# Manual for *CRest.py*

## a computer program for estimating reflection coefficient $C_\mathrm{R}$ for wave absorbing layers in flow simulations of free-surface wave propagation

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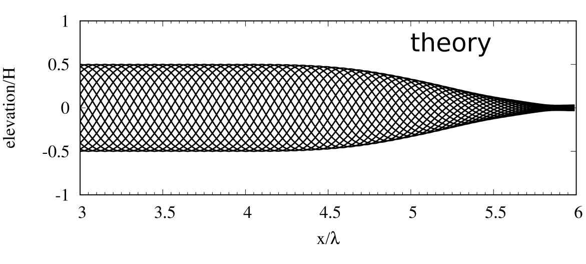


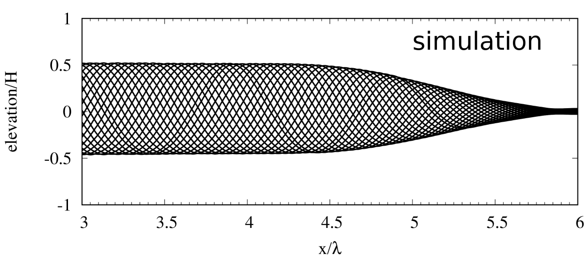

# Contents

# 1 One-minute-explanation of the code

When to use this code?

- You perform flow simulations of free-surface wave propagation
- You want to minimize undesired wave reflections at the domain boundaries
- To do so, you want to use *absorbing-layer-type approaches* (e.g. forcing layers, sponge layers, damping zones, Euler overlay method, relaxation zones, etc.)

What does the code do?

- The user can enter wave period, wavelength, layer thickness, blending function, and specify in which governing equations the source terms are introduced
- The code calculates reflection coefficient $C_\mathrm{R}$ for various forcing strengths $\gamma$ according to [1] and writes these results to the file $'\mathrm{C_R.csv}'$ in the same folder
- If matplotlib is installed: A window will open with an interactive plot of $C_\mathrm{R}$ over $\gamma$
- Thus the code can be used to quickly fine-tune the case-dependent absorbing layer parameters

Requirements:

- Check that your absorbing layer can be formulated in terms of Eqs. (2) and (1)
- Install *python* programming language
- For full functionality, install *matplotlib*
- Operating systems: Linux, macOS, Windows

Tuning absorbing layers:

- Use higher order blending functions such as Eqs. (5) to (7)
- Increasing the layer thickness $x_\mathrm{d}$ widens the range of wavelengths which will be damped satisfactorily, and lowers the reflection coefficient for the optimum setting
- Often confidence in reflection absorption is more important than the last few percent efficiency $\Rightarrow$ use slightly thicker layers than necessary
- Typical values for layer thickness are $1\lambda \leq x_\mathrm{d} \leq 2\lambda$
- For irregular waves, tune the layer to the peak period or the longest period (quick approach [2]) or calculate the reflection coefficient for each wave component's period and then tune accordingly (more accurate approach)

Benefits and Limitations:

- The code gave satisfactory predictions for regular and irregular long-crested waves in deep water; preliminary results for steep waves, shallow water waves, breaking waves and 3D flow problems with oblique wave incidence indicate that the theory gives satisfactory results for such cases as well
- However, for complex flows (e.g. steep waves, breaking waves or 3D oblique wave incidence) reflection may be larger than predicted, so that thicker layers are recommended to ensure satisfactory wave absorption

- Undesired reflections can also be due other mechanisms, e.g. the use of inappropriate grids
- Therefore, tuning the absorbing layer parameters according to this code does NOT guarantee that the actual reflection coefficient in the simulation will equal the prediction

# 2 Requirements

The programming language python version 2.7 or 3.0 or higher (`https://www.python.org/downloads/`) must be installed.

It is recommended to also have matplotlib (`https://matplotlib.org/users/installing.html`) installed. Then the code will open a window with an interactive plot of the results.

# 3 Theory and code description

## 3.1 Motivation and theory behind the code

Absorbing layers (forcing layers, sponge layers, damping zones, ...) can reduce undesired wave reflections at boundaries of the computational domain. However, the absorbing function contains user-defined parameters; these parameters are case-dependent and must be tuned for every simulation. Otherwise strong reflection may occur.

The present code can guide the tuning of these case-dependent parameters. The code is an implementation of the theory from [1]. Please see [1] to find out if and how the theory applies to the absorbing layer implementation that you use.

In [1], a theory was presented which predicts the reflection coefficient for a given absorbing layer setup. The reflection coefficient $C_{\mathrm{R}}$ is the ratio of the reflected wave amplitude to the incidence wave amplitude. Thus the theory can be used to tune the case-dependent parameters *before running the simulation.*

The theory preditions were demonstrated to be of satisfactory accuracy for regular long-crested waves of steepness up to $\approx 70\%$ of breaking steepness in deep water, and also for irregular long-crested waves in deep water[1, 2]. Future research is necessary to verify how accurate the theory predicts the damping of three-dimensional waves, irregular waves and highly non-linear waves, such as rogue waves, waves close to breaking steepness and even breaking waves; literature results are promising that the theory covers these cases as well [2, 3, 4, 5].

