APPENDIX A. SIMULATION TESTS - SWASH

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Before starting with the following modelling process I worked previously on other created scenarios in order to get acquainted with SWASH. I had some discussions with Marcel Zijlema, who helped me a lot in understanding the meaning of the resulting output I was obtaining. Once familiarized with the software, I focused on studying the concerned scenario on the current project. Below I have reported all the steps I had to follow to get the final results, as well as the trouble I was facing to and all the conclusions I came up with.

All the tests are conducted in 1D domains. Parameter values and commands have been settled according to the User Manual [13].

A1. MODELLING PROCEDURE

The real situation in the Zeebrugge breakwater has to be modelled in SWASH so that the program can compute the required output values. In order to bring the scenario in, it has been thought a stepwise construction will be useful; it will allow us to check whether every input has been properly introduced or not.

The regarded steps are the following:

1. Create the wave spectrum and propagate it in a deep-water flat flume, so that bottom does not affect it.
2. Propagate the spectrum in a shallow-water flat flume to be aware of the bottom effects on the waves.
3. Introduce the impermeable dike at the end of the shallow-water flume to check the behaviour of the waves hitting the structure. Overtopping can be computed in this case.

4. Introduce porosity in the created dike in order to turn it into a breakwater; that will already simulate the real scenario. Therefore, wave overtopping discharges can be computed and compared with the collected real data in Zeebrugge.

A2. DEEP WATER FLUME

To start with, the flat deep scenario is going to be considered. Before generating the wave spectrum however, we are going to deal with a regular propagation in order to test if everything runs as it is expected to.

A2.1 Propagation of regular waves:

S1_deepreg.sws

Period (Tm) and height (Hs) are taken from the CLASH report [5] according to the values reported for storm 1. In order to deal with a deep-water situation, it has been found through hand-calculation a depth of 40m to be used. A sponge layer has to be placed on the eastern boundary so that it absorbs the propagated wave avoiding this way any possible reflection; such layer has to be around 3 times the wave length. Spatial and temporal meshes have been defined accounting for the problem data and the software requirements such as the number of vertical layers or the Courant number, which limits the computational time step.

Summing up the input parameters:
Hs=3.04m Tm=6.88 sec d=40m $L_{sponge}=3L_{wave}$ $L_{wave}=73.75$m

With regard to the computational mesh, 2 vertical layers have been used, which is reported to be enough in the User Manual, according to the problem characteristics. Around 50 cells have been taken for each L_{wave} since H/d=0.075<<1. The maximum time step has been computed according to the Courant expression; hence, it has been determined to be Δt=0.05 sec.

The flume has been created with a length of 300m plus 225m of sponge. The total simulation time is 756sec, accounting for both the spin-up and the wave propagation times.

Demanded outputs are the water level at several points over the flume:

X=0m X= 150m X= 225m X=300m

as well as Hrms averaged during the last minute of simulation over the whole domain, the setup profile and a snapshot of the water level in the last instant.

Plotting the results in Matlab:

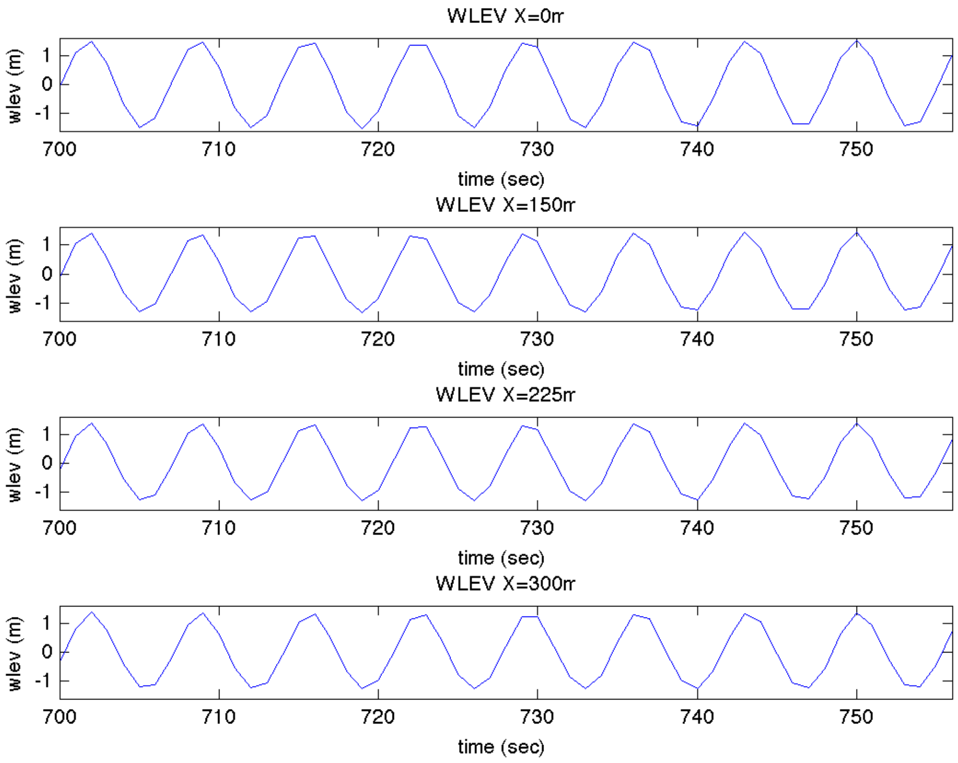

Figure 1. Water elevation over time at different points of s1_deepreg.sws

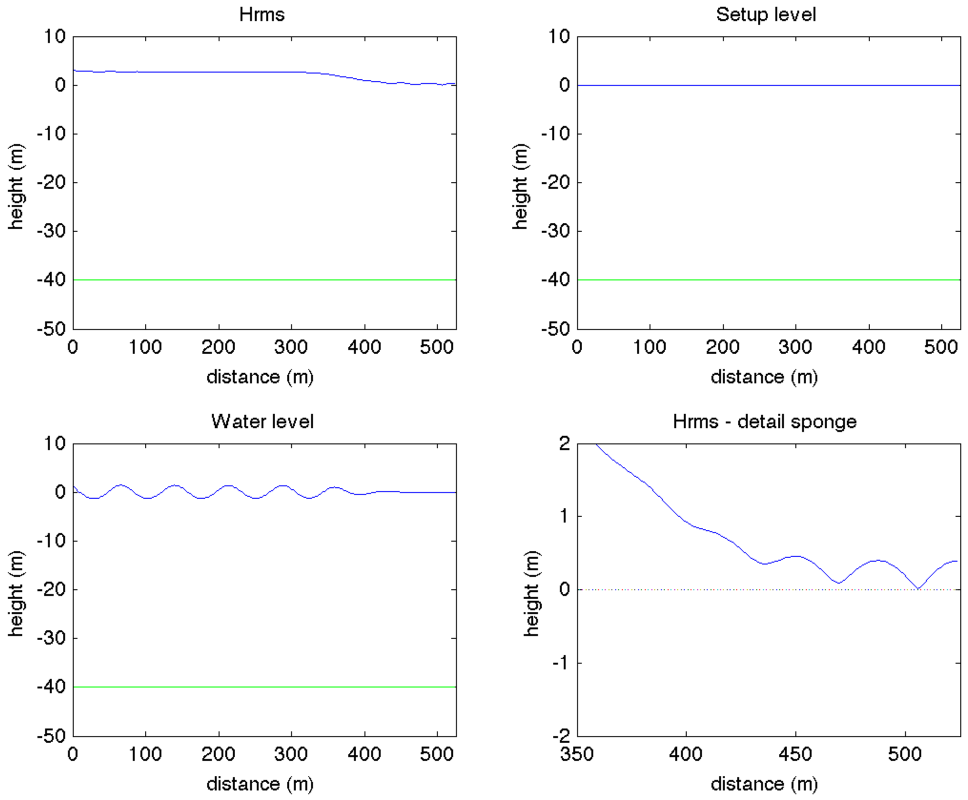

Figure 2. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_deepreg.sws

At a first glance it is possible to observe a non-completely sinusoidal pattern in the time records. To check the performance of the sponge layer, an Hrms detail at the end of it has been displayed (Fig.2); the value does not get to be constantly null as it is supposed to. Moreover, Hrms is decreasing over the flume length where it is expected to remain constant.

Since the first thing it made up to my mind was the non-proper performance of the sponge layer allowing some kind of reflection, I have tried to enlarge it in order to check if significant changes are seen with the naked eye. For this purpose, the script below has been created:

S1_deepreg2.sws

The only change with respect to the previous script is the enlargement of the sponge layer from 3L to 4L; hence, the overall domain requires to be enlarged. Total domain is therefore 600m, accounting for the 300m flume plus the sponge layer longitude.

It results in the following:

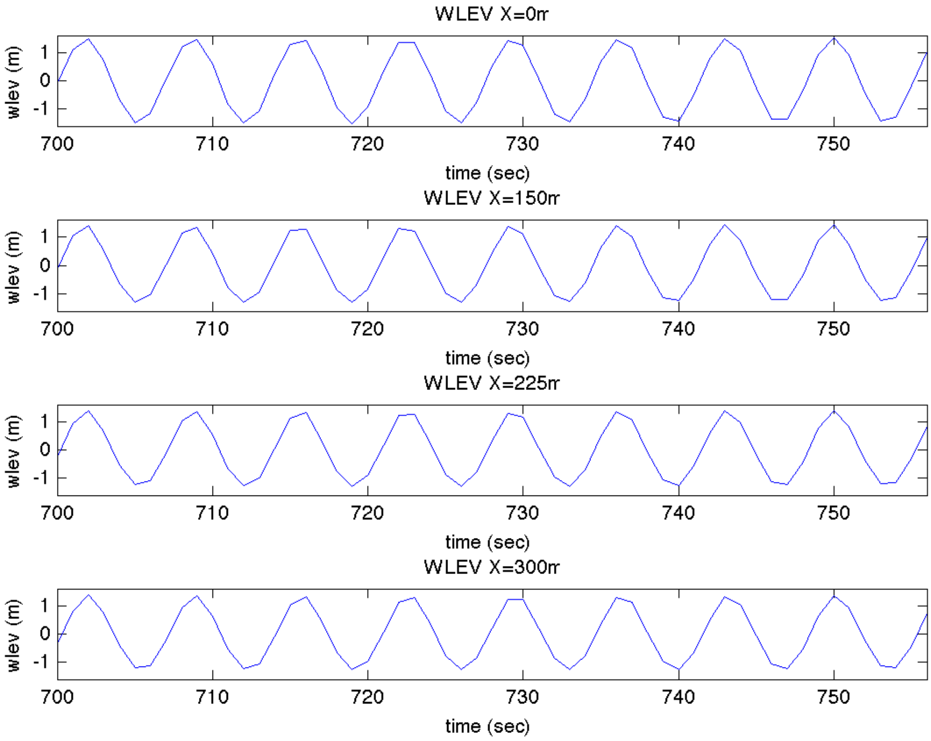

Figure 3. Water elevation over time at some points of s1_deepreg2.sws

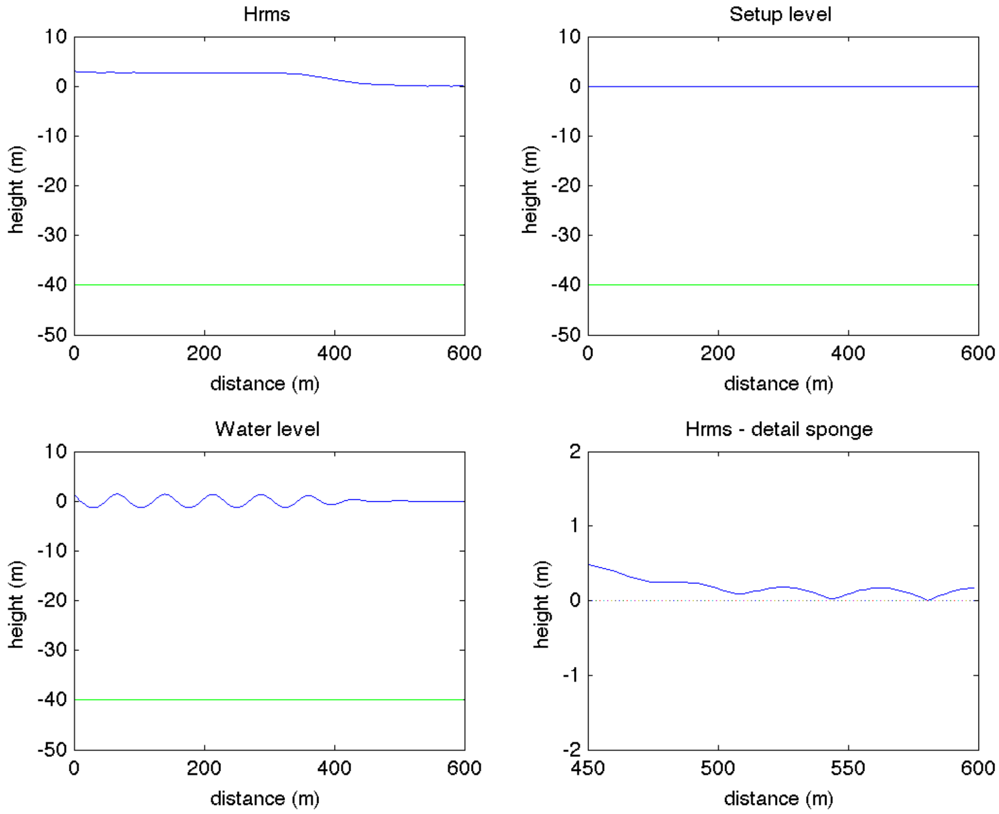

Figure 4. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_deepreg2.sws

Hrms does not get to be a constant zero in this situation neither, even though values decrease and it seems to stabilise a little bit more the height parameter.

From that we can guess nothing was wrong with the sponge, which makes complete sense since in the User Manual it is said the proper longitude is around three times L_{wave}.

Reading Martínez Pés, V. thesis (2013) [8] I saw he had problems when it comes to the main water level; it had a decreasing tendency through time. To make sure the same was not happening in my scenario I decided it would be wise to plot a longer propagation time period (even though in regular waves it is supposed to be not necessary since the pattern should remain always the same).

S1_deepreg3.sws

This script has the same characteristics as s1_deepreg2.sws, which means I have kept the longitude of the sponge as 4L, just in order to remain in the safer side in case some reflection existed indeed. Simulation time has been enlarged so that around 500 waves travel the flume.

Running the script I obtained:

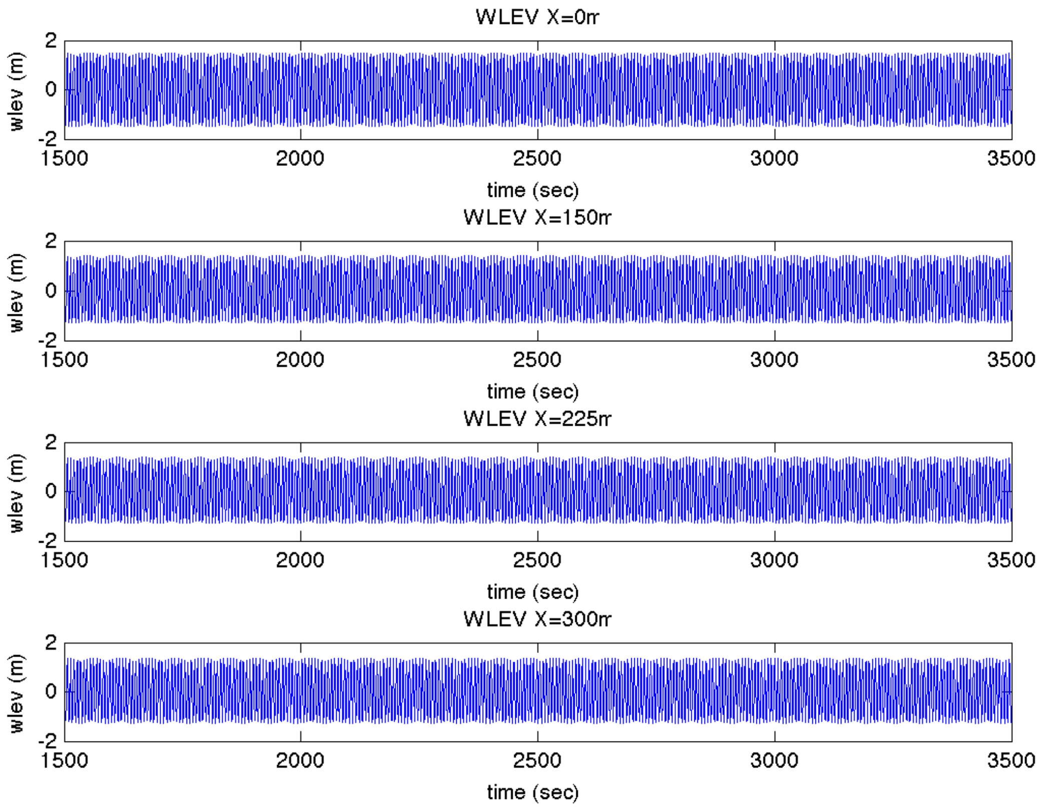

Figure 5. Water elevation over time at some points of s1_deepreg3.sws

It is clear that the mean water level has tendency to remain null, as it should be expected. However, oscillations are easily distinguished throughout time in the above records (Fig.5). Is it due to some kind of reflection at the end of the flume?

So far, as an overview, the problems appeared are:

- Reduction of the wave height as it propagates over the flume. It is loosing energy somewhere but I cannot understand why.
- Non-sinusoidal wave pattern
- Oscillations in the mean water level through time, even though the averaged value is zero as it should be.

Possible explanations coming up to my mind:

- The sponge layer, even being large enough, is still playing some role in such situation.
- The scenario is not deep enough and some bottom effects are disturbing the wave propagation.

The two following scripts have been created in order to find out if the above possibilities are indeed causing the non-expected waves behaviour.

S1_deepreg4.sws

Coming back to a sponge length of $3L_{wave}$ I want to observe how the oscillations (Fig.5) develop in such circumstances; are they larger than with a 4L sponge? Therefore, this script is equal to s1_deepreg.sws but enlarging the time period of the output.

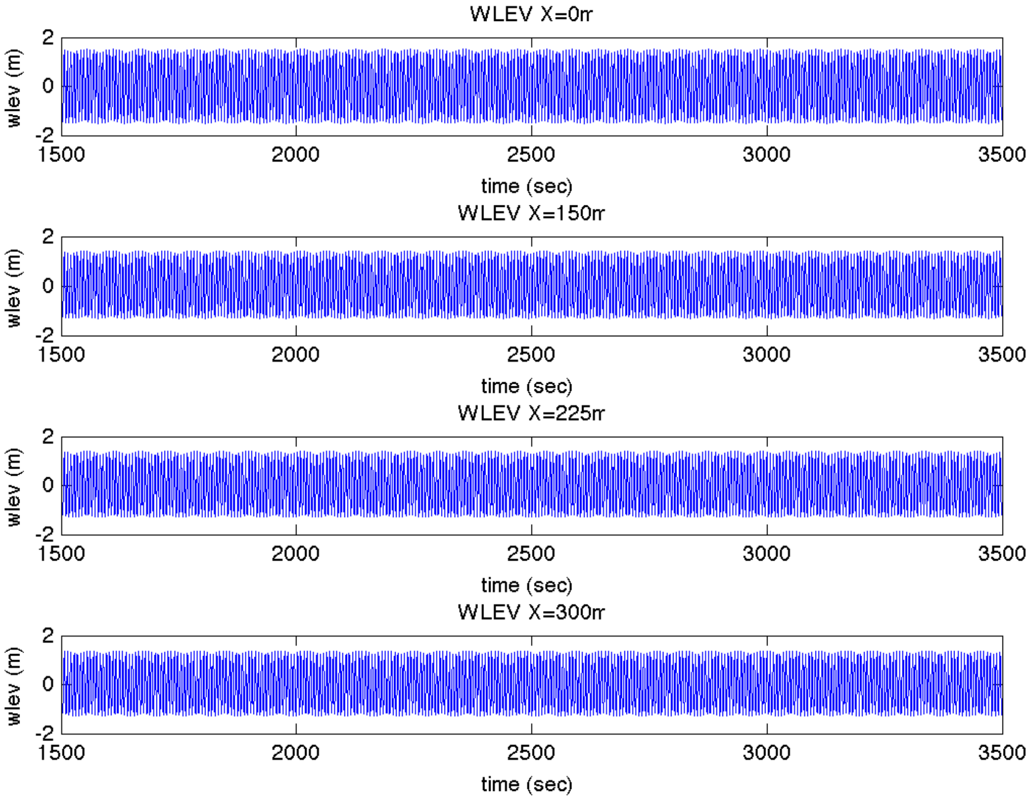

Figure 6. Water elevation over time at some points of s1_deepreg4.sws

In deepreg3.sws (with a sponge of 4L) at x=225m, the maximum and minimum values of the water level series were:

WL_{max} = 1.3915m WL_{min} = -1.2854m

So that the range is 2.6769m

Analysing the current case at the same point, x=225m:

WL_{max} = 1.3941m WL_{min} = -1.2879m

So that the range is 2.6820m

No significant differences are observed; the resulting plots are almost equal. If the sponge was affecting, larger oscillations should have been displayed. Hence, it confirms once more the sponge layer is not causing any of the instabilities taking place in my modelling.

Therefore, as commented before, the only explanation left I can think of is the bottom interfering to the generated waves. A new simulation of regular waves is going to be considered on a deeper scenario.

S1_deepreg5.sws

Features from s1_deepreg3.sws are going to be considered, namely the sponge length of $4L_{wave}$ and long simulation time period.

So far we have been considering a water depth of 40m. Hence, to make sure we are erasing any possible bottom effect, let's consider a new water depth of 60m, for instance.

The oscillations are still present and also the height reduction is taking place. Nothing has changed with respect to the prior scenarios; the existing problems remain the same.

A2.2 Overview and conclusions so far – regular waves:

Observed behaviour:

- Reduction of the wave height as it propagates over the flume. It is loosing energy somewhere but I cannot understand why.
- Non-sinusoidal wave pattern
- Oscillations in the mean water level through time, even though the averaged value is zero as it should be.

Possible explanations:

- The influence of the sponge layer has been checked with no successful results
- The influence of the water depth has been also check with no successful results neither.

Checking results in Martínez Pés, V. (2013), I have seen the same happened to him when it comes to the wave height declination, but in the end it turned out to be an issue with the sponge layer length, which it is not the case here as it has been proved.

I still do not know if the fact of the Hrms not reaching a 0-value is significant and if it has consequently something to do with the observed behaviour.

Anyway, albeit not exact, the results are roughly the expected ones.

A2.3 Propagation of spectrum waves

We are going to proceed to the propagation of spectrum waves (non-regular waves) in the same deep flume.

To analyse these results Matlab post process might be needed. In order to perform a wave per wave analysis, the Matlab code created by Martinez Pes, V. (2013) is going to be used.

- WAVE PER WAVE ANALYSIS

As a first validation for the script, I have applied it to one of the previous computed simulations with regular waves (S1_deepreg2.sw). The results have been satisfactory.

Having introduced an Hs=3.04m and Tm=6’88sec, the values returned by Matlab have been de following:

X=0m	X=225m
• MWL= 0.0162 ≈ 0 Hm= 2.9042 Tm=6.8571 Hs= 2.9325 Hrms=2.9044m	• MWL = -0.0111 ≈ 0 Hm= 2.4317 Tm=6.7500 Hs= 2.4661 Hrms=2.4319m

Table 1. Wave per wave analysis in s1_deepreg2.sws

We can see at x=0 the values agree with the generated wave, so that it has been correctly introduced. Moreover, the results also agree with the previous observed behaviour; T remains approximately constant whilst H is decreasing.

That means we are already able to use this code for the following simulations.

S1_deepir.sws

We are going to take the same scenario as in s1_deepreg3.sws (40m deep, sponge length of $4L_{wave}$). The time of simulation is going to be long as well, since dealing with irregular waves requires around 500 propagated waves in order to obtain reliable results. The spectrum is going to be governed by the commands:

```
BOU SHAP JON 3.3 SIG MEAN DSPR DEGREES
BOU SIDE W BTYPE WEAK CON SPECT 3.045 6.88 0 5 MIN
```

Value 3.3 for the spectrum refers to young sea states, on average.

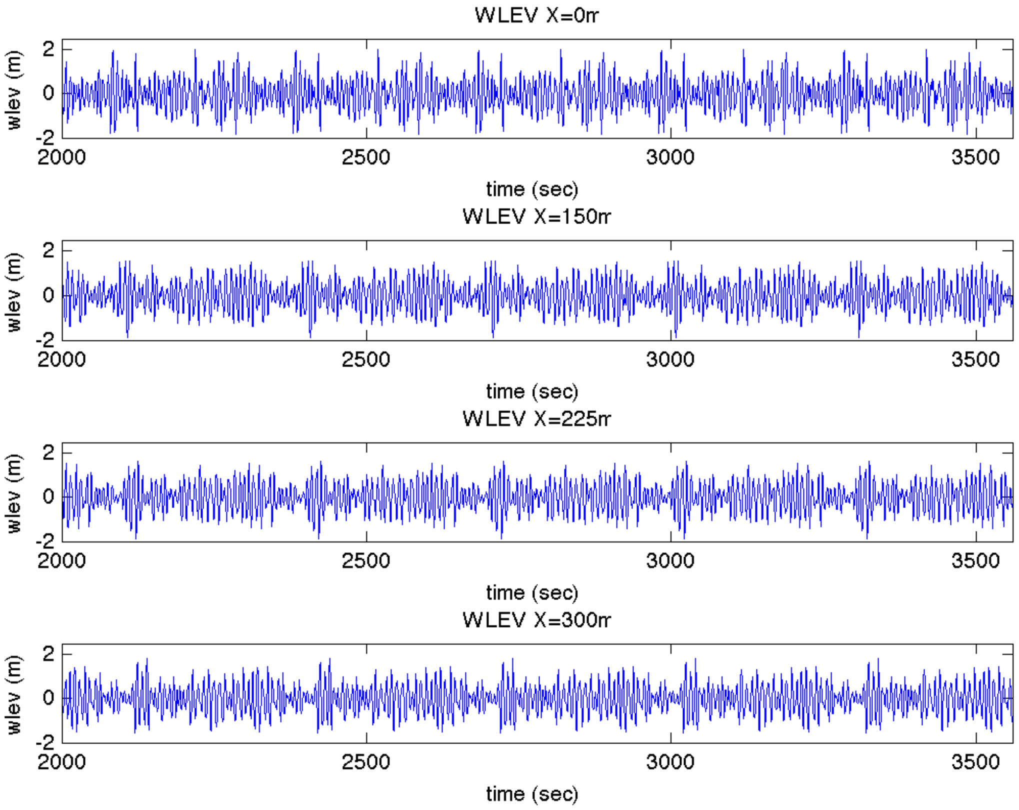

Figure 7. Water elevation over time at some points of s1_deepir.sws

Wave per wave analysis:

X=0m	X=300m
• MWL =-1.0573E-04 ≈ 0 Hm= 1.8475 Tm=6.9704 Hs=2.7639 Hrms=2.0181 From the variance: Hmo=2.9766 Hs=2.8277 Hrms=2.1047	• MWL = -0.0033 ≈ 0 Hm=1.7054 Tm=7.5176 Hs=2.4837 Hrms=1.8400 From the variance: Hm0=2.6840 Hs=2.5498 Hrms=1.8979

Table 2. Wave per wave analysis in s1_deepir.sws

When introducing the spectrum information I am introducing Hmo, so that since the value Hmo in x=0 m is really close to the generated data, I can conclude the spectrum is well introduced.

