I test a rubble mound breakwater with a crest level 2.5 m above water level and slope 1:2. The crest width is 5 m. The structure height over the bottom level is defined in Mound01.hst, the grain size in Mound02.psz, and the porosity in Imp_Mound01.n.

I have introduced the same spectrum waves, defined by a Jonswap spectrum with $\gamma = 3.3$, $H_{m0} = 3.5\ m$, $T_p = 11\ s$ and a storm duration of 2 h. I have simulated 50 minutes and recorded the last 45 min. The two tables below summarize the wave parameters.

Measured data at x=0 m (Imp_Mound01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.89\ m$	$T_m = 9.04\ s$	$H_{m0} = 4.03\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.03\ m$	$3.8 \cdot \sigma = 3.83\ m$	$T_{m01} = 9.47\ s$	$T_{m-1,0} = 11.85\ s$

Table A.53. Wave parameters at x=0 m of Imp_Mound01.sws.

Measured data at x=780 m (Imp_Mound01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.64\ m$	$T_m = 10.24\ s$	$H_{m0} = 2.95\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.95\ m$	$3.8 \cdot \sigma = 2.80\ m$	$T_{m01} = 11.37\ s$	$T_{m-1,0} = 21.69\ s$

Table A.54. Wave parameters at x=780 m of Imp_Mound01.sws.

At the toe of the breakwater (x=780 m) a bimodal spectrum with a second peak at 11.4 s and some long waves with T=30-80 s is observed. Notice that the wave heights are smaller than in Dike01.sws due to the breakwater armour porosity.

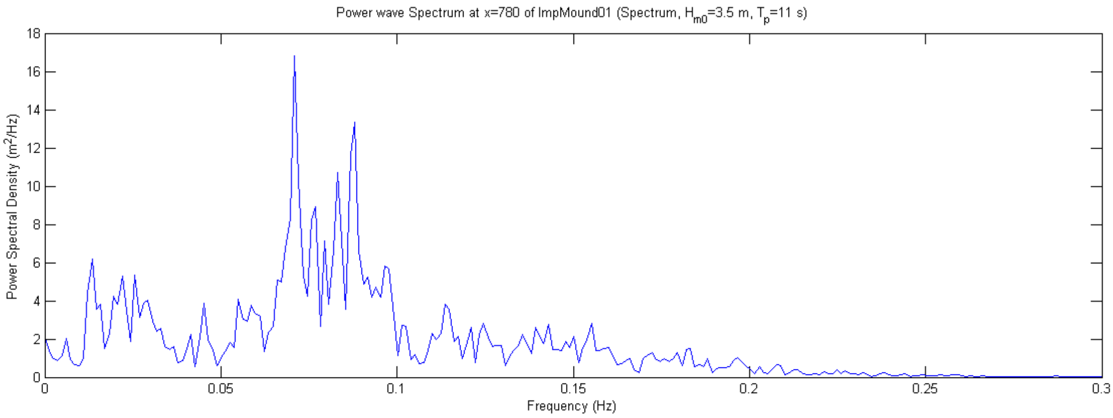

Figure A.129. Wave spectrum at x=780 m of Imp_Mound01.sws.

The input parameters to compute wave overtopping are: $R_C = 2.5\ m$, $h = 10\ m$, $\tan\alpha = 0.5$, $H_{m0} = 2.95\ m$, $T_{m-1,0} = 21.69\ s$ ($\xi_{m-1,0} = 7.89$), $\gamma_\beta = 1.0$ and $\gamma_f = 0.6$; and the expected run-up is $R_{u2\%} = 9.17\ m$ and the mean overtopping is $q = 19.4\ l/sm$ (including crest width reduction). If I do not consider the effect of the breakwater on waves and I only use the incoming wave parameters (measured in Propagation01.sws), I obtain $H_{m0} = 3.23\ m$, $T_{m-1,0} = 15.42\ s$ ($\xi_{m-1,0} = 5.36$), $R_{u2\%} = 8.38\ m$ and $q = 38.1\ l/sm$. Notice that the expected overtopping is very small compared with any dike. It is much lower than the dike with the same slope and freeboard (8%) and same slope and twice as high (55%).

At x=805 m (top of the seaward slope) I measure a mean discharge of $q = 582.6\ l/sm$, whereas at the end of the crest, I measure $q = 580.9\ l/sm$. I can see how each wave has an associated discharge with some zoom. The explanation is simple: SWASH measures the discharge that goes through this cross-section including all the water that flows through the breakwater. I did not have this problem with dikes, because they were impermeable and introduced as a bottom variation, so I could only measure the water that travelled over it. Now I have water that overtops and water that goes through the breakwater, which is a kind of box with an average porosity for SWASH rather than 2 layers with different permeability. In fact, I have measured water elevation inside the breakwater, which have reduced due to the lower porosity compared with water.

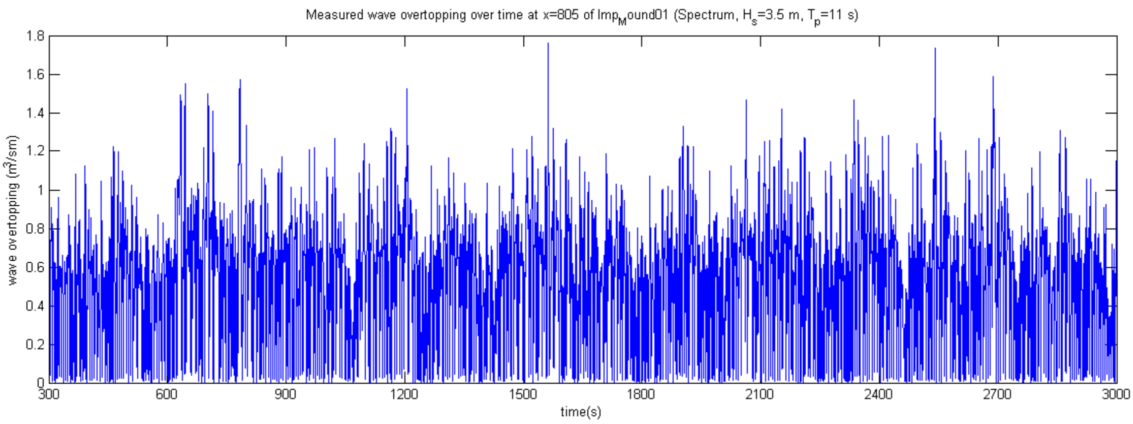

Figure A.130. Discharge at the cross-section of the beginning of the crest of Imp_Mound01.sws.

