

# Transmission of waves through structures in ARTEMIS, and long-term time series of wave data in harbours

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**Abstract** – ARTEMIS is a tool that is often used to calculate the wave field in a harbour based on the mild slope equation. Special boundary conditions exist in ARTEMIS to include the (partial) reflections of wave on structures like breakwaters or groynes. However, ARTEMIS currently has two limitations that are addressed in this paper:

1. ARTEMIS cannot take account of the transmission of wave energy through porous structures,
2. ARTEMIS cannot be used to generate long time series of wave conditions for calibration or extreme value analysis.

Therefore, in this paper, first an adaptation to ARTEMIS is presented, which allows the transmission of wave energy through permeable structures. This is implemented as an extra functionality on the model boundaries that determines which fraction of the incoming wave potential is to be transmitted to another nearby node on the boundary (depending on the user-defined transmission coefficients). This feature is compatible with reflection of the incoming wave energy. Schematic test cases are shown that demonstrate the correct function of this module.

Then a method is presented, which allows the generation of long time series of wave conditions inside harbours. It uses the time series of wave spectra at the boundary of the ARTEMIS model (for example obtained from a wave transformation model like TOMAWAC) and the results of a large set (order 10000) of monochromatic ARTEMIS wave runs. The applicability of this method is demonstrated with the calibration of an ARTEMIS wave model against wave data measured in a marina.

**Keywords:** ARTEMIS, Wave, Harbour agitation, Transmission, Wave time series

## I. INTRODUCTION

ARTEMIS is a numerical model that is often used to calculate the wave field in a harbour based on the mild slope equation. Using this equation, the effects of refraction, diffraction and propagation of waves can be taken into account. Special boundary conditions exist in ARTEMIS to include the (partial) reflections of wave on structures like breakwaters or groynes. However, ARTEMIS cannot yet account for the transmission of wave energy through porous structures. The implementation of transmission would allow many new applications of ARTEMIS, including the simulation of floating breakwater and porous structures.

The mild slope equation does not have any time dependency. Therefore ARTEMIS is typically used to calculate the wave conditions given a single set of wave boundary conditions. While it is in principle possible to perform independent ARTEMIS simulations for each moment in time, the computational costs of doing so would be prohibitively expensive. This makes it difficult to obtain time series of wave conditions, for example for calibration purposes.

Therefore, the objectives of this paper are twofold:

1. To implement a new functionality to allow wave transmission through structures to be simulated in ARTEMIS,
2. To develop a methodology for obtaining time series of wave data from ARTEMIS, with reasonable calculation times.

The first part of this paper deals with the implementation of wave transmission. The section starts with a theoretical explanation of the physics involved and is followed by details of the implementation in ARTEMIS. Verification tests are presented to show that the correct behaviour is obtained. In a second part, a methodology is presented to generate time series of wave conditions using ARTEMIS and wave spectra at the boundary of the ARTEMIS model. This methodology is applied for the calibration and validation against wave data inside a marina. The paper ends with some brief conclusions.

## II. IMPLEMENTATION OF WAVE TRANSMISSION

### A. Theoretical background

In ARTEMIS, the mild slope equation [1] is solved for the wave potential  $\Phi$ . The potential is a complex variable, such that the amplitude and phase of the wave are both considered. The transmitted potential is  $\Phi_t$  is obtained from the incoming wave potential  $\Phi_i$  by:

$$\Phi_t = T\Phi_i. \quad (1)$$

Here  $T$  is the transmission coefficient. The current implementation assumes that there is no phase shift of the waves (this might be added relatively straightforwardly in a future update), and that the direction of the transmitted wave is equal to the direction of the incoming wave. The magnitude of the reflected wave potential  $\Phi_r$  is given:

$$|\Phi_r| = R|\Phi_i|. \quad (2)$$

Here  $R$  is the reflection coefficient. The reflected waves have a different direction to that of the incoming waves. Note that in ARTEMIS, a phase shift can also be applied to the reflected wave potential.