The spectrum deforms as it propagates through the flume. As it happened with regular waves, their height decreases over the distance, so that energy is dissipating. Furthermore, in the spectrum waves propagation it is also possible to see a slightly increasing tendency of the mean wave period.

In the governing command that defines the spectrum I have defined the parameter "CYCLE = 5 MIN ". I did not understand at all what this value defined, but after the above simulation I have realized the irregular pattern on the time records is repeated every 5min as settled in 'CYCLE'; this means that only computing the last 5 minutes would lead me to the same wave height and period statistics.

Therefore and in order to check its effect, I am going to create a new script.

S1_2deepir.sws

In this case 'CYCLE' has been settled at 30MIN.

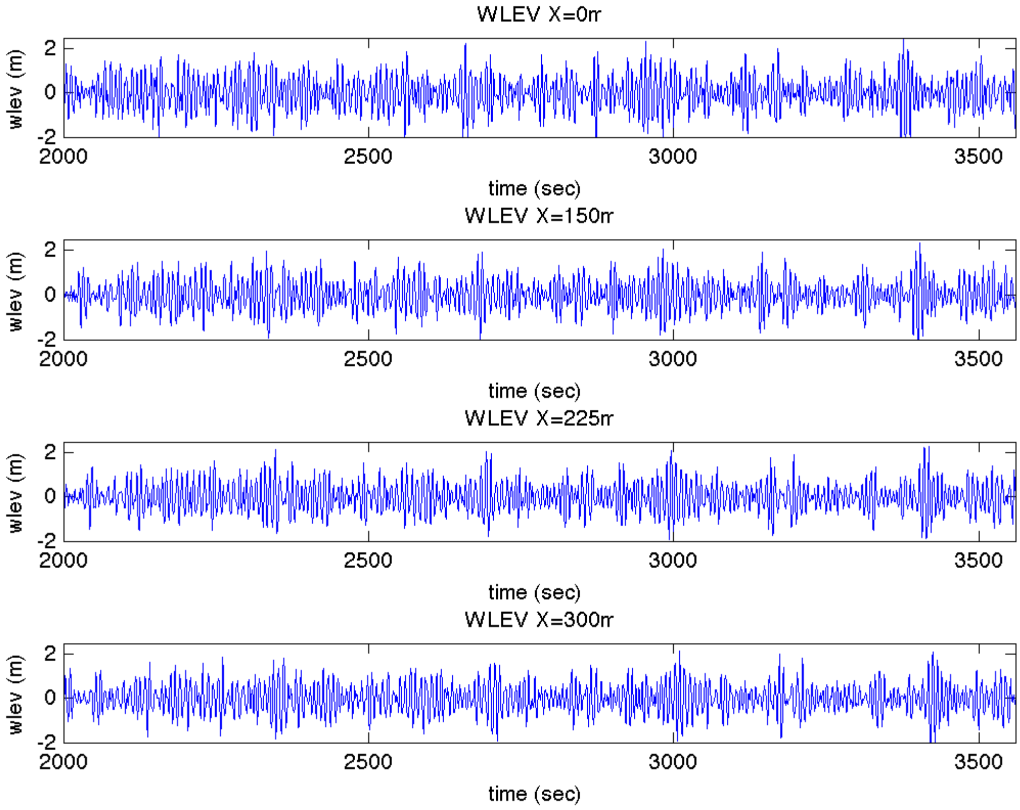

Figure 8. Water elevation over time at some points of s1_2deepir.sws

Wave per wave analysis:

X=0m	X=300m
• MSL = -6.4924E-04 ≈ 0 Hm=1.7916 Tm=7.0449 Hs=2.7872 Hrms=1.9892 From the variance: Hmo=2.9556 Hs=2.8078 Hrms=2.0899	• MSL = -0.0023 ≈ 0 Hm=1.6463 Tm=7.4730 Hs=2.5974 Hrms=1.8365 From the variance: Hmo=2.6670 Hs=2.5337 Hrms=1.8859

Table 3. Wave per wave analysis in s1_2deepir.sws

Hmo and Hrms have slightly decreased. Tm has slightly increased. The same effects as in the above situation are observed.

- SPECTRAL ANALYSIS

Apart from the post process of data through the wave per wave analysis, I have decided to start working with a spectral analysis as well. It will allow me to have a clearer idea of the results and to compare values from both methods in order to make sure everything is correct.

To do that, I will take again the Matlab script from Martínez Pés, V. (2013) [8], (spectral_analysis.m); I will find out how it works and afterwards I am going to run it for the case s1_2deepir.sws.

As an input, the code only requires the time and the water level series, as well as the number of periodograms to be considered. In order to get reliable results it is recommended to take between 10 and 30 periodograms. However, Martínez Pés, V. could not appreciate any difference between using 5 or 10 and therefore, I am going to change my simulation time to 45 min in order to divide the data into 5 periodograms.

I proceeded to run the code but, to my surprise, it was not working.

"Undefined function 'periodogram' for input arguments of type 'double'."

Even I searched the so-called function "periodogram" in my Matlab, it looks like it does not exist, it seems not to be defined in my software version.

I have contacted Martínez, V. in order to ask him about what should be wrong. He told me some points he thought about which could be a problem.

1- To have called the script with an incorrect name or having it kept in another folder.
2- To have created the input tables properly.
3- Check not having any change in time intervals.
4- To have the time input defined in seconds, which was required for running the script.

5- Check the wave record with a previous analysis wave per wave to make sure the error is not located in the wave data.

Everything was already accounted for, so none of these points seemed to overcome the issue.
Martínez, V. also told me he would look for some of his created scripts where the problematic function was not used and the development of it was made step by step instead.

He could manage to find a code where “periodogram” was not used (spectral_analysis6.m), and when I introduced it in Matlab I could finally obtain output values and spectrum plots with no error messages anymore.
I run the program for the scenario s1_2deepir.sws. Results obtained through both the spectral analysis and the wave per wave analysis at x=0:

X=0m	
Spectral analysis	Wave per wave analysis
Hm0 = 2.1364 Tm01 =7.1740 Tp = 8.2581 Hrms = 1.5107	• MWL = 0.0011≈ 0 Hm = 1.8607 Tm =7.1588 Hs =2.8367 Hrms = 2.0436 From the variance: Hm0 =3.0220 Hs = 2.8709 Hrms = 2.1368

Table 4. Wave parameters at x=0m of s1_2deepir.sws - error

I obtain different values whilst they should be the same. It looks like something is wrong in the spectral analysis since values in the wave per wave analysis make complete sense.

- ERROR FOUND:

I have observed that values from spectral analysis Hm0 and Hrms differ both around a factor of 1.42 from the ones computed through the wave per wave analysis; that means a factor of √2 of difference between them.

Checking the definitions of both values in the script, we can confirm they are well introduced. That would mean the parameter 'm0' is wrongly computed, and thus, it has to be the same for 'm1', since T=m0/m1 and it showed no problems in the obtained results.

I came up with a solution: multiplying the obtained value from the fast Fourier derivatives per 2 will solve the error in the code (code available in *Appendix B*).

Martínez, V. told me the code was wrong indeed. Since he finally used another script, that one was a former sketch never corrected.

Therefore, having corrected the script, the new results are:

X=0m			
Spectral analysis		Wave per wave analysis	
Hm0 = 3.0214	Tm01 =7.1740	• MWL = 0.0011≈ 0	
Tp = 8.2581	Hrms = 2.1364	Hm = 1.8607	Tm =7.1588
		Hs =2.8367	Hrms = 2.0436
		From the variance:	
		Hm0 =3.0220	Hs = 2.8709
		Hrms = 2.1368	

Table 5. Wave parameters at x=0m of s1_2deepir.sws

Which match perfectly with the values from the wave per wave analysis. The spectrum obtained is:

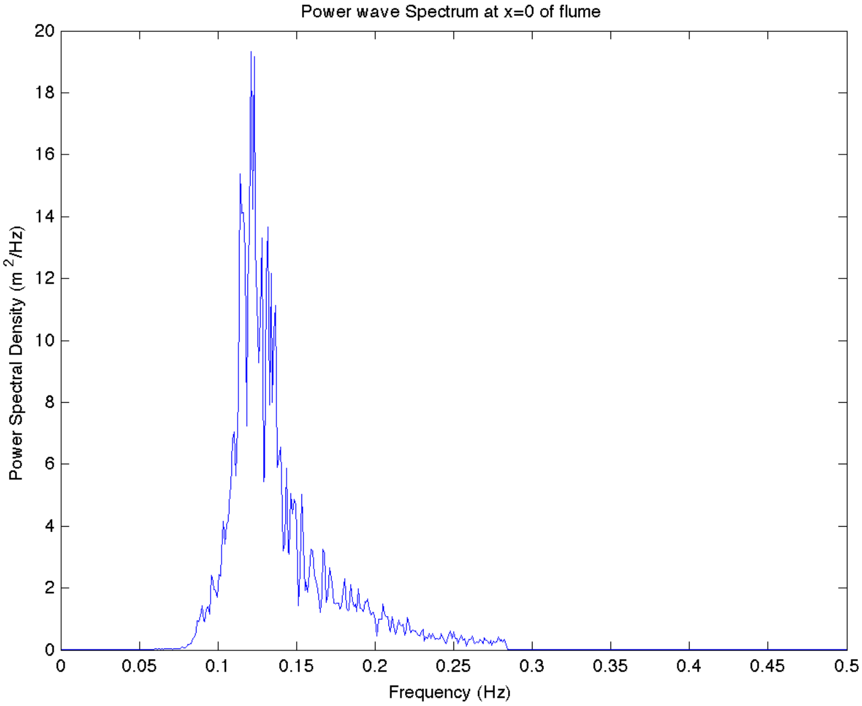

Figure 9. Wave spectrum at x=0m in s1_2deepir.sws

Therefore, we can finally say both wave per wave and spectrum analysis are well calibrated.

Now, checking it for the same wave at x=300 in the flume

X=300m			
Spectral analysis		Wave per wave analysis	
Hm0 = 2.6788	Tm01 =7.5173	• MWL = -0.0019 ≈ 0	
Tp =8.1270	Hrms =1.8942	Hm = 1.6835	Tm =7.5396
		Hs =2.5791	Hrms =1.8525
		From the variance	
		Hm0 =2.6793	Hs =2.5453
		Hrms =1.8946	

Table 6. Wave parameters at x=300m of s1_2deepir.sws

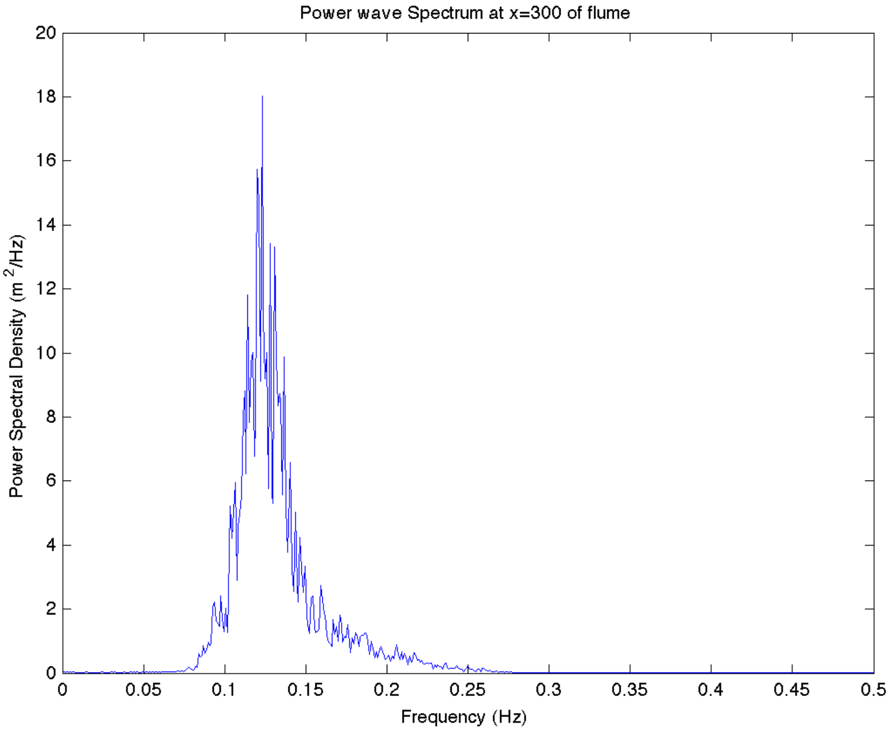

Figure 10. Wave spectrum at x=300m in s1_2deepir.sws

We can confirm again that the values from both analysis match. Once more, comparing the results from spectral analysis in both locations, we get to the same observations as before. Hs and Hrms decrease, Tm slightly increase and now we can also see the behaviour of Tp; contrarily to Tm, the peak period decreases a little bit.

A2.4 Overview and conclusions so far – spectrum waves:

The observed behaviour is similar to the already discussed behaviour in regular waves propagation. The height is diminishing for some reason I cannot explain and, moreover, a change in the period value is also present in spectrum propagation: Tm is increasing whilst, conversely, Tp decreases.

Doubts:

- How is the parameter ‘CYCLE’ in the spectrum governing command affecting the waves?
- Why is the spectrum deforming along the flume?

A3. SHALLOW WATER FLUME

I am going to generate the same wave signals as in the deep flume, which are taken from the CLASH report [5] according to the values reported for storm 1, as mentioned at the starting of this document. This way, I am going to be able to make a comparison between both behaviours.

As done in deep water, it is wise to start modelling with regular waves.

A3.1 Propagation of regular waves:

S1_shallreg.sws

According to the report from CLASH project in Zeebrugge, the depth in the original scenario is about 12m.

In fact the simulation is located in intermediate water instead of shallow ($L_{wave}/20<d<L_{wave}/2$). Anyway we are going to refer at it as shallow flumes since comparing to deep flumes, they are much shallow situations.

I will use 100 cells per L_{wave} length instead of 50 as it has been used in deep flumes since a/d= 0.125 is not that much smaller than 1, and it will require more precision in the computations.

Hand-calculation is done to define all the needed parameters to create the script.

As we are not in deep water, the bottom influences wave propagation. Nevertheless, the effects should not be very important due to we are far from breaking conditions.

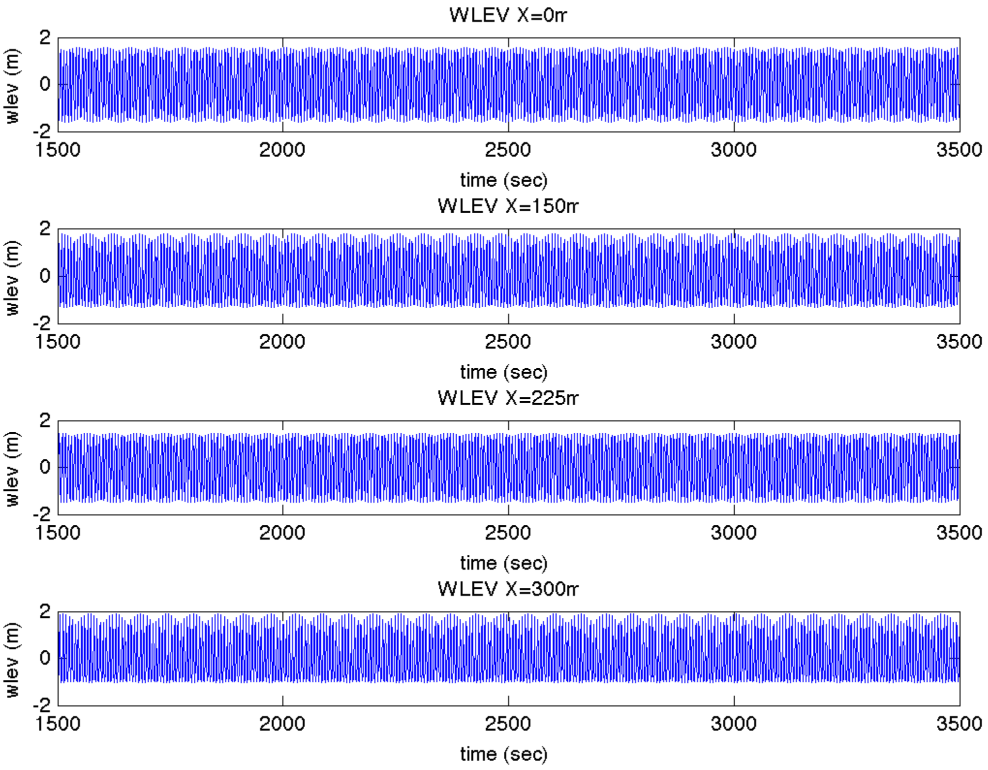

Figure 11. Water elevation over time at some points of s1_shallreg.sws

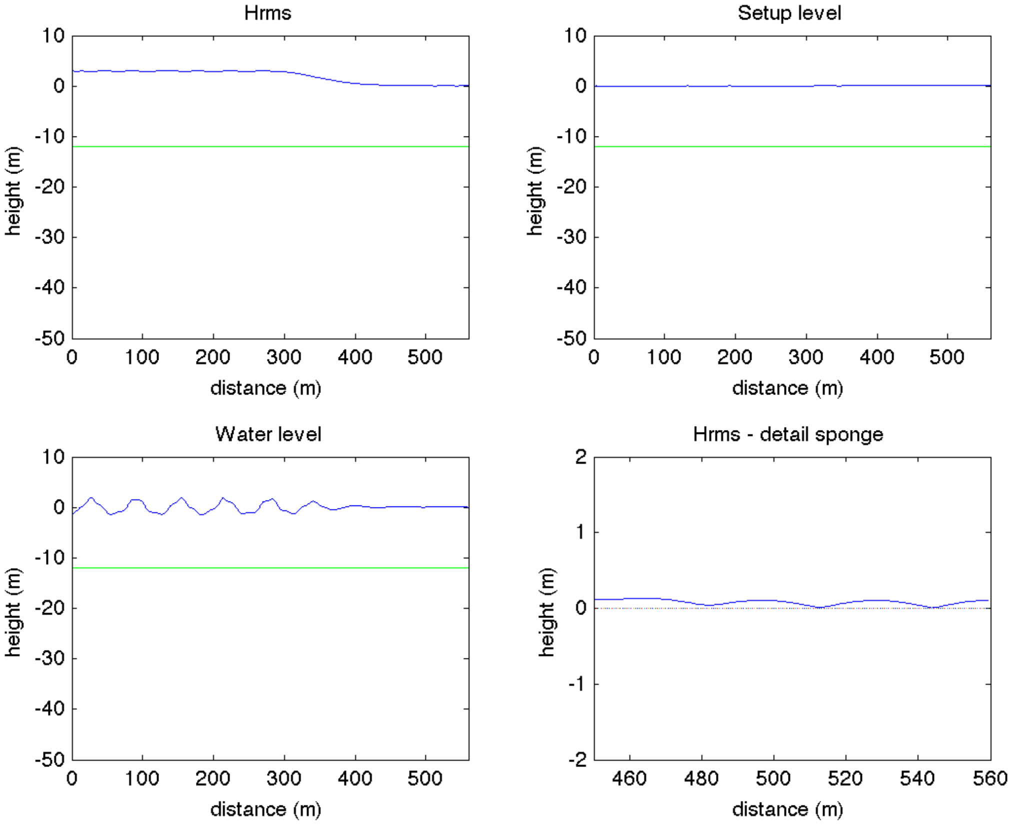

Figure 12. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_shallreg.sws

Wave per wave analysis:

X=0m	X=300m
• MWL = -0.0013 ≈ 0 Hm = 3.0308 Tm = 6.8773 Hs = 3.0820 Hrms = 3.0311	• MWL = 0.0051 ≈ 0 Hm = 2.7251 Tm =6.8802 Hs =2.8803 Hrms =2.7292

Table 7. Wave per wave analysis in s1_shallreg.sws

According to the images in the time records it seems that the main water level differs from 0 at some points. However, the setup doesn't show the same, and furthermore, when analysing wave per wave, the results doesn't reflect such mentioned behaviour neither. Further analysis has to be carried about that issue later on.

H decreases whilst Tm remains the same.

A3.2 Propagation of spectrum waves:

Check behaviour for irregular waves in shallow water and compare it to the seen in deep water.

S1_shallir.sws

We are going to generate the spectrum in the same scenario as in the above regular propagation case. However, the simulation time is going to be changed to 45min, as it is required to run the spectrum analysis code in Matlab.

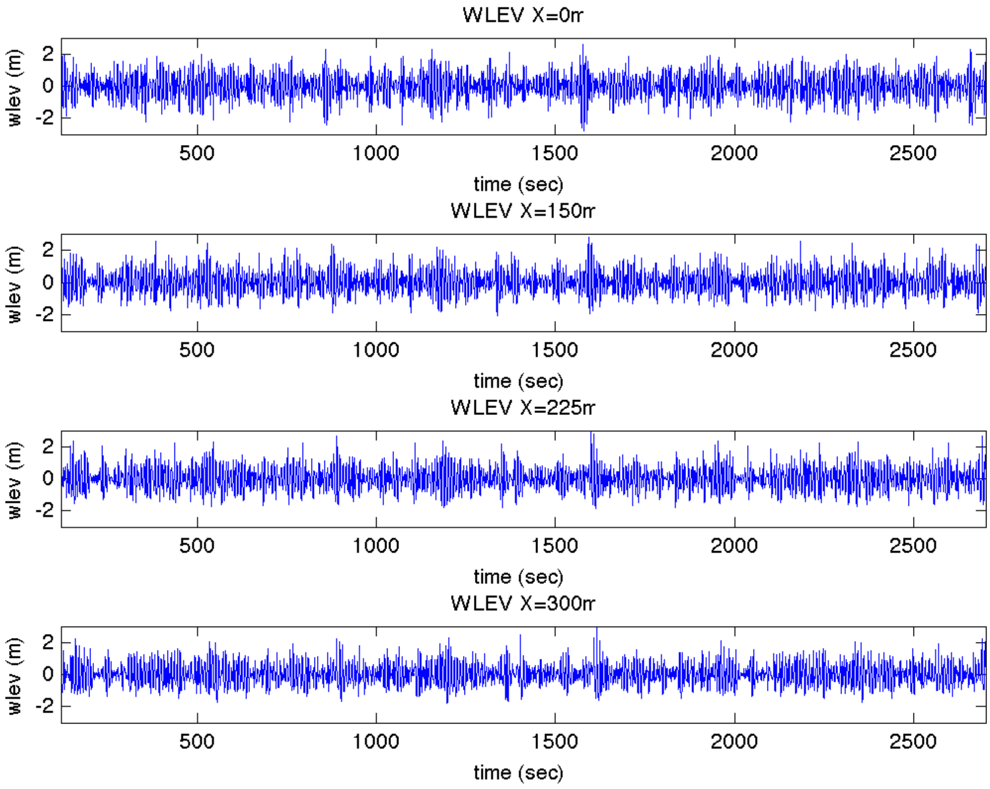

Figure 13. Water elevation over time at some points of s1_shallir.sws

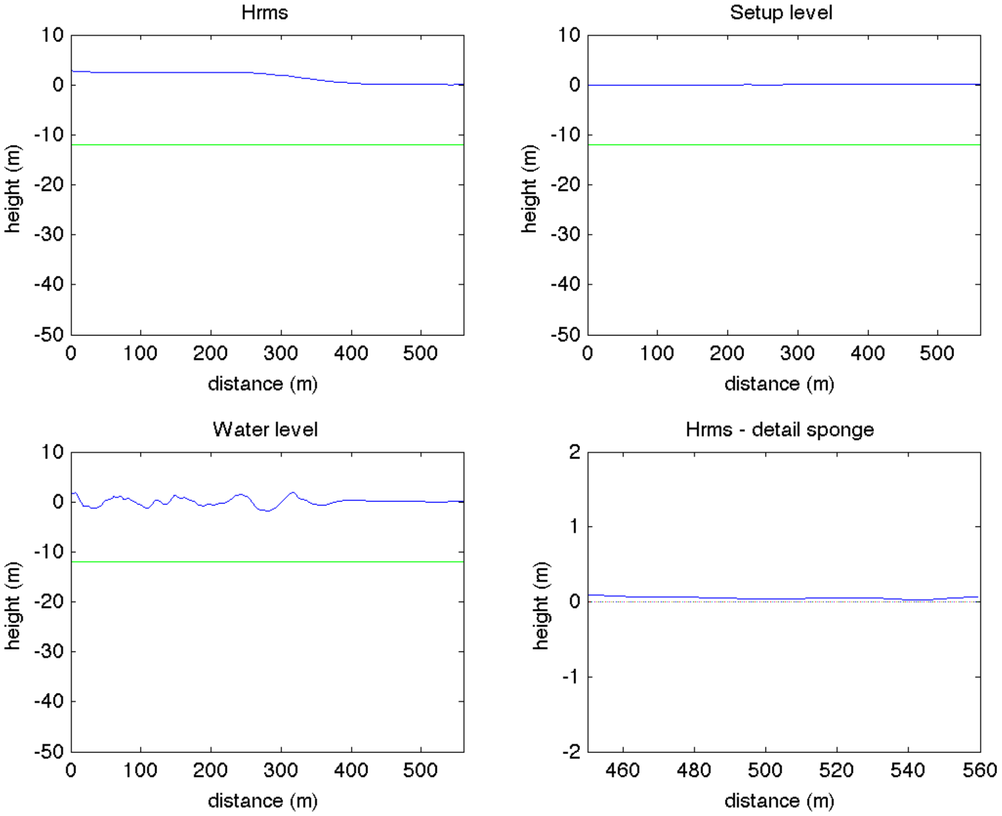

Figure 14. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_shallir.sws

X=0m	
Spectral analysis	Wave per wave analysis
Hm0 = 3.1453 Tm01 =6.8792 Tp = 8.1755 Hrms = 2.2240	• MWL = 2.14e-05 ≈ 0 Hm = 1.9412 Tm =6.9647 Hs=2.9595 Hrms =2.1370 From the variance Hm0 = 3.1459 Hs =2.9886 Hrms =2.2245

Table 8. Wave parameters at x=0m of s1_shallir.sws

X=300m			
Spectral analysis		Wave per wave analysis	
Hm0 = 2.7761	Tm01 = 6.9980	• MWL = 0.0035 ≈ 0	
Tp =8.0457	Hrms =1.9630	Hm = 1.7173	Tm = 7.0796
		Hs =2.5646	Hrms = 1.8806
		From the variance	
		Hm0 = 2.7766	Hs = 2.6378
		Hrms = 1.9634	

Table 9. Wave parameters at x=300m of s1_shallir.sws

Values at x=0m match with the introduced spectrum.

