ROYAL BELGIAN INSTITUTE FOR NATURAL SCIENCES
OPERATIONAL DIRECTORATE NATURAL ENVIRONMENT

Section Ecosystem Data Analysis and Modelling
Suspended Matter and Sea Bottom Modelling and Monitoring Group

Measuring, using ADV and ADP sensors, and modelling bottom shear stresses in the Belgian coastal waters

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ZAGRI-MOZ4/1/DVDE/201502/EN/TR02

Prepared for ZAGRI and MOZ4 projects

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1. Introduction

The bottom shear stress is an important factor for the calculation of sediment transport. The bottom shear stress determines the erosion and resuspension of the material or the deposition of the material on the sea bed. Furthermore, different total load and bottom load formulae take into account the bottom shear stress. The calculation of the bottom shear stress, under the combined influence of currents and waves, is however not a trivial task. Different methods and techniques are available in literature, sometimes using many parameters, which are not well known. The methods can vary from very simple models to very complex and time-consuming models. Also for the bottom roughness length, one of the main parameters determining the bottom shear stress, different models are available in literature. All these different models can give results that can vary over a large range.

Furthermore the measuring of the bottom shear stress is very complex and reliable bottom shear stress measurements, that could be used to validate the model predictions, are at the moment not available. Different methods are available to "measure" the bottom shear stress. In Francken and Van den Eynde (2010) a method was described, to calculate the bottom shear stress from the measurements from a high frequency point velocity meter (Acoustic Doppler Velocimeter ADV). Using the turbulent velocity spectrum in the high frequency range, the bottom shear stress can be calculated. Also the turbulent kinetic energy, which is calculated from the high frequency velocity variations, can be used to calculate the bottom shear stress. Finally, the bottom shear stress can be calculated from the logarithmic profile of the water currents in the lower water column. These current profiles can be measured using an Acoustic Doppler Profiler (ADP), installed on a bottom lander, or using a bottom mounted Acoustic Doppler Current Profiles (ADCP).

In the present report, some measurements of the bottom shear stress are discussed. Furthermore, a new module is presented to calculate the bottom shear stress, using different methods. This module can be used in the two sediment transport models, which are currently available at the OD Nature. Some first results of the validation of the bottom shear stress are discussed. First of all, the measurements of two deployments are discussed in detail, one offshore and one near shore deployment. Further the overall conclusions from the comparison of the model results with the measurements for all deployments are presented. Some conclusions and plans for further work are given at the end.

2. Measurements of the bottom shear stress

2.1. *Material*

In the framework of different projects (MOMO, ZAGRI, MOZ4, monitoring wind parks), several measuring campaigns were executed since 2005. Measurements were executed with bottom landers that are deployed at the bottom of the sea (see Figure 1 and Figure 2). The frame is equipped with a SonTek ADV Ocean point velocity meter, at 36 cm above the bottom (measuring at 18 cm above the bottom), a downward looking SonTek 3 MHz ADP current profiler, at 228 cm above the bottom, a Sequoia LISST-100X Laser In-Situ Scattering & Transmissometer, at 231 cm above the bottom and a Sea-Bird SBE37 thermosalinograph at 80 cm above the bottom. Furthermore 2 D&A OBS sensors, measuring turbidity, were attached to the frame at 29 cm and 234 cm above the bottom. The LISST measures the particle size distribution in the water column and the volumetric concentration of the material in suspension. During some deployments, the LISST was coupled with a third OBS sensor, measuring the turbidity at 125 cm above the bottom.

Additionally a RDI bottom mounted Acoustic Doppler Current Profiler (ADCP), type Sentinel 1200 kHz Workhorse (see Figure 3), could be deployed. This ADCP measured the current profile in the complete water column. However, these ADCP measurements will not be used in the current study.

As will be explained further in more detail, measurements of the ADP could be used to calculate the bottom stress from the current profile, while the measurements of the ADV could be used to calculate the bottom stress, using the inertial dissipation method or the turbulent kinetic energy method.

2.2. *Overview of the measurements*

In the period 2005-2013 69 measuring deployments with the bottom landers have been executed, mostly (48 deployments, i.e. 69.6 %). near the measuring station MOW1. From 2006 to 2009, 7 deployments were executed near Blankenberge, one deployment at MOW0. In the framework of the monitoring of the effects of the wind farms, 2 deployments were executed at the Gootebank, and 3 on the Bligh Bank in the period 2009-2010. From 2013, 9 campaigns have been executed near the WZ-buoy, near Zeebrugge in the framework of the “terreinproef Zeebrugge”. An overview of the deployments, with the position and the starting and ending date is given in Table 1.

The position of the stations is presented in Figure 4.

Figure 1: Tripod bottom lander.

Figure 2: Tripod bottom lander.

Figure 3: Bottom mounted ADCP.

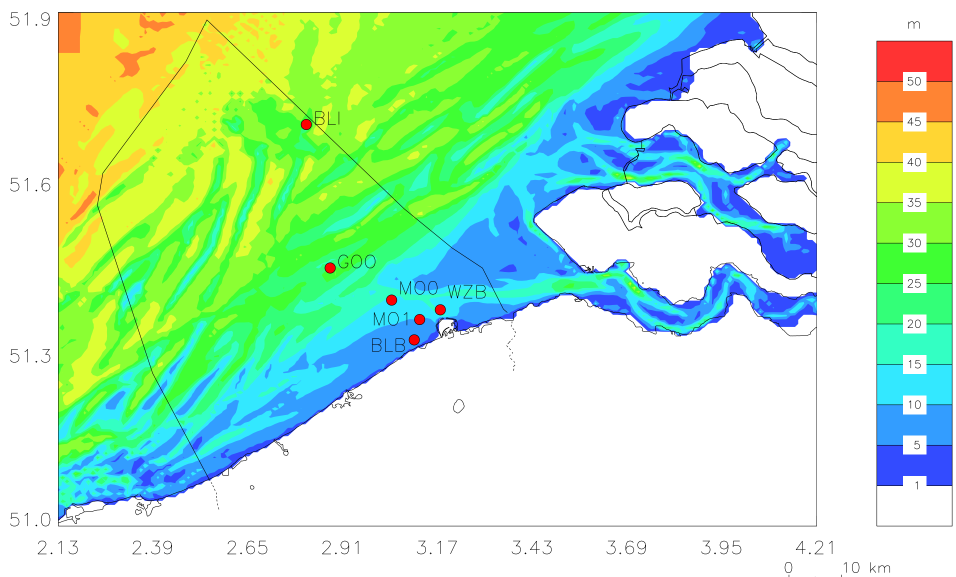

Figure 4: Position of the measuring stations: BLI: Bligh Bank, GOO: Gootebank, MO0: MOW0, BLB: Blankenberge, MO1: MOW1, WZB: WZ-Boei.

Table 1: Overview of the deployments.