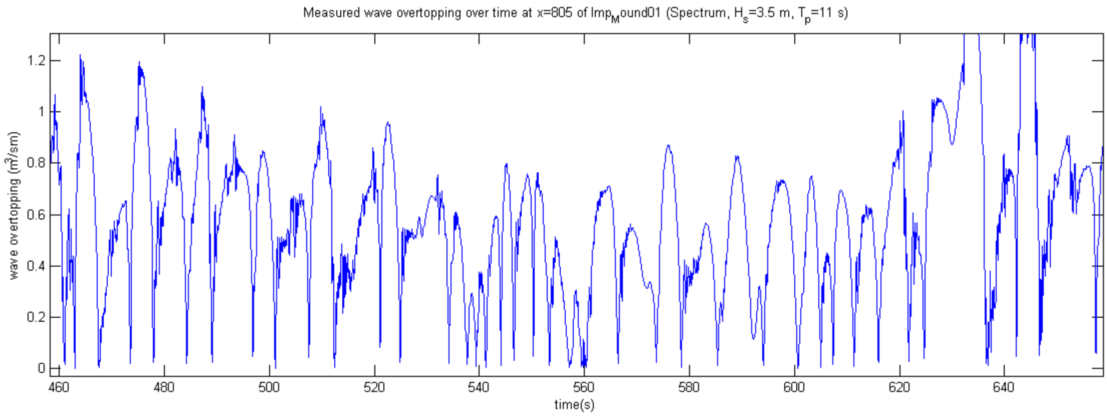

Figure A.131. Zoom in the recorded time-discharge at the cross-section x=805 m of Imp_Mound01.sws.

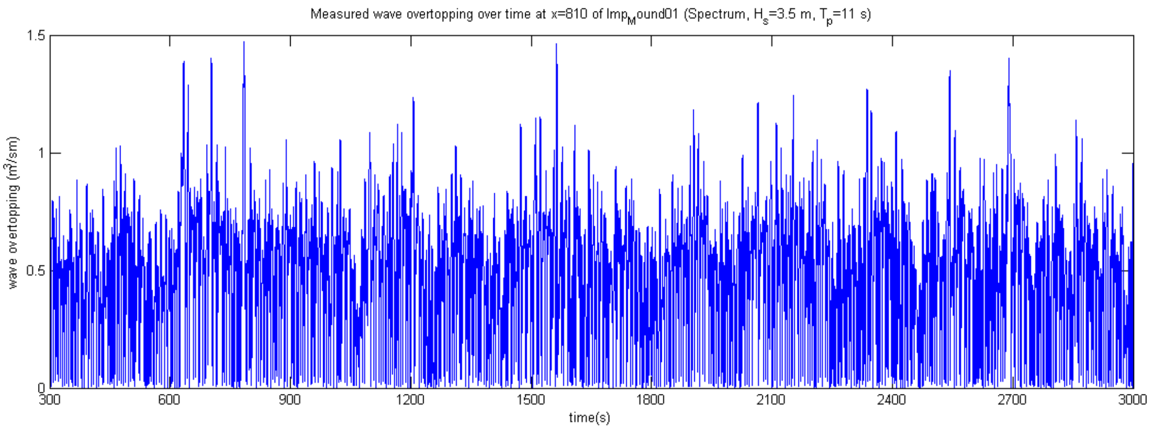

Figure A.132. Discharge at cross-section of the end of the crest of Imp_Mound01.sws.

I have measured the absolute discharge, but in each wave, particles move forward and backwards. If I measure the discharge as a vector with the command DISCH, I can compute the net discharge, which is $q = 17.45\ l/sm$. This includes the net flow of water over and through the structure. This was not necessary before, because in dikes this flow only takes place in one direction over the crest (not on the seaward slope).

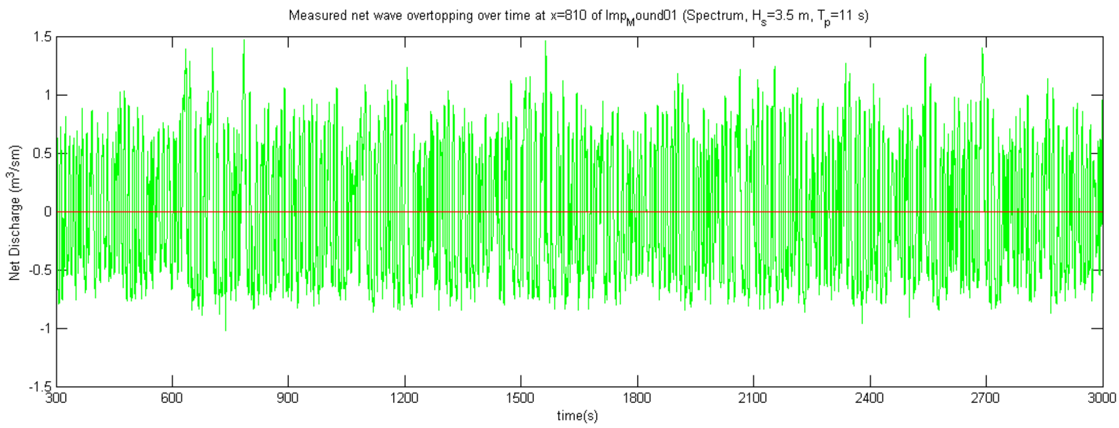

Figure A.133. Net discharge at the cross-section of the end of the crest of Imp_Mound01.sws.

Surprisingly, the net discharge $q = 17.45\ l/sm$ is the 90% of the expected one if I use the data measured at the toe of the breakwater including its influence. This value looks right even though it includes all the water going through the breakwater. But if I use the waves that are not affected by the breakwater, I have measured the 46% of the expected one and it has the same magnitude, which is also a good result though there is a considerable relative difference. From the Neural Network of the Deltares website, the 90% confidence interval is defined between $q = 21.39\ l/sm$ and $q = 2245\ l/sm$, so the measured value is not within these limits, but it is within the 95% confidence interval ($q_{2.5\%} = 12.1\ l/sm$). The mean value is $q = 195.4\ l/sm$. However, the limits of the confidence interval have a difference of 2 orders of magnitude, whereas in dikes the difference was one order. Then, it is likely that the reliability of this prediction is lower than the previous ones. When I introduced this breakwater I got a message telling me: "For prototype, rough-sloping structures a correction factor is applied". I do not know what correction factor it is, but probably it is related to scaling from small-scale tests.

However, I do not know if the flow splits in 2 components (over and through the breakwater). I do not think that is not possible, because SWASH considers the breakwater not as a physical obstacle with some porosity that deviates the flow, but as a kind of sponge layer in which the wave goes through and some energy is dissipated. As a result, there is no water travelling over the structure, unless there is a thick water layer running up. I have measured the water depth and the absolute and net velocities and from them I get the same absolute and net discharge. This would prove that the flow does not split. Furthermore, waves do not break on the slope, but before reaching it. This is not physically true.

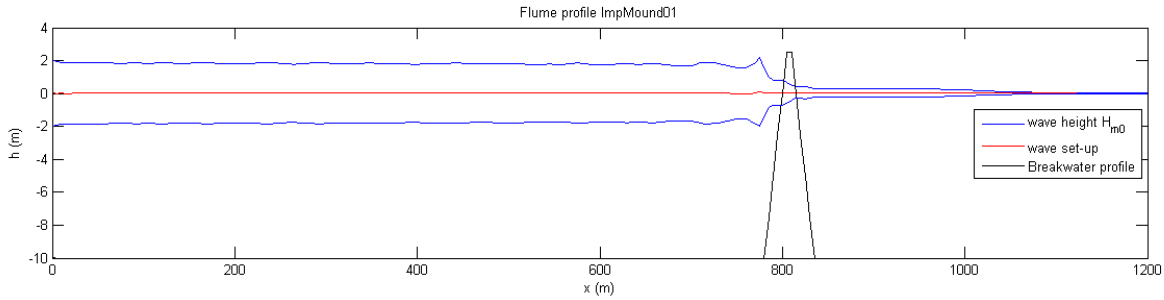

Figure A.134. Waves along the flume in Imp_Mound01.sws.