As seen in deep water, H diminishes. Here, unlike in deep water, no significant period differences occur; Tm remains more or less constant (slightly increase), Tp decreases as before.

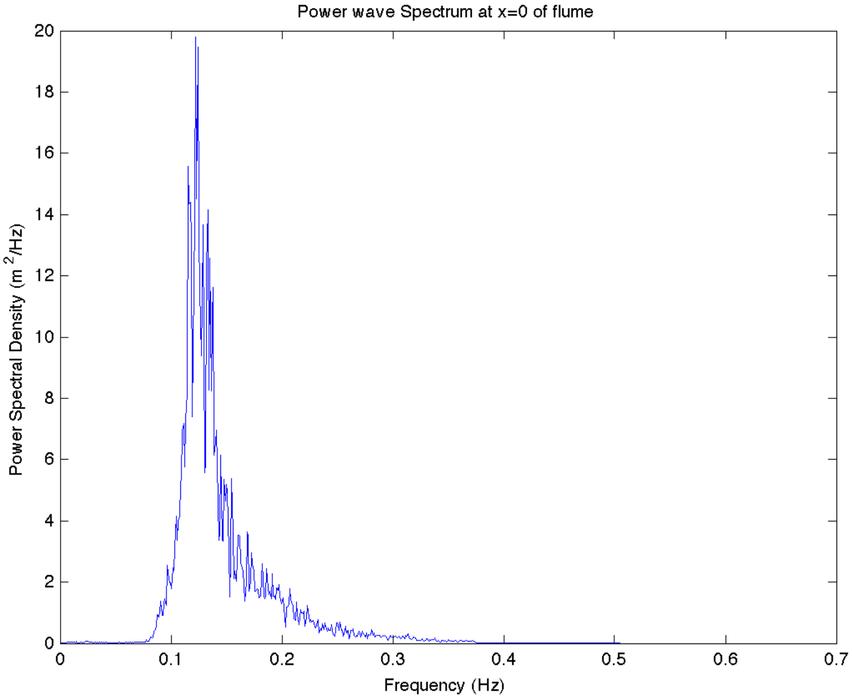

Figure 15. Wave spectrum at x=0m of s1_shallir.sws

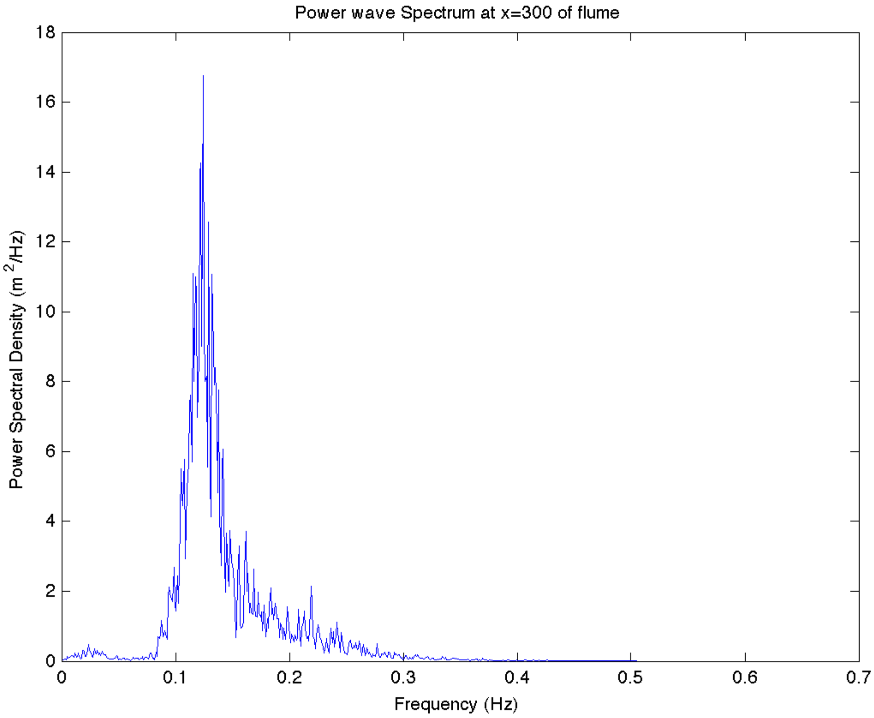

Figure 16. Wave spectrum at x=300m of s1_shallir.sws

COMMENTS OF MARCEL ZIJLEMA

- DEEP WATER:

About the regular waves propagation results in deep water I was told the following:

- The observed non-sinusoidal pattern might be caused by an insufficient time step resolution when getting the output. Therefore, reducing time step should result in a smoothing of the wave record.
- The oscillations could appear due to existing nonlinearities. Even the scenario we are dealing with is considered to be deep water, the parameter a/d=1.5/40 is around 4%, which means it is not deep enough to avoid completely nonlinear effects taking place.
- Also the decreasing of wave height in such situation could be explained by the mentioned nonlinearities (transfer of energy to the high harmonics).

- Moreover, about the absorption capacity of the sponge layer, I was told SWASH will not be capable to erase the totality of the incoming energy and it explains then my results when plotting the Hrms at the end of the sponge. However, this effect can be corrected somehow by adding the command SOMMERFIELD on the eastern boundary.

About the spectrum waves:

- I was told a value of 5 minutes for the command CYCLE when settling the introduced spectrum will be not enough, since it defines the amount of time the statistic results are to be computed. Hence, the larger this value is the better statistics we get. In the regarded scenario a value of 30 minutes will be fine.
- The observed variations both in height and period might be an effect caused by existing nonlinearities (wave-wave interaction). Nonetheless, a first reduction in height could be triggered by the way SWASH computes the incoming spectrum data when turning it into water surface information (Fourier transformations) since it considers free waves without accounting for the fact that waves travel in group. Adding the command ADDBOUND will take bound waves into account and it will therefore improve the final water surface output.
- Applying 2 vertical layers might be enough concerning the dimensionless depth (kd) as it is reported in the User Manual. However, it should be taken into account that for a given number of layers and a given depth, there is a maximum frequency above which a wave component has an incorrect celerity. For 2 layers and 40m deep, this value is reported to be 0.22Hz. Since the obtained spectrum at x=0m shows existing frequencies above 0.22Hz, I was recommended to add an extra vertical layer and increase thus the mentioned frequency to 0.32Hz. By doing that the celerity of those waves will be properly computed and it will improve spectral analysis along the flume.

- SHALLOW WATER:

When it comes to the regular wave propagation I was told:

- The observed water level elevation on time records is coherent indeed since the modelling is performed in shallow water where nonlinearities occur. Therefore, something might be wrong when computing or interpreting the resulting mean water level values.
- Output about Hrms and setup should be averaged over about the last 30 minutes. 1minute as settled above is not enough to obtain reliable results.

And about the spectrum waves:

- It makes sense to have a variation in both height and period when dealing with shallow water, since nonlinearities are expected and as mentioned before, they cause such effects. Command ADDBOUND can be also implemented in this case.

FURTHER ATTEMPTS AND DRAWN CONCLUSIONS ABOUT DEEP AND SHALLOW PROPAGATION

Having in mind all the above comments, I will perform new modelling in order to solve the problems encountered so far.

1. Solving trouble about regular waves propagation in deep water:

S1_deepreg6.sws

Taking the script s1_deepreg3.sws I will create a new version of it modifying the output time step (which is going to be shifted from 1 second to 0.5 seconds), decreasing H in order to reduce the parameter a/d and thus get rid of possible nonlinearities, and adding the boundary condition SOMMERFIELD to improve avoiding reflection. Hrms and setup will be averaged over the last 30 minutes.

First of all, by changing only the time step, we can effectively solve the non-sinusoidal pattern issue and, what is more, oscillations are not perceptible anymore (Fig.17).

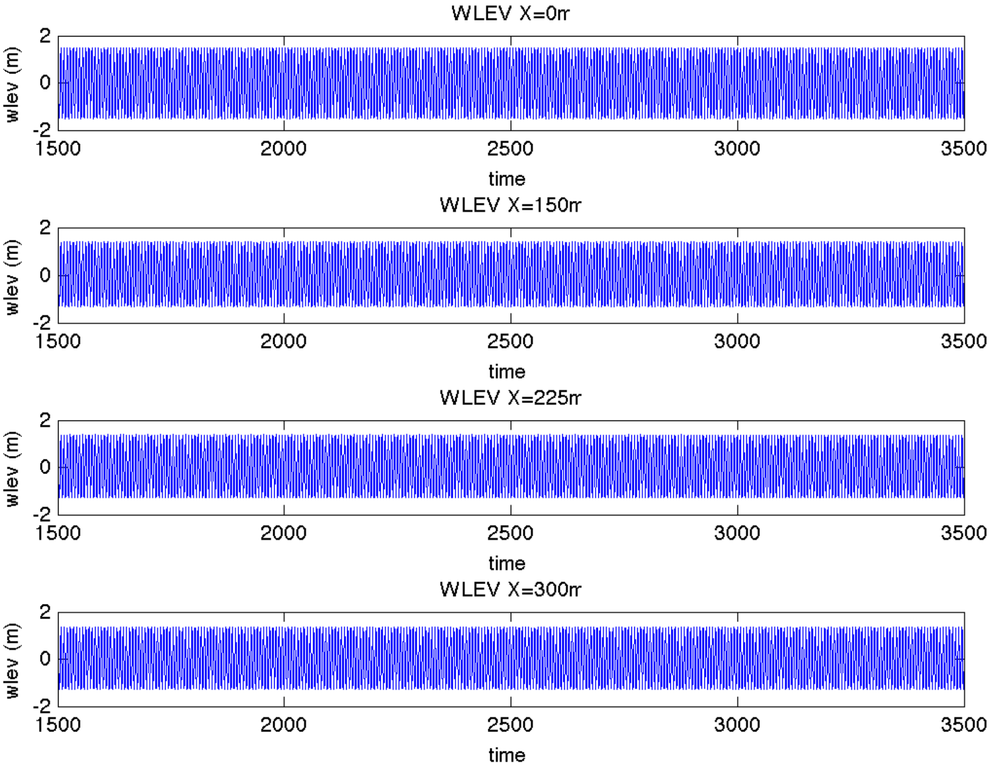

Figure 17. Water elevation over time at some points of s1_deepreg6.sws

By adding SOMMERFIELD command Hrms values slightly diminish at the end of the sponge (Fig.18). Even the change is not significant at all some correction is observed and therefore I will keep this command activated in the following modelling.

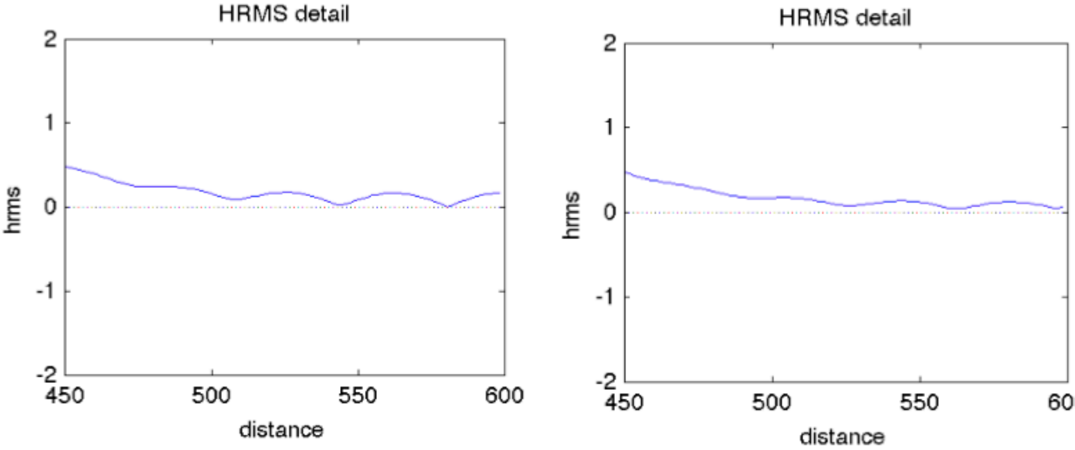

Figure 18. Comparison of the sponge layer absorption capacity adding SOMMERFIELD command

Finally, reducing the parameter a/d by changing H from 3.04 to 1m or even to 0.5m has not been seen to be effective for oscillations to disappear. This would mean they were not caused by nonlinear effects as firstly thought, but they related instead to the available output data according to the time step.

However, this last change in height has been reported to be effective when it comes to H reduction over the propagation (Table 10).

H=3.04m (a/d 4%)		**H=1m (a/d 1%)**	
X=0	X=300	X=0	X=300
Hs=3.004	Hs=2.63	Hs=0.98	Hs=0.911
Around 12% reduction		Around 7% reduction	

Table 10. Effect of nonlinearities in the reduction of the significant height along the flume

From that analysis we can conclude nonlinearities considered by SWASH were triggering the observed energy loss.

Therefore, problems related to the propagation of regular waves in a deep scenario seem to be already solved.

2. Solving trouble about spectrum waves propagation in deep water:

S1_3deepir.sws

This script will be based on s1_2deepir. The following modifications are going to be added in order to solve the existing problems: 3 vertical layers are going to be considered, the command ADDBOUND is going to be activated.

Before doing any changes:

X=0				
Wave per wave analysis		Spectral analysis		
Hs=2.8937	Tm=7.1403	Hm0=3.0214	Tm=7.1568	Tp=8.258

Table 11. Wave parameters at x=0m of s1_3deepir.sws before modifications

X=300				
Wave per wave analysis		Spectral analysis		
Hs=2.6115	Tm=7.4738	Hm0=2.68	Tm=7.5001	Tp=8.127

Table 12. Wave parameters at x=300m of s1_3deepir.sws before modifications

- Hs decreases around 9.7% and Hm0 around 11%
- Tm from the wave per wave analysis increases around 4% and in the spectral analysis around 4.7%
- Tp decreases around 1.5-1.6%

And analysing s1_3deepir.sws results:

X=0				
Wave per wave analysis		Spectral analysis		
Hs =2.9529	Tm =6.9099	Hm0=3.086	Tm =6.9983	Tp=8.2581

Table 13. Wave parameters at x=0m of s1_3deepir.sws

X=300				
Wave per wave analysis		Spectral analysis		
Hs =2.6567	Tm =7.4738	Hm0=2.7237	Tm=7.4558	Tp=8.127

Table 14. Wave parameters at x=300m of s1_3deepir.sws

As expected, Hs in the wave per wave analysis has improved thanks to the introduced correction ADDBOUND; loss becomes less significant. Yet, height and period variation along the flume:

- Hs decreases around10% and Hm0 around 11.7%, which falls within the same order of magnitude as before.
- Tm from the wave per wave analysis increases around 8% and in the spectral analysis around 6.5%, it has not improved! – The other way around, but this makes sense when accounting for higher frequencies, since Tm at x=0 will be lower.
- Tp decreases around 1.5-1.6%, which is the same variation as before.

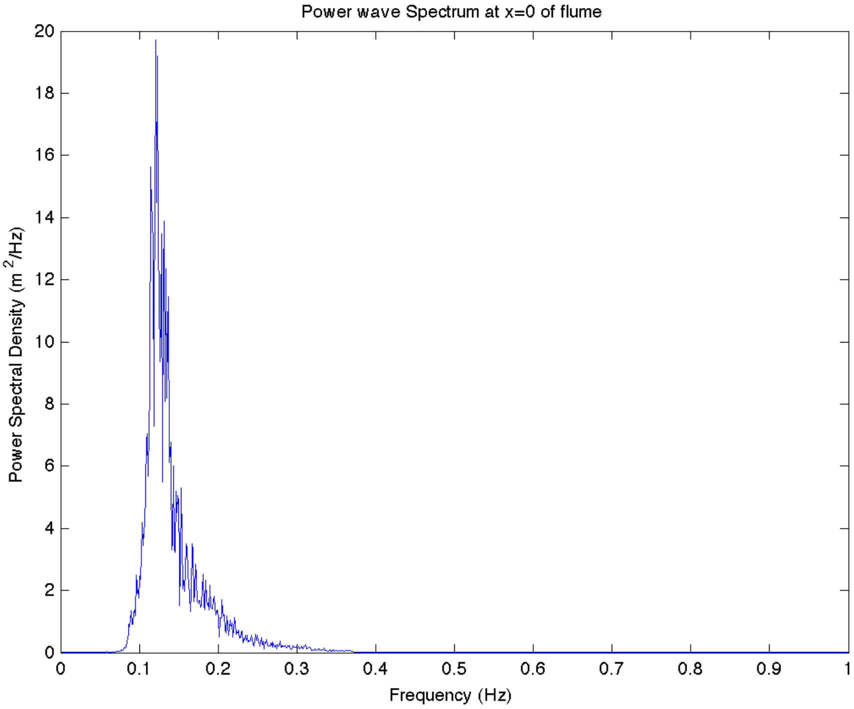

Figure 19. Wave spectrum at x=0m of s1_3deepir.sws

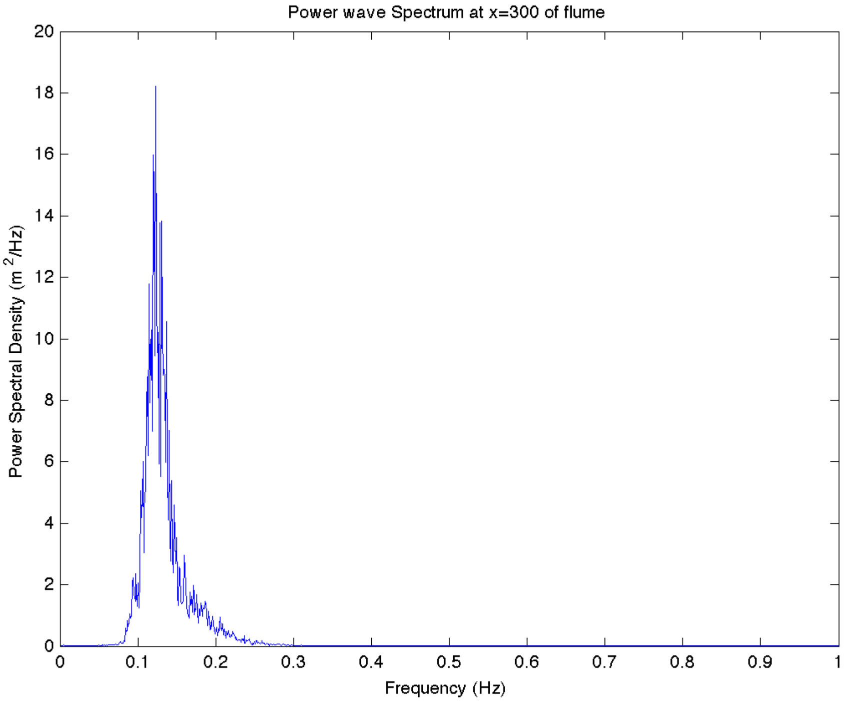

Figure 20. Wave spectrum at x=300m of s1_3deepir.sws

Nonlinearities are supposed to be the cause for the H and T changes over the flume. The following script has been created in order to check that:

S1_4deepir.sws

The only difference with respect to s1_3deepir is the reduction of the wave height. H has been lowered from 3.04 to 0.5 (a/d 0.625%).

X=0				
Wave per wave analysis		Spectral analysis		
Hs =0.4792	Tm = 6.9473	Hm0=0.5013	Tm=7.0137	Tp =8.2581

Table 15. Waves parameters at x=0m of s1_4deepir.sws

X=300				
Wave per wave analysis		Spectral analysis		
Hs =0.4592	Tm = 7.2219	Hm0=0.4750	Tm=7.2531	Tp=8.1270

Table 16. Waves parameters at x=300m of s1_4deepir.sws

- Hs decreases around 4% and Hm0 around 5%; these values decrease in comparison with the ones observed before.
- Tm from the wave per wave analysis increases around 4.4% and in the spectral analysis around 3.4%; these values decrease in comparison with the ones observed before.
- Tp decreases around 1.5-1.6%, which is the same variation as in the previous cases.

It can be confirmed nonlinearities affect the variation of the spectrum along the flume when it comes to H and Tmean. However, Tmean might be expected to diminish instead of rise; still some explanation should be found for that phenomenon.

On the other hand, Tp has been observed not to change in any case. Reduction of Tp makes completely sense by considering wave-wave interaction, whereby higher frequencies are generated. Therefore, a reduction in the peak period value is to be expected.

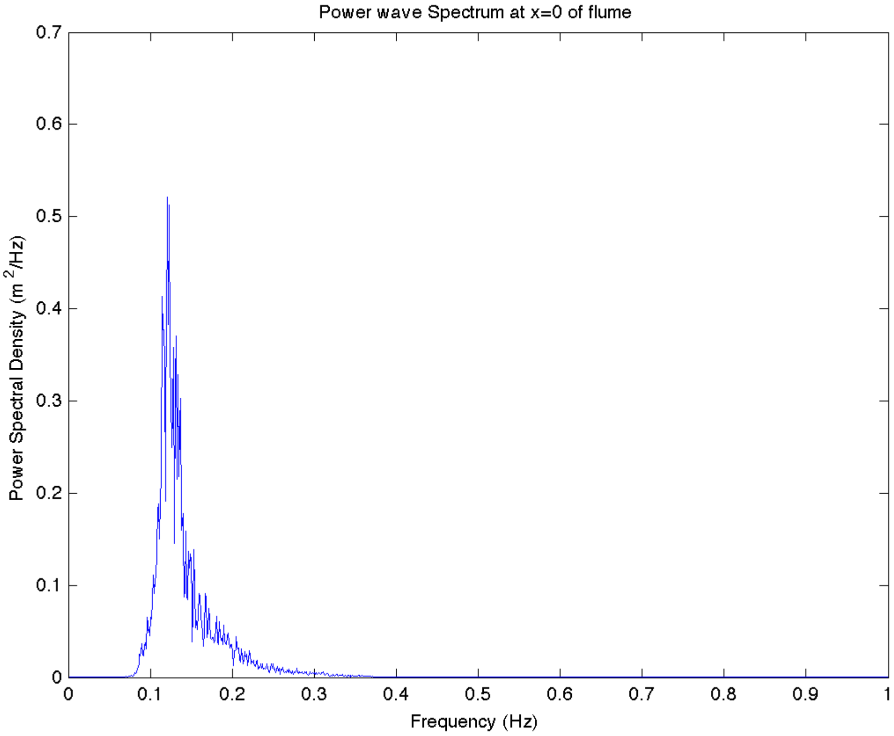

Figure 21. Wave spectrum at x=0m of s1_4deepir.sws

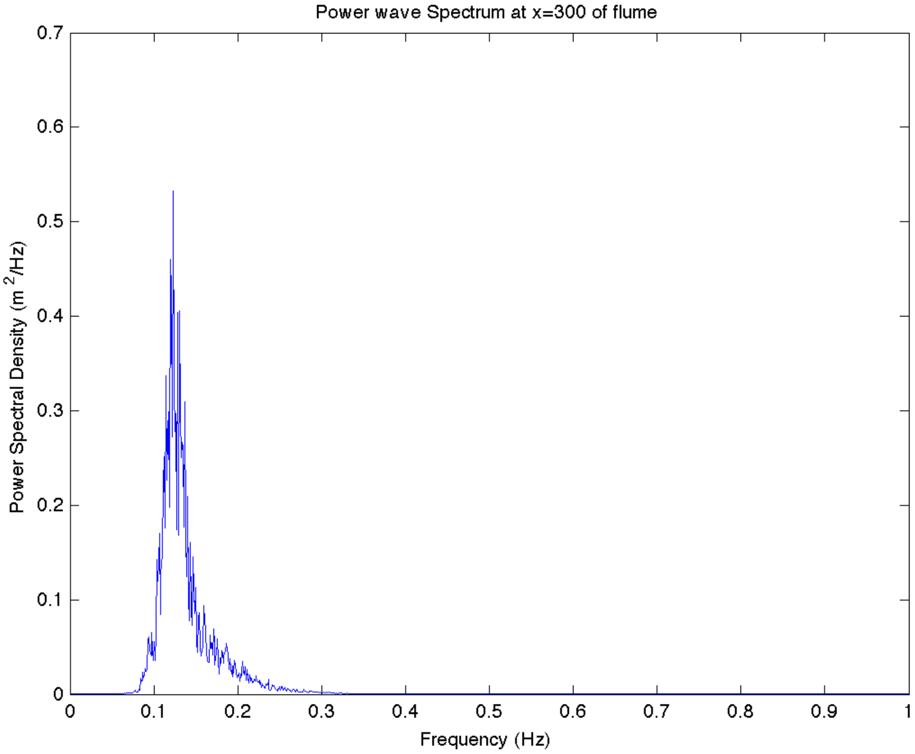

Figure 22. Wave spectrum at x=300m of s1_4deepir.sws

3. Solving trouble about regular waves propagation in shallow water:

S1_2shallreg.sws

All the corrections implemented so far for regular wave propagation are going to be applied.