	Station	ADP	ADV	Start	End	Model
5	MOW1	X	X	07/02/2005	18/02/2005	
6	MOW1	X	X	04/04/2005	15/04/2005	
7	MOW1		X	22/06/2005	12/07/2005	
8	MOW1	X	X	22/11/2005	05/12/2005	
9	MOW1	X	X	13/02/2006	27/02/2006	
10	MOW1	X	X	27/03/2006	18/04/2006	
11	MOW1	X	X	15/05/2006	15/06/2006	
12	Blankenberge	X	X	08/11/2006	27/11/2006	
13	Blankenberge	X	X	27/11/2006	15/12/2006	
14	Blankenberge	X	X	18/12/2006	07/02/2007	
15	MOW1	X	X	10/07/2007	19/07/2007	X
16	MOW1		X	23/10/2007	28/11/2007	
17	Blankenberge	X	X	28/01/2008	24/02/2008	
18	Blankenberge	X	X	06/03/2008	08/04/2008	
19	Blankenberge	X	X	15/04/2008	05/06/2008	
20	MOW0	X		23/06/2008	11/07/2008	
21	MOW1	X	X	17/11/2008	12/12/2008	
22	MOW1	X	X	09/02/2009	19/03/2009	
23	MOW1	X	X	26/03/2009	29/04/2009	
24	Blankenberge	X	X	04/05/2009	15/06/2009	
25	Gootebank	X	X	23/06/2009	13/07/2009	X
26	Blighbank	X	X	24/06/2009	14/07/2009	X
27	MOW1	X		10/09/2009	21/10/2009	
28	Gootebank	X	X	19/10/2009	09/12/2009	
29	Blighbank	X		21/10/2009	09/12/2009	
30	MOW1	X	X	06/11/2009	08/12/2009	
31	MOW1	X	X	11/12/2009	25/01/2010	
32	MOW1	X	X	25/01/2010	25/03/2010	X
33	MOW1	X	X	25/03/2010	20/05/2010	X
34	MOW1	X	X	20/05/2010	31/05/2010	X
35	MOW1	X	X	31/05/2010	23/07/2010	X
36	Blighbank	X	X	05/05/2010	01/06/2010	X
37	MOW1	X	X	06/09/2010	18/10/2010	X
38	MOW1	X	X	18/10/2010	17/11/2010	X
39	MOW1	X	X	17/11/2010	15/12/2010	X
40	MOW1	X	X	15/12/2010	31/01/2011	X
41	MOW1		X	31/01/2011	21/03/2011	X
42	MOW1		X	21/03/2011	24/03/2011	X
43	MOW1		X	24/03/2011	29/04/2011	X
44	MOW1	X	X	29/04/2011	23/05/2011	X
45	MOW1	X	X	23/05/2011	11/07/2011	X
46	MOW1	X	X	11/07/2011	18/08/2011	X

47	MOW1	X	X	18/08/2011	09/09/2011	X
48	MOW1	X	X	09/09/2011	12/10/2011	X
49	MOW1	X	X	12/10/2011	24/11/2011	X
50	MOW1	X	X	24/11/2011	19/01/2012	X
51	MOW1	X	X	24/02/2012	19/03/2012	X
52	MOW1	X	X	19/03/2012	25/04/2012	X
55	MOW1	X	X	29/06/2012	23/08/2012	X
58	MOW1		X	05/12/2012	24/01/2013	X
59	MOW1	X		24/01/2013	07/03/2013	X
60	MOW1	X	X	07/03/2013	28/03/2013	X
61	WZ Boei	X	X	28/03/2013	23/04/2013	X
62	MOW1	X	X	28/03/2013	22/04/2013	X
63	MOW1	X	X	22/04/2013	17/05/2013	X
64	WZ Boei	X	X	25/04/2013	16/05/2013	X
65	MOW1	X	X	17/05/2013	27/06/2013	X
66	WZ Boei	X		10/03/2013	27/03/2013	X
67	MOW1	X	X	27/06/2013	30/07/2013	X
68	WZ Boei	X		28/06/2013	30/07/2013	X
69	MOW1	X	X	24/07/2013	21/08/2013	X
70	WZ Boei	X	X	29/07/2013	21/08/2013	X
71	MOW1	X	X	21/08/2013	27/09/2013	X
72	WZ Boei		X	23/08/2013	09/09/2013	X
73	MOW1	X	X	23/09/2013	16/10/2013	X
74	WZ Boei	X	X	11/09/2013	14/10/2013	X
75	MOW1	X	X	16/10/2013	28/11/2013	X
77	WZ Boei	X	X	13/11/2013	27/11/2013	X
78	MOW1	X	X	28/11/2013	09/12/2013	X
79	WZ Boei		X	27/11/2013	10/12/2013	

2.3. *Measurements of the bottom shear stress*

For the measurement of the bottom shear stress, different methods are available, using either the current profile above the bottom, or using high frequency measurements of the currents. Giardino and Monbaliu (2006) describe four methods, with are the "mean flow method", the "turbulent kinetic energy method", the "inertial dissipation method" and the "eddy correlation method". The first three methods are used in this report.

The mean flow method uses the fact that close to the bottom, the current profile is supposed to be logarithmic and can be written as:

$$u = \frac{u_*}{\kappa} ln \frac{z}{z_0} \tag{1}$$

with	u	horizontal velocity at height z above the bottom
	κ	von Kármán constant = 0.4
	u_*	shear velocity, with $\tau = \rho u_*^2$
	τ	bottom shear stress
	ρ	water density
	z_0	bottom roughness length

By fitting the measured current profile to the logarithmic function, the bottom shear stress (and the bottom roughness) can be calculated.

The turbulent kinetic energy method assumes that the bottom shear stress is linear related to the turbulent kinetic energy, which is calculated from the variance of the high frequency three-dimensional current fluctuations (Andersen et al., 2007; Verney et al., 2007).

The inertial dissipation method finally, uses the spectrum of the current components. In this method, the shear velocity is related to the energy dissipation velocity, which is calculated from the spectrum of the three-dimensional currents in the region where the spectrum decreases with the wave number with the characteristic -5/3 power. Remark that Sherwood et al., 2006 and Trowbridge and Elgar, 2001 adapted the method to take into account the effect of the advection of the waves. More information this last method can be found in Francken en Van den Eynde (2010).

3. Calculation of the bottom shear stress

3.1. *Introduction*

The calculation of the bottom shear stress is the topic of much research. The bottom shear stresses under the influence of currents alone and under the influence of waves alone over a flat bed are quite well known. However, the calculation of the bottom stress under the combined influence of currents and waves, over a rippled sea bed is complex. First of all the calculation of the bottom shear stress under the influence of currents and waves is not the simple vectorial addition of the bottom stress vectors for the currents and the waves alone. Non-linear interactions increase the bottom shear stress.

Furthermore, the bottom roughness length, which is an important factor for the calculation of the bottom shear stress, is influenced by different factors. At the bottom itself, the roughness is a function of the grain size. This bottom shear stress, felt by the sediments is called the skin friction. However, at a distance more than a tenth of the length of the bottom ripples, the bottom roughness is also influenced by the bed load and by the height and the length of the bottom ripples. Further away from the bottom, a new logarithmic profile is followed with an apparently increased bottom roughness. The ratio between the skin bottom roughness and the total bottom roughness varies between 1.5 and 20.

At the OD Nature, two different sediment transport models are at the moment available. The mu-STM model calculates the advection and diffusion of suspended particulate matter. The model was developed to simulate the dispersion of dredged material, but can also be used to calculate the sediment balance for the Belgian Continental Shelf. The mu-SEDIM model calculates the transport of sand, using a total load formula. Erosion and deposition is calculated using the divergence of the local sediment transport.

In both models, the calculation of the bottom shear stress is of great importance. In the mu-SEDIM model, the bottom roughness is calculated in the model, taking in account the grain size, the calculated bottom load and ripple roughness. In the mu-STM model, only the total bottom roughness is taken into account.

3.2. *Calculation of currents and waves*

Both sediment transport models use the currents, calculated by a two-dimensional hydrodynamic model mu-BCZ, or the three-dimensional model OPTOS-BCZ. In the first case, the depth-averaged current has to be used. When using a three-dimensional model, also the current in the lowest layer of the water column can be used to calculate the bottom shear stress.

The waves are calculated with the mu-WAVE model, based on the second generation model HYPAS model, or with the third generation WAM model. These models give the significant wave height, the mean wave period and the wave direction.