The theory in [1] was derived so that it works for any continuous or discontinuous blending function. A few common blending functions are already implemented. Custom blending functions can be entered at the location indicated in the source code.

## 3.2 Introduction to absorbing layers

The theory in [1] is based on the following general absorbing layer formulation, which applies to many existing absorbing-layer-type approaches.

Undesired wave reflections can be reduced by applying source terms for volume fraction, $q_{\alpha}$, and momentum, $q_i$, as

$$q_\alpha = \gamma b(x)\left(\alpha_{\text{ref}} - \alpha\right) \quad , \tag{1}$$

$$q_{\text{i}} = \gamma b(x)(u_{i,\text{ref}} - u_i) \quad , \tag{2}$$

with reference volume fraction $\alpha_{\text{ref}}$, reference velocity component $u_{i,\text{ref}}$, forcing strength $\gamma$ and blending function $b(x)$; see [1] for details.

Outside the absorbing layer holds $q_{\text{i}} = 0$. Let the reference solution be the medium at rest, so $u_{i,\text{ref}} = 0\,\frac{\text{m}}{\text{s}}$ and $\alpha_{\text{ref}}$ corresponds to the volume fraction for the calm free-surface.

The forcing strength $\gamma$ with unit $\left[\frac{1}{\text{s}}\right]$ regulates how strong the solution at a given cell is forced against the reference solution.

The blending term $b(x)$ regulates the distribution of the source term over the domain, where $x$ is the wave propagation direction. Many different types of blending functions can be applied. The following common choices are implemented in the code: Constant blending

$$b(x) = 1 \quad , \tag{3}$$

linear blending

$$b(x) = \frac{x - x_{\text{sd}}}{x_{\text{ed}} - x_{\text{sd}}} \quad , \tag{4}$$

quadratic blending

$$b(x) = \left(\frac{x - x_{\text{sd}}}{x_{\text{ed}} - x_{\text{sd}}}\right)^2 \quad , \tag{5}$$

cosine-square blending

$$b(x) = \cos^2\left(\frac{\pi}{2} + \frac{\pi}{2}\frac{x - x_{\text{sd}}}{x_{\text{ed}} - x_{\text{sd}}}\right) \quad , \tag{6}$$

or exponential blending such as

$$b(x) = \left(\frac{e^{\left(\frac{x - x_{\text{sd}}}{x_{\text{ed}} - x_{\text{sd}}}\right)^2} - 1}{e^1 - 1}\right) \quad , \tag{7}$$

with start coordinate $x_{\text{sd}}$, end coordinate $x_{\text{ed}}$, and thickness $x_{\text{d}} = |x_{\text{ed}} - x_{\text{sd}}|$ of the absorbing layer. These blending functions are illustrated in Fig. 1. Though so far the optimum blending function is not known, several investigations showed that higher order blending functions are more effective than constant or linear blending.

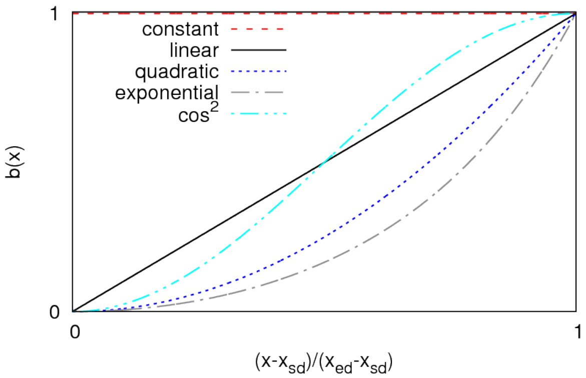


**Figure 1:** Different blending functions $b(x)$ over location in absorbing layer

As shown in [2], parameters $\gamma$ and $x_\mathrm{d}$ scale with angular wave frequency $\omega$ and wavelength $\lambda$ as

$$\gamma \propto \omega \quad , \quad x_\mathrm{d} \propto \lambda \quad . \tag{8}$$

Therefore these parameters must be tuned for every simulation; as [1] shows, there is not one configuration that fits all wave problems.

### 3.3 Benefits and limitations

The code gave satisfactory predictions for the absorption of regular and irregular long-crested waves in deep water. Further, it is expected that the theory will also be of value for tuning absorbing layers for more complex flows, since absorbing layers are frequently used, especially for complicated 3D flows with fluid-structure-interaction, and also since literature results for their application to three-dimensional, irregular and highly non-linear waves are promising.

Although the code's predictions are often quite accurate [1], please keep in mind that every theory has its limitations! For highly non-linear waves, such as breaking waves, or for oblique wave incidence in 3D, reflection may be larger than predicted. Further, undesired reflections can be due other mechanisms as well, e.g. the use of inappropriate grids. Therefore, tuning the absorbing layer parameters according to the present theory does NOT guarantee that the actual reflection coefficient in the simulation will equal the prediction. See [1] for a detailed discussion.