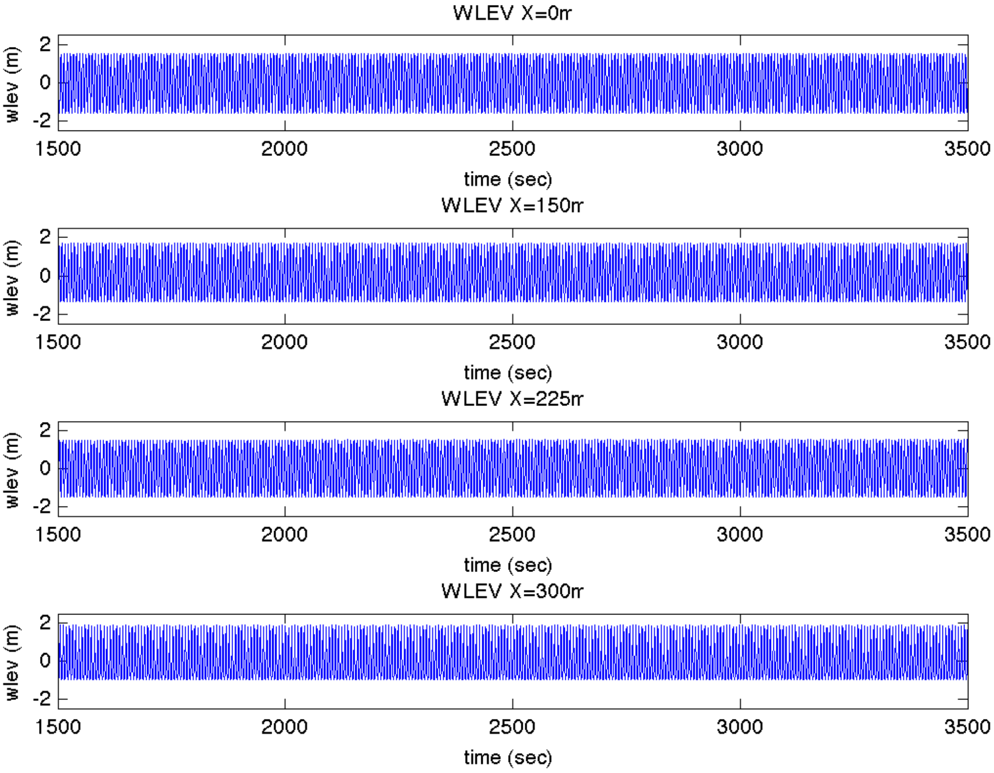

Figure 23. Water elevation over time at some points of s1_2shallreg.sws

As the oscillations problem has already been solved, they do not appear in the plot anymore. Water elevation is present, which makes sense since we are testing on a shallow scenario.

However, in the second figure no setup is visible (Fig.24) and according to wave analysis, the mean water level is shown to be constantly null along the flume as well.

- X=0m Wm = -0.0149

- X=300m Wm = -0.0091

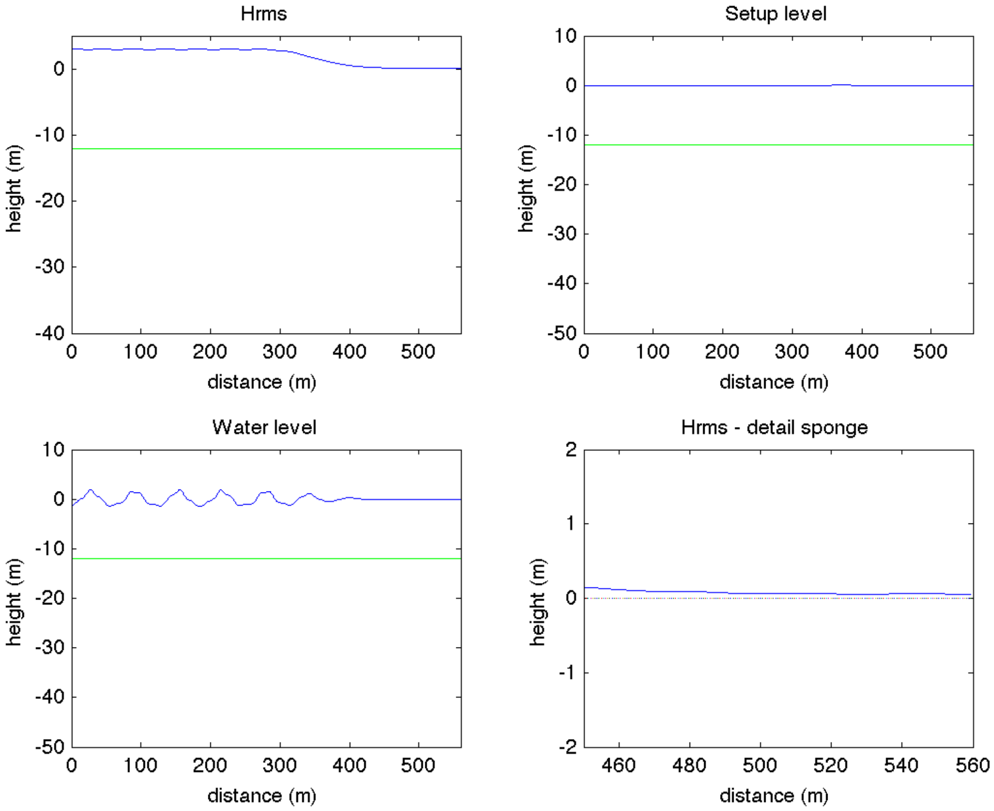

Figure 24. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_2shallreg.sws

Zooming in the time records:

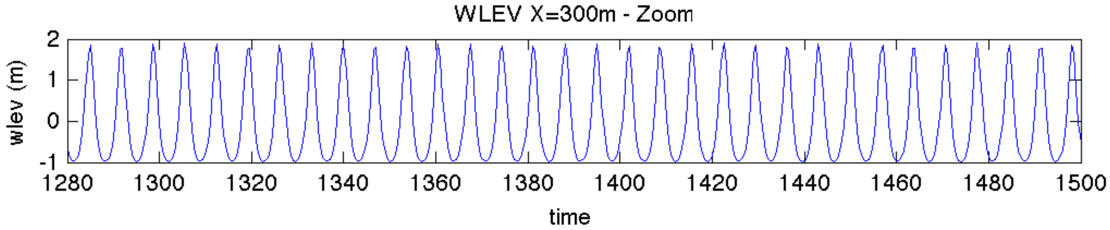

Figure 25. Detail in water elevation over time at X=300m of s1_2shallreg.sws

A skewed signal is reported, as a consequence of nonlinear effects obviously present in the shallow scenario. That is concluded to be the reason of the computed mean water level being zero; lower elevations stay longer than peaks.

Wave per wave analysis:

X=0m		**X=300m**	
Hm =3.1189	Hs =3.1419	Hm = 2.8261	Hs =2.8671
Tm =6.8794	Hrms = 3.1190	Tm =6.8794	Hrms =2.8264

Table 17. Wave per wave analysis in s1_2shallreg.sws

The fact of H decreasing has already been discussed; nonlinearities explain this behaviour.

4. Solving trouble about spectrum waves propagation in shallow water:

S1_2shallir.sws

Including the corrections done for spectrum waves scripts:

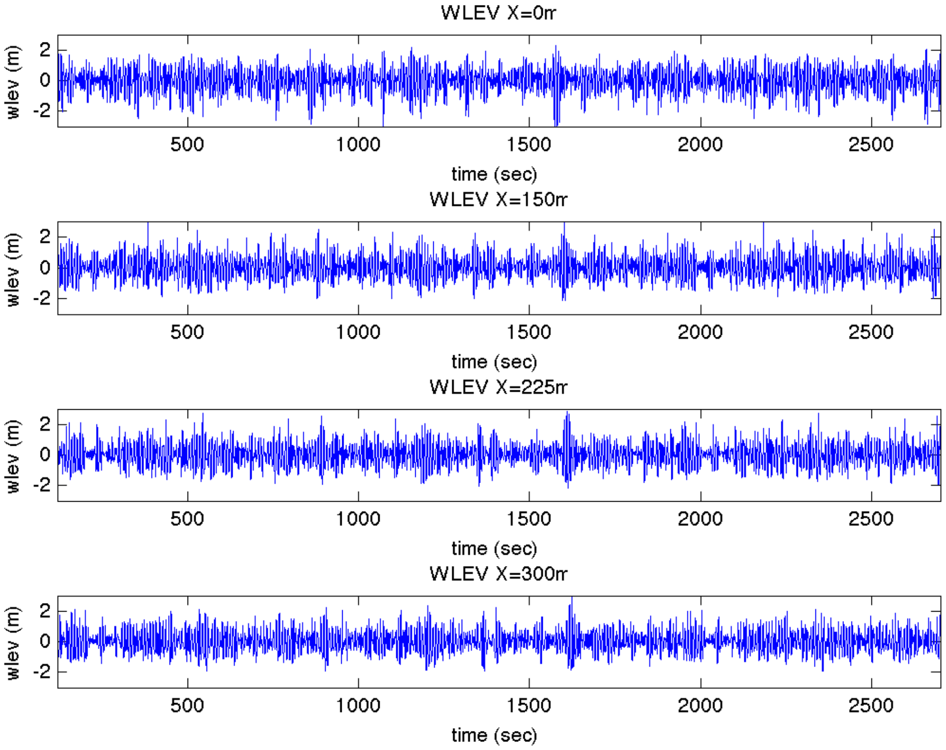

Figure 26. Water elevation over time at some points of s1_2shallir.sws

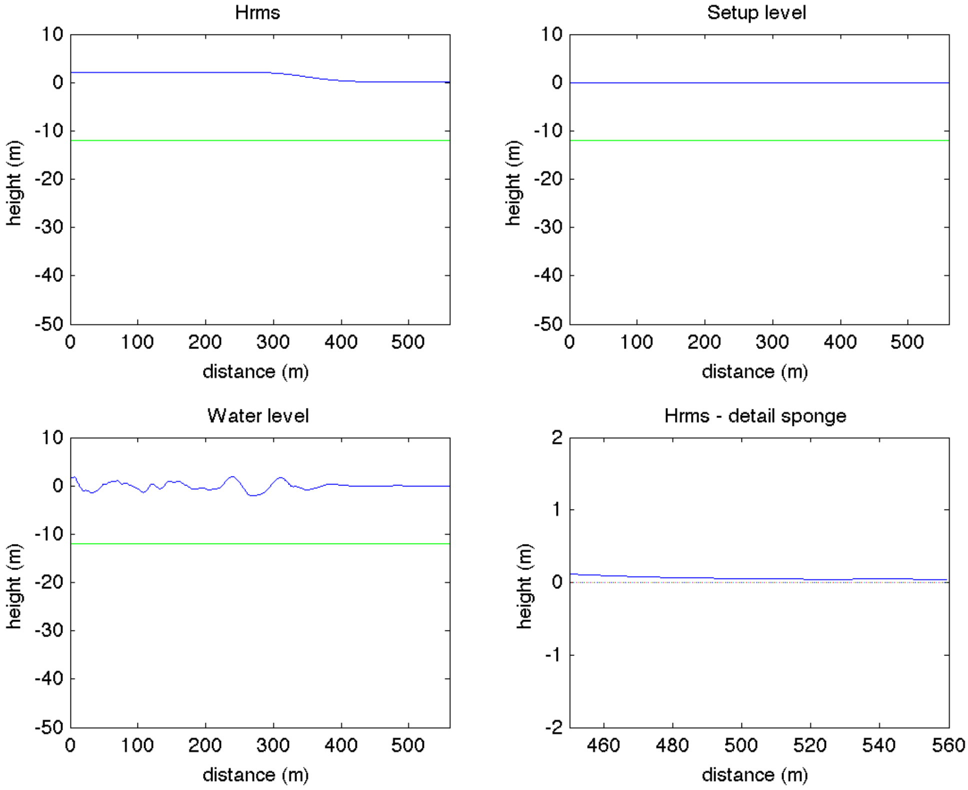

Figure 27. Hrms, setup, water level snap-shot at the last instant and Hrms detail in s1_2shallir.sws

Water level tends to be higher along the propagation as in regular waves. It has been seen nonlinearities explain such behaviour through skewness.

According to the wave analysis:

<table>
<tr><th colspan="2">X=0</th></tr>
<tr><th>Spectral analysis</th><th>Wave per wave analysis</th></tr>
<tr><td>Hm0 = 3.1818 Tm01 =7.1169
Tp = 8.4232 Hrms = 2.2498</td><td>• MWL = -0.0095 ≈ 0
Hm = 1.9836 Tm =6.9113
Hs = 3.0642 Hrms =2.1990
From the variance
Hm0 =3.1818 Hs = 3.0227
Hrms =2.2499</td></tr>
</table>

Table 18. Wave parameters at x=0m of s1_2shallir.sws

<table>
<tr><th colspan="2">X=300</th></tr>
<tr><th>Spectral analysis</th><th>Wave per wave analysis</th></tr>
<tr><td>Hm0 = 2.7991 Tm01 =7.0516
Tp = 8.2895 Hrms = 1.9793</td><td>• MWL = -0.0043 ≈ 0
Hm = 1.7694 Tm = 6.9086
Hs = 2.6822 Hrms =1.9522
From the variance
Hm0 =2.7993 Hs = 2.6593
Hrms =1.9794</td></tr>
</table>

Table 19. Wave parameters at x=300m of s1_2shallir.sws

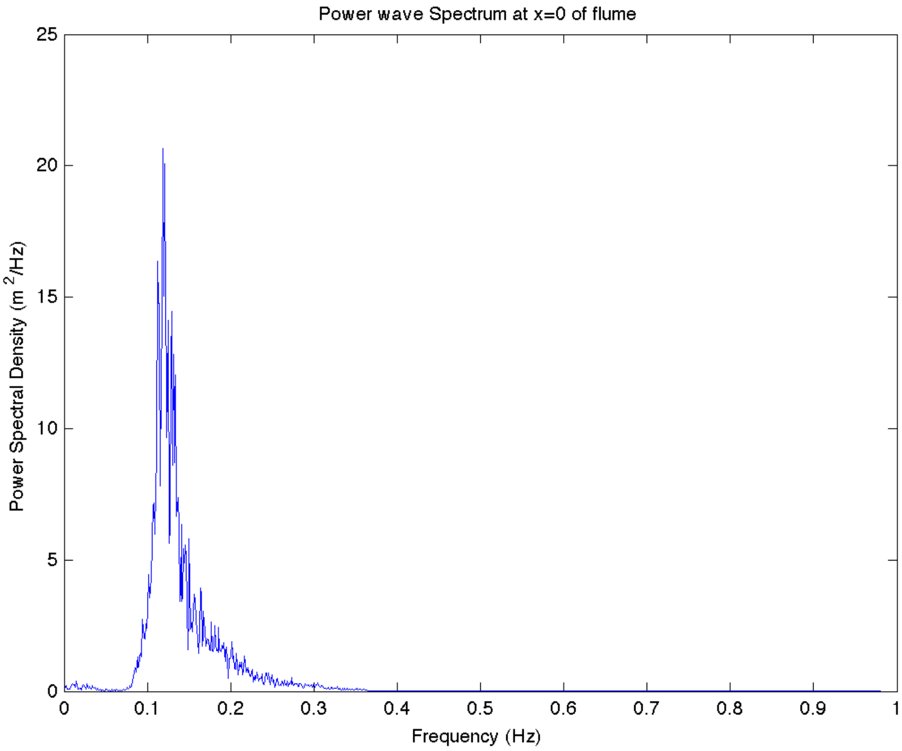

Figure 28. Wave spectrum at x=0m of s1_2shallir.sws

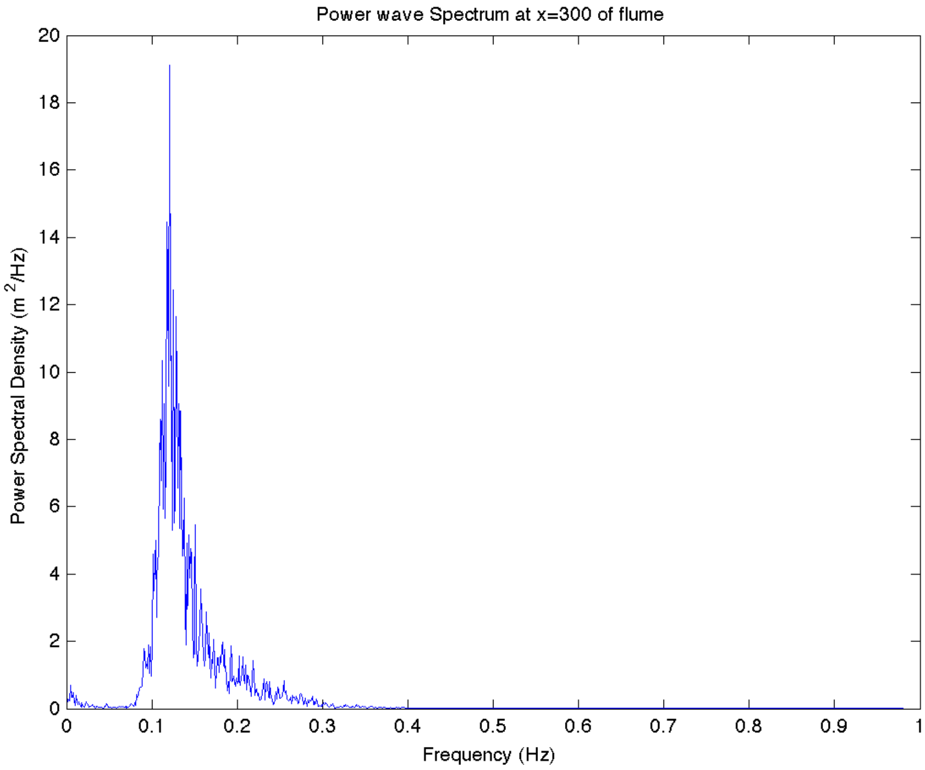

Figure 29. Wave spectrum at x=300m of s1_2shallir.sws

H decreases as expected, Tm remains constant in this case, and Tp still decreases. Since in this case, with 3 vertical layers and depth around 12m, the maximum frequency accounted in the spectrum is higher (around 0.5Hz-0.6Hz), Tm being constant instead of increasing would prove that the number of vertical layers in relation to the maximum frequency might be the cause of the problem above.

A4 IMPERMEABLE SMOOTH DIKE

According to the cross-section in the Zeebrugge report I will introduce the information in the bathymetry script (Fig.30). Waves simulating storm 1 are going to be propagated in such scenario. The overtopping tank is supposed to be located at the eastern point of the crest, about 150m far from the wave maker, where buoys are recording the sea level, so that overtopping measurements are to be taken in there in order to be compared with the real data in the studied section.

Just behind the dike, a sponge layer of 200m is placed so that it will absorb the possible water energy triggered by the overtopped water volumes.

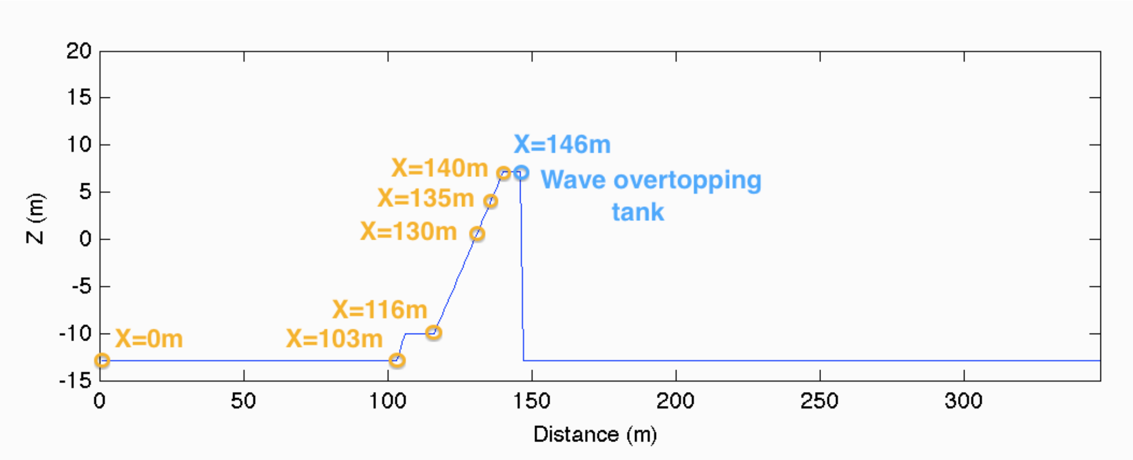

Figure 30. Modelled bathymetry in the Zeebrugge breakwater (1)

Before, though, I am going to conduct regular wave propagation tests in order to check their behaviour and the occurring phenomena.

A4.1 Propagation of regular waves:

Since wave breaking and higher nonlinear effects are to be expected, commands BREAK and DISC UPW MOM will be activated. A sponge layer is going to be settled behind the dike in order to absorb any possible water coming from wave overtopping. When running the first simulation attempts several warnings and errors were given back saying water level was too far below bottom and that I should reduce time step. Still by doing that instabilities remained:

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

*** Message : Please reduce the time step!*

As Martínez Pés, V. was recommended in his thesis (2013), the DISCRET commands were changed to DISC UPW UMOM BDF and DISC UPW WMOM BDF.

- DISCRET UPW UMOM H BDF: Second order backward upwind scheme applied for the horizontal advective terms of the horizontal components of the momentum equations.

- DISCRET UPW WMOM H BDF: Second order backward upwind scheme applied for the horizontal advective terms of the vertical component of the momentum equations.

After that, stabilities were still occurring. To prove the problem does not come from how the scenario is defined, a new situation is going to be tested.

S1_4dikereg.sws

In this new case, the dike has been simplified to a single sloped face. On the east side a sponge layer has also been located, but further away than in the former tests. Time step has been settled to 0.001 sec.

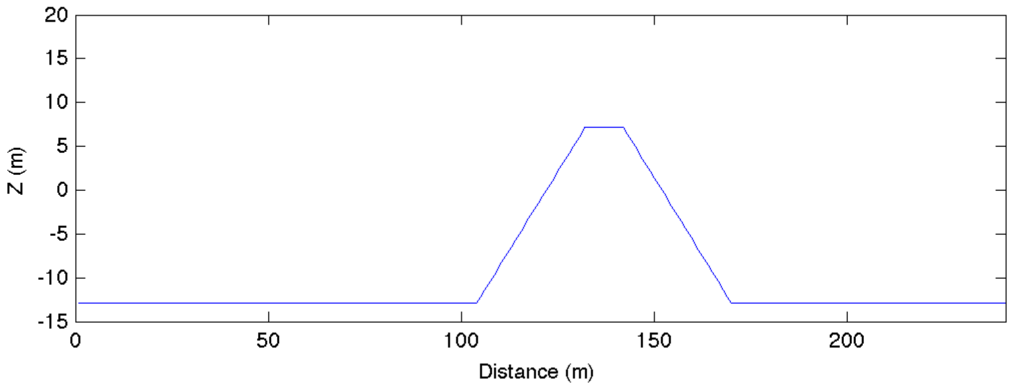

Figure 31. Simplified bathymetry used in s1_3dikereg.sws

Wave propagation was not allowed at first; computations did not start until I changed the 3 applied vertical layers to a single one. After that, for the first time when dealing with dikes, no instability errors showed thorough the PRINT file; the test has been successfully run.

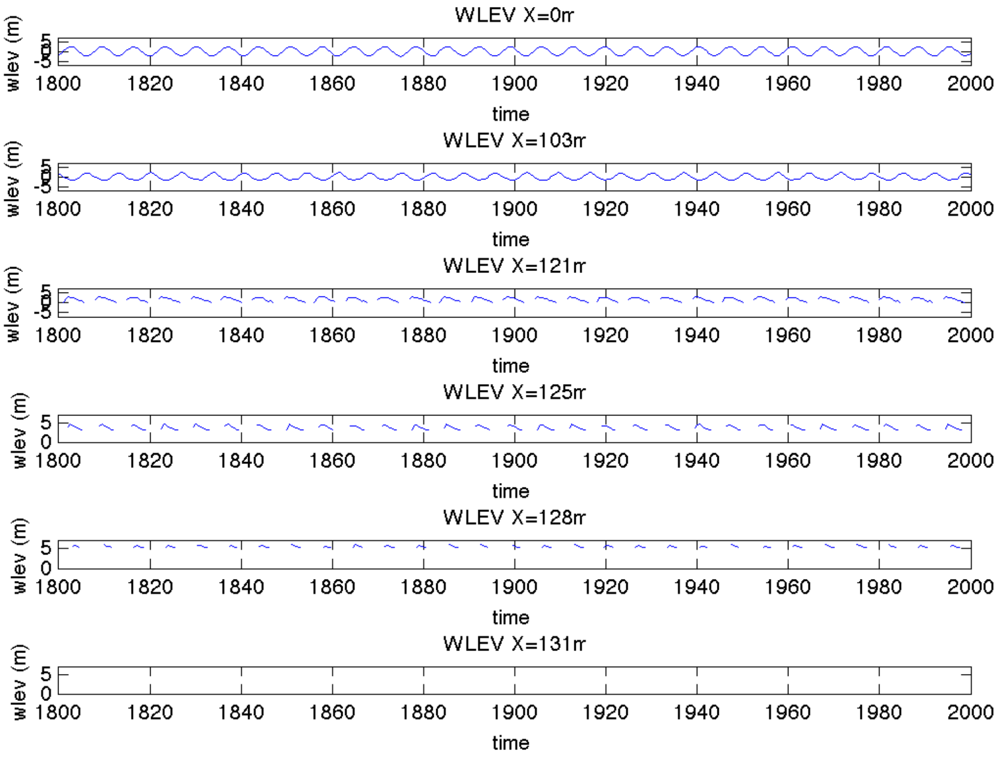

Figure 32. Water elevation over time at some points of s1_4dikereg.sws

Regarding Figure 31, X=0m is located at the wave maker, X=103m regards the toe of the structure, X=121m is the point where MWL meets the dike slope and X=131m represents the higher point over the slope, the crest of the dike.