In order to have energy conservation, the reflection and transmission coefficients need to be chosen such that:

$$T^2 + R^2 \leq 1. \quad (3)$$

### B. Implementation in ARTEMIS

The transmission is always applied between two nodes, that are on a transmissive boundary (defined by the code 2 1 1 in the .cli file see section II.D). We will call the node with the incident wave the **source node**; and the node where the transmitted wave is released the **receiver node**. The method is designed for infinitely thin structures in the first instance. Source and receiver nodes may be located at a distance of 0 m from each other. So there are two nodes at the same place, but they are separated topologically, because there is no mesh edge connecting them. The limiting assumption in the current implementation is that the source and receiver nodes need to be closer than a threshold distance. In order to implement the transmission of waves in ARTEMIS, the following algorithm is used:

1. During the initialization step, a corresponding source node is searched for each receiver node on a transmission boundary. This source node is taken to be the first node within a distance to the receiver node that is smaller than the threshold distance specified in the .cas file (Figure 1).
2. At each iteration in the loop for automatic calculation of TETAP, the incoming potential at a source node is multiplied with the transmission coefficient (1), and this is added to the potential at the receiver node.

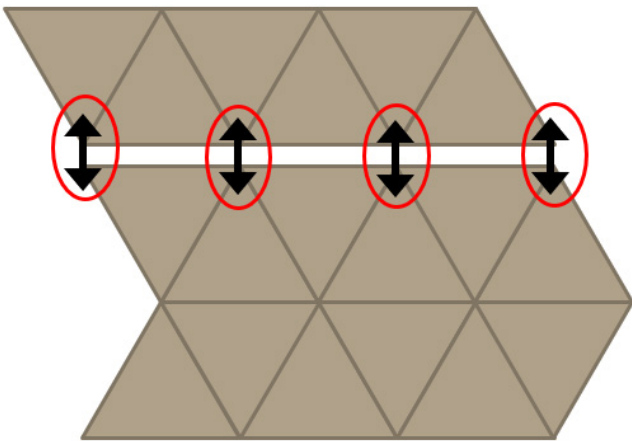


Figure 1 Connections in the mesh, through which waves are transmitted.

The current implementation only works on a single processor. The parallelisation of this algorithm will be implemented in the future.

### C. Validation tests

In order to verify the correct implementation of the wave transmission feature, a schematic test case was made. It consists of two basins with a width of 400 m and a length of 100 m each, and a depth of 5 m. The mesh resolution is 4 m (Figure 2). The two basins are separated by a 2-m thick wall. There are two very small openings connecting the two basins; an initial test showed that the wave energy penetrating through this opening is limited. Monochromatic waves are prescribed on the left boundary, with a wave height of 1 m and a wave period of 5 s. These waves have a wavelength of 30 m. With a mesh resolution of 4 m, 7.5 nodes define a wavelength, which is sufficient. The direct solver is used. Wave dissipation is neglected.