### 3.4 Recommendations for tuning absorbing layers

The use of higher order blending functions such as Eqs. (5) to (7) is recommended. Constant or linear blending, i.e. Eqs. (3) to (4), are generally less efficient, meaning that to obtain the same reflection coefficient they require greater layer thickness and thus also greater computational effort. Currently it is not clear which blending function is the best choice: Although blending functions in Eqs. (5) to (7) look different, the differences in wave absorption between them was comparatively small, with perhaps a slight preference towards exponential blending[1].

Increasing the layer thickness $x_\mathrm{d}$ widens the range of wavelengths which will be damped satisfactorily, and lowers the reflection coefficient for the optimum setting; thus if the wave absorption is not satisfactory, then layer thickness $x_\mathrm{d}$ should be increased.

Although for regular waves it may be possible to achieve satisfactory damping with layers as thin as $x_\mathrm{d} \approx 0.5\lambda$, such thin layers should be avoided or at least used with caution, since then the reflection coefficient is very sensitive to the wave parameters.

In engineering practice, usually confidence in wave absorption is more important than the last few percent efficiency. Therefore it is recommended to use layer thicknesses $x_\mathrm{d}$ slightly larger than possibly necessary. Typical values are $1\lambda \leq x_\mathrm{d} \leq 2\lambda$.

For irregular waves, a quick approach is to tune the layer to the peak period or the longest period[2]. A more accurate approach is to calculate the reflection coefficient for each wave component's period and in this manner tune the layer parameters accordingly.

# 4 How to run the code

In windows, double click on the executable file *CRest.py*.

In Linux and macOS, open a terminal and type:
python CRest.py

Example output:

```
python CRest.py

Please enter wave period (s):
1.6

Please enter wavelength (m):
4

Please enter layer thickness per wavelength (enter 2 if thickness = 2 * wavelength):
2

Available blending functions are:
Constant blending: 1
Linear blending: 2
Quadratic blending: 3
Cosine**2 blending: 4
Exponential blending: 5
Custom blending: 6

Please enter number of blending function:
5

Damping/forcing can be applied to different variables:
Horizontal velocities: u
Vertical velocities: w
Volume fraction: a
All velocities: uw
Volume fraction and all velocities: uwa

Please enter variable(s):
u
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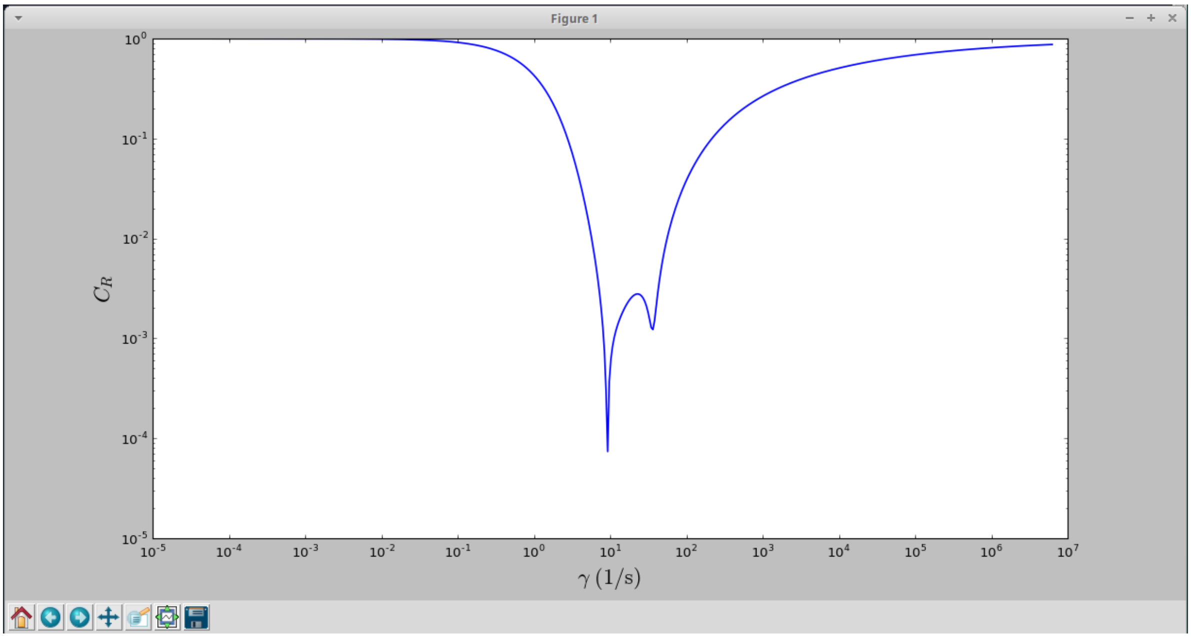


## 5 Reporting bugs

So far, no bugs are known.

If you find bugs, or if you have questions or suggestions, please contact the author:

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## 6 Copyright



## 7 References

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[2] R. Perić and M. Abdel-Maksoud. Reliable damping of free-surface waves in numerical simulations. Ship Technology Research, 63, 1, 1–13 (2016).

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