3.3. *Calculation of the bottom shear stress*

3.3.1. Bottom stress under the influence of currents

The bottom stress under the influence of currents can be written as:

$$\tau_c = \rho C_D \bar{u}^2 = \rho \left(\frac{\kappa}{ln \frac{h}{e z_0}} \right)^2 \bar{u}^2 = \rho u_*^2 \tag{2}$$

with	τ_c	bottom shear stress under the influence of currents
	C_D	drag coefficient
	$\bar{u}$	depth averaged current
	h	water depth
	e	2.7182

As stated above, for the bottom roughness length, a difference has to be made between the skin bottom roughness, felt by the grains itself at the bottom, and the total bottom roughness that is felt by the currents and that is also influenced by the bottom load and by the bottom ripples, see further.

When a three-dimensional model is used, one can also use the current in the lowest layer of the water column. Assuming a logarithmic profile of the currents over the (lower part) of the water column, the bottom shear stress can be calculated as:

$$\tau_c = \rho \left(\frac{\kappa}{\ln \frac{h_1}{z_0}} \right)^2 u_1^2 \tag{3}$$

with	u_1	current in the lowest layer of the water column
	h_1	height above the bottom where u_1 is calculated

3.3.2. Bottom shear stress under the influence of waves

The bottom shear stress under the influence of waves is calculated using the (maximum) orbital velocity at the bottom. Using linear wave theory, the maximal orbital velocity of a monochromatic wave can be calculated as:

$$u_w = \frac{\pi h_s}{T \sinh(kh)} \tag{4}$$

with	h_s	significant wave height
	T	wave period
	k	wave number

When calculating the wave orbital velocity of a wave spectrum, most of the time the significant wave height and the mean water period are taken as characteristics, although some other recommendations can be found in literature. The wave orbital excursion A can be calculated as:

$$A = \frac{u_w T}{2\pi} \tag{5}$$

The (maximum) bottom shear stress under the influence of waves is then calculated as:

$$\tau_w = \frac{1}{2}\rho f_w u_w^{\ 2} \tag{6}$$

with τ_w bottom shear stress under the influence of waves
f_w wave factor

Also for the wave factor, different theories or models are available, however, with relative small differences.

3.3.3. Bottom shear currents under influence of currents and waves

For the calculation of the bottom shear stress under the influence of currents and waves, many different models can be found in literature, varying from simple model to very complex iterative models, resolving the stresses in the wave boundary layer and during a complete wave cycle. These very complex models are however very time consuming and not really useful to be used in the current sediment transport models. In Van den Eynde en Ozer (2003), different simple models were compared with each other and with the results of more complex model, as they were presented in Dyer and Soulsby (1988). The Bijker (1966) model was selected as a good model, giving realistic model results. The model however doesn't give realistic results for the bottom shear stress under the influence of waves with very small currents, see further. Additionally, no formulation was given for the mean bottom shear stress over a wave cycle, taking into account the increase in mean bottom shear stress under the influence of currents, when waves are available.

Furthermore, recently, more realistic and simple models for the combined bottom shear stress were proposed in literature. Therefore, three new formulations were implemented and tested.

First of all the Soulsby (1995) formulae was implemented which was the results of a two-coefficient optimisation of a simple model to 131 data points, from more complex theoretical models.

More recent, Soulsby and Clarke (2005) developed a new model, assuming an eddy viscosity varying over the water column, but constant in time. The eddy viscosity varies linearly above the bottom in the thin wave boundary layer and has a parabolic function outside the wave boundary layer. Remark that the eddy viscosity is much higher in the thin wave boundary layer than outside. Furthermore the eddy viscosity in the wave boundary layer is only a function of waves and currents, so that no iterative calculations are needed.

In the wave boundary layer, the shear stress is constant, outside the wave boundary layer, the shear stress varies linearly, to zero at the water surface. A current profile can be calculated, integration of the current profile over the water depth gives the depth-averaged current, giving a quadratic equation that can be used to solve the bottom shear stress. The model of Soulsby and Clarke (2005) gives both a formulation for the maximal bottom shear stress during a wave cycle, and the mean bottom shear stress, averaged over a wave cycle. Furthermore, the theory was developed, both for flow over rough and over smooth bottom.

Finally, Malarkey and Davies (2012) developed the theory of Soulsby and Clarke further to include additional non-linearity in the model, which is present in the more complex theoretical models, but is not found in the Soulsby-Clarke model.

A comparison of the non-linearity in the four models is presented for z_0/h=0.0001 and A/z_0=10000 in Figure 5. These are the same values as the figure presented in Soulsby (1997).

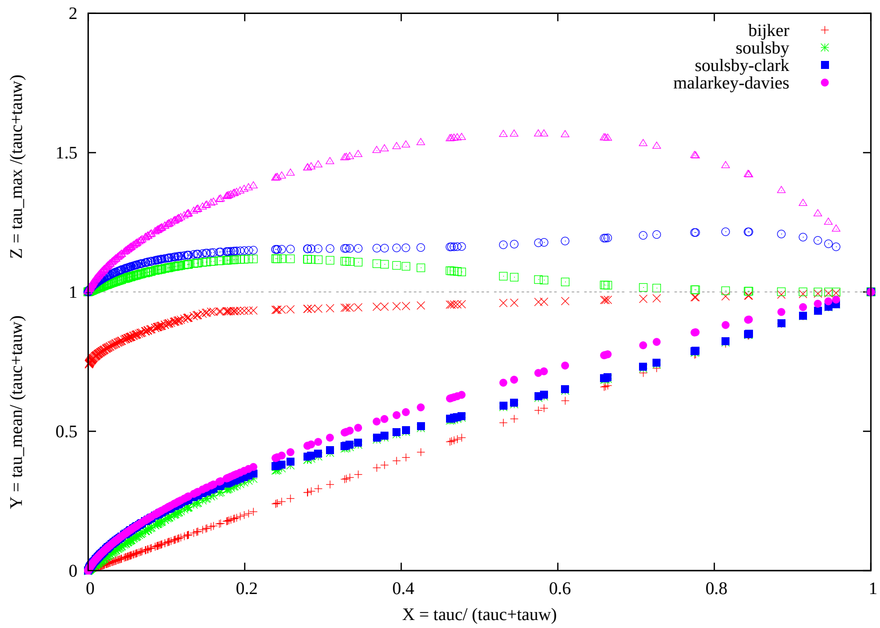

Figure 5: Intercomparison of the four models for the prediction of the mean (tau_mean) and maximum (tau_max) bed shear stresses due to waves plus currents as a function of the non-dimensional currents and the waves. Results for z_0/h=0.0001; A/z_0=10000.

One can clearly observe that, at least for these parameters, the Malarkey-Davies formula includes the most non-linearity in the calculated bottom shear stress. For the Bijker formula, the maximum combined bottom shear stress for currents and low waves is clearly below the value that is obtained for bottom shear stress under waves alone.

A comparison between the results of the mean and the maximum bottom stresses as predicted by the four models for $\bar{u}$ = 1 m/s in a water depth of 10 m and with a (constant) bottom roughness of 0.053 m for varying wave orbital velocities, is given in Figure 6 and Figure 7. The differences between the models seem not very large, except for the fact that the current implementation of the Bijker formulae has no modelling of the mean bottom stress. It is assumed that the mean bottom stress of the waves, averaged over a wave cycle is zero, so that the mean bottom stress is equal to the bottom stress under the influence of the currents alone.