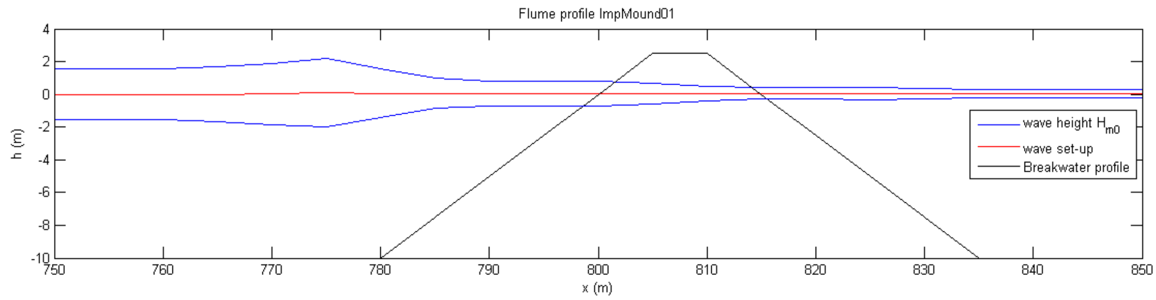

Figure A.135. Breakwater cross-section of Imp_Mound01.sws.

Nevertheless, the introduced breakwater has an impervious core and one layer of one-meter size rock placed on it, which means that water can only flow through the armour layer and over it. Assuming this stone size and this single rock layer, the armour width will be around 2 meters ($2 \cdot D_{n50}$), so little water can go through. Thus, I think that I can consider that a large part of the water flow through the cross-section would be overtopping. However, this is a risky assumption since little is really known about permeable crests and its influence on overtopping. Since the measured net discharge, which includes no overtopping, is smaller than the expected one by the empirical formulas of Eurotop, it seems that SWASH computes quite accurate wave overtopping discharge for this rubble mound breakwater with an impervious core.

To sum up, SWASH models the breakwater as a kind of sponge box that dissipates energy of the waves going through rather than a set of big stones. The water body is continuous and there is no splash going over the breakwater or water tongue running up and down the slope. As a consequence, the only water particles that will go over the crest will be the wave itself if it is enough big. I have measured the net water discharge through the cross-section, but it includes all the water, so I am not able to distinguish wave overtopping discharge from the flow inside the breakwater. Even then, the measured net discharge (including all water flow) is smaller than the predicted wave overtopping. For this reason, the wave overtopping component itself should be even smaller. From the considerations made about our rubble mound breakwater cross-section, I think that the inner flow will be small, because of the thickness of the single rock porous layer over an impervious thick core. As a result, big part of the water flow should be overtopping, which is enhanced by the impermeable core, because water can not go through and cumulates (as commented in Eurotop). Then, SWASH could give a reasonable good estimation, because in reality water only travels over the core. However, research results do not agree how much water goes over and through the crest, so any hypothesis about this division is doubtful and it is clear that SWASH does not model waves breaking on rubble mound breakwaters as we physically understand. Therefore, I conclude that this is not a good model to study wave overtopping on rubble mound breakwaters (yet). Or at least I am not sure if the model is complete enough and at the moment the output should be interpreted as flow through and over the crest.

Afterwards I tested a rubble mound breakwater with a permeable core (see Per_Mound01.sws). I only changed the porosity of the breakwater and I obtained a larger net discharge, but closer to the computed in Imp_Mound01.sws. However, it was “much” larger than the predicted by the formulas due to the inner water flow. For this reason, I conclude that fully permeable rubble mound breakwater cannot be modelled through this method although it may be possible for low permeable ones.

Mound01.sws

However, there could be a way to model a rubble mound breakwater with an impermeable core if I model the core itself as the bottom boundary. The idea is to model the core as a bottom variation, making it smooth and impervious as I did with the previous dikes and add a porous structure as thick as the armour layer over it. This should be easy to model, since the hydraulic structure is defined over the bottom level and I know the porosity and grain size of the rock armour.

Since I am not able to measure the water discharge over a certain height and only the total discharge through the cross-section, I will only place the armour over the outer slope, so I will be sure that I have measured all water going over the impermeable core at both edges of the core crest. This is a model more close to the real physical situation than the first introduced in SWASH, and a way to cheat the software to get an output easier to interpret.

The impermeable core modelled as a bottom variation is described in Core01.bot. The core itself has 1:2 slopes, a top level of 2.5 m above SWL and a top width of 5 m. The armour layer that covers the outer slope has a vertical thickness of 2.5 m and it is described as a porous structure in Slope01.hst. The grain size is 1.12 m (Slope01.psz). The porosity of this rock layer is 0.4 m, but I had some problems in defining the porosity at the part of the impermeable core that was above water level and not covered by the armour layer. Finally at these points I considered a porosity value of 0.1 as it is written on the user manual for emerged land points though I am not sure about these values. The porosity grid is defined in Slope01.n.

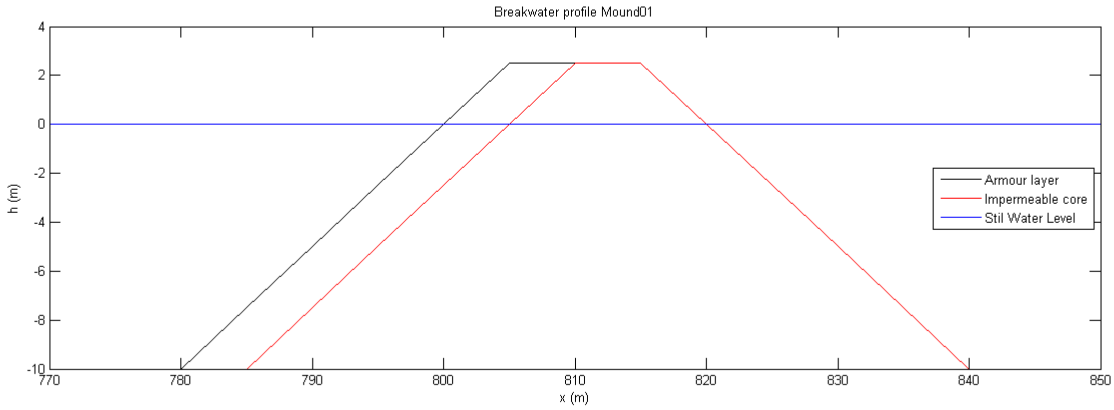

Figure A.136. Breakwater cross-section of Mound01.sws.

As it can be seen on figure A.136, the crest freeboard is 2.5 m and there is no permeable crest.

The usual spectrum waves with a significant wave height of 3.5 m and a peak period of 11 s are generated.