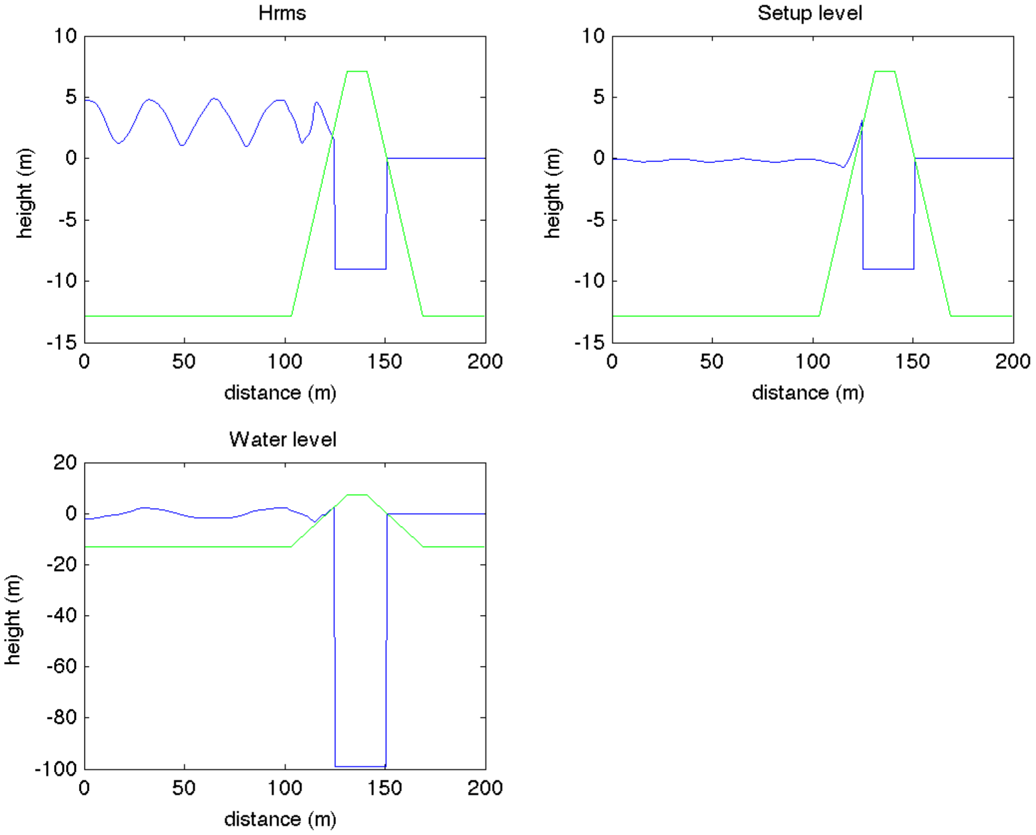

Figure 33. Hrms, setup and water level snap-shot at the last instant in s1_4dikereg.sws

S1_5dikereg.sws

Once more, I am going to consider the real bathymetry in Zeebrugge. I will reduce the number of vertical layers. Using 2 layers seems to be enough to get some results (Fig.34)

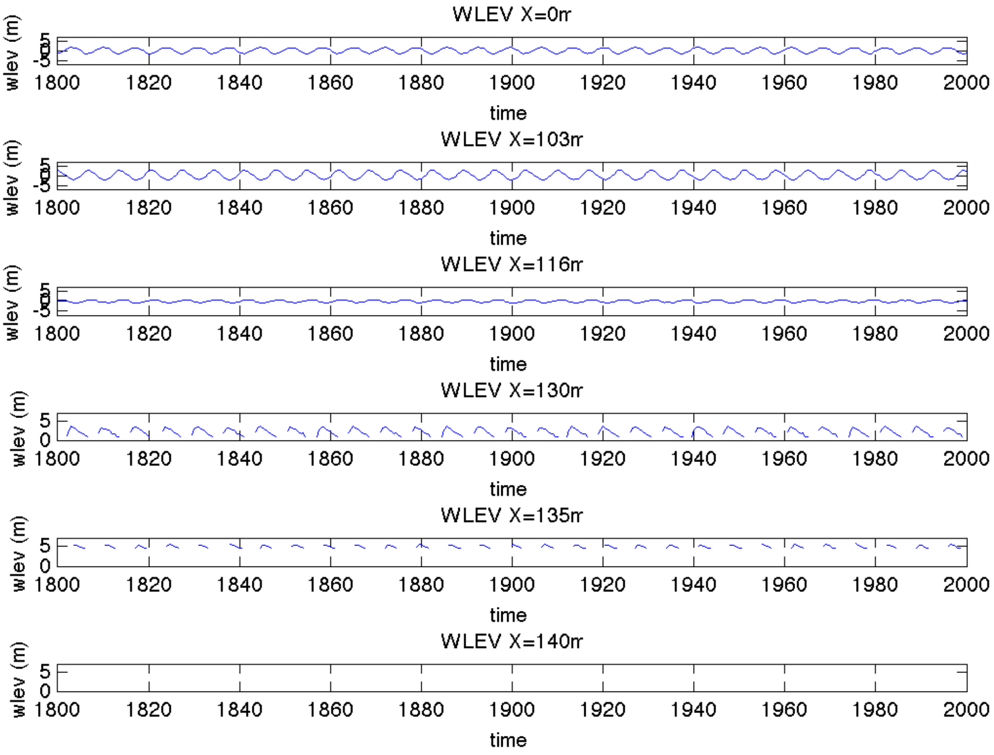

Figure 34. Water elevation over time at some points of s1_5dikereg.sws

Point X=0m is located at the wave maker boundary, X=103m regards the toe of the structure, X=116m is at the toe of the main slope in the dike, at X=130m the MWL intercepts the dike and, X=140m represents the point where the highest elevation is reached in the structure (Fig.30).

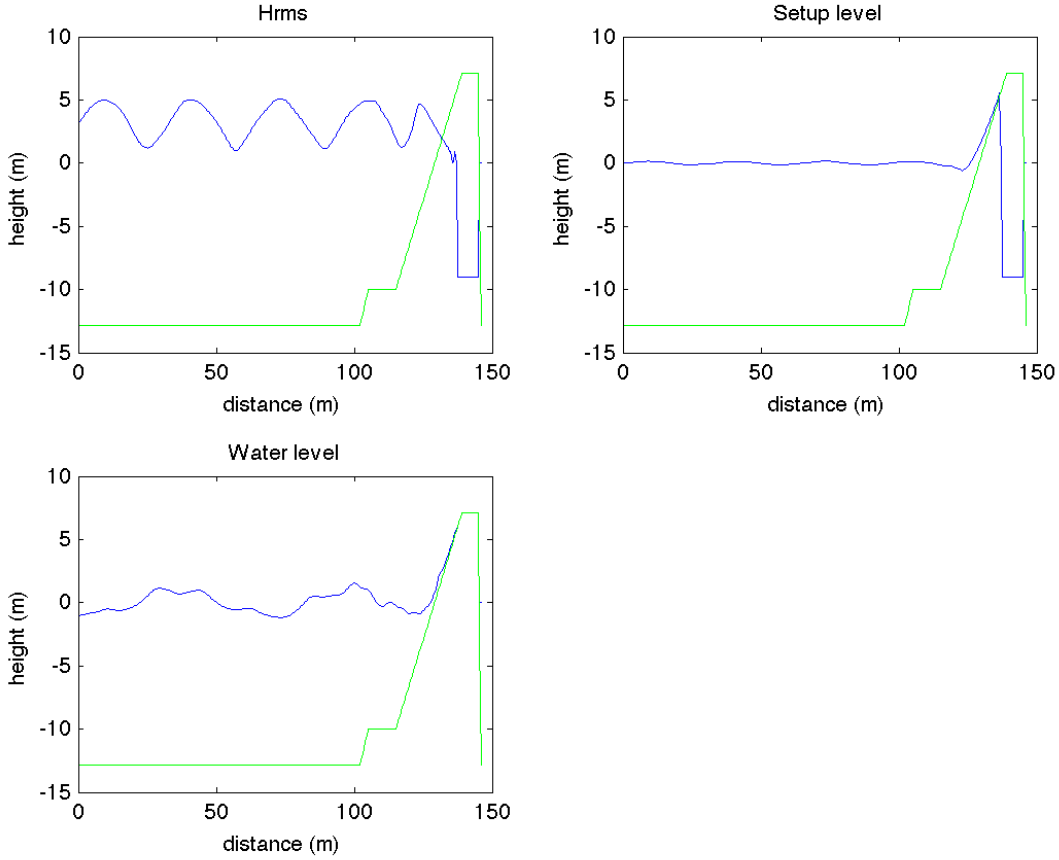

Figure 35. rms, setup and water level snap-shot at the last instant in s1_5ikereg.sws using the BDF discretization scheme

Attempting with different commands in order to see their effect on the output, I found that the obtained plots when using the MINM discretization scheme instead of the BDF (Fig.35) resulted to look smother, (Fig.36). As it is also recommended to use it in the User Manual when instability problems occur, I thought MINM would be therefore more stable.

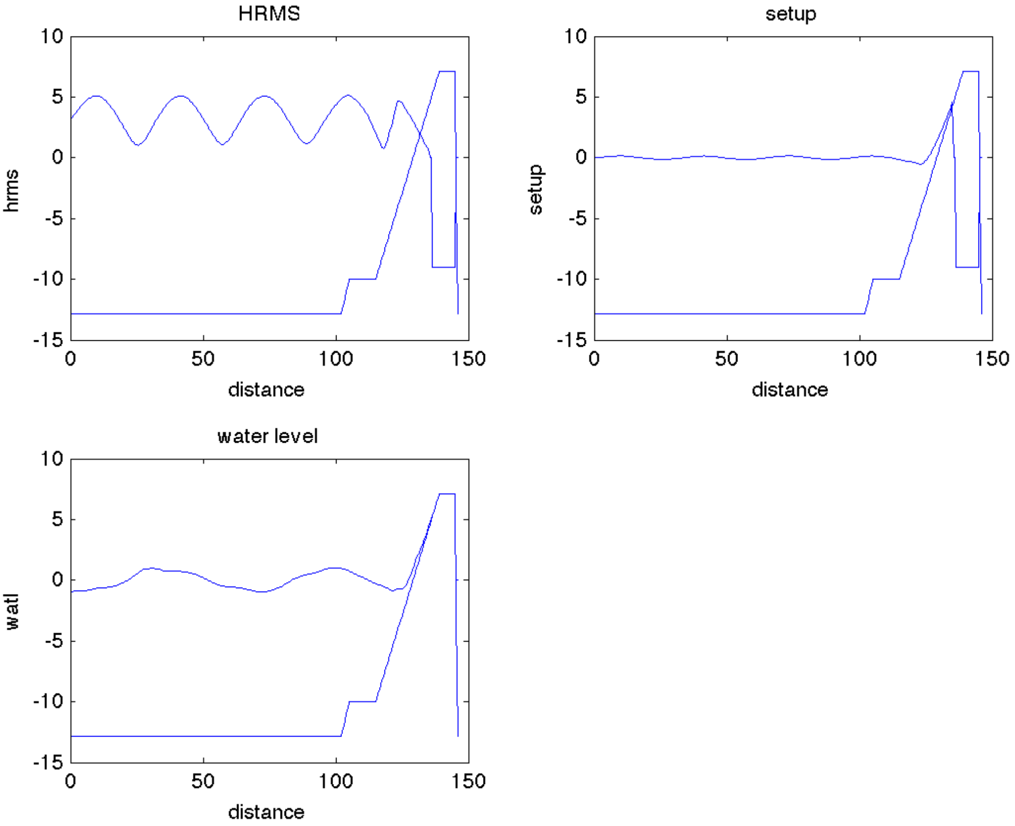

Figure 36. Hrms, setup and water level snap-shot at the last instant in s1_5dikereg.sws using the MINM discretization scheme

The effect of reflection triggered by the dike is easily noticed when analysing the Hrms plot. Large oscillations in that value are caused by the presence of a reflected wave travelling with the same period than the generated component but on the opposite direction. Since breaking is taking place near the dike wall, energy dissipation also occurs and therefore, not the whole amount of energy is reflected back; a partially standing wave develops.

Such reflections allow the presence of higher water levels

Observed discharge values over time:

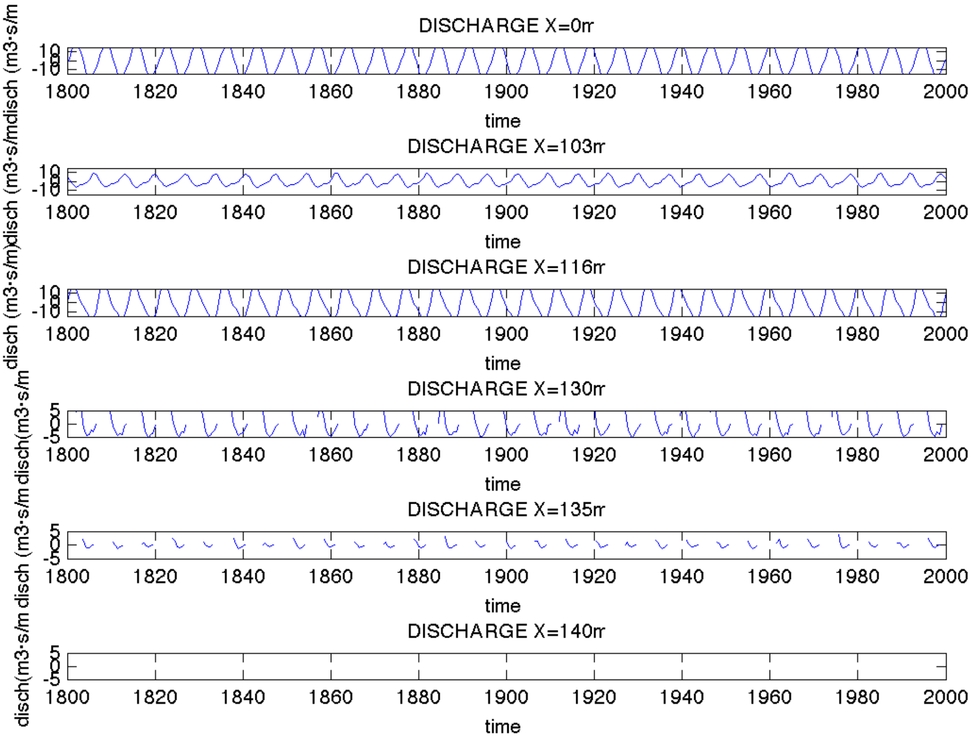

Figure 37. Discharge volumes over time at some points of s1_5dikereg.sws

A4.2 Overview and conclusions so far – regular waves:

- The description of the scenario was not a problem. Input parameters were not well adjusted in order to let the software start the simulation.
- The less number of vertical layers, the more stable seems to be the model.
- It is important to use a proper discretization scheme for the conservation of momentum along the propagation. Even though I still do not know the difference between BFD and MINM, both seem to be suitable for the concerned scenario.
- Obtained results show waves do not reach the dike crest in the designed situation, and therefore, no overtopping takes place.

As instability problems have been overcome and quite satisfactory results have been reached, the following step is to deal with spectrum waves propagation.

4.3 Propagation of spectrum waves:

S1_dikeir.sws

The same scenario as in s1_5dikereg.sws is considered but this time spectrum waves are going to be generated. The introduced spectrum will be exactly the same as the one defined previously when conducting flat flume tests.

Even settling 2 vertical layers, SWASH still does not allow computations to start. Reducing to 1 layer the scenario seems to become more stable, since computations are at least started. Discretization scheme has been settled as MINM. Computations do not get to a “normal end”, still error messages regarding instability appear.

I have read it might be useful to activate the command TIMEI in order to limit the Courant number. Such practice can be useful in case of existing nonlinearities. Since the mesh size used is 0.5m and time step 0.001sec, Courant number results to be around 0.04, and therefore the command TIMEI 0.01 0.25 has been implemented.

Moreover, in order to obtain detailed information, I have requested output data every 0.05sec instead of every 0.5 sec.

This seems to solve stability problems indeed.

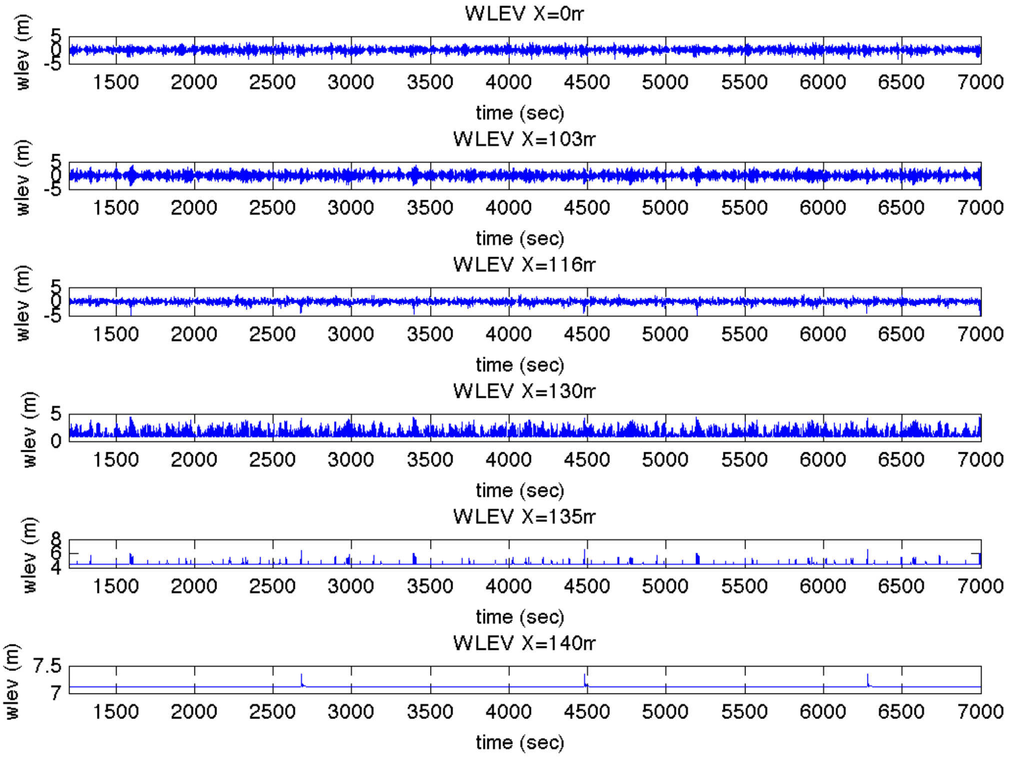

Figure 38. Water elevation over time at some points of s1_dikeir.sws

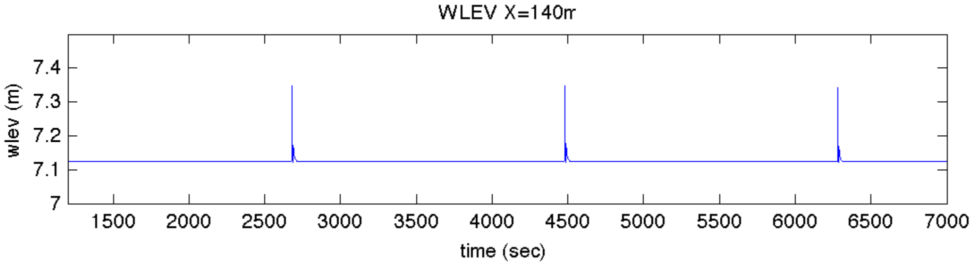

Figure 39. Zoom in on Fig.38- water elevation at X=140m of s1_dikeir.sws

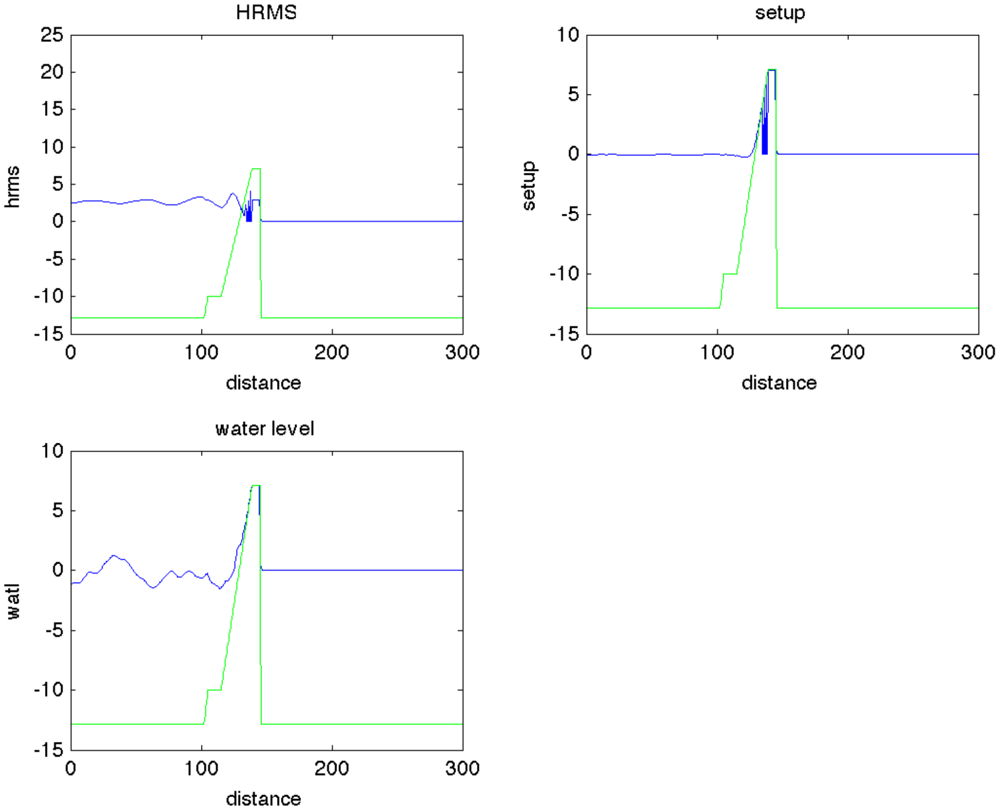

Figure 40. Hrms, setup and water level snap-shot at the last instant in s1_dikeir.sws

Performing a wave analysis will allow us to better understand the occurring phenomena.

X=0	
Spectral analysis	Wave per wave analysis
Hm0 = 3.1818 Tm01 =7.1169 Tp = 8.4232 Hrms = 2.2498	• MWL = -0.0087 ≈ 0 Hm = 2.2048 Tm =6.9458 Hs = 3.345 Hrms =2.4591 From the variance Hm0 =3.5987 Hs = 3.4187 Hrms =2.5446

Table 20. Wave parameters at x=0m of s1_dikeir.sws

X=103 (toe structure)			
Spectral analysis		Wave per wave analysis	
Hm0 = 4.2488	Tm01 =6.7415	•MWL = -0.0448 ≈ 0	Tm =6.4107
Tp = 7.9534	Hrms = 3.004	Hm = 2.6323	Hrms =2.9742
		Hs = 4.2285	
		From the variance	Hs = 4.0328
		Hm0 =4.2451	
		Hrms =3.0017	

Table 21. Wave parameters at x=103m of s1_dikeir.sws

The drawn conclusions from the analysis are:

- At X=0m the recorded significant wave height is larger than what has been introduced in the spectrum. Also higher Tm is observed. Such effects might be related to the presence of a reflected wave triggered by the dike. Reflection implies new components are to be added to the former ones, which consequently means amplitudes are going to change. Moreover, it has to be considered the fact that long waves tend to reflect rather than short waves, which are more likely to break. This last statement would explain the presence of longer periods heightening the value of Tm.
- Also at the wave generation point, it can be observed the value of Tp has not changed with respect to the recorded Tp in a shallow flume. Thus, the peak period does not seem to be affected by reflection.
- As already commented, adding reflected waves imply a variation on the recorded amplitudes all over the propagation (Fig.40). That is the reason for the obtained significant wave height at X=103m.
- Along the propagation Tm is observed to decrease. This behaviour can be explained by the presence of nonlinearities in such a shallow scenario. Wave-wave interaction takes place allowing new high harmonics to appear. It has to be borne in mind that a single vertical layer is being used, so that its effects on accounting for high

frequency components are to be regarded. Enlarging the number of layers would even increase such lowering.

- Declining of Tp was already seen on the shallow flume scenario. It was concluded non-linarites could be the cause of such behaviour.

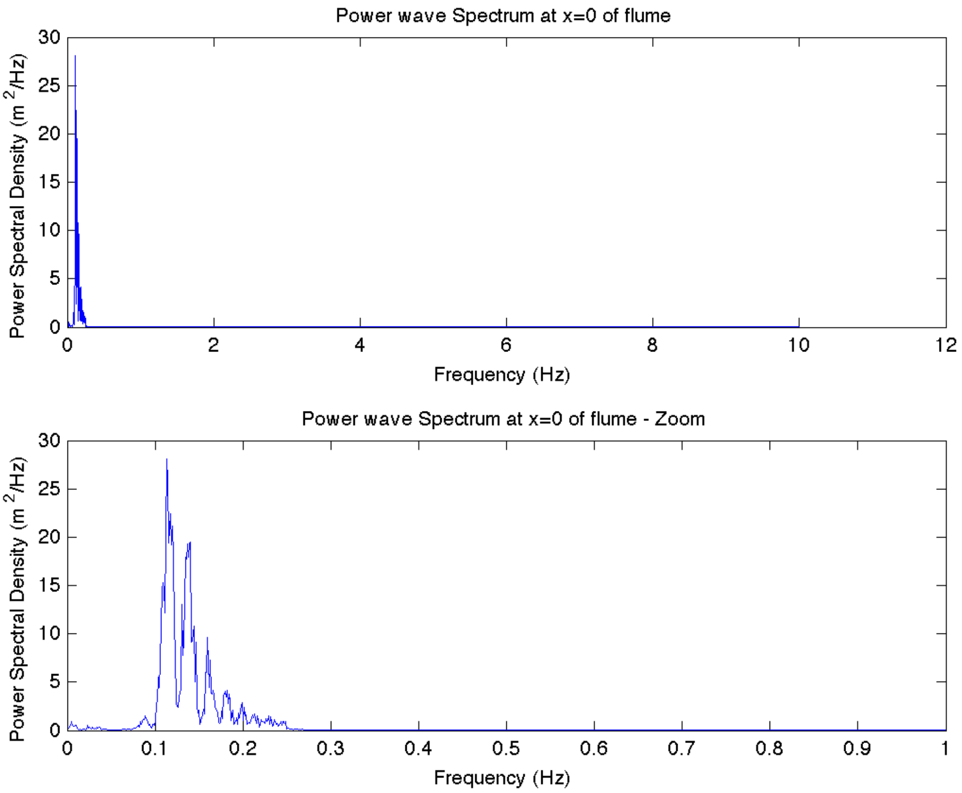

Figure 41. Wave spectrum at x=0m of s1_dikeir.sws

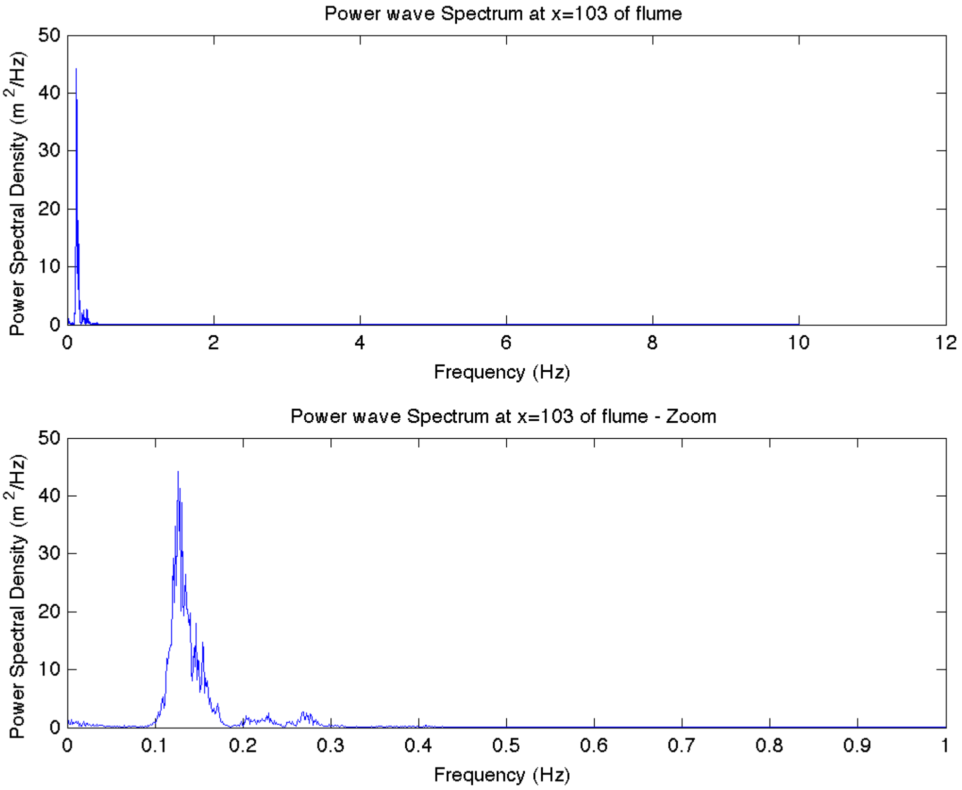

Figure 42. Wave spectrum at x=103m of s1_dikeir.sws

Wave spectrums illustrate the aforementioned behaviour.