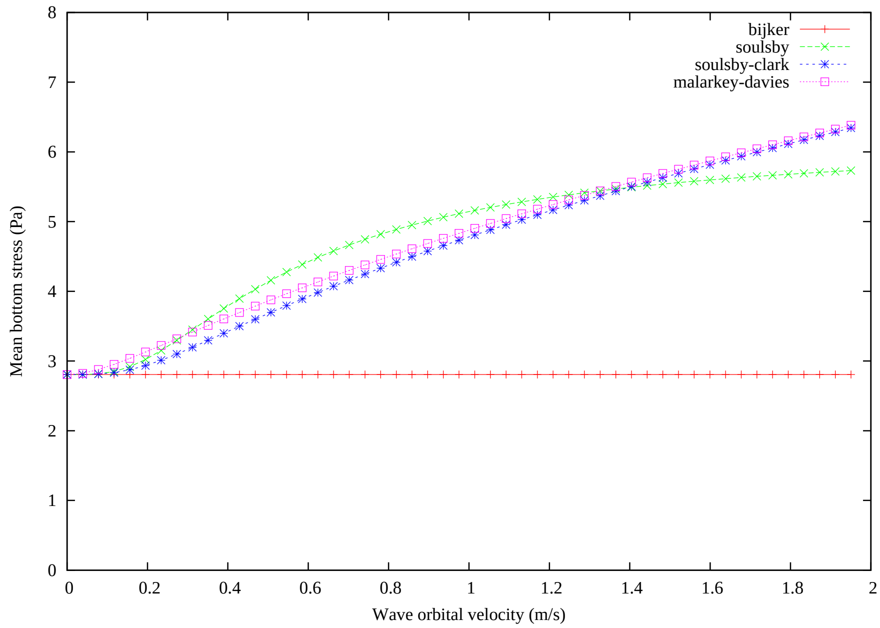

Figure 6: Intercomparison of the four models for the prediction of the mean bed shear stresses due to waves plus currents as a function of the wave orbital velocity for depth-averaged current of 1 m/s, water depth of 10 m and bottom roughness length of 0.053 m.

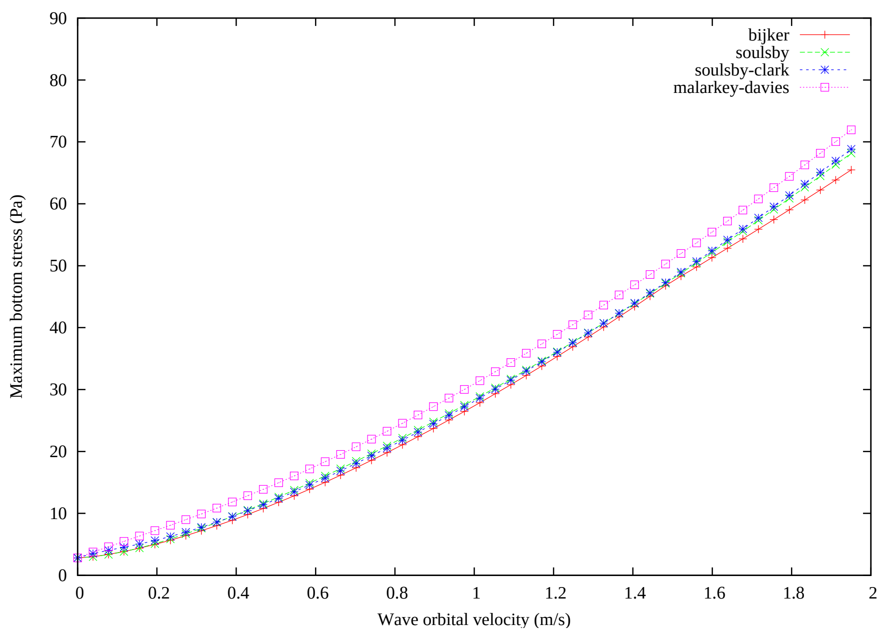

Figure 7: Intercomparison of the four models for the prediction of the maximum bed shear stresses due to waves plus currents as a function of the wave orbital velocity for depth-averaged current of 1 m/s, water depth of 10 m and bottom roughness length =f 0.053 m.

In Figure 8 and Figure 9 the mean and maximum bottom stresses are given as a function of the depth-averaged current for a wave orbital velocity of 0.78 m/s, i.e. for a significant wave height of 2 m, and wave period of 8 s. The Bijker formulae gives obviously smaller bottom stresses than the three other models. In Figure 9, it can be seen that for low currents, the maximum bottom shear stress in the (implemented) Bijker formula is lower than the bottom shear stress under waves alone, which is of course not realistic. The fact that the maximum bottom shear stress, calculated by the Soulsby-Clarke model is much lower for the case, where the depth-averaged currents is zero, is caused by the fact that this model takes into account the flow regime, and calculates the bottom stress is a different way for laminar flow, turbulent flow with a smooth bottom and turbulent flow with a rough bottom. While in realistic cases, the flow is almost always turbulent with a rough bottom, in this case (for depth-averaged current zero) a laminar flow is modelled, with a much lower bottom stress as a result. Remark that for laminar flow and for turbulent flow with a smooth bottom, the bottom roughness is not accounted for.

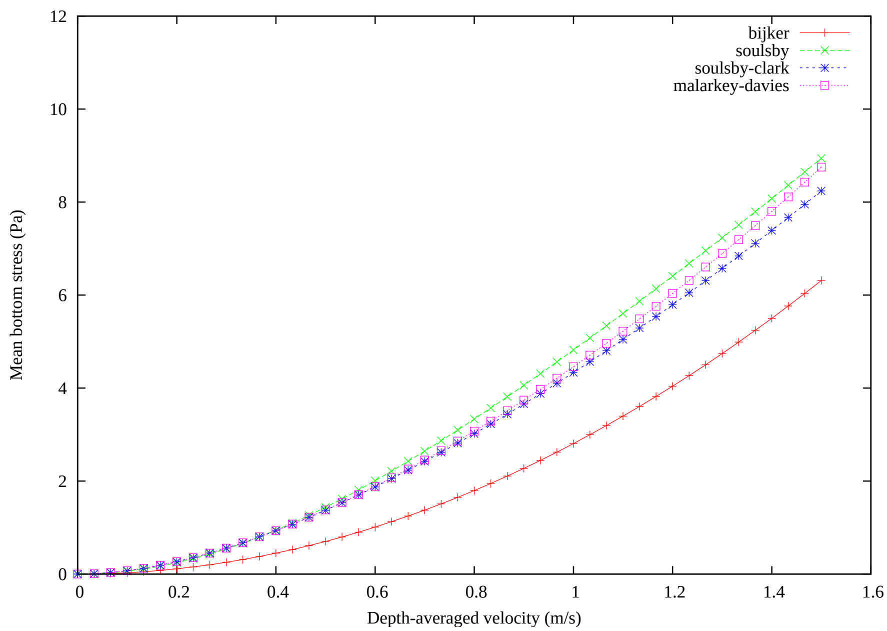

Figure 8: Intercomparison of the four models for the prediction of the mean bed shear stresses due to waves plus currents as a function of the depth-averaged currents for a wave orbital velocity of 0.78 m/s (hs=2 m, T=8 s), water depth of 10 m and bottom roughness length of 0.053 m.

3.3.4. Calculation of the bottom roughness

As indicated above, the bottom stress under the influence of currents and waves is a function of the bottom roughness length z_0 (for turbulent flow with a rough bottom). A division has to be made between the bottom roughness length at the bottom itself, the skin bottom roughness, caused by the bottom material itself, and the total roughness, felt by the currents and the waves, which are also influenced by the bottom load and the bottom ripples. The skin and the total bottom roughness can be specified by the user itself, or can be calculated by the model. The bottom roughness length, the height above the bottom where the logarithmic current profiles becomes zero, is normally written as a function of the Nikuradse bottom roughness k_s, of the viscosity of the water ν and the friction velocity:

$$z_0 = \frac{k_s}{30} + \frac{\nu}{9u_*} \qquad (7)$$

For hydrodynamically rough flows (as is the case in the current flows), the second part of the bottom roughness length can be neglected.