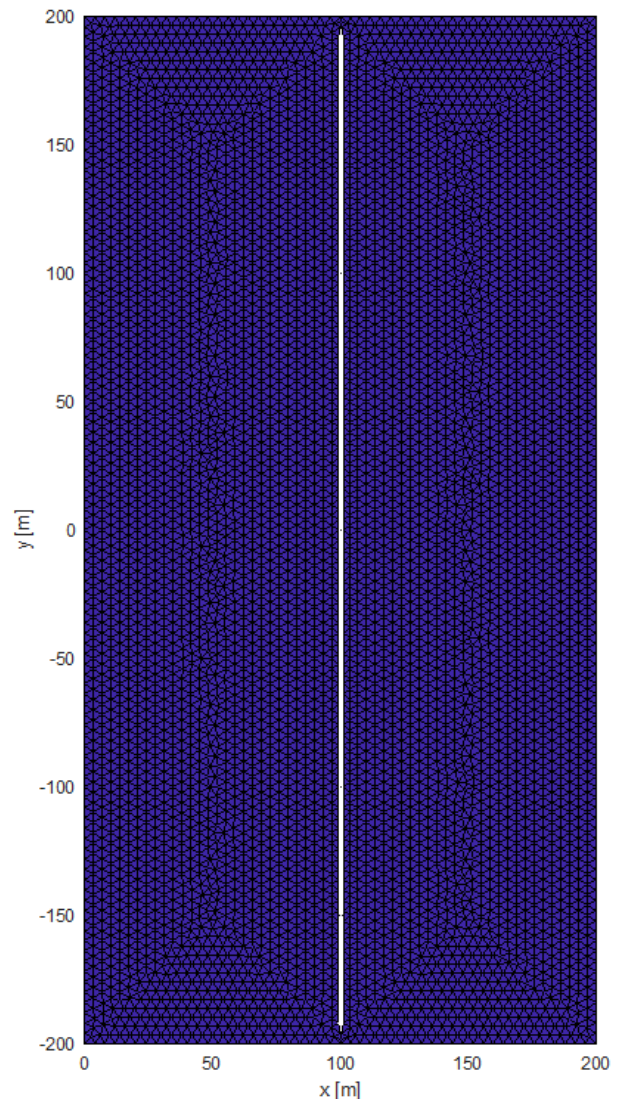


Figure 2 Mesh used in the schematic test case.

Different cases were studied, changing transmission coefficients, reflection coefficients and the incoming wave direction. In Figure 3, the wave height is plotted along the centre line ( $y=0$ ) for a case with  $R = 0.5$  (on the left side of the wall) and  $T = 0.5$  (on the right side of the wall) with a wave angle of 0 degrees at the boundary (cartesian convention), i.e.

waves propagating from left to right, parallel to the centre line of the basins. The waves in the left basin (partially) reflect against the wall. In the right basin, the wave height is 0.5 m, which corresponds to the expected value (incoming waves of 1.0 m multiplied by a transmission coefficient  $T$  of 0.5).

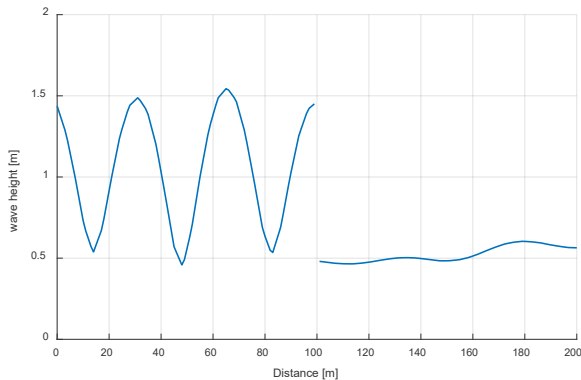


Figure 3 Wave height along the centre line of the basins for waves of 0 degrees,  $R = 0.5$  (left side of the wall), and  $T = 0.5$  (right side of the wall).

A second case was tested, also with a wave angle of 0 degrees at the open boundary, with a transmission coefficient  $T$  of 1.0 (fully transmissive), hence  $R = 0$  at the structure (on both sides). At the right boundary, a reflection coefficient of  $R = 0.5$  is applied. The wave height at the centre line is shown in Figure 4. This figure shows a standing wave in both basins, caused by reflections off the right boundary. The full transmission lets the waves propagate from either side. This is needed to get the correct standing wave patterns. There is a small discontinuity in wave height at the location of the wall. This might be related to the thickness of the structure separating the two basins (2 m), to neglecting the phase difference between both sides of the structure, or a combination of the two. Changing the mesh, such that the wall becomes thinner, might reduce this discontinuity.