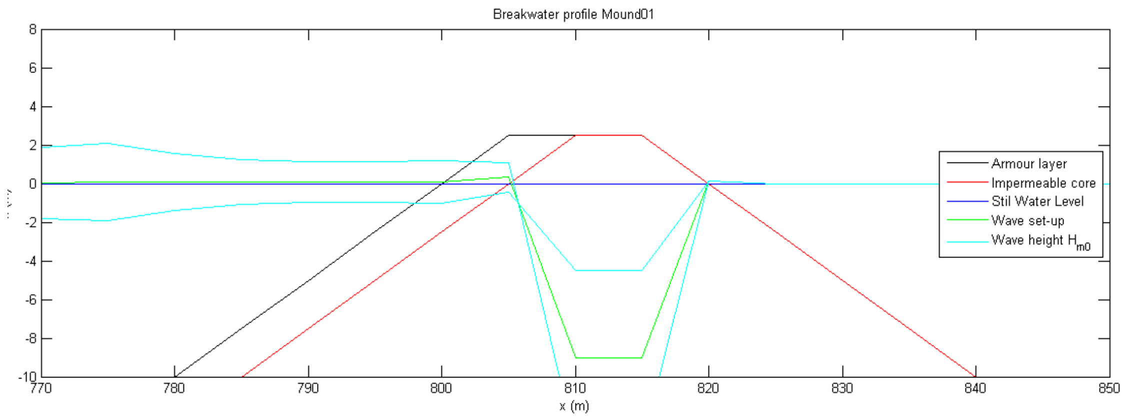

Figure A.137. Breakwater cross-section interacting with waves in Mound01.sws.

On figure A.137 it can be seen how there is some wave set-up inside the armour layer. The strange values within the breakwater are due to the unreliable data given by SWASH for “dry points”, which are not covered by water all time, so they should be omitted. It is very important to notice that there is absolutely no wave agitation behind the breakwater. I do not like it, because with an impermeable dike (and the impermeable core has the same cross-section) there was some agitation behind it. The reason would be the low porosity values given at the crest and the dry part of the back slope. Something must be done to improve it.

The next tables A.55 and A.56 summarize the recorded waves at the beginning and at the toe of the structure. Very important long waves with periods between 60 and 90 s are observed at the toe of the breakwater. However, there are not big differences with the waves recorded in Imp_Mound01.sws and Per_Mound01.sws.

Measured data at x=0 m (Mound01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.84\ m$	$T_m = 9.10\ s$	$H_{m0} = 3.97\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.97\ m$	$3.8 \cdot \sigma = 3.77\ m$	$T_{m01} = 9.53\ s$	$T_{m-1,0} = 12.63\ s$

Table A.55. Wave parameters at x=0 m of Mound01.sws.

Measured data at x=780 m (Mound02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.64\ m$	$T_m = 10.62\ s$	$H_{m0} = 3.00\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.99\ m$	$3.8 \cdot \sigma = 2.84\ m$	$T_{m01} = 12.30\ s$	$T_{m-1,0} = 27.12\ s$

Table A.56. Wave parameters at x=780 m of Mound01.sws.

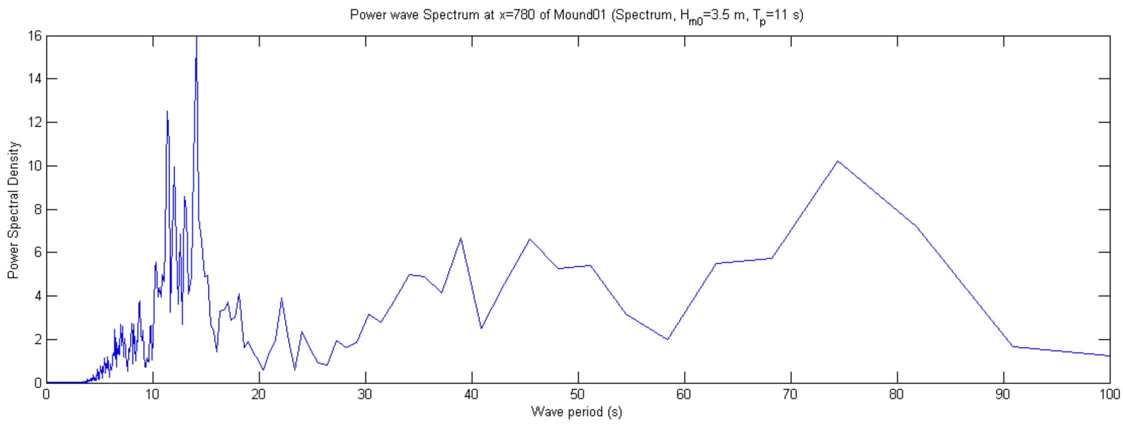

Figure A.138. Wave spectrum at x=780 m of Mound01.sws.

At x=805 m, which is the seaward edge of the armour crest, the measured net discharge is $q = -14.9\ l/sm$. This means that the net water flow goes seawards, which makes no sense. The absolute discharge is $q = 62.6\ l/sm$.

At both edges of the core crest (x=810 and x=815 m), which is directly exposed, no discharge is measured at any point of the time. It is really strange, because considering a freeboard of 2.5 m and a permeable crest width of 5 m in front of the core level (which corresponds to the armour layer), the expected total discharge should be $q = 127.1\ l/sm$ at the top of the seaward slope and $q = 38.1\ l/sm$ at the interphase between armour and core.

Mound02.sws

This simulation models the whole breakwater with a continuous rock armour layer over an impermeable berm. The target was to compare the results with the previous one.

Here no problems with porosity definitions appeared. The impermeable core is described in Core01.sws, and the rock armour layer in Armour01.hst, Armour01.psz and Armour01.n.

The top level of the core is 2.5 m above water level and the crest freeboard, 5 m. The crest is now permeable.

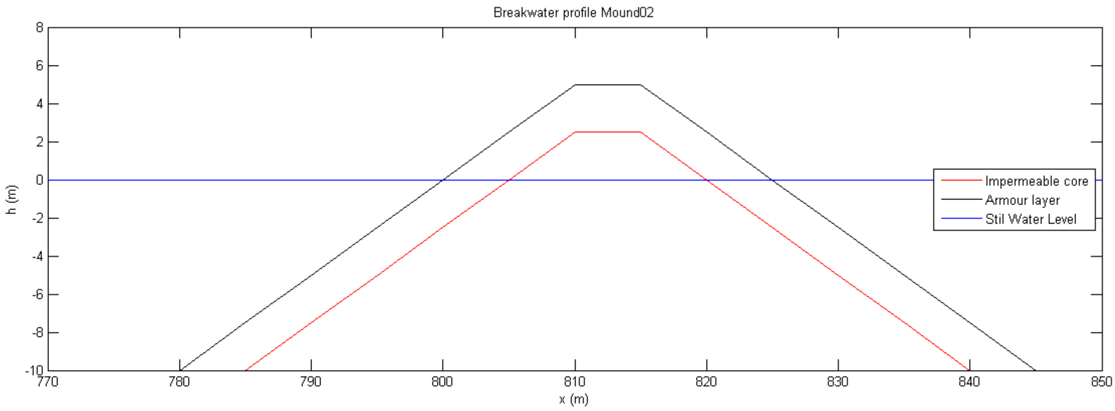

Figure A.139. Breakwater cross-section of Mound02.sws.