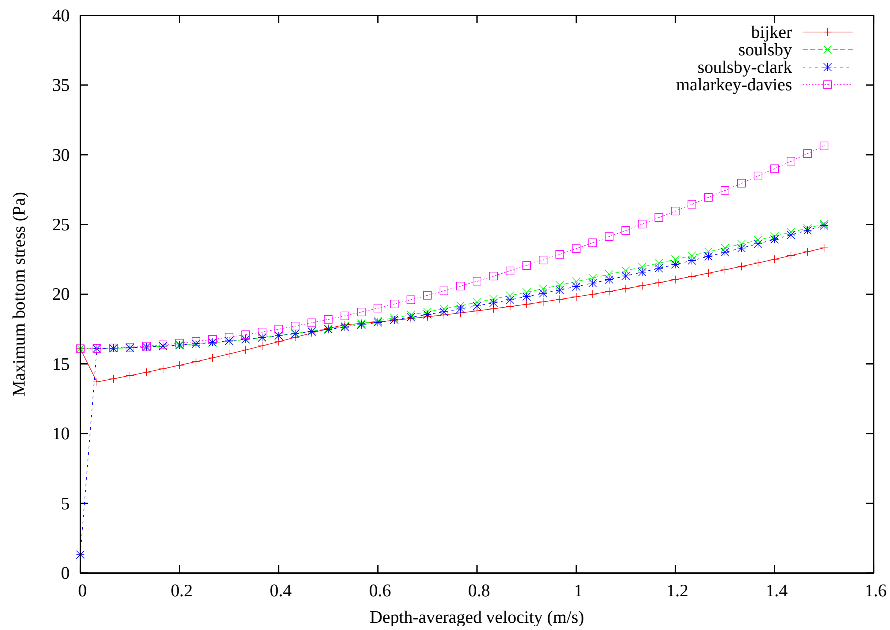

Figure 9: Intercomparison of the four models for the prediction of the maximum bed shear stresses due to waves plus currents as a function of the depth-averaged currents for a wave orbital velocity of 0.78 m/s (hs=2 m, T=8 s), water depth of 10 m and bottom roughness length of 0.053 m.

The skin bottom roughness is most of the time written as a function of the grain size distribution. A much used formulation is:

$$k_{ss} = 2.5d_{50} \qquad (8)$$

with d_{50} the grain size for which 50 % is smaller.

Values for the total bottom roughness can be found in tables. Typical values, found in literature, are k_s=0.2 mm for a mud bottom or k_s=6 mm for a rippled sand bottom. They can however be calculated in the model itself.

For the roughness as a function of the bottom load, a division is made between current-domination and wave-domination. For current-domination, the formula, proposed by Wilsen (in Soulsby, 1997) is used. For wave-domination, depending on a flag, five different possibilities are presented, which are: 1) the Grant and Madsen (1982) model; 2) the Soulsby model; 3) the Grant and Madsen (1982), assuming wave-domination (K=1); 4) the Nielsen model and 5) the Raudkivi formulation (all in Soulsby, 1997). For the exact formulations, the reader is referred to Soulsby (1997). Due to the fact that bottom roughness, due to bed load, is a function of the skin bottom friction, the model used to calculate the skin bottom friction influences the calculated bottom roughness. In Figure 10, the bottom roughness length is presented for the Grant-Madsen model and for the different models for the bottom stress. On can see that the bottom roughness length is much smaller for the current-dominated case than for the wave-dominated case (for wave orbital velocities larger than 0.6 m/s). For the wave-dominated case that bottom roughness length can be several orders of magnitude larger than the skin bottom roughness length, which values up to 0.2 m. Furthermore the influence of the bottom stress model is apparent. The fact that the Bijker model gives much lower bottom roughness lengths is due to the fact that the Bijker model gives lower skin bottom stresses than the other models.

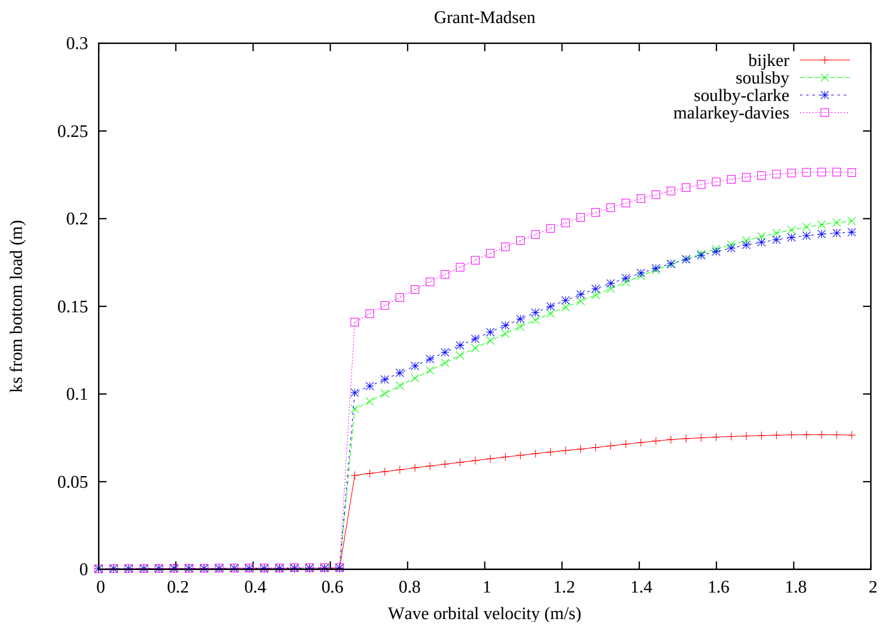

Figure 10: Intercomparison of the bottom roughness length, due to bed load, for the Grant-Madsen formulation (1), when wave-dominated, and for the four different bottom stress models.

In Figure 11, the bottom roughness length for the different formulations available are presented when the Malarkey-Davies formulation is used for the calculation of the bottom shear stress The Raudkivi formulation gives unrealistic values for larger waves, and is therefore not recommended. The Grant-Madsen model overall gives the largest values, while the Nielsen formulation gives the lowest values for the bottom roughness length, due to bed load.

Finally, the bottom roughness length is a function of the bottom ripples. Normally the bottom roughness, due to bottom ripples is written as:

$$k_{sv} = 27.7\frac{\eta^2}{\lambda} \qquad (9)$$

with η the ripple height
λ the ripple length

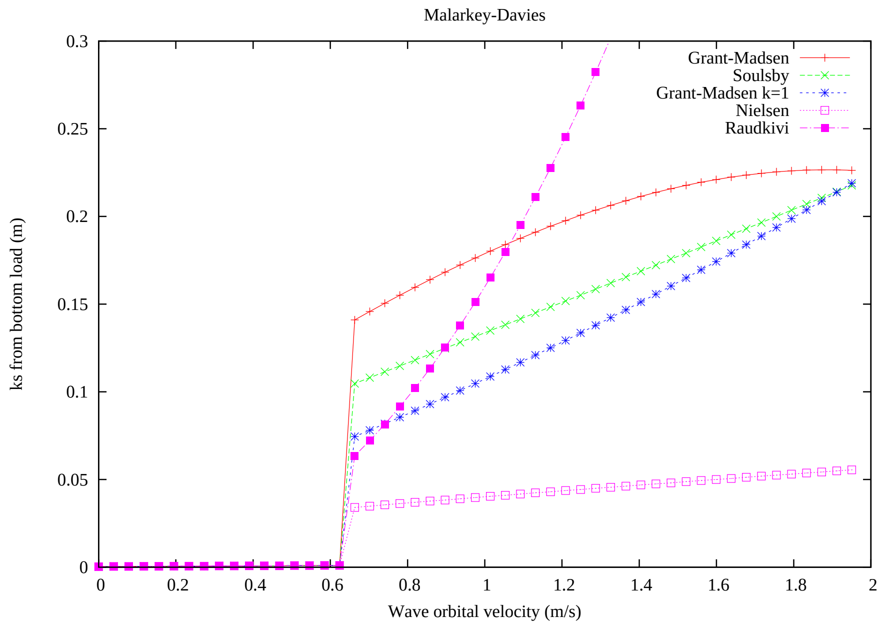

Figure 11: Intercomparison of the bottom roughness length, due to bed load, for the different formulations and for the bottom stress model of Malarkey-Davies.