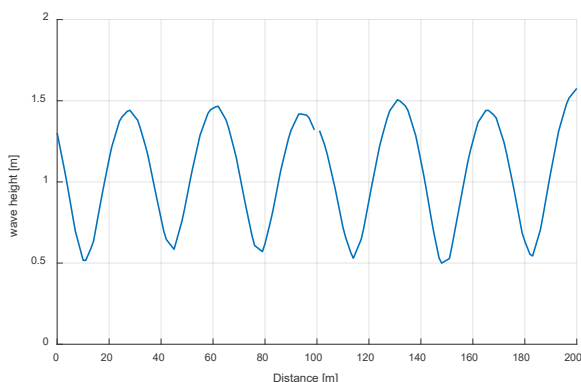


Figure 4 Wave height along the centre line of the basins for waves of 0 degrees,  $T = 1.0$  (both sides of the wall), and  $R = 0.5$  (right boundary).

The results of a case with waves at 30 degrees, a transmission coefficient of  $T = 1.0$  (fully transmissive), and a reflection coefficient of  $R = 0$  (no reflection) is shown in Figure 5. In this case, we see that the waves pass through the structure without

change in wave direction and wave height (as if the structure were not there). This is the expected behaviour.

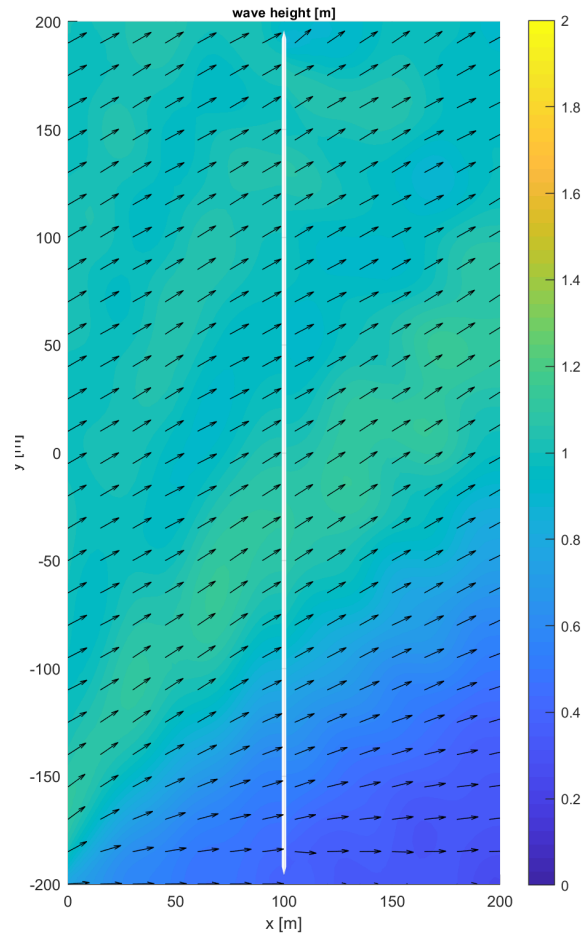


Figure 5 Wave height and wave direction for a case with waves at an angle of 30 degrees,  $T = 1.0$  and  $R = 0.0$ .

Results from the three examples presented here are in line with the expected behaviour of the wave transmission through a structure. Therefore, it can be concluded that the wave transmission is correctly implemented in ARTEMIS.

#### D. User procedure

In order to use the wave transmission feature, the following steps need to be taken:

1. Adapt the mesh in such way that at the boundary, in which one want to apply wave transmission there are two nodes at a short distance from each other (Figure 1). The wave energy will transferred between these two nodes. This distance between these nodes needs to be smaller than the distance between the node and the closest node on the boundary. This requirement is similar to that when using weirs and culverts in TELEMAC-2D and TELEMAC-3D.
2. Set the maximum distance between pairs of nodes to be connected, using the keyword in the .cas file:

```
THRESHOLD DISTANCE FOR TRANSMISSION
```