The next tables A.57 and A.58 summarize the recorded waves at the beginning and at the toe of the structure. I have recorded exactly the same waves as in Mound01.sws, which could be expected, since the seaward slope is exactly the same in both structures, and so will be the wave response.

Measured data at x=0 m (Mound02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.84\ m$	$T_m = 9.10\ s$	$H_{m0} = 3.97\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 3.97\ m$	$3.8 \cdot \sigma = 3.77\ m$	$T_{m01} = 9.53\ s$	$T_{m-1,0} = 12.63\ s$

Table A.57. Wave parameters at x=0 m of Mound02.sws.

Measured data at x=780 m (Mound02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.64\ m$	$T_m = 10.62\ s$	$H_{m0} = 3.00\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.99\ m$	$3.8 \cdot \sigma = 2.84\ m$	$T_{m01} = 12.30\ s$	$T_{m-1,0} = 27.12\ s$

Table A.58. Wave parameters at x=780 m of Mound02.sws.

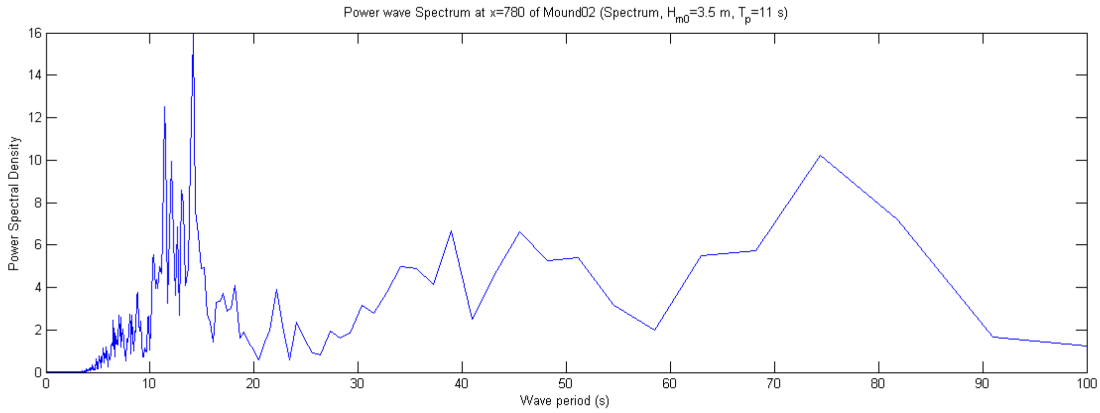

Figure A.140. Wave spectrum at x=780 m of Mound02.sws.

At x=805 m, which is the seaward edge of the armour crest in Mound01.sws, the measured net discharge is $q = -14.9\ l/sm$, which goes seawards too. Also the same value as in Mound01.sws is obtained, which means that both structures produce exactly the same effect on incoming waves.

At the beginning of the crest at x=810 m the net discharge is nil. In fact, there is not a single overtopping wave, which I found very strange. Obviously, zero discharge is found at the back of the crest.

With the wave data recorded in Propagation01.sws, the input parameters to compute wave overtopping are: $R_C = 5.0\ m$, $h = 10\ m$, $\tan\alpha = 0.5$, $H_{m0} = 3.23\ m$, $T_{m-1,0} = 15.42\ s$ ($\xi_{m-1,0} = 5.36$), $\gamma_\beta = 1.0$ and $\gamma_f = 0.6$. The expected run-up is $R_{u2\%} = 8.38\ m$ and the mean overtopping is $q = 4.4\ l/sm$ at the beginning of the crest, and $q = 1.3\ l/sm$ at the back. Considering the freeboard reduction proposed by Krom, the overtopping should be $q = 20.0\ l/sm$ at the beginning, and $q = 6.0\ l/sm$ at the back. There is something clearly wrong.

Imp_Mound02.sws

I have come back to the model simulated in Imp_Mound01.sws with a uniform average permeability of 0.35, but now with a different breakwater section with a higher freeboard (5 m). The slope does not change and continues being 1:2. The files Mound02.hst, Mound03.psz and Imp_Mound02.n describe the structure.

The next tables summarize the wave parameters recorded, which are almost the same as in Imp_Mound01.sws. This is reasonable, because the slope characteristics are the same and only the freeboard changes.

Measured data at x=0 m (Imp_Mound02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.91\ m$	$T_m = 9.10\ s$	$H_{m0} = 4.03\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.03\ m$	$3.8 \cdot \sigma = 3.83\ m$	$T_{m01} = 9.47\ s$	$T_{m-1,0} = 11.89\ s$

Table A.59. Wave parameters at x=0 m of Imp_Mound02.sws.

Measured data at x=780 m (Imp_Mound02.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.63\ m$	$T_m = 10.20\ s$	$H_{m0} = 2.95\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.94\ m$	$3.8 \cdot \sigma = 2.80\ m$	$T_{m01} = 11.37\ s$	$T_{m-1,0} = 21.98\ s$

Table A.60. Wave parameters at x=780 m of Imp_Mound02.sws.

At the seaward edge of the crest (x=810 m), the net measured discharge is $q = 15.8\ l/sm$, while at the back (x=815 m) is $q = 15.5\ l/sm$. Despite the structure is twice as high, the measured net discharge is very close to the one obtained in Imp_Mound01.sws. The reason has been already commented, it is the way how SWASH models the breakwater as a porous structure that dissipates the waves going through. According to the Eurotop formulas, the overtopping at the back would be $q = 1.3\ l/sm$. I can see how the breakwater dissipates the waves along the flume.

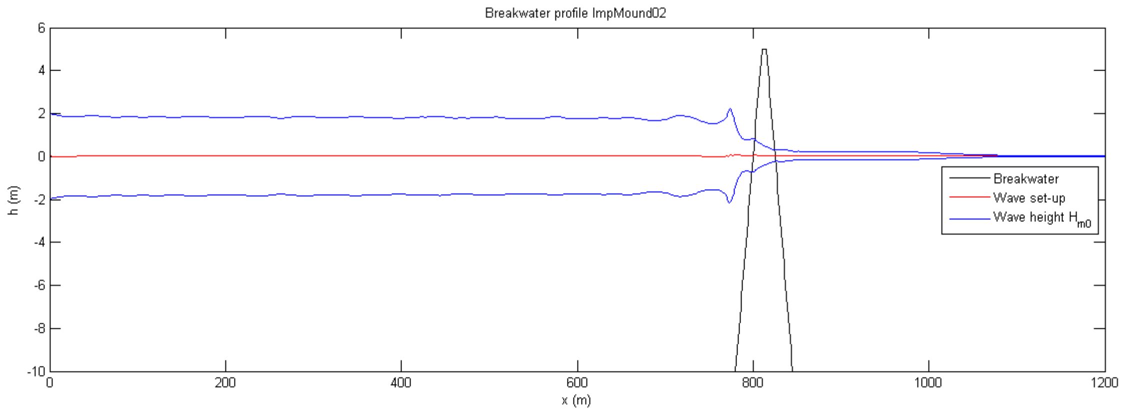

Figure A.141. Waves along the flume in Imp_Mound02.sws.