At x=0m (Fig.41) a larger amount of energy has been focused on lower frequencies in comparison to the obtained spectrum for the flat flume (Fig.28). As mentioned above, that must be caused by the interaction with the opposite-directed reflective waves. Also at X=103m (Fig.42) the total energy is displayed to be higher than at X=0m, as it was expected according the analysed height values, and two small peaks grow on higher frequencies, triggered by nonlinearities. At the same time, the main peak seems to be focusing on low frequencies.

In order to prove which is the developing tendency of the spectrum when getting even closer to the dike, it has been thought to be a good idea checking it in a middle point of the slope, as it is at X=130m (Fig.43).

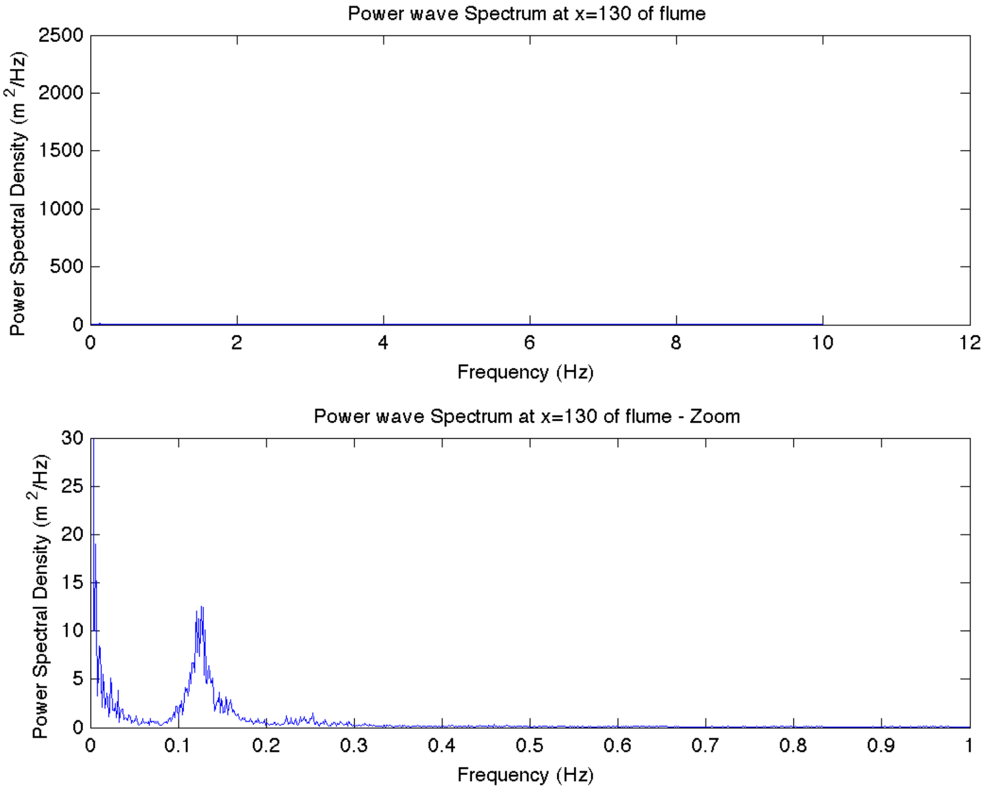

Figure 43. Wave spectrum at x=130m of s1_dikeir.sws

On the one hand, the fact that the spectrum displays much lower energy is due to at X=130m, as stated before, reflection causes small amplitudes to occur. On the other hand, this latter graph allows us to realise about the large concentration occurring at low frequencies, which triggered by reflective waves, shows how strong is their influence when approaching the dike. Reflection turns out to be stronger than nonlinear effects.

As SWASH seems to be properly accounting for the propagating phenomena in such scenario, we can proceed to analyse overtopping values.

- <u>DISCHARGE VALUES</u>

Bear in mind that SWASH is not able to account for the so-called “white water” or spray-overtopping, so that the obtained volumes are going to concern only for the overtopping caused by waves running up the slope of the structure.

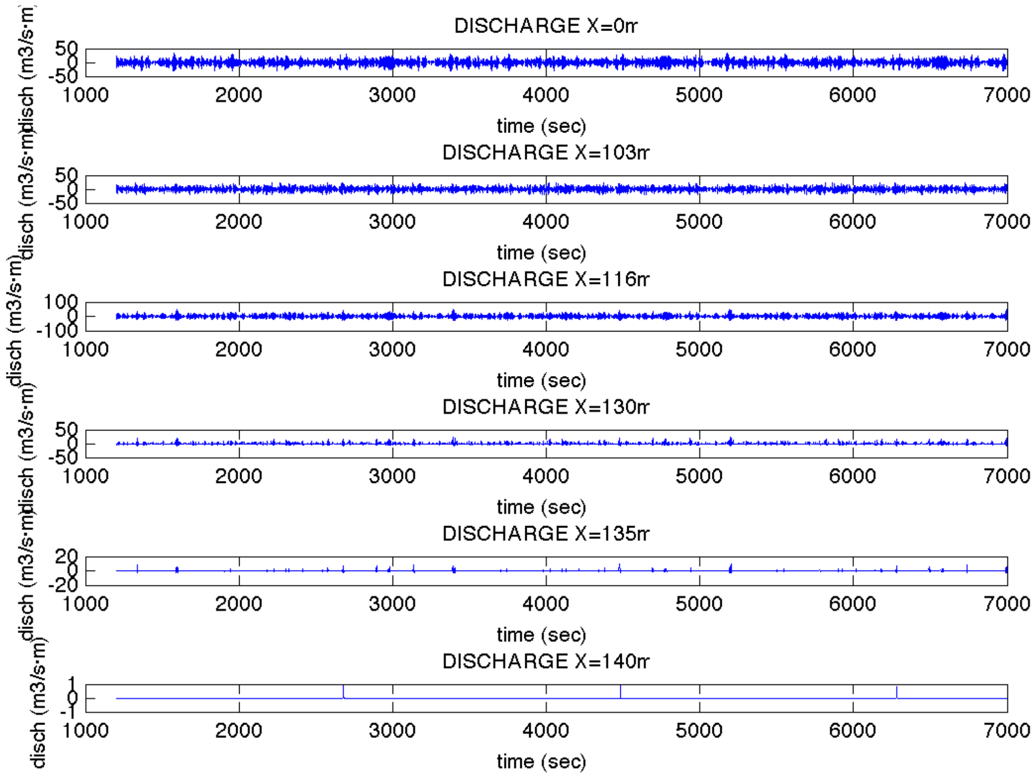

Figure 44. Discharge volumes over time at some points of s1_dikeir.sws

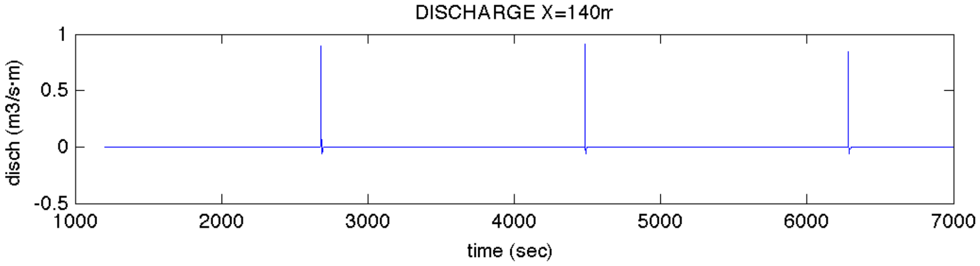

Figure 45. Zoom in on Fig.44- discharge volumes at X=140m of s1_dikeir.sws

The peak is observed to happen exactly every 30min (Fig.45); that must be related to the introduced 30min value to the command CYCLE when defining the spectrum. Hence, in order to statistically enhance the results, I shifted CYCLE to 90min. It certainly led to more reliable output (Fig.46).

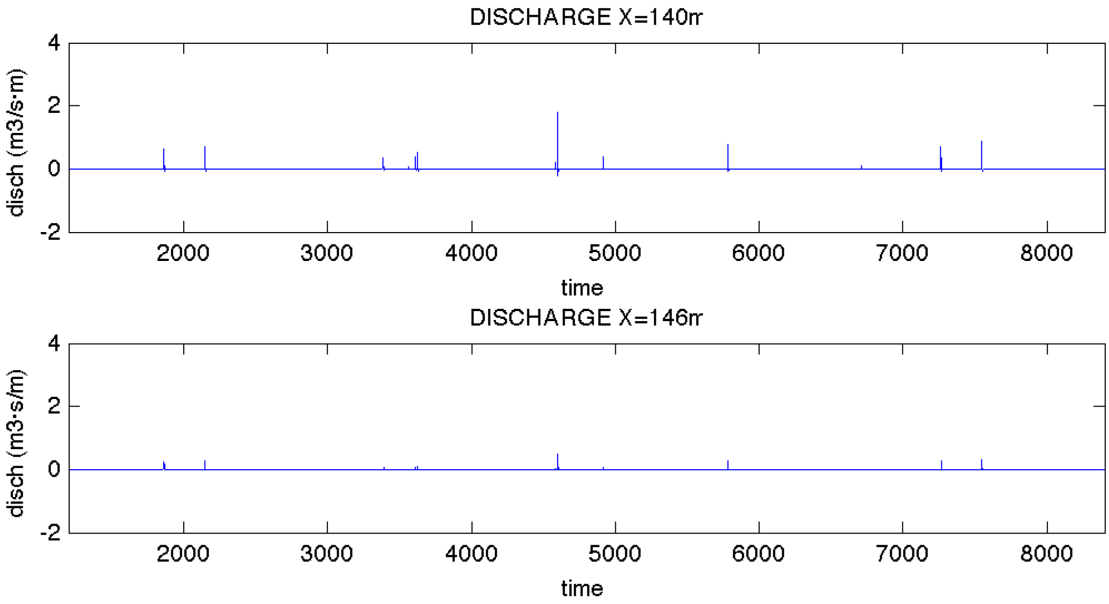

Figure 46. Discharge volumes at X=140m and X=146m of s1_dikeir.sws using CYCLE as 90min

According to the obtained so far, total discharge during Storm 1 can be computed for the impermeable smooth dike situation. As real values in Zeebrugge are measured on the wave overtopping tank, volumes are going to be analysed at X=146m, where the tank is supposed to be in the reproduced scenario.

At the concerned point, 11 waves are seen to overtop during the record of 7200sec (storm duration). Thus, the amount of crossing waves is very similar to the recorded in the real breakwater (10 waves). SWASH computes a total discharge of 89.94m^3/m along the whole storm; that is to say the averaged overtopping rate is q=12.49L/sm. Comparing to the reported values within the CLASH document (q_{Vi}=0.05709 L/sm) the achieved value makes sense, since a higher runup is expected on impermeable structure rather than in porous.

A4.4 Overview and conclusions so far – spectrum waves:

- To limit the Courant number turns out to be an important factor enhancing stability for the simulations.
- It has been proved reflection plays a relevant role in waves propagating. Consequently, their effect might influence overtopped volumes in some way. That point will be analysed later on.
- Discharge values have been obtained. Impermeable structures seem to allow higher amounts of overtopped water crossing to the landward side.

A4.5 Results for real storms in Zeebrugge

So far, only simulations for data in Storm 1 have been conducted. In section 1.3.3 some values have been finally reached for overtopping, even not regarding the real case yet. Results have shown much larger amounts of crossing water volumes than the amounts reported for the real porous structure. In order to validate the used model for impermeable smooth dikes and also to verify the observed tendency on the obtained data, the same model is going to be applied simulating the overall storms reported within the CLASH project for the concerned section in Zeebrugge.

- **Storm 2:** No overtopping is observed, which is strange provided that on the prior case in Storm 1, values were increased with respect to the real ones on the breakwater. Anyway, a possible explanation could be given by the already mentioned fact that SWASH is not able to account for the spray-volumes generated due to waves impact with the structure, which are also crossing the structure.

- **Storm 3:** Non-sense values are obtained. Whilst at X=140m volumes fall within the expected amount, at X=146m these are extremely increased. (Fig.47)

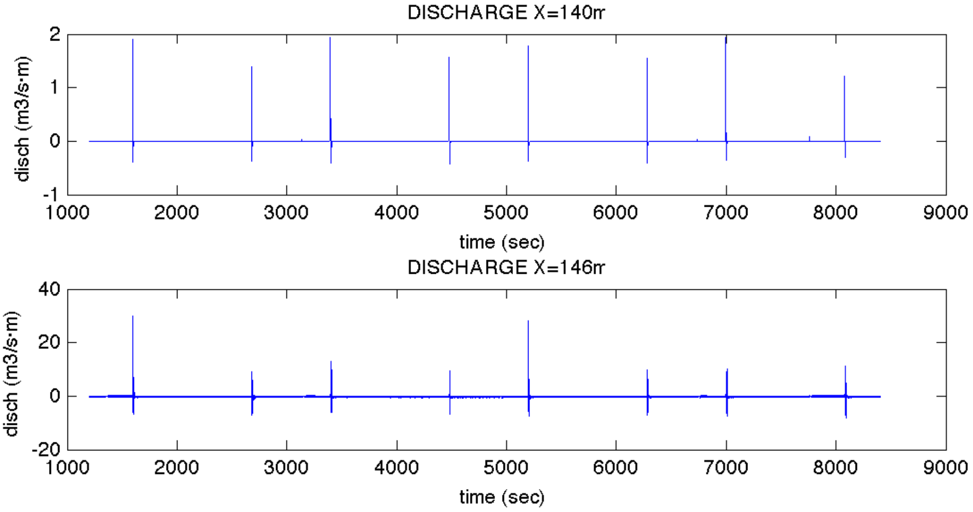

Figure 47. Discharge volumes at X=140m and X=146m in Storm 3 (s3_dikeir.sws)

Something is clearly wrong.

COMMENTS OF PIETER SMIT:

- I was told probably SWASH does not handle properly with the steep slope introduced in at x=146m in the bathymetry, and that might be the reason of wrong output at that point. I was recommended to smooth it.
- Moreover, I was also recommended to add some friction. Zero friction is far from real situation, so that even a low value will make the model much more realistic and it would assure no extreme results are obtained.
- Since the sponge is not developing any function, I was told it is better to remove it.
- Since DISCH is an instantaneous output, command QUANT DISCH does not make sense, SWASH is simply ignoring it. Therefore, it is better to remove it.

About some prior doubts related to the used commands:

- BDF discretization scheme would give more stability than the MINM, but it would not make much difference, so it is fine to keep it.
- Indeed, the less number of vertical layers, the more stable will become the

model, but also the less precise the output will be. For the computed scenario 2 layers would be optimum (it relates to the value kd). Anyway, for the current purpose, the results will not change significantly and 1 layer can be kept.

Therefore, I will try to model storm 3 again according to the stated recommendations.

S3_2dikeir.sws

Figure 48 shows the new scenario bathymetry.

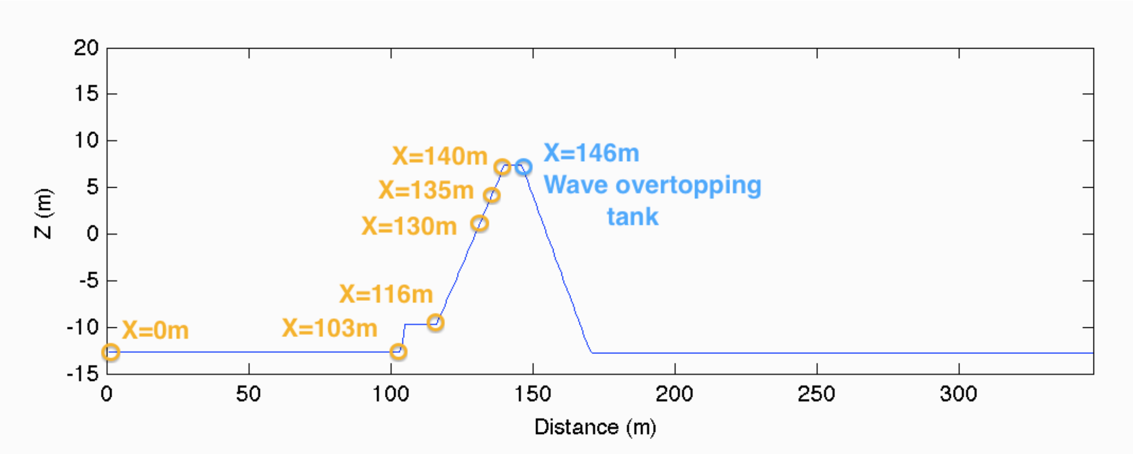

Figure 48. Modelled bathymetry in the Zeebrugge breakwater (2) - Final version

As a first step, I will only smooth the slope behind X=146m and erase the sponge in order to check that effect.

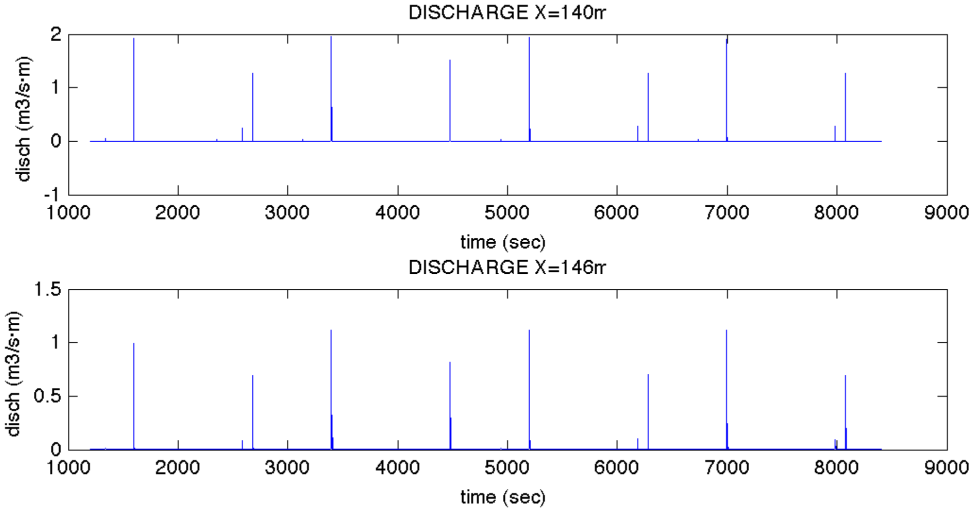

Figure 49. Discharge volumes at X=140m and X=146m in Storm 3 with no friction (s3_2dikeir.sws)

Overtopped volumes have reduced a lot at X=146m. Therefore, the steep slope was clearly the source of the problem.

Adding FRIC 0.01 (Manning coefficient - which could be something as a very smooth asphalt) output results look almost the same as before, a small diminishment is observed.

Furthermore, as I made the model more stable, in order to get faster simulations (they were taking a lot of time) I have tried increasing the time step value to 0.01, and consequently Courant limits can also be increased 0.2-0.6. As a result of that change, much higher overtopping values were obtained. Since interpolation processes might be triggering the observed variation, I decided to reduce the time step a little bit again.

Settling a time step of 0.005, and TIMIEI 0.02-0.3 does not show the prior interpolation errors and the model run faster indeed.

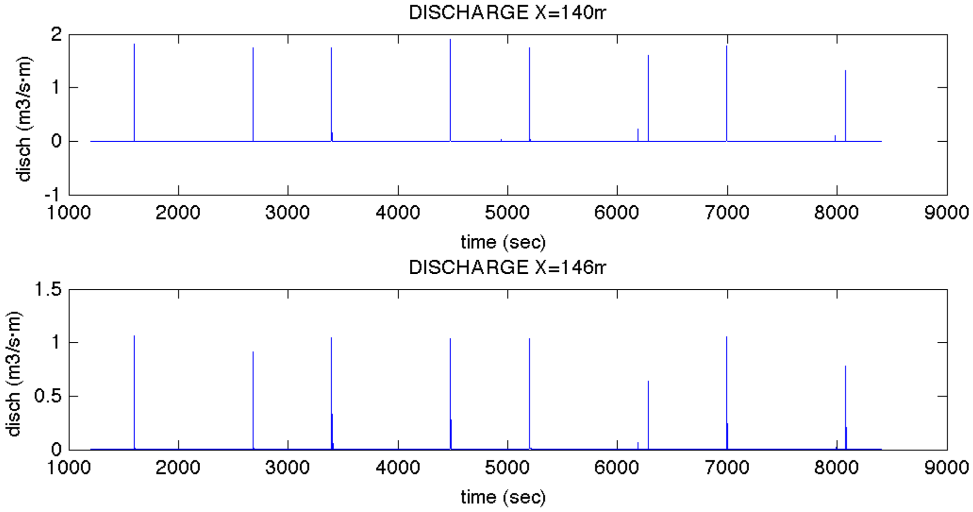

Figure 50. Discharge volumes at X=140m and X=146m in Storm 3 with FRIC 0.01 (s3_2dikeir.sws)

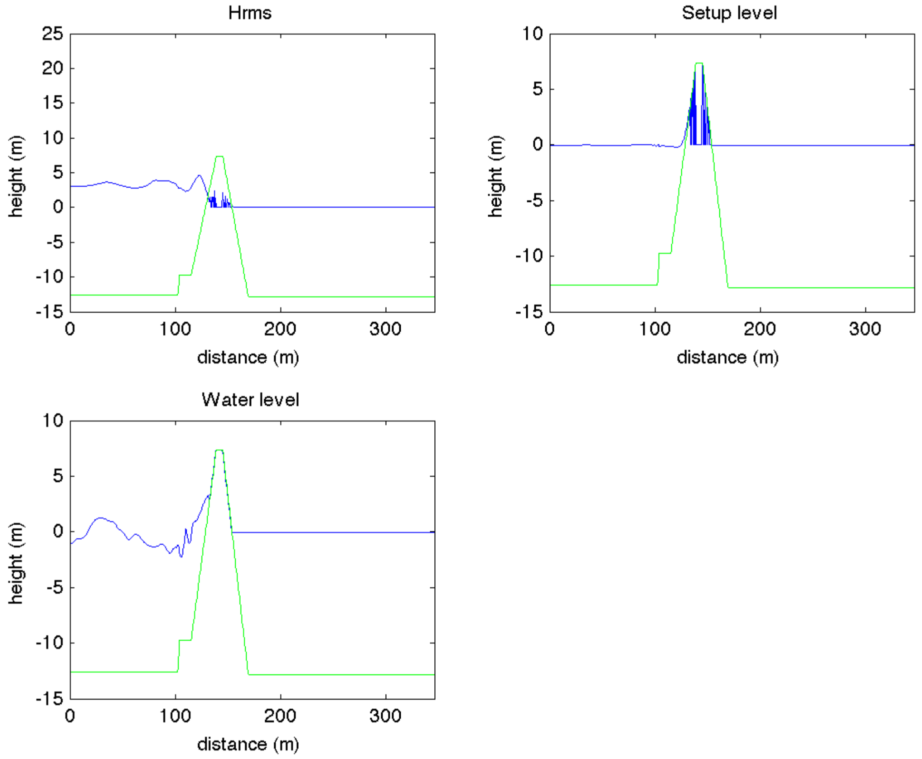

Figure 51. Hrms, setup and water level snap-shot at the last instant in s3_2dikeir.sws

As the results seem to be successful, I will apply the same changes to all the storms. The input file can be found in *Appendix B*.

Command CYCLE in the spectrum definition is going to be changed according to the period over which surface elevation is outputted after steady-state condition has been established; that is to say it will be the same as the storm duration.

	Storm No.										
	1	**2**	**3**	**4**	**5a**	**5b**	**5c**	**6**	**7**	**8**	**9**
Nov (-)	10	0	18	0	1	7	5	2	6	10	33
q (L/sm)	29.51	0	35.40	0	21.12	26.05	26.52	15.73	15.58	23.86	87.32

Table 22. Number of waves overtopped (Nov) and discharge volumes (q) recorded during the concerned storm events according to SWASH simulations for a smooth impermeable dike

The results looked confusing at first. In storm 9 for instance, extremely high values have been obtained whereas, coming to the real data, the higher overtopping event is not recorded in that case. Just in order to make sure an interpolation error was not overestimating volumes, I have tried reducing the time step on the input file, but still the result fell within the same order of magnitude.