3. Use `AUTOMATIC TETAP CALCULATION : YES` in the `.cas` file (with a minimum of two iterations), to make sure that sub-iterations are used.
4. Adapt the `.cli` file. For a boundary with transmission, a new code (2 1 1) is needed on both sides of the transmitting boundary in the first three columns of the `.cli` file (Figure 6).
5. Add the transmission coefficient in column 9 of the `.cli` file. Note that this is consistent with the definition of the reflection coefficient (RP) and reflection phase shift (ALFAP) in columns 7 and 6. Therefore, it is possible to define different reflection and transmission coefficients on each side of the structure, thus allowing to model a complex structure. Thus in this implementation, reflection works on boundaries with code (2 2 2) as well as with (2 1 1), but only the latter always transmission of wave energy.

```

2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.0000 0.0000 0.0000 5980 395 # transmission
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.0000 0.0000 0.0000 5979 396 # transmission
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.0000 0.0000 0.0000 5978 397 # transmission
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.0000 0.0000 0.0000 5977 398 # transmission
2 2 2 0.0000 0.0000 0.0000 0.0000 2 0.0000 0.0000 0.0000 16 399 #
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.5000 0.0000 0.0000 30 400 # transRight
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.5000 0.0000 0.0000 44 401 # transRight
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.5000 0.0000 0.0000 58 402 # transRight
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.5000 0.0000 0.0000 72 403 # transRight
2 1 1 0.0000 0.0000 0.0000 0.0000 2 0.5000 0.0000 0.0000 86 404 # transRight

```

Figure 6 Extract of a `.cli` file, which contains a transmissive boundary.

### III. GENERATION OF LONG TIME SERIES OF WAVE CONDITIONS IN ARTEMIS

#### A. Methodology

In many practical applications, one is interested in obtaining long time series of wave conditions including the effects of refraction, reflection, transmission and diffraction. Possible applications include statistical analysis of extreme values, which is often required for design purposes. In principle, it is possible to do so in ARTEMIS, by calculating the wave field for every set of conditions (water depth, wave height, wave period and wave direction at the boundary of the ARTEMIS model). However, in practice, this is too computationally expensive to do in real cases. Therefore, a new methodology is presented in this paper, which is faster. It has the additional benefit that the output spectral resolution can be much higher than in a standalone ARTEMIS simulation where resolution is typically reduced in favour of computational efficiency.

In the absence of dissipation terms (depth induced wave breaking and bottom friction), the processes modelled in ARTEMIS are linear. Therefore, the superposition principle applies. Whether or not the dissipation of wave energy can be neglected is case dependent. However, in many practical applications, which deal with the wave field inside ports and harbours, the water depth is relatively deep and neglecting the wave dissipation is justified.

The new methodology uses the linearity of ARTEMIS to reconstruct spectra in the ARTEMIS model domain from spectral input of data (Figure 7). Thereto the following steps are performed:

1. A time series of wave data (ideally in the form of wave spectra) is obtained from wave buoys or a large-scale wave model (such as ERA5) in the region of interest.

2. Depending on the location of the available time series with respect to the boundary of the ARTEMIS model, a wave transformation model (e.g. SWAN or TOMAWAC) is used to obtain time series of wave spectra at the boundary of the ARTEMIS model [2].
3. Water level data are obtained at the boundary from measurements or an appropriate numerical model such as iCSM [3].
4. The ARTEMIS model is run to generate a database of wave transformation in the area of interest. This is done by performing multiple runs with monochromatic waves, without any wave dissipation, for a wave height at the boundary of 1 m with the wave directions and wave frequencies that correspond exactly to the spectral bins in the time series of wave spectra at the boundary (e.g. the spectral mesh of the wave model used in the wave transformation in step 2). Iterations to estimate the incoming wave direction on reflecting boundaries are applied, as these iterations are not related to any non-linearity, and hence the superposition principle can still be used. These runs are performed for a range of water levels covering the data obtained in step 3. Typically, this results in thousands of simulations, but these simulations are very fast (order of seconds to minutes on a single processor) and can easily be executed simultaneously. Typically, we use the Linux `xarchs` command to make sure that these ARTEMIS runs are executed simultaneously in order to save on the total time needed to obtain all simulation results.
5. A MATLAB script is used to reconstruct the wave spectra inside the ARTEMIS model domain from 1) the ARTEMIS wave transformation database and 2) the time series of wave spectra at the ARTEMIS boundary and water levels, which are assumed to be continuous in the full model domain. This script determines at each moment in time the nearest water level in the ARTEMIS database to the observed water level and selects the wave results for this water level. These wave spectra are then used to determine the spectral wave parameters (significant wave height, peak and mean wave period and mean wave direction). These results are stored in a Selafin file.
6. A separate postprocessing can be performed on the Selafin file generated in step 5 to determine extreme value distributions or to compare to measurements.