Imp_Mound03.sws

In this script I have modelled a breakwater with a crest freeboard of 5 m and a slope 1:1. The files Mound03.hst, Mound04.psz and Imp_Mound03.n contain the description.

Measured data at x=0 m (Imp_Mound03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.88\ m$	$T_m = 9.01\ s$	$H_{m0} = 4.00\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.00\ m$	$3.8 \cdot \sigma = 3.80\ m$	$T_{m01} = 9.47\ s$	$T_{m-1,0} = 11.85\ s$

Table A.61. Wave parameters at x=0 m of Imp_Mound03.sws.

Measured data at x=780 m (Imp_Mound03.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.48\ m$	$T_m = 10.62\ s$	$H_{m0} = 2.81\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.80\ m$	$3.8 \cdot \sigma = 2.66\ m$	$T_{m01} = 12.09\ s$	$T_{m-1,0} = 23.25\ s$

Table A.62. Wave parameters at x=780 m of Imp_Mound03.sws.

At the toe of the breakwater slightly smaller waves are observed. Also, fewer short waves are found in the spectrum.

Hardly any net discharge reduction is found along the crest width, since the recorded net discharge at the top of the outer slope is $q = 19.1\ l/sm$, and at the top of the inner slope, $q = 18.9\ l/sm$. The expected discharge at the back of the crest is $q = 1.3\ l/sm$. Because the slope is quite steep, there is a large run-up of $R_{u2\%} = 20.59\ m$.

The measured net discharges in Imp_Mound02.sws and Imp_Mound03.sws are too high if we take into account that the breakwater core is impermeable, so water can only go through the breakwater cross-section as overtopping or inner crest flow.

Imp_Mound04.sws

In this script I tested the same breakwater introduced in Imp_Mound01.sws (1:2 slope and 2.5 m freeboard) with lower waves. The waves were defined by $H_{m0} = 2\ m$ and $T_p = 7\ s$.

The tables below summarize the waves conditions measured at the beginning and at the toe of the dike. In contrast with the previous tests, long waves were not recorded at the toe.

Measured data at x=0 m (Imp_Mound04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.17\ m$	$T_m = 5.77\ s$	$H_{m0} = 2.24\ m$	$T_p = 7.06\ s$
$4 \cdot \sigma = 2.24\ m$	$3.8 \cdot \sigma = 2.13\ m$	$T_{m01} = 6.00\ s$	$T_{m-1,0} = 6.77\ s$

Table A.63. Wave parameters at x=0 m of Imp_Mound04.sws.

Measured data at x=780 m (Imp_Mound04.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 1.38\ m$	$T_m = 6.69\ s$	$H_{m0} = 1.48\ m$	$T_p = 7.12\ s$
$4 \cdot \sigma = 1.48\ m$	$3.8 \cdot \sigma = 1.41\ m$	$T_{m01} = 7.09\ s$	$T_{m-1,0} = 10.34s$

Table A.64. Wave parameters at x=780 m of Imp_Mound04.sws.

At the back of the crest, the measured wave net discharge is $q = 6.2\ l/sm$. However, if I consider the wave data recorded in Propagation09.sws ($H_{m0} = 1.87\ m$ and $T_{m-1,0} = 8.20\ s$), I compute $\xi_{m-1,0} = 14.99$, $R_{u2\%} = 12.16\ m$ (due to the large Iribarren number), $q = 4.9\ l/sm$ at the beginning of the crest and $q = 0.27\ l/sm$ at the back. Considering the proposed freeboard reduction by Krom (1.5 m instead of 2.5 m), both discharges multiply by 10.

A.7. Rubble mound breakwater with a permeable core

Per_Mound01.sws

It is the same script as Imp_Mound01.sws changing the breakwater porosity from $n = 0.35$ to $n = 0.4$. The roughness factor is now $\gamma_f = 0.45$ (one rock layer over a permeable core). (0.4 for 2 layers). This simulation was performed just after Imp_Mound01.sws to compare the output data.

Measured data at x=0 m (Per_Mound01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 3.88\ m$	$T_m = 9.01\ s$	$H_{m0} = 4.01\ m$	$T_p = 10.91\ s$
$4 \cdot \sigma = 4.01\ m$	$3.8 \cdot \sigma = 3.81\ m$	$T_{m01} = 9.45\ s$	$T_{m-1,0} = 11.75\ s$

Table A.65. Wave parameters at x=0 m of Per_Mound01.sws.

Measured data at x=780 m (Per_Mound01.sws)			
Wave per wave analysis		Spectral Analysis	
$H_s = 2.62\ m$	$T_m = 10.14\ s$	$H_{m0} = 2.94\ m$	$T_p = 14.11\ s$
$4 \cdot \sigma = 2.94\ m$	$3.8 \cdot \sigma = 2.79\ m$	$T_{m01} = 11.35\ s$	$T_{m-1,0} = 21.60\ s$

Table A.66. Wave parameters at x=780 m of Per_Mound01.sws.

Both at the beginning of the flume and at the toe of the breakwater, the recorded waves are the same as in Imp_Mound01.sws.

The input parameters to compute wave overtopping are: $R_C = 2.5\ m$, $h = 10\ m$, $\tan\alpha = 0.5$, $H_{m0} = 2.94\ m$, $T_{m-1,0} = 21.60\ s$ ($\xi_{m-1,0} = 7.87$), $\gamma_\beta = 1.0$ and $\gamma_f = 0.45$. The expected run-up is $R_{u2\%} = 8.73\ m$ and the mean overtopping is $q = 5.5\ l/sm$ (including crest width reduction). Notice that the expected overtopping is very small compared with any dike and much lower than the dike with the same slope and freeboard. If I use the wave data recorded in Propogation01.sws taking into account only the incoming wave, the expected run-up is $R_{u2\%} = 7.46\ m$ and the mean overtopping is $q = 41.5\ l/sm$ at the top of the seaward slope and $q = 12.5\ l/sm$ at the end of the crest. The difference is quite important if we consider or not the reflected wave.

At the top of the outer slope the measured mean net discharge is $q = 21.0\ l/sm$, while at the top of the inner slope it is $q = 20.6\ l/sm$. It can be seen that SWASH does not consider any overtopping discharge reduction due to the permeable crest width of about 5 meters. This is contradictory with the physical modelling, but it is consistent with how SWASH works. Remember that there is a wave propagating through the breakwater and that the net flow instead of percolating through the rocks it is simply “slowed down”. Furthermore, I have measured all discharge going through the cross-section and overtopping is only a (probably small) fraction here, so it is difficult to extract some conclusions.