The ripple geometry itself can be calculated by the model again. Also here, a distinction is made between current-dominated ripples and wave-dominated ripples.

Two models to calculate the ripple geometry were implemented. The first model uses the ripple geometry, proposed by Soulsby (1997) for the current-dominated ripples and the ripple geometry, proposed by Grant and Madsen (1982) for the wave-dominated ripples. More recently, a new ripple predictor was proposed by Soulsby and Whitehouse (2005). The model was validated against many laboratory and field experiment results and has the advantage that the time evolution of the ripples can be accounted for. Furthermore for the current-dominated ripples, sheet flow and ripples that are washed out for larger currents are taken into account. Some results of the bottom roughness length for the two models are given in Figure 12 and Figure 13.

From Figure 12, it is clear that in the Soulsby-Grant&Madsen model, the bottom roughness length in the wave-dominated case is a function of the (calculation of the) bottom shear stress. Furthermore, it is shown that for lower currents and waves and using the Bijker formulation for the calculation of the bottom shear stress, unrealistic values can be obtained. Furthermore, it is shown that the bottom roughness length, due to bed ripples, is larger for current-dominated ripples than for wave-dominated ripples. For larger waves, the bottom roughness length decreases. Figure 13 shows the bottom roughness length for the both models. Both models have a comparable behaviour, but can differ with a factor of 2. Remark that for depth-averaged current of 1.0 m/s, the Soulsby-Whitehouse model assumes that all ripples are washed out.

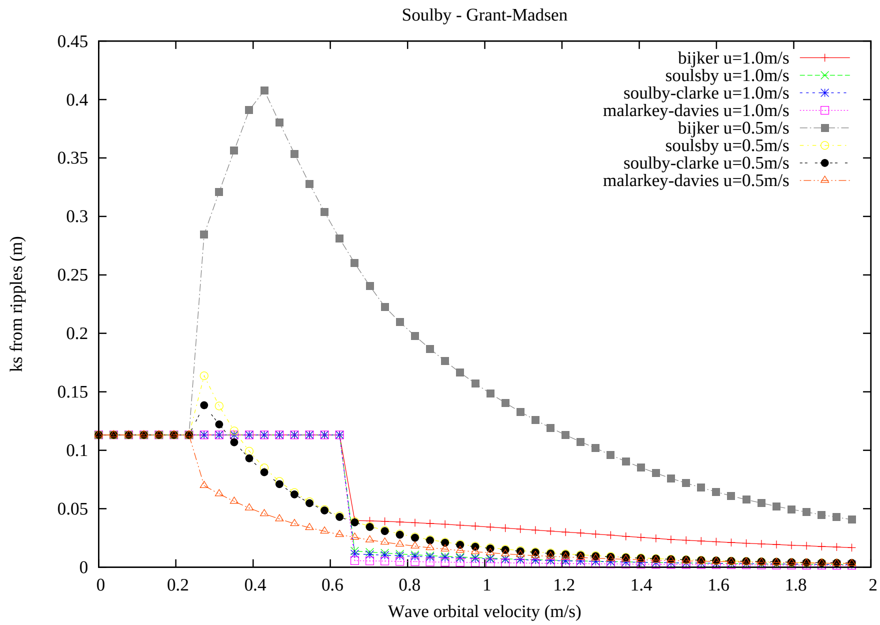

Figure 12: Intercomparison of the bottom roughness length, due to bed ripples, for the Soulsby-Grant& Madsen model and for different bottom stress models, for depth-averaged currents of 1 m/s and 0.5 m/s as a function of the wave orbital velocity. (T2/para05)

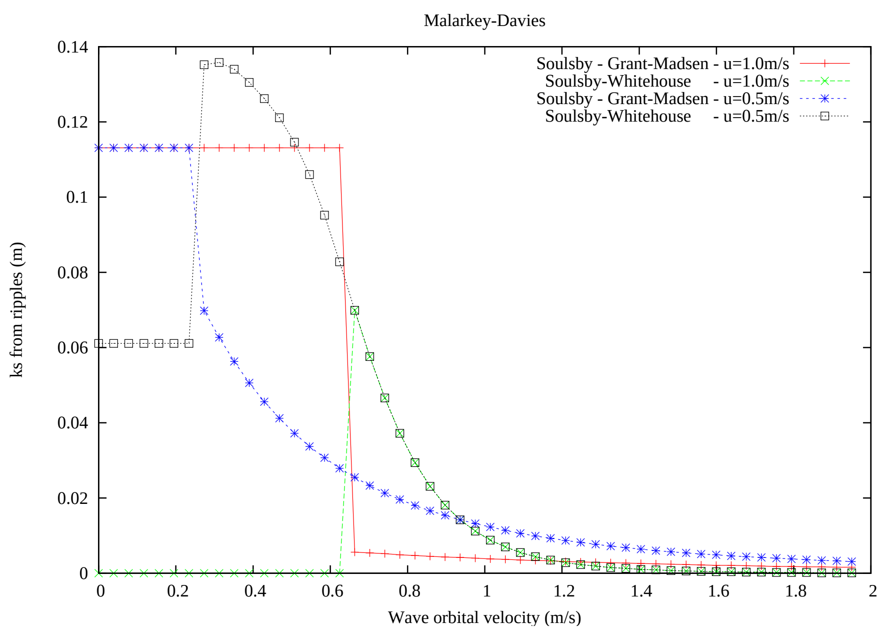

Figure 13: Intercomparison of the bottom roughness length, due to bed ripples, for the Soulsby-Grant&Madsen model (using the Malarkey-Davies model for the calculation of the bottom stress) and for the Soulsby-Whitehouse model, for depth-averaged currents of 1 m/s and 0.5 m/s as a function of the wave orbital velocity.

4. Analysis of the bottom stress measurements

4.1. *Bottom stress from current profile*

As explained in section 2.3, the bottom shear stress can be measured using different methods, including using the current profile, which is assumed to be logarithmic in the lower part of the water column. However, it is important to realise that the measured profile does not always shows a logarithmic profile. This is illustrated in Figure 14, where, as an example, the measured profiles for the first 8 minutes of the measuring campaign 025 on the Gootebank are shown, together with the logarithmic regressions. One can clearly see that sometimes the profile is not logarithmic at all (see profiles 1 (left, row 1), 6 (right, row 3) or 7 (left, row 4). The changes around 1 m above the bottom could be due to the influence of the tripod frame and the instruments itself, more especially of the acoustic transponder (yellow ball – see Figure 2), that was installed on the tripod during the first years of the deployments.