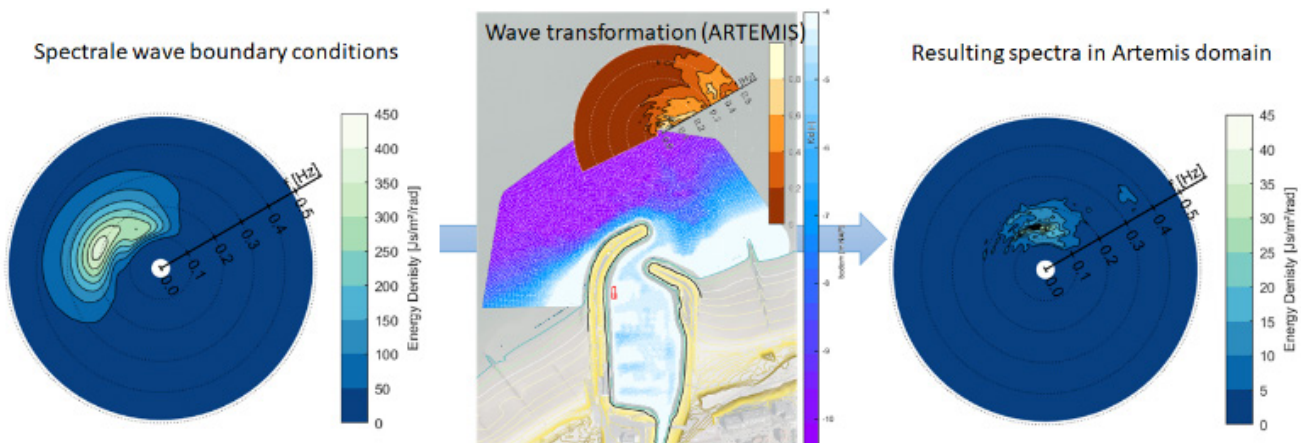


Figure 7 Schematic image of the wave transformation methodology.

**B. Application for the calibration of an ARTEMIS model of a marina**

The methodology presented in section III A is used to calibrate an ARTEMIS model of the marina of Cadzand in the Netherlands (Figure 8).

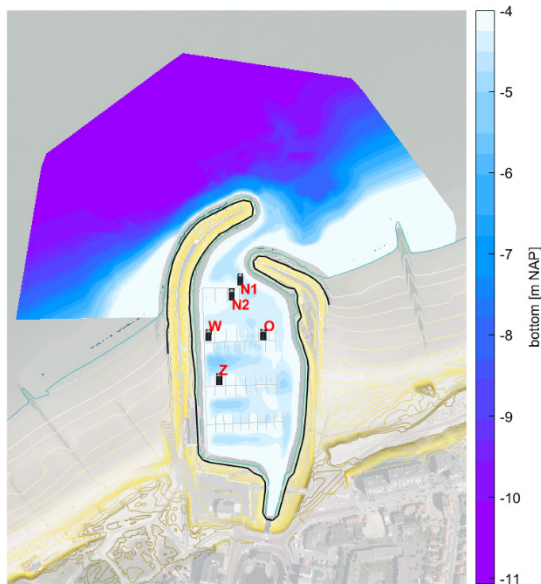


Figure 8 Bathymetry of the marina of Cadzand and location of the observations

A database was made of 25380 ARTEMIS simulations, using the discretisation in Table 1. Time series of wave data were generated from observed wave spectra in the vicinity of the model domain, such that no wave transformation modelling was necessary in this case. The observed wave spectra data consisted of one-dimensional wave spectra with the mean wave direction and directional spreading for each frequency bin. These data were converted to two-dimensional wave spectra using the  $\cos^{2s}$  directional spreading distribution.