In rubble mound breakwaters with a permeable core water percolates through the blocks and the inner flow is more important. This dissipates more energy and reduces wave run-up and overtopping, but there is an increase of water flow through the core. Wave transmission is thought to be more important. As a result, the ratio between overtopping flow and inner flow will reduce compared with breakwaters with an impermeable core. Hence, the reduction of overtopping due to the larger permeability of the structure is hidden by a larger inner flow when measuring the whole discharge and the share is not known. For this reason and the commented problems with porous structures, SWASH is not able to predict accurately wave overtopping in this kind of structures.

A.8.Chronological sequence

I computed the commented scripts in the following order. This sequence may be important to understand some of the problems and conclusions I reached.

- Deep_Flume01.sws, Deep_Flume02.sws and Deep_Flume03.sws (none of them are commented here).
- Shallow_Flume01.sws, Shallow_Flume02.sws and Shallow_Flume02_3.sws, Shallow_Flume03.sws, Shallow_Flume04.sws and Shallow_Flume04_2.sws.
- Shallow_Flume05.sws, Shallow_Flume06.sws, Shallow_Flume07.sws and Shallow_Flume07_2.sws (only commented as a transition between the previous tests to deep water).
- Deep_Flume05.sws and Deep_Flume05_2.sws, Deep_Flume06.sws, Deep_Flume04.sws and Deep_Flume07.sws.
- Shallow_Flume03_2.sws, Shallow_Flume03_3.sws, Shallow_Flume03_4.sws, Shallow_Flume03_5.sws and Shallow_Flume03_6.sws.
- Shallow_Flume04_3, Shallow_Flume04_4.sws, Shallow_Flume04_5.sws, Shallow_Flume04_6.sws.
- Deep_Flume05_3.sws and Deep_Flume05_4.sws.
- Deep_Flume07_2.sws and Deep_Flume07_3.sws.
- First discussion with Marcel Zijlema
- Shallow_Flume08.sws, Shallow_Flume08_2.sws, Shallow_Flume09.sws, Shallow_Flume09_2.sws, Shallow_Flume09_3.sws.
- Deep_Flume08.sws, Deep_Flume09.sws
- Second discussion with Marcel Zijlema
- Shallow_Flume10.sws, Shallow_Flume10_2.sws, Shallow_Flume11.sws and Shallow_Flume11_2.sws
- Error found on SWASH code and reported to Marcel Zijlema
- Smooth01.sws, Smooth02.sws, Smooth03.sws, Smooth04.sws, Smooth04_2.sws and Smooth04_3.sws
- Discussions with Pieter Smit and Marcel Zijlema
- Dike01.sws, Dike02.sws, Dike03.sws and Dike04.sws
- Smooth05.sws, Smooth06.sws
- Propagation01.sws, Propagation02.sws, Propagation03.sws, Propagation04.sws, Propagation05.sws, Propagation06.sws, Propagation07.sws and Propagation08.sws
- Imp_Mound01.sws
- Per_Mound01.sws
- Discussions with Marcel Zijlema, Jeroen van den Bos and Bert van den Berg.
- Mound01.sws and Mound02.sws
- Imp_Mound02.sws, Imp_Mound03.sws, Imp_Mound04.sws
- Propagation09.sws, Propagation10.sws and Propagation11.sws
- Dike05.sws, Dike06.sws, Dike07.sws, Dike08.sws, Dike09.sws, Dike10.sws, Dike11.sws, Dike12.sws and Dike13.sws.

A.9. SWASH codes

In this section the codes of 3 scripts are added. They are not commented in detail and the script files that they call (bottom, porosity, height of the structure and grain size) are not included.

Each file is a representative script simulating wave propagation (Propagation03.sws), overtopping on dikes (Dike05.sws) and rubble mound breakwaters (Imp_Mound01.sws).

Propagation03.sws

```
PROJECT 'Propagation03' '1'
            'Shallow water flume'
            'Thesis Overtopping of rubble mound berm breakwaters'
            'Víctor Martínez Pés'
$
$ Wave propagation in the flume.
$ Since the introduced waves are small compared to the water depth,
they are not
$ breaking. Intermediate water conditions.
$
$ **** Model Input ****
$
$MODE DYN ONED
MODE NONSTATIONARY ONEDIMENSIONAL
$
CGRID REG 0. 0. 0. 1200. 0. 1200 0
$
VERT 1 $Number of vertical layers.
$
$Bottom depth %Horizontal
INPGRID BOTTOM 0. 0. 0. 1 0 1200 0
READINP BOTTOM 10. 'Flume01.bot' 1 0 FREE
$
FRIC CONST 0
VISC 0
$
INIT ZERO
$
$ Boundary conditions
BOUNd SHAPespec JONswap 3.3 SIG PEAK DSPR DEGR
$
BOUNdcond SIDE W CCW BTYPE WEAK CON SPECTrum 3.5 11. 90 0 2 HR
BOUNDCOND SIDE E CCW BTYPE RADIATION
SPONgelayer RIght 280
$
$
$Other
BREAK
$With sufficient vertical layers (10 or so), BREAK should not be
activated.
NONHYDROSTATIC BOX PREC ILU
$
DISCRET UPW UMOM H BDF
DISCRET UPW WMOM H BDF
$
TIMEI 0.01 0.25
$
```

```
$ **** Model Output ****
$
POINTS 'origin' 0. 0. $Wave generator x=0
POINTS 'x20' 20. 0. $20m far from the wave generator
POINTS 'toe' 780. 0. $Toe of the structure, x=780
$
QUANTITY HSIG 'Hs' 'Significant wave height' DUR 90 MIN
QUANTITY SETUP 'St' 'Wave Set-up' DUR 90 MIN
QUANTITY WATLEV 'WL' 'Water Level' DUR 90 MIN
QUANTITY BOTLEV 'BL' 'Bottom Level'
QUANTITY XP 'Xp' 'X distance' HEXP 1000
$
TABLE  'toe' NOHEAD 'Propagation03_x780.tab' TSEC WATLEV OUTPUT
000500.000 0.05 SEC
TABLE 'origin' NOHEAD 'Propagation03_x0.tab' TSEC WATLEV OUTPUT
000500.000 0.05 SEC
TABLE 'x20' NOHEAD 'Propagation03_x20.tab' TSEC WATLEV OUTPUT
000500.000 0.05 SEC
$
FRAME 'PT'   0. 0. 0. 1200. 0. 240 0
TABLE 'PT'   HEAD   'Propagation03.tab' XP HS SETUP BOTLEV
$
TEST 1 0
COMPUTE 000000.000 0.001 SEC 013500.000 $5+90 min
STOP
$
```