Furthermore, the height above the bottom, where the ADP was mounted varied over time, as well as the number of bins and the bin size. Where in the beginning, the currents were measured at 12 heights above the bottom, later deployments sometimes used 16 bins. The height, where the currents, closest to the bottom was measured, varied over the campaigns between 0.05 m and 0.25 m. Furthermore, sometimes the lowest bin was below the sea bottom, while for other deployments, the lowest bin measured was above the bottom.

When measurements were taken very close to the bottom, the lowest currents could sometimes be less reliable. This is shown in Figure 15, where for deployment 025 at the Gootebank, the U-currents are shown for the 7th bin, at 0.33 m above the bottom, and the 8th bin, at 0.08 m above the bottom. It can be seen that the currents, measured in the 8th bin show much more noise than the current in the 7th bin.

The number of points taking into account to calculate the logarithmic profile can be important and can influence the results quite drastically. This is shown in Figure 14, where 4 different logarithmic profiles are presented, and in Figure 16, where the bottom shear stress averaged over 30 minutes, calculated with 7 points is compared with the averaged bottom stress, calculated with 8 points, including the current measured at 0.08 m above the bottom for the first days of campaign 025. The two time series show the same tidal cycle, but the bottom shear stress, calculated with 8 points, is a factor 2 to 3 lower. It is a priori not clear which is the most realistic result.

4.2. *Comparison between the three measured bottom shear stresses*

In this report, three different techniques are used to measure the bottom shear stress, i.e., 1) the bottom stress, calculated from the current profile, 2) bottom stress, calculated from the turbulent kinetic energy, or 3) bottom stress, calculated using the inertial dissipation method. Unfortunately, the bottom shear stresses, calculated using the different methods, do not correlate with each other very well.

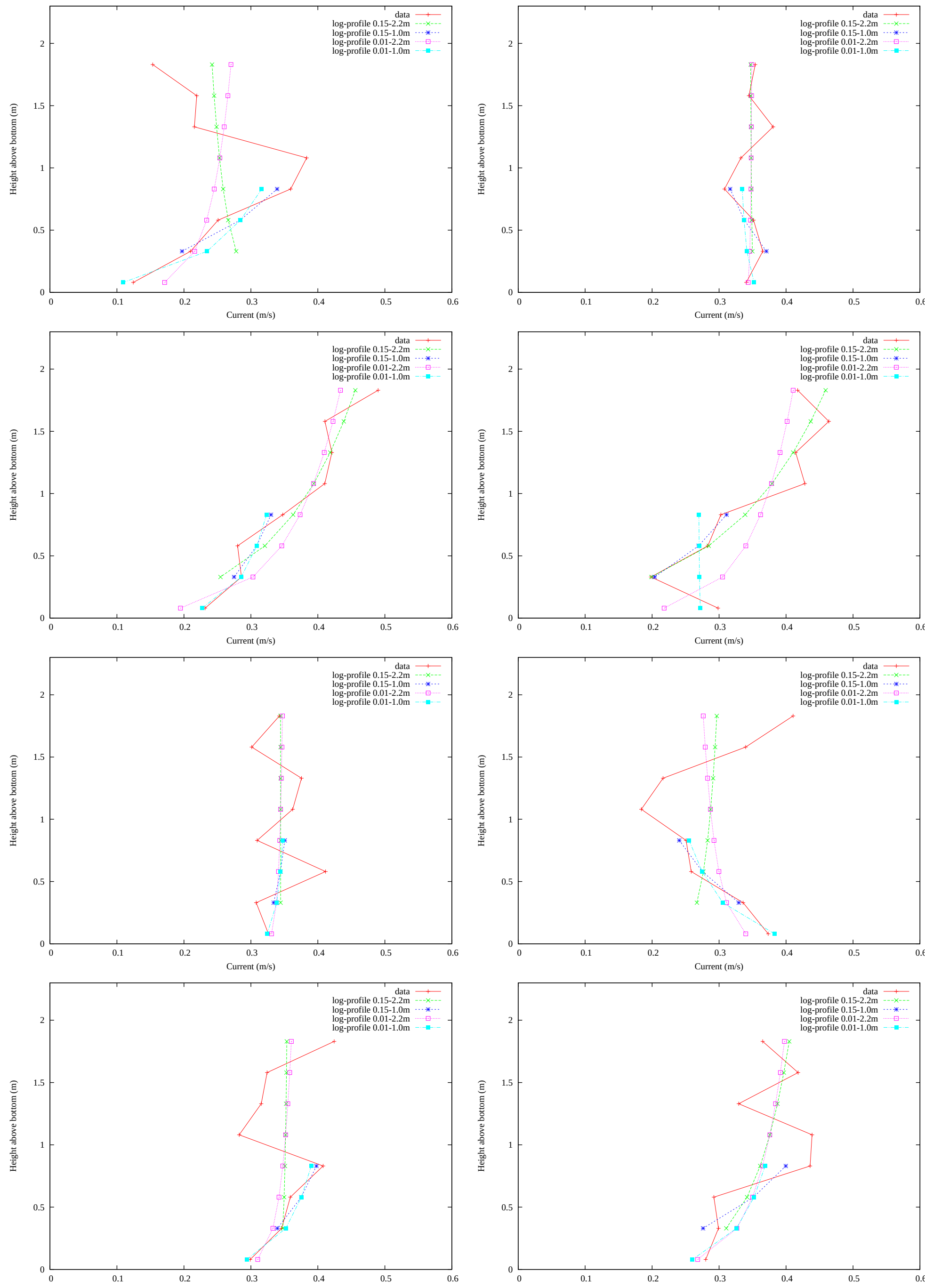

Figure 14: Profiles of currents and logarithmic regression for the currents at the Gootebank from 2009/06/23 18:29:50 till 2009/06/23 18:36:50.

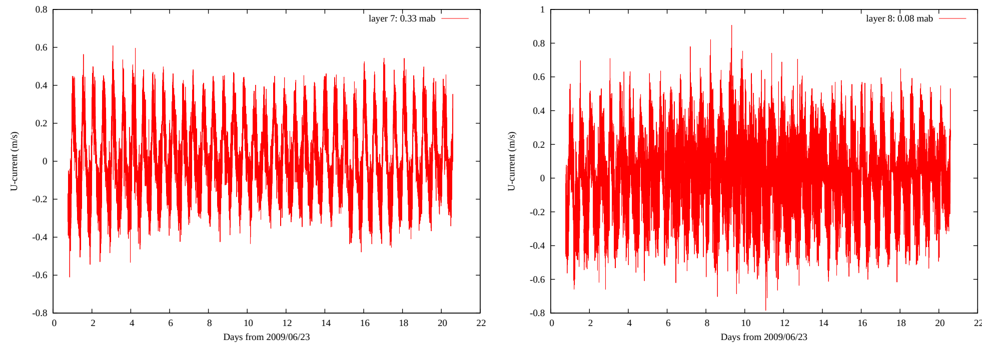

Figure 15: U-currents measured during campaign 25 at the Gootebank, in the layer 7, at 0,33 m above the bottom (left) and the layer 8, at 0.08 m above the bottom (right).