Table 1 Classes used for the wave transformation database in ARTEMIS

Variable	Nr of classes	Range	Resolution
Water level	12	-2.5 m to +3.0 m	0.5 m
Frequency	47	0.03 Hz to 0.49 Hz	0.01 Hz
Direction	45	116 deg to 60 deg	4 deg

The model was calibrated by changing the reflection coefficients at the breakwaters inside the marina. For the calibration, measurements were performed inside the marina using Aquadopp and OBS sensors at different locations inside the marina.

The results are presented in Figure 9 and Figure 10. The presented methodology has made it possible to obtain time series of significant wave height and peak period from the ARTEMIS model, which can be compared directly to the observed measurement data. From the presented data, it appears further that ARTEMIS can represent the wave height and wave period in the marina rather well using the presented methodology.

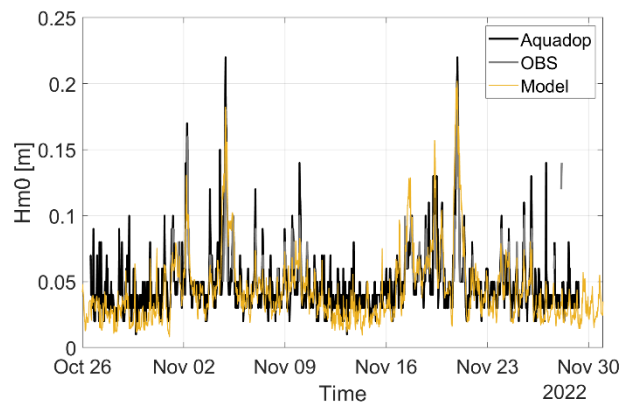


Figure 9 Comparison of measured wave height and modelled wave height inside the marina.

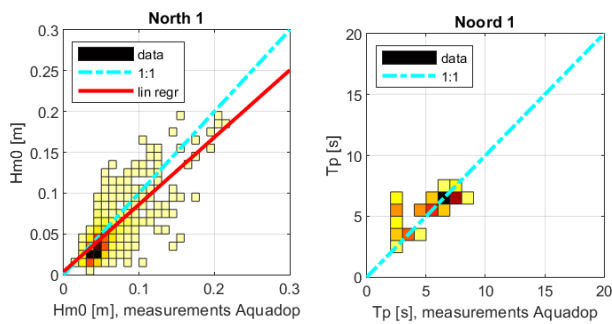


Figure 10 Summary of the calibration results at one of the observation points

#### IV. SUMMARY AND CONCLUSIONS

In this paper, first a new implementation is presented, that allows to use wave transmission through porous structures in ARTEMIS. This is done by copying the imaginary wave potential from one point at the boundary representing the structure to a point on the opposite side of that boundary after applying a transmission coefficient. Any phase shift in the potential is currently neglected. At present, the method only works on a single processor, but parallelisation of the code is foreseen for the near future. This approach can be combined with reflection at the boundary. Theoretical tests are performed in order to verify the correct implementation of the feature.

Then, a methodology is presented to determine time series of wave conditions in the ARTEMIS domain. In this methodology, a large set (ten thousands) of monochromatic ARTEMIS simulations is performed to obtain a database of wave results for each component in the two-dimensional wave spectrum inside the ARTEMIS domain. Together with timeseries of wave spectra at the boundary and water levels in the domain, this database can be used to reconstruct the wave conditions in the model domain, provided that wave dissipation can be neglected. This method was applied to perform a calibration of a wave model of a marina. The time series obtained using this procedure are directly compared to the time series measured inside the marina and show a good agreement.

#### REFERENCES

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