Dike05.sws

```
PROJECT 'Dike05' '1'
            'Impermeable Dike'
            'Thesis Overtopping of rubble mound berm breakwaters'
            'Víctor Martínez Pés'
$
$ Flume test in shallow water to measure wave overtopping on an
impervious dike.
$ Since the introduced waves are small compared to the water depth,
they are not
$ breaking.
$
$ **** Model Input ****
$
$MODE DYN ONED
MODE NONSTATIONARY ONEDIMENSIONAL
$
CGRID REG 0. 0. 0. 1200. 0. 1200 0
$
VERT 1 $Number of vertical layers.
$
$Bottom depth %Horizontal bottom+dike profile
INPGRID BOTTOM 0. 0. 0. 240 0 5 0
READINP BOTTOM 10. 'Dike01.bot' 1 0 FREE
$
FRIC CONST 0
VISC 0
$
INIT ZERO
$
$ Boundary conditions
```

```
BOUNd SHAPespec JONswap 3.3 SIG PEAK DSPR DEGR
$
BOUNdcond SIDE W CCW BTYPE WEAK CON SPECTrum 3.5 11. 90 0 2 HR
BOUNDCOND SIDE E CCW BTYPE RADIATION
SPONgelayer RIght 280
$
$
$Other
BREAK
$With sufficient vertical layers (10 or so), BREAK should not be
activated.
NONHYDROSTATIC BOX PREC ILU
$
DISCRET UPW UMOM H BDF
DISCRET UPW WMOM H BDF
$
TIMEI 0.01 0.25
$
$ **** Model Output ****
$
POINTS 'origin' 0. 0. $Wave generator, x=0
POINTS 'x20' 20. 0. $20m far from the wave generator, x=20
POINTS 'toe' 780. 0. $Toe of the structure, x=780
POINTS 'shore' 800. 0. $Initial water level on the structure sea
slope, x=800
POINTS 'topsea' 805. 0. $crest of the structure, x=805, top of the
seaward slope
POINTS 'topback' 810. 0. $Gauge at the crest of the structure x=810,
top of the back slope
$
QUANTITY HSIG 'Hs' 'Significant wave height'  DUR 90 MIN
QUANTITY SETUP 'St' 'Wave Set-up' DUR 90 MIN
QUANTITY WATLEV 'WL' 'Water Level'
QUANTITY BOTLEV 'BL' 'Bottom Level'
QUANTITY XP 'Xp' 'X distance' HEXP 1000
QUANTITY QMAG 'Qm' 'Absolute discharge' DUR 90 MIN
QUANTITY DISCH 'Qn' 'Net discharge' DUR 90 MIN
$
TABLE  'toe' NOHEAD 'Dike05_x780.tab' TSEC WATLEV OUTPUT 000500.000
0.05 SEC
TABLE 'origin' NOHEAD 'Dike05_x0.tab' TSEC WATLEV OUTPUT 000500.000
0.05 SEC
$
TABLE 'topsea' NOHEAD 'Dike05_x805.tab' TSEC QMAG DISCH OUTPUT
000500.000 0.05 SEC
TABLE 'topback' NOHEAD 'Dike05_x810.tab' TSEC QMAG DISCH OUTPUT
000500.000 0.05 SEC
$
FRAME 'PT'   0. 0. 0. 1200. 0. 1200 0
$BLOCK 'PT'   NOHEAD 'Dike05.mat' LAY 3 XP BOTL WATL HS OUTPUT
000000.000 0.05 SEC
TABLE 'PT'   HEAD   'Dike05.tab' XP HS SETUP BOTLEV DISCH
$
TEST 1 0
COMPUTE 000000.000 0.001 SEC 013500.000 $5+90 min
STOP
$
```

Imp_Mound01.sws

```
PROJECT 'Imp_Mound01' '1'
            'Rubble Mound with an impermeable core'
            'Thesis Overtopping of rubble mound berm breakwaters'
            'Víctor Martínez Pés'
$
$ Flume test in shallow water to check if a rubble mound breakwater
with an impermeable
$ core is well introduced.
$ Since the introduced waves are small compared to the water depth,
they are not
$ breaking.
$
$ **** Model Input ****
$
$MODE DYN ONED
MODE NONSTATIONARY ONEDIMENSIONAL
$
CGRID REG 0. 0. 0. 1200. 0. 1200 0
$
VERT 1 $Number of vertical layers.
$
$Bottom depth
INPGRID BOTTOM 0. 0. 0. 1 0 1200 0
READINP BOTTOM 10. 'Flume01.bot' 1 0 FREE
$
$Porosity
INPGRID POROSITY 0. 0. 0. 240 0 5 0
READINP POROSITY 1. 'Imp_Mound01.n'1 0 FREE
$
$Porous size
INPGRID PSIZE 0. 0. 0. 240 0 5 0
READINP PSIZE 1. 'Mound02.psz' 1 0 FREE
$
$Structure height
INPGRID HSTRUCTURE 0. 0. 0. 240 0 5 0
READINP HSTRUCTURE 1. 'Mound01.hst' 1 0 FREE
$
FRIC CONST 0
VISC 0
$
INIT ZERO
$
$ Boundary conditions
BOUNd SHAPespec JONswap 3.3 SIG PEAK DSPR DEGR
$
BOUNdcond SIDE W CCW BTYPE WEAK CON SPECTrum 3.5 11. 90 0 2 HR
BOUNDCOND SIDE E CCW BTYPE RADIATION
SPONgelayer RIght 280
$
$Other
BREAK
$With sufficient vertical layers (10 or so), BREAK should not be
activated.
NONHYDROSTATIC BOX PREC ILU
$
DISCRET UPW UMOM H BDF
DISCRET UPW WMOM H BDF
DISCRET CORRDEP NONE
```

```
$
TIMEI 0.01 0.25
$
$ **** Model Output ****
$
POINTS 'gauge' 810. 0. $Gauge behind the crest of the structure x=810,
at the top of the inner slope.
POINTS 'origin' 0. 0. $Wave generator x=0
POINTS 'x20' 20. 0. $20m far from the wave generator
POINTS 'toe' 780. 0. $Toe of the structure, x=780
POINTS 'shore' 800. 0. $Initial water level on the structure sea
slope, x=800, shoreline
POINTS 'crestsea' 805. 0. $crest of the structure, x=805. Gauge at the
top of the seaward slope
$
QUANTITY HSIG 'Hs' 'Significant wave height'  DUR 45 MIN
QUANTITY SETUP 'St' 'Wave Set-up' DUR 45 MIN
QUANTITY WATLEV 'WL' 'Water Level' $DUR 45 MIN
QUANTITY BOTLEV 'BL' 'Bottom Level'
QUANTITY XP 'Xp' 'X distance' HEXP 1000
QUANTITY QMAG 'Qm' 'Average discharge' DUR 45 MIN
$
TABLE  'toe' NOHEAD 'Imp_Mound01_x780.tab' TSEC WATLEV OUTPUT
000500.000 0.05 SEC
TABLE 'origin' NOHEAD 'Imp_Mound01_x0.tab' TSEC WATLEV OUTPUT
000500.000 0.05 SEC
$
TABLE 'crestsea' NOHEAD 'Imp_Mound01_x805.tab' TSEC QMAG OUTPUT
000500.000 0.05 SEC
TABLE 'gauge' NOHEAD 'Imp_Mound01_x810.tab' TSEC QMAG DISCH DEPTH VMAG
VEL OUTPUT 000500.000 0.05 SEC
$
FRAME 'PT'   0. 0. 0. 1200. 0. 240 0
TABLE 'PT'   HEAD   'Imp_Mound01.tab' XP HS SETUP
$
TEST 1 0
COMPUTE 000000.000 0.001 SEC 005000.000 $5+45 min
STOP
$
```