Therefore, since the two studied scenarios behave very different one from the other, we assume obtained output to be correct even not similar to the real data. Then, the next step is to study the performance of SWASH on the introduced models and to compare it with the real situation. To do that, results are going to be plotted on a graph in order to allow an easier comprehension of the statistical tendency. As it in done in literature when assessing wave overtopping, dimensionless parameters, both the freeboard $R*$ and the discharge $Q*$ are going to be used. These parameters were defined by Owen as:

$$Q^* = \frac{q}{g \cdot Tm \cdot Hs} \qquad R^* = \frac{Rc}{Tm \cdot \sqrt{g \cdot Hs}}$$

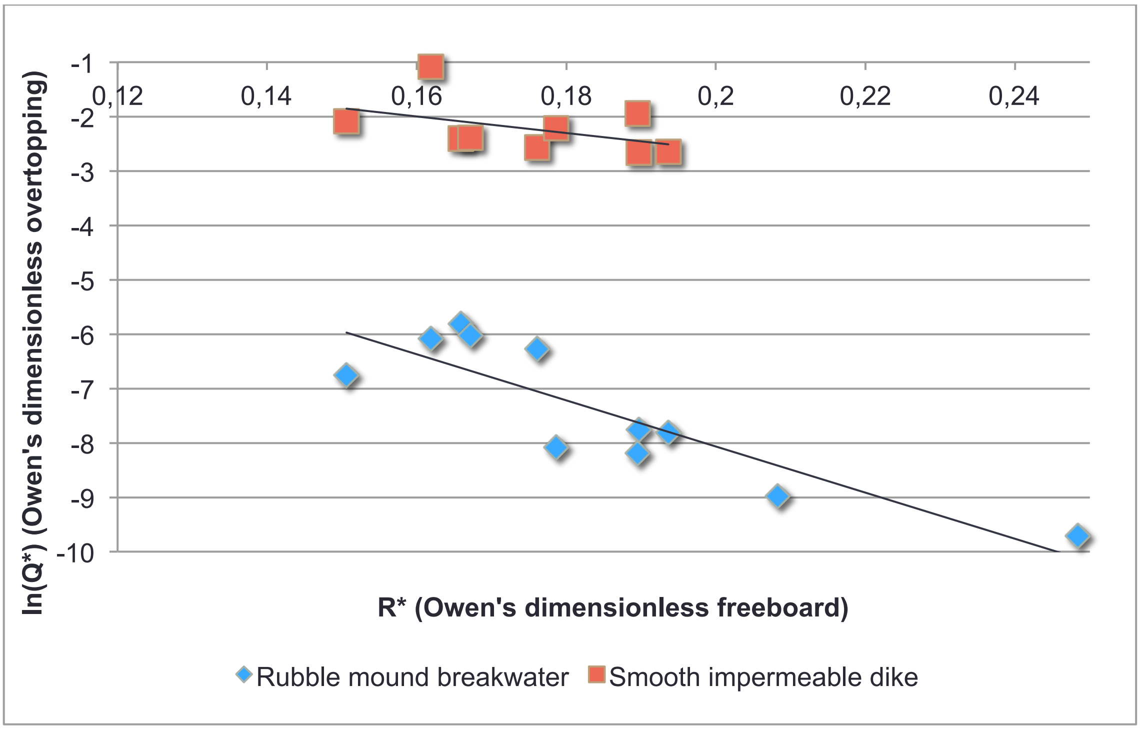

Figure 52. Dispersion graph comparing the obtained discharge in SWASH for a smooth impermeable dike and the measured discharge in a real breakwater scenario

From all the presented information so far, I came up with the following conclusions:

- Higher discharges on dikes are due to their lack of friction and permeability. That allows higher runup levels at the same time than higher volumes carried on each wave.
- The number of overtopping waves is generally higher in real storms because some of them might be caused by splash volumes, which are not taken into account in SWASH. This is not the case for storms 8 and 9, whose behaviour is going to be further explained later on in this document, when comparing also with data from the breakwater tests.
- According to Figure 52, heighten the freeboard looks more efficient in reducing overtopping for the breakwater than for the dike, at least up to some extent. However, when the freeboard reaches a certain longitude, no more volumes are seen to cross over the dike, whereas water is still overtopping the real breakwater crest. As already discussed, this might be a consequence of SWASH not accounting for splash volumes.
- Overtopping volumes depend not only on R* but also on the steepness of the

waves. That is why when looking for example at storms 3 and 9 (the ones with lower R*), storm 9, even not having a lower dimensionless freeboard than storm 3, presents higher discharges. That is explained through waves on event 3 being smoother (higher Iribarren number), which means more reflection is going to occur when reaching the structure. Therefore, more energy reflected back seawards will imply lower runup and hence, lower overtopping rates.

A5 RUBBLE MOUND BREAKWATER

Porosity has to be introduced to the dike in order to turn it into a breakwater.

According to the User Manual, rubble mound breakwaters have a typical porosity value of n=0.4, while the stone size of the armour layer is typically 0.5 m. The berm of the breakwater can be specified by means of the structure heights (relative to the bottom). This way of schematization permits to simulate partial reflection and transmission of the waves through breakwaters.

My first attempts were using the version of the bathymetry with a very steep slope (Fig.30). I have introduced the breakwater by defining it through a structure height above the bottom level and by a porosity mesh and grain size (grain size = 0.5 as recommended in the User Manual). To start with, regular waves were propagated according to the parameters recorded during Storm 1.

At first I introduced a 0-porosity over the whole domain except where the breakwater was supposed to be located; there, a porosity of 0.45 was defined. It didn’t show results. (s1_pororeg.sws, s1_pororeg.n)
In order to prove the proper functioning of the porosity mesh, I decided to apply

porosity n=1 everywhere. That lead to some results, and they agreed with what it should be expected; a normal propagation was observed, as if there was no structure, only the effect of the present sponge on the right side is noticed (Fig.53). (s1_pororeg_v2.n)

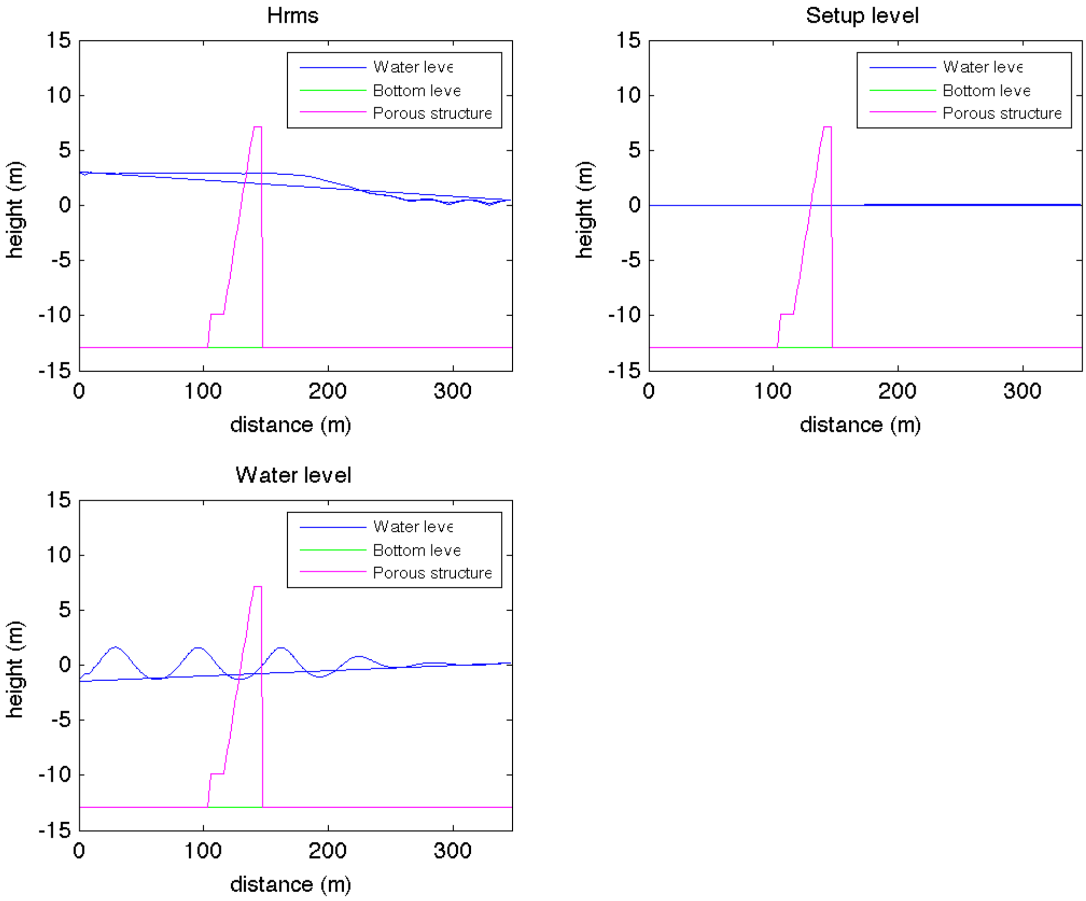

Figure 53. Porous structure (n=1). Sponge layer present on the right side. Hrms, setup and water level snap-shot at the last instant

Martínez Pés, V in his thesis (2013) found that SWASH was not able to handle with porosities close to 0, so that in order to check if that is still a problem I will try a new situation where 0-porosities are used as well.

Porosity 1 has shown not to present any problem; hence, I will define a new scenario with n=1 along the domain where structure height is 0, and 0-porosity where the breakwater is supposed to be placed. (s1_pororeg_0.n)

In this case results were obtained (Fig.54); it can be said therefore that no problems exist anymore when applying values close to 0 for the porosity parameter “n”.

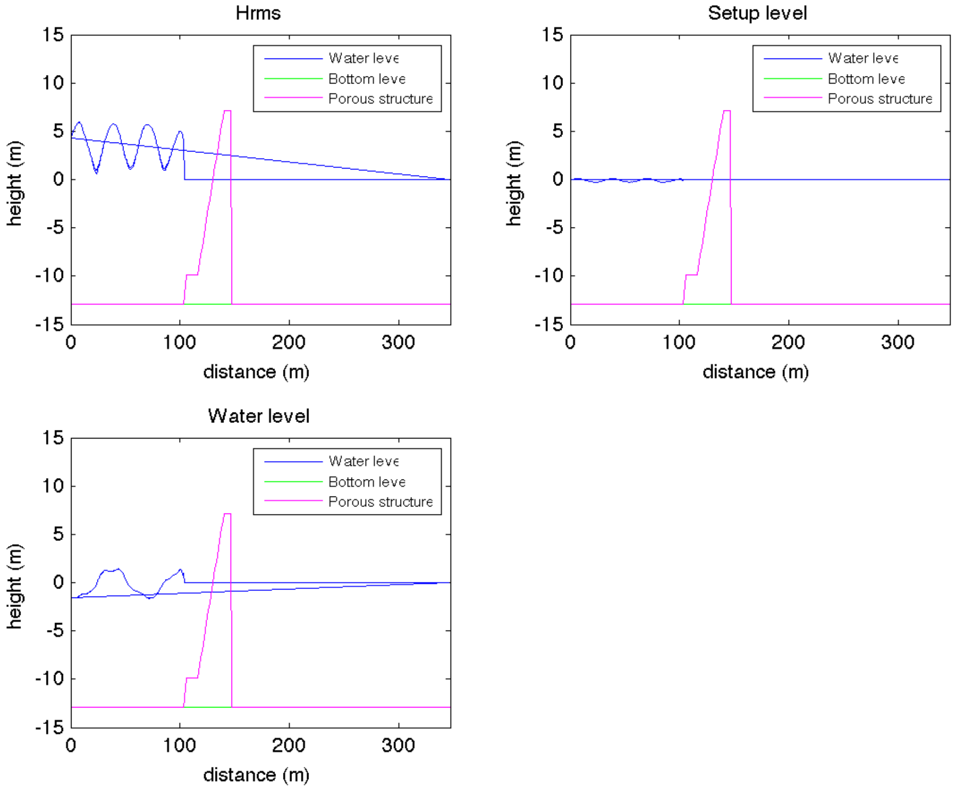

Figure 54. Porous structure (n=0). Sponge layer present on the right side. Hrms, setup and water level snap-shot at the last instant

However, looking at the obtained figures, SWASH seems to be considering the introduced n=0 along the whole vertical where the porous structure starts to erect (x=103m), completely disregarding the defined structure height.

To make sure this has nothing to do with the fact of using a single vertical layer, I tried shifting to 2 layers, but the results were the same anyway.

After the conducted tests attempting with porosities, I thought maybe the structure height was not correctly introduced. It is for this reason that I performed some other simulations changing the structure height definition (s1_2pororeg.sws). However, I came to the same results and, since in the User Manual it was clearly stated that the height must be relative to the bottom level, I forgot about this issue and I assumed it was already well defined in the prior tests.

As I was told by Smit, P. to get rid of very steep slopes, and it was proved to be a problem indeed, the following tests are going to regard the defined scenario with a smoother landward slope (Fig.48). That means the structure height mesh is going to change (not the bottom level, which remains completely flat in these breakwater cases). The sponge layer on the right side is also going to be erased. Friction is going to be added (FRIC 0.01) and the time step and Courant number are also going to be shifted as it has been done in the dike scenario (time step 0.005, TIMIEI 0.02-0.3).

Considering again the porosity mesh n=1 in the whole domain except the structure, defined with n=0, the results (s1_3pororeg.sws, s1_3pororeg_0.n), the same behaviour as in Figure 54 is obtained.
The possible effect of the berm has been checked in another test, where a simplified slope gave equal results as with the berm, so there is no influence of it.

A new test is going to be conducted defining the porosity mesh n=1 in the whole domain except the structure, defined with n=0.45 this time (s1_3pororeg_045.n). In this case it is possible to distinguish both reflection and transmission through the structure (Fig. 55). Also the porosity does not look to behave as in the prior case, it can be interpreted to be changing gradually instead, as Martínez Pés, V. defined in his thesis (2013)

Martínez Pés, V. (2013) concluded that when introducing a porous structure in SWASH it behaves as if we were introducing a sponge layer, dissipating wave energy as waves move through it. The structure height is only considered as a weight parameter to compute an equivalent porosity to be applied in the total water depth, and the structure itself is ignored, it is not considered as a physical boundary, so that runup is not taking place.

Then, what could be the difference when applying n=0? Why does it look like SWASH is not accounting for the structure height in this case?

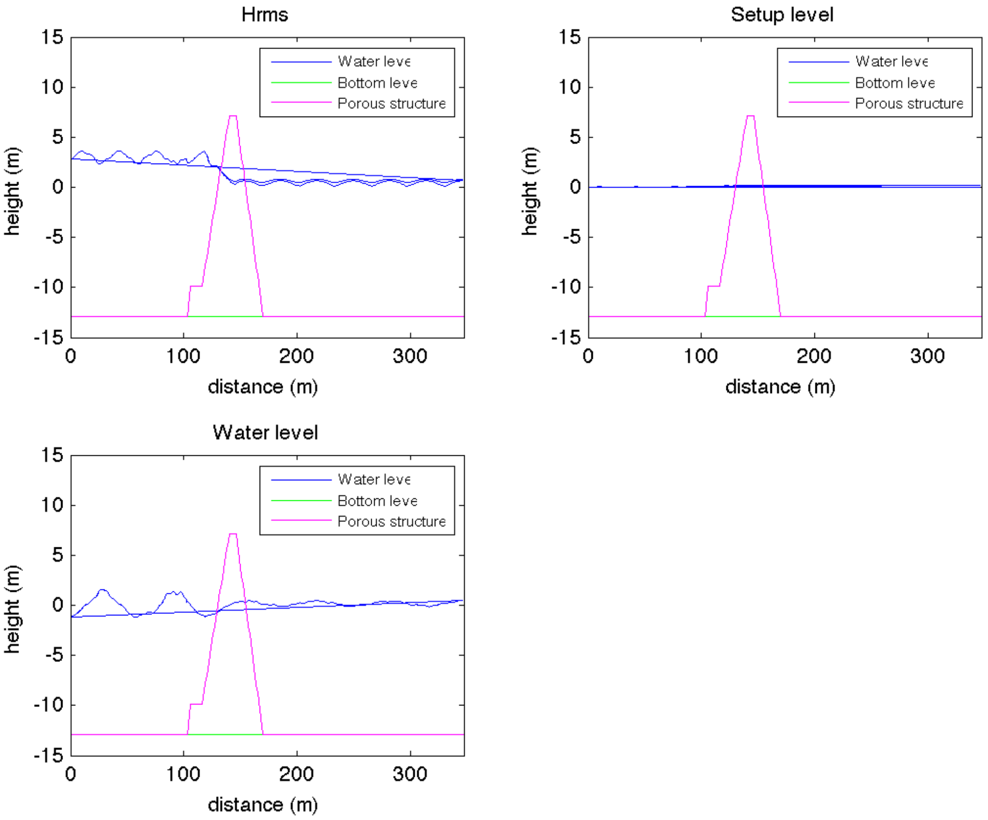

Figure 55. Porous structure (n=0.45). Hrms, setup and water level snap-shot at the last instant

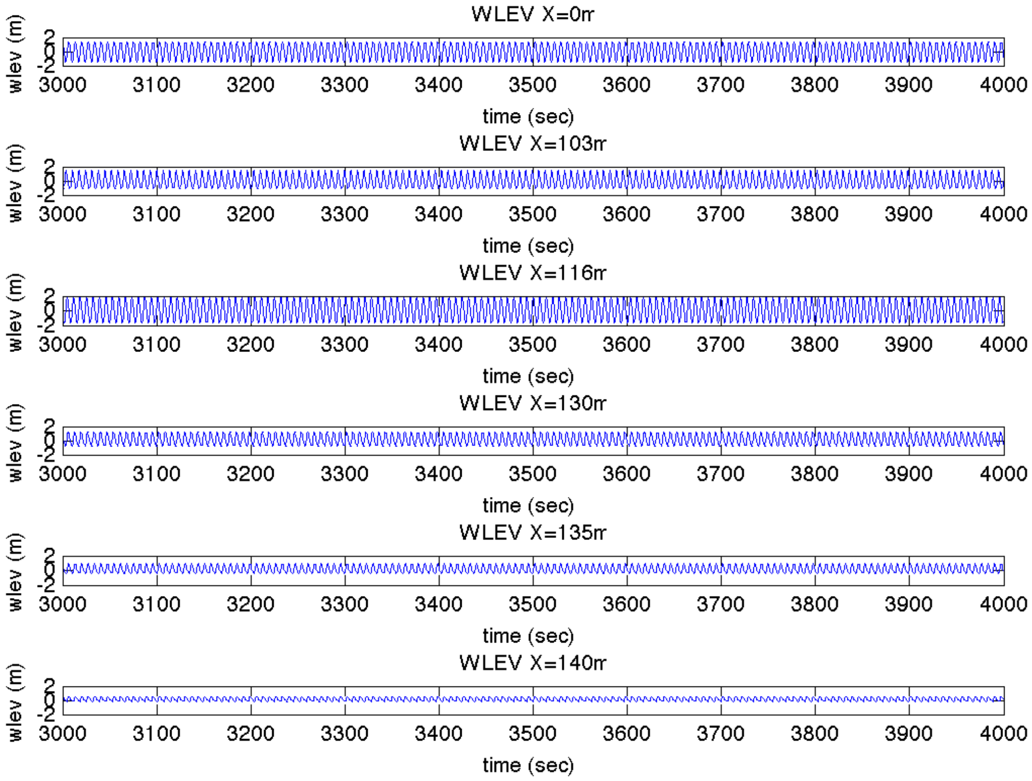

Figure 56. Water elevation over time at some points of the porous structure scenario (n=0.45)

Performing a new attempt with porosity 0.1 it is seen that it behaves the same as n=0, so that we conclude that equal results are observed for small porosities (n<0.1).

Checking the User Manual again, it says porosity can be defined between 0 and 1; hence, I understand no problems should appear. However, it also details that small values (<0.1) should be interpreted as impermeable regions, and according to my results, I conclude the whole vertical is therefore taken as impermeable, no matter which the height of the structure is. It also says a value n=1 represents water points; that was well defined in the prior tests.

It is not much clear from my tests how SWASH deals with porosity structures. However, as M. Zijlema confirmed the explained behaviour in Martínez Pés, V. (2013), we will assume it as a valid conclusion. Consequently, SWASH is not able to model porous structures properly, and it will not be possible to define a rubble mound breakwater scenario through this methodology.

As the goal of the current project is to check if SWASH is able to model the real scenario in Zeebrugge when it comes to overtopping discharges, an alternative model is going to be tested to get a more realistic approach.

It has been thought new simulations can be performed using an impermeable core below a porous layer. The core would allow waves running up the slope to reach the crest, whilst porosity could act as the armour layer dissipating energy thorough its voids.

A5.1 Rubble mound breakwater with an impermeable core

S1_impcoreir.sws

I modelled a new scenario considering a breakwater with an impermeable core, as shown in Figure 57. An armour layer is placed on the seaward side of the structure.

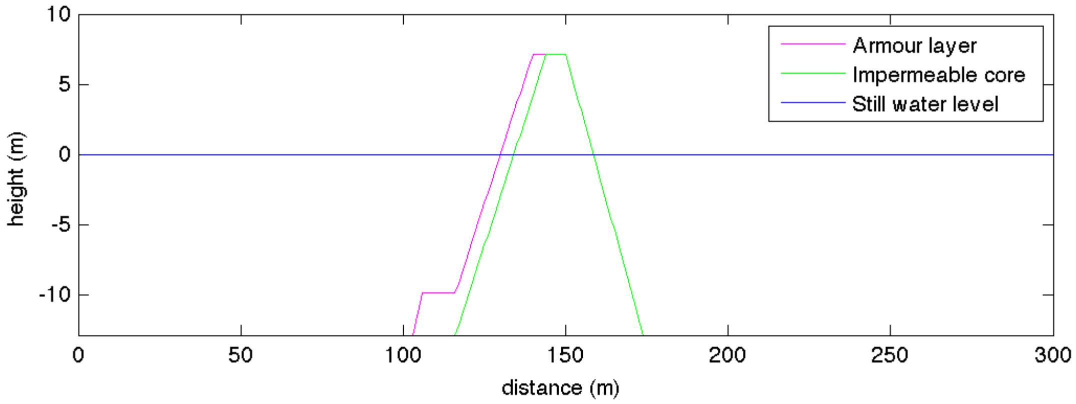

Figure 57. Modelled bathymetry in the Zeebrugge breakwater. Impermeable core with an armour layer accounting for porosity

As in the case of the dike, 1 vertical layer is going to be used for the computations and also the commands FRIC 0.01 and TIMIEI 0.02 0.3 are going to be activated (TIMEI according to the time step 0.005, as seen before). The grain size of the armour layer has been settled to 1m, and the porosity to n=0.45. Spectrum waves in Storm 1 are considered for the present propagation (Hs=3.04m and Tm=6.88sec).

However, the regarded situation does not lead to overtopping events (Fig.58), and that means that the model does not approach the real situation properly. As the goal is to calibrate a model for the real situation, where water volumes are seen to overtop, porosity is going to be increased by shifting the value n=0.45 to n=0.7.
Even that, still no overtopping is occurring. I have also tried lowering 1m the armour layer (which was defined with a structure height of 3m), but again, no volumes are seen to cross the breakwater.

I have tried propagating a 5m-height wave instead of the 3m-height one recorded in Storm 1. Such a high wave was observed to suffer from large dissipation and therefore, it could not cross the structure neither.

In order to check if the model was working properly, I used a new porosity mesh defining n=1 everywhere, including the armour layer. The result showed waves overtopping indeed, so it fulfils the expected behaviour and it proves the model is correctly functioning.

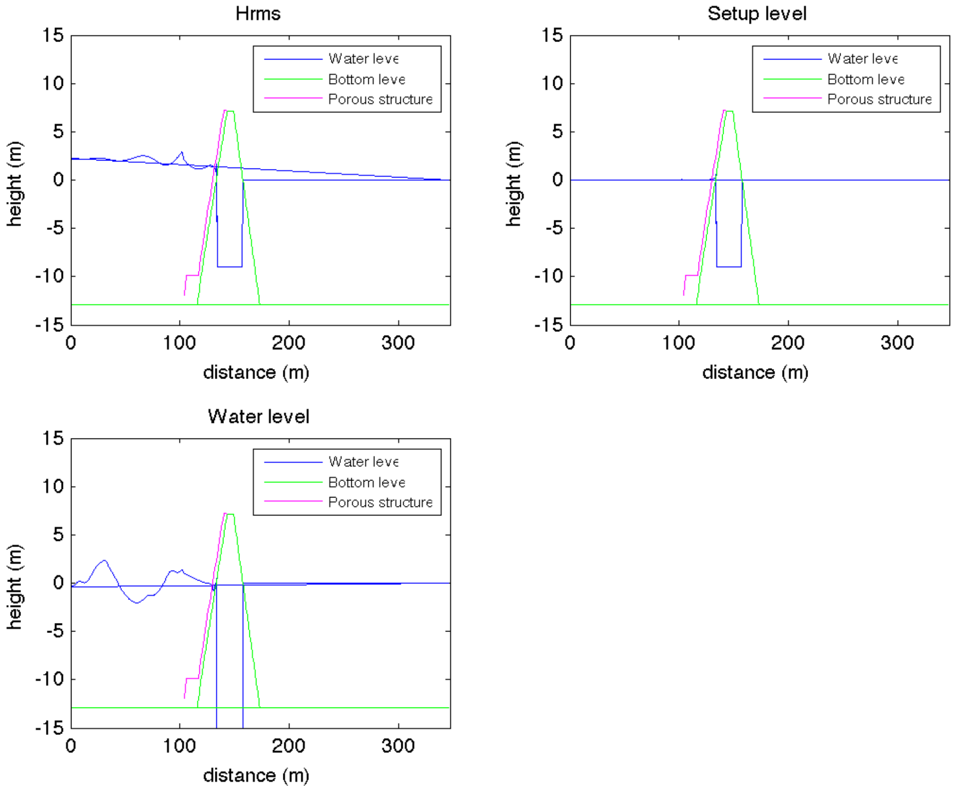

Figure 58. Hrms, setup and water level snapshot at the last instant for storm 1 in s1_impcoreir.sws

The more likely explanation for the observed behaviour is the porous layer strongly affecting the wave energy. Dissipation is already taking place at the toe of the structure, which is not realistic, so that in order to reduce this effect I will model a new scenario where porosity starts at the middle slope, when waves are already in contact with the structure; in the rest of the structure n=1 (Fig.59) (s1_2impcoreir.sws).

S1_2impcoreir.sws

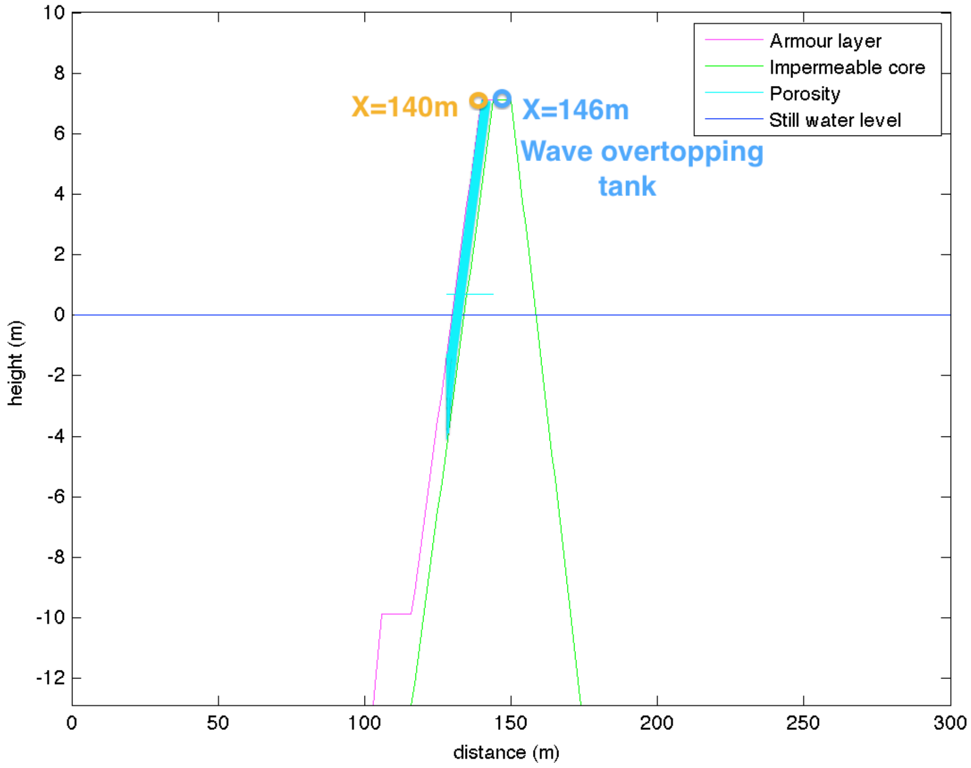

Figure 59. Modelled bathymetry in the Zeebrugge breakwater. Impermeable core not with the whole armour layer

Porosity is fixed again at n=0.7 and wave height around 3m. In this case less dissipation effects are observed, but still water level is not reaching X=140m (Fig.60 and Fig.61). Therefore, simulation for the real scenario is not achieved yet.

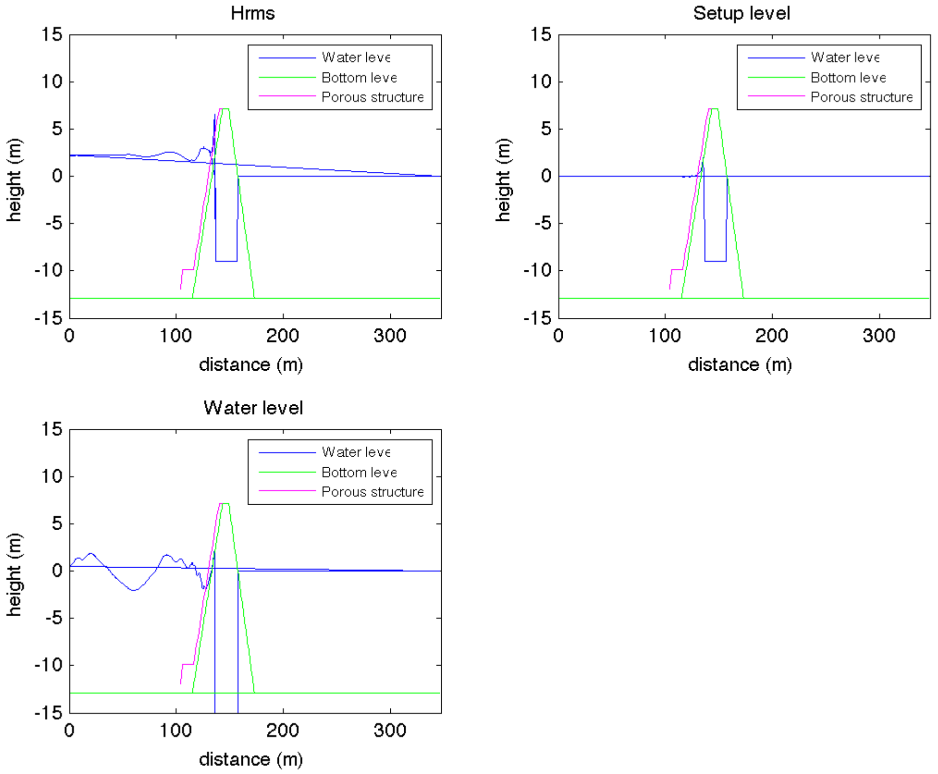

Figure 60. Hrms, setup and water level snapshot at the last instant for storm 1 in s1_2impcoreir.sws

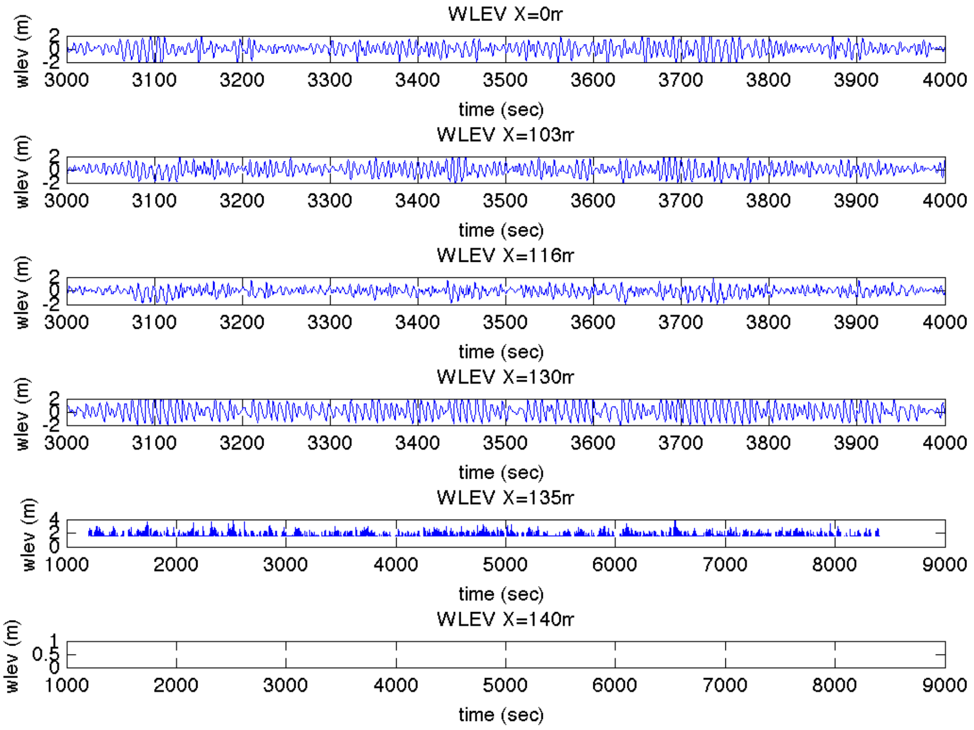

Figure 61. Water elevation over time at some points in s1_2impcoreir.sws

At this point, it looks like dissipation needs to be more reduced. This can be done by two means, both by lowering the thickness of the armour layer or by further increasing porosity. According to the assumed behaviour of SWASH when dealing with porous structures, both ways would lead to the same effect, which is the rise of the computed equivalent porosity; therefore, the easiest one when it comes to computational costs is to increase the porosity value, since the model does not need to be changed.

Porosity is going to be shifted from n=0.7 to n=0.9, but still water levels do not reach the overtopping tank located at X=146m; hence, the results are still not good enough. Neither n=0.95 has been observed to be sufficiently high to simulate the real breakwater.
I also tried some attempts changing the grain size, but no successful results were reached by doing that.

Observing the obtained results so far, it makes me start thinking that the problem might not be the dissipation but some other thing.

Taking a look at Martínez Pés, V. (2013), I can say my results up to now agree with the conclusions he came up to: when a porous structure is located over an impermeable core, SWASH is indeed interpreting the emerged part of the core as an impermeable wall so that waves are not able to cross that point. This explanation matches with the fact that the model is working when I settle n=1, since no porous structures have to be dealt with in that case. To be sure of that, I will run once more the model considering a wave height of 5m, porosity n=0.95 and grain size of 1.5m, situation that must lead to overtopping records.

Surprisingly, this time the model got to record water levels at X=146m; water can be therefore recorded after the emerged part of the core (Fig. 62).

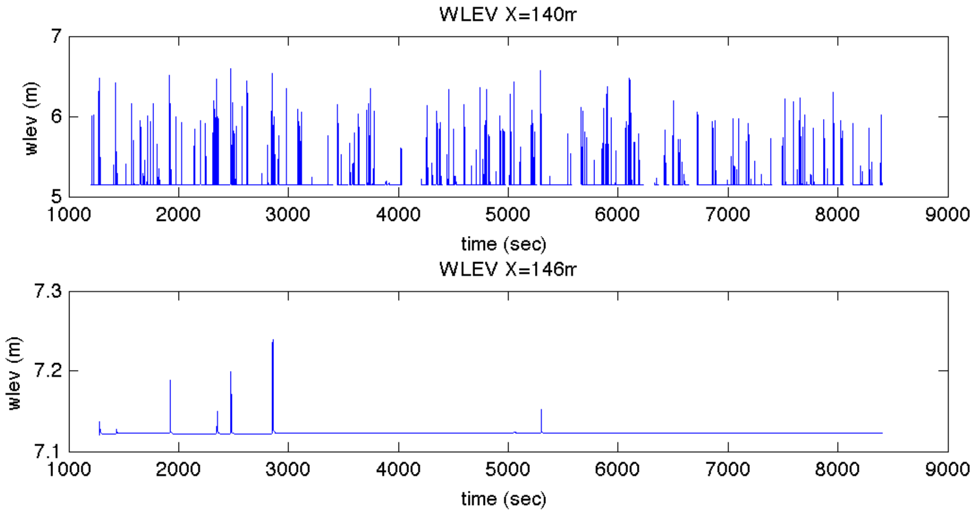

Figure 62. Water level at X=140m and at X=146m for Hs=5m in the scenario not with the whole porosity layer and n=0.95

Does the problem come from strong dissipation then? A new scenario is going to be defined decreasing even more dissipation effects

S1_5impcoreir.sws

This simulation is defined as s1_2impcoreir.sws but this time lowering the armour layer height from 3m to 1.4m and using a porosity of n=0.8. Particle size is also going to be shifted from 1.5 to 1.4 in order not to be bigger than the thickness of the porous layer. Waves from Storm 1 are going to be propagated in there, expecting overtopping to occur. Again, however, no volumes are obtained at X=140m.

Trying with porosity n=0.95, runup is observed to reach the slope at X=140m, but it does not arrive yet to the overtopping tank location at X=146m.

As the more likely explanation for the obtained results has to do with a strong dissipation effect of the armour layer, I will perform some simulations to test the behaviour of such porosity layer.

- Propagated spectrum waves with Hs=5m and a porosity of n=0.4 for the armour layer gives no runup neither at X=140m nor X=146.
- Propagated spectrum waves with Hs=5m and a porosity of n=0.95 for the armour layer gives the results plotted in Figure 63, which shows even higher overtopping rates than in case of the previous test in s1_2impcoreir.sws using the same input values. The difference comes from a thinner porosity layer.

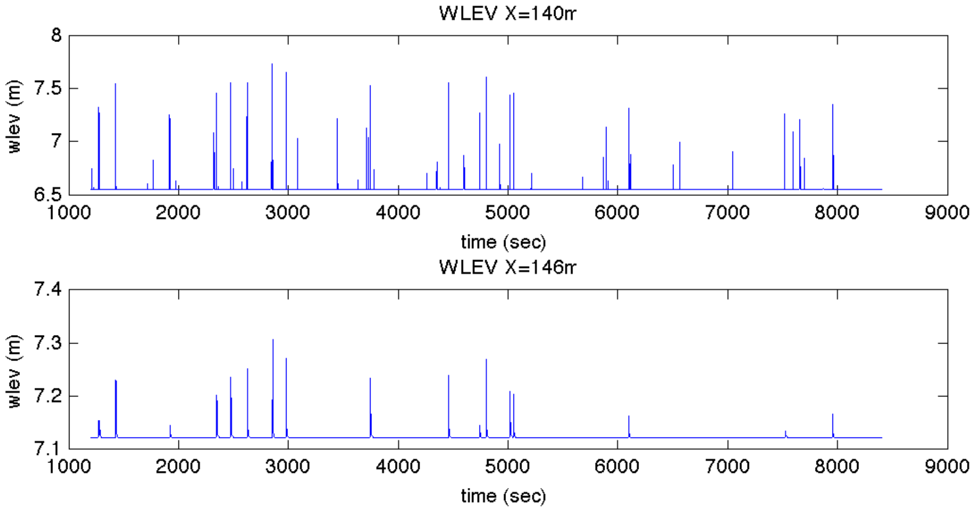

Figure 63. Water level at X=140m and at X=146m for Hs=5m in the scenario not with the whole porosity layer, reduced thickness and n=0.95

- Performing the same test as the last one (Hs=5m, n=0.95) but applying porosity in the whole length of the armour layer, no values were recorded running up the slope. It seems to agree with the hypothesis of a very strong dissipation through the porosity. Only by shifting n=0.95 to n=0.98 some values could be recorded. These latter results show lower runup than in case of n=1. Therefore, it is seen that even performing very small changes in the porosity value, large differences are observed in wave behaviour on the breakwater slope.

Hence, regarding the observed behaviour so far and in order to obtain some overtopping values for storm 1, I think it would be wise to make a new trial using Hs=3m and applying a porosity of n=0.98 only in the upper part of the armour layer (as shown in

Fig.59). Such simulation led to the possible recording of water levels both at X=140m and, reaching the breakwater crest, at X=146m.

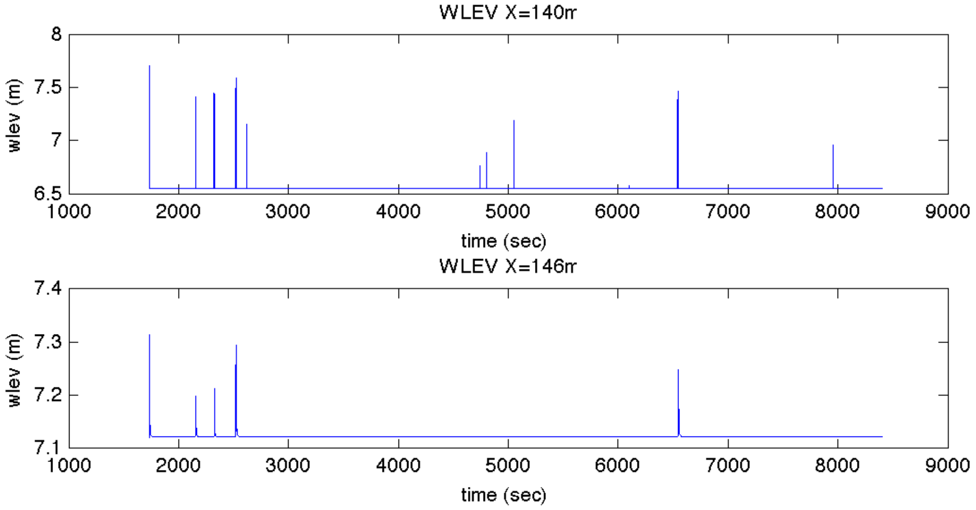

Figure 64. Water level at X=140m and at X=146m in storm 1 for the scenario not with the whole porosity layer, reduced thickness and n=0.98.

Since the wave overtopping tank is placed at X=146m, discharge has been analysed at that point, obtaining a discharge rate of q=10.96 L/ms (Fig.65). This value is seen to be lower than in case of smooth impermeable dikes but still much higher than the real measured value.

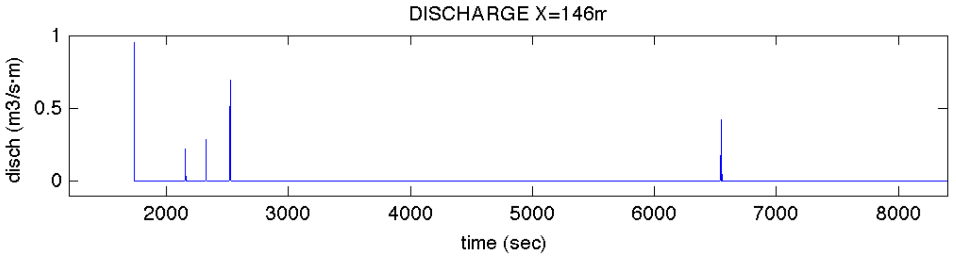

Figure 65. Discharge volumes at X=146m in storm 1 for the scenario not with the whole porosity layer, reduced thickness and n=0.98.

Even the used model does not fit with the definition of the real breakwater and hence it will not be representative for it, just in order to analyse how SWASH performs in the created scenario, the model will be run for the other reported storms in Zeebrugge within the CLASH project. Results are shown in Table 23.

	Storm No.										
	1	**2**	**3**	**4**	**5a**	**5b**	**5c**	**6**	**7**	**8**	**9**
Nov (-)	7	1	12	0	2	6	5	6	7	5	19
q (L/sm)	10.96	1.44	16.62	0	6.6	9.64	13.6	8.68	16.65	6.34	45.08

Table 23. Number of waves overtopped (Nov) and discharge volumes (q) recorded during the concerned storm events according to SWASH simulations for an impermeable core breakwater

As in the case of a smooth impermeable dike, obtained results for the model of an impermeable core will be plotted on a dispersion graph using the same dimensionless parameters as before, the freeboard *R** and the discharge *Q** defined by Owen (Fig.66).

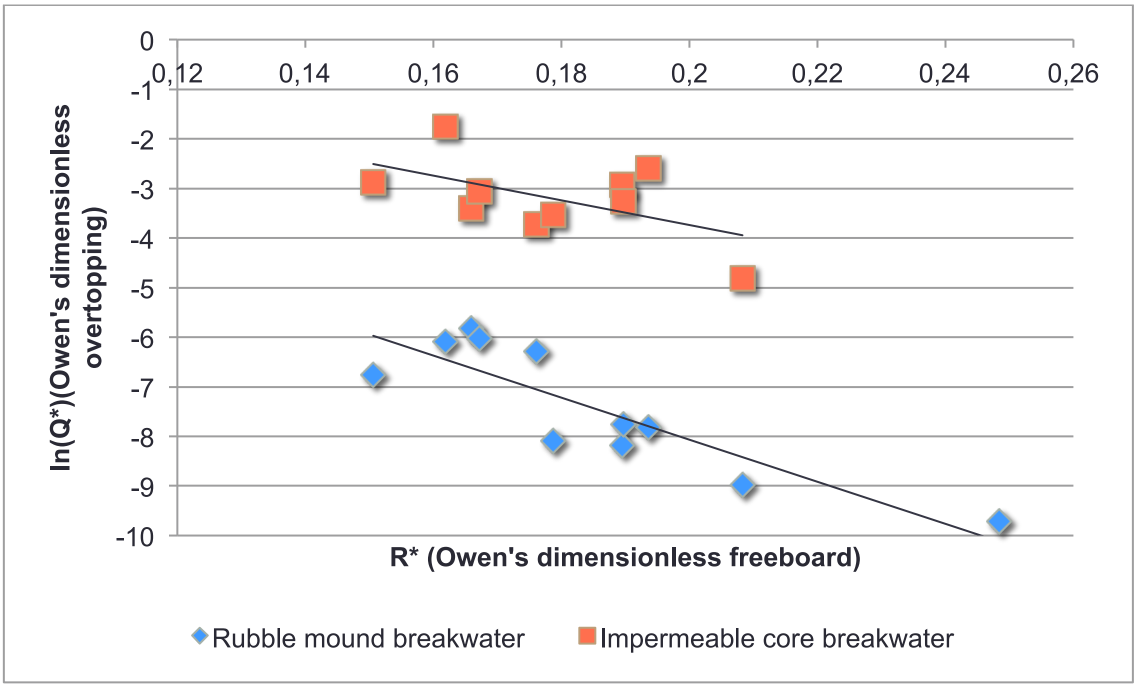

Figure 66. Dispersion graph comparing the obtained discharge in SWASH for a smooth impermeable dike and the measured discharge in a real breakwater scenario

Drawing conclusions from the above chart:

- The first issue to be remarked on the above chart has to do with the amount of overtopped volumes. Comparing the obtained values with the results in case of a smooth impermeable dike (Fig.52) it is clearly noticed a declination of such figures.

This fact falls within the expected behaviour, since an outer porosity layer has been added to the dike in this case, and it acts dissipating incoming energy. However, real values have not been reached by the designed model, it still predicts higher amounts of water crossing to the landward slope.

- It was stated before that enlarging the freeboard has more influence in case of the real breakwater than for a smooth impermeable slope, since on the first case porosity is playing a role dissipating energy along the slope. This effect can be confirmed indeed by the results on Figure 66, where the tendency line for the SWASH values (impermeable core with an outer porosity layer) shows higher steepness than in case of the smooth slope. However, the reached slope does not equal yet the real one, and that shows a lower dissipation capacity of the used porosity (n=0.98) in the armour layer with respect to the existing one. The problem I faced to in this case was that, by slightly diminishing the value for the parameter “n”, dissipation seemed to increase too much and no overtopping values could be obtained therefore.
- Also in these circumstances, as it occurred with a smooth impermeable dike, when the freeboard reaches a certain longitude, no more volumes are detected to cross over the structure. As already discussed, this might be a consequence of SWASH not accounting for splash volumes.
- The number of overtopping waves is generally higher in real storms because some of them might be caused by splash volumes, which are not taken into account in SWASH. However, this is not the case for all the situations. In order to analyise this behaviour the number of overtopping events has been plotted against the feeboard height in Figure 67.

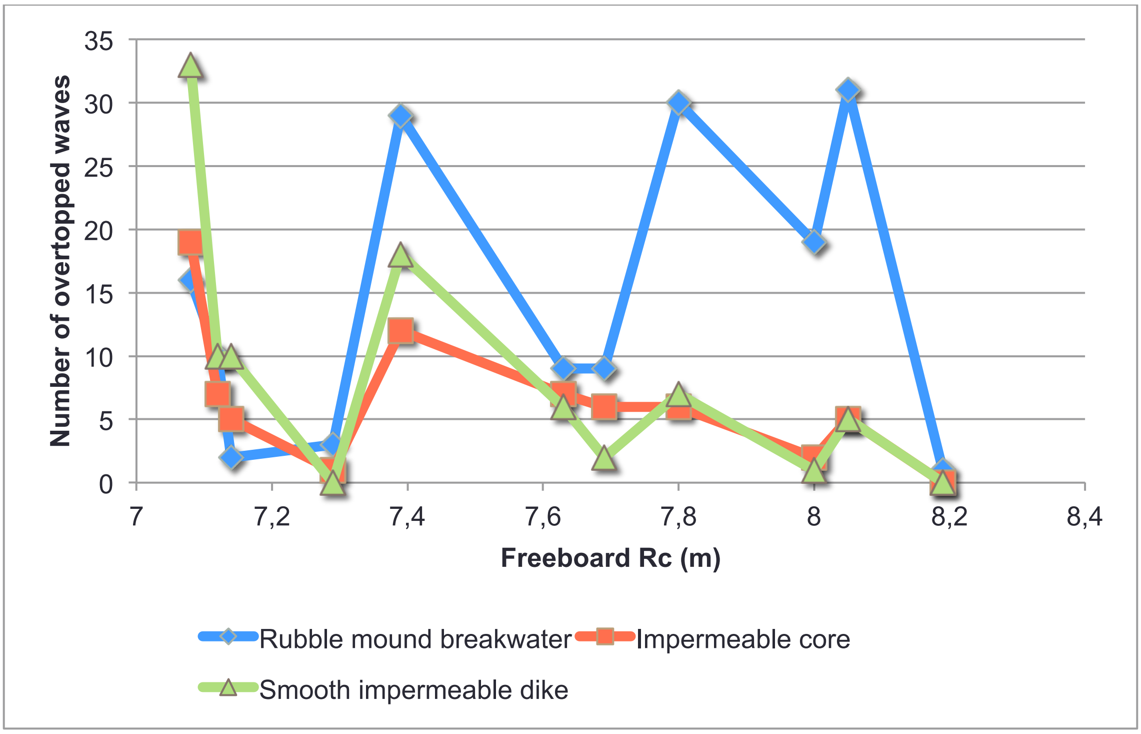

Figure 67. Number of overtopped waves for the real situation and for analysed scenarios in SWASH, an smooth impermeable dike and and impermeable core breakwater

The graph does not show a clear tendency, but still it can be noticed that mainly the computed amount of overtopping waves by SWASH exceeds the real value in situations with lower freeboards. In fact, as a rough approach, 3 different tendencies could be distinguished from the above chart:

For larger freeboards, the reported values for the real situation are much larger than the computed ones from the model since, as aforementioned, large part of the events might be caused by droplets instead of by runup. As the freeboard becomes lower, the difference on the number of overtopped waves is observed to decrease (but still real values remain higher). However, up to a point, the mentioned tendency inverts, and computed values by SWASH become bigger than the real ones.

This fact might be explained by the fact that SWASH, in both designed models (smooth impermeable dike and impermeable core) has been proved to be provided by less dissipative surfaces, and that enhances higher runup levels. Thus, even disregarding splash events, larger amount of waves will be able to cross lower freeboard levels.

We have to attribute to the Iribarren number, which plays also an important role in runup, the fact of not reaching clearer results when plotting the number of overtopped waves accoring to the available freeboard.

A5.2 Overview and conclusions so far

From the above tests it is clear that the proper way to model a breakwater in SWASH is by defining an impermeable core and by adding a porosity layer on the top of it. Otherwise, a single porous structure is not able to account for runup processes, behaving only as a kind of dissipation box able to dissipate and also reflect incoming energy.

Even though some values have been reached for overtopping, the required layout for the model does not relate to the real definition for the existing breakwater. When using a more realistic model of the breakwater it has not been possible to get good prediction for crossing water volumes, since energy dissipation seems to be too strong. Moreover, the obtained overtopping discharge does not get to proper prediction either.

COMMENTS OF MARCEL ZIJLEMA

It could be that the overestimation of energy dissipation processes in SWASH comes from some problems with the calibration of the pore pressure attenuation.

The software fixes as a default value of $\beta = 2.8$. This β parameter accounts for the particle-form constant for turbulent friction loss within porosity and it can be defined as $1.8 \leq \beta \leq 3.6$.

Hence, to analyse the effect of this parameter on the obtained results, new simulations will be conducted lowering β. This way it would be possible to check if energy dissipation can be reduced in SWASH until getting reliable predictions for the real case.

S1_Bimpcoreir.sws

First of all, the previous simulation for storm 1 (latter version of s1_5impcoreir.sws) is going to changed only by lowering β to its allowable minimum value in SWASH, β=1.8.
As expected, overtopping rates have increased indeed; the prior value of q=10 L/ms has risen to q=27.07 L/ms. Consequently, it proves the mentioned influence of β over the energy dissipation within the porous structure.

In the following test a more realistic layout of the breakwater is going to be introduced by considering porosity for the whole armour layer and by diminishing n=0.98 to n=0.45. The turbulent friction is going to be kept as β=1.8. Running the simulation, it results that no runup can be recorded at X=140m.
Even lowering n=0.8, which it does not hold for a realistic value, no runup is reaching X=140m neither.

It is concluded therefore that lowering the turbulent friction parameter is not enough to overcome underestimation of energy dissipation in SWASH. Thus, the software underestimates waves reaching the crest of breakwaters so that it is not possible to properly model the desired situation.