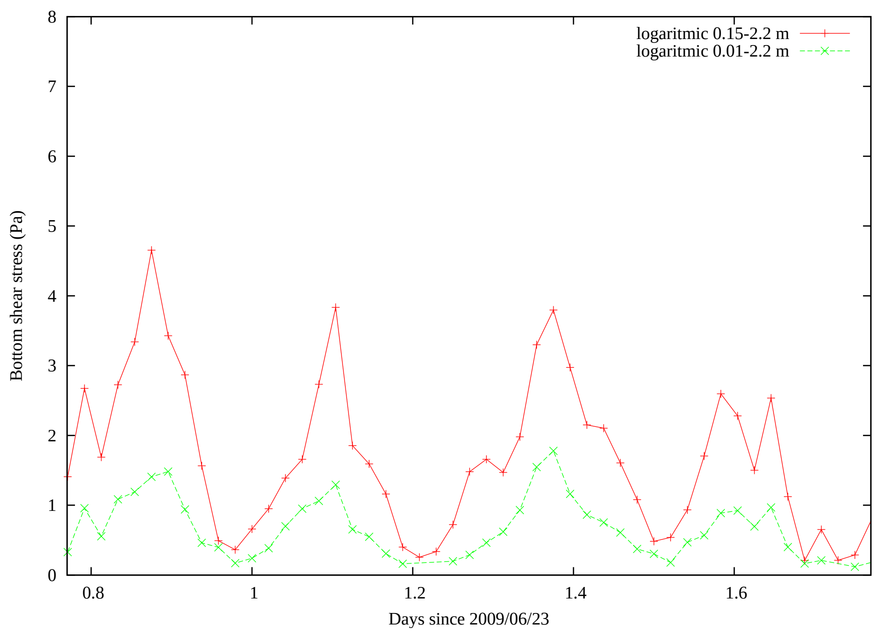

Figure 16: Bottom shear stress (averaged over one half hour) for the first days of campaign 025, calculated with or without the lowest measured point (at 0.08 m above the bottom) taken into account.

First tests showed that the mean correlation (over all deployments) between the bottom stress calculated using the turbulent kinetic energy or the bottom stress using the inertial dissipation method on the one side and the bottom stress, calculated using the current profile on the other side, is the highest when the current measurements between 0.01 m and 2.2 m are used, thus taking all data into account. The mean bias however is the lowest when the data between 0.15 m and 2.2 m are used. Remark however, that the correlation between the different bottom shear stress measurements is very low, while the bias can be considerable. This is illustrated in Figure 17 and Figure 18 where the correlation coefficient and the bias are presented for the different deployments between the measured bottom shear stresses, using the different techniques.

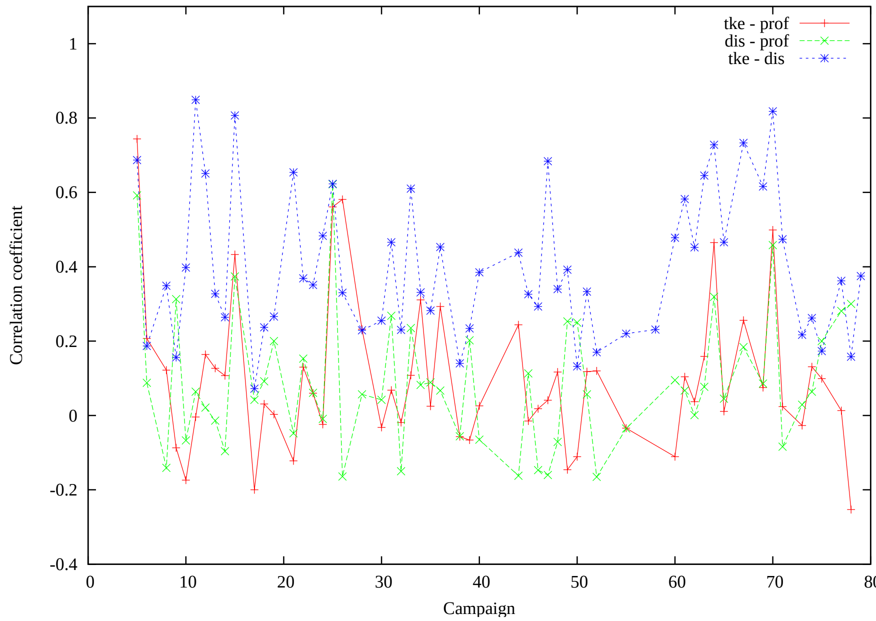

Figure 17: Correlation between the measured bottom shear stresses, using the turbulent kinetic energy method (tke), using the inertial dissipation method (dis) or from the current profile (prof).

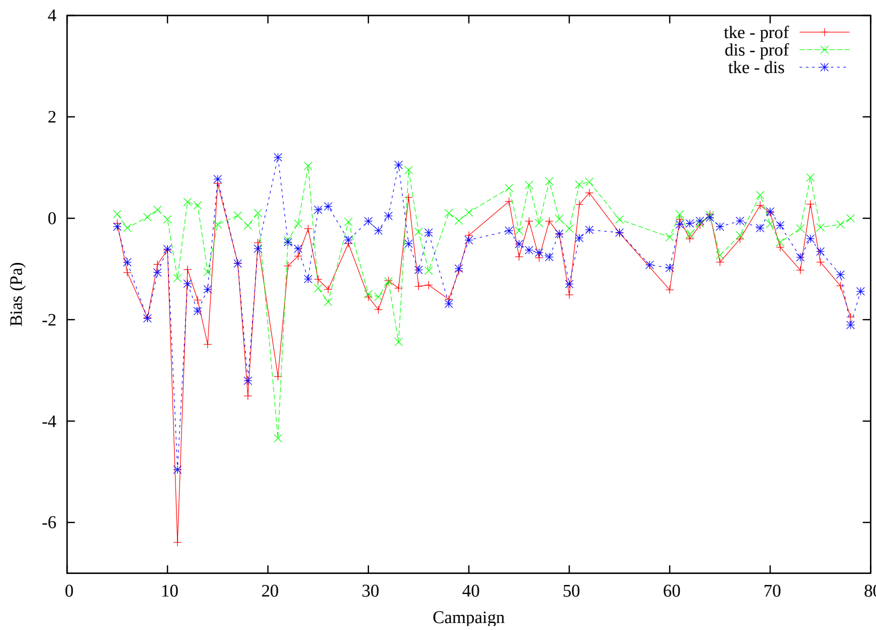

Figure 18: Bias between the measured bottom shear stresses, using the turbulent kinetic energy method (tke), using the inertial dissipation method (dis) or from the current profile (prof).

It is clear that the correlation between the measured bottom shear stress, using the turbulent kinetic energy method and the measured bottom shear stress, using the current profile, is very low and lies around 0.10. Only for the campaigns 5, 15, 25, 26, 64 and 70, the correlation coefficient is higher than 0.40. Also the correlation between the bottom shear stress, calculated using inertial dissipation method and bottom shear stress, calculated using the current profile, is very low.

The correlation between the measured bottom shear stresses, using the turbulent kinetic energy method and the measured bottom shear stress, using inertial dissipation method, is higher. The mean correlation over all campaigns is 0.40. However, the bias between the bottom shear stresses is again rather high, with variations between -2 Pa and +2 Pa. Overall it is clear that the measured bottom stresses, using the different techniques, do not correlate very well with each other. It is therefore not clear which measurement should be used to validate the model results.

4.3. *Mean of the bottom shear stress measurements*

As mentioned in section 2.2, 48 of the deployments have been executed at the station MOW1, near the harbour of Zeebrugge, starting in 2005, until the end of 2013. In this case it is possible to get (longer) time series of the mean of the measured bottom shear stress over the deployments, for the different methods of measurements. This is presented in Figure 19. One can see that before 2010, the mean of the bottom shear stress, measured using the turbulent kinetic energy method or the inertial dissipation method, can vary over a larger range. This is probably due to the fact that the burst of the high frequency (25 Hz) measurements with the Acoustic Doppler Velocimeter (ADV) was probably not long enough to get reliable measurements of the bottom shear stress. Starting from campaign 037, in September 2010, the burst for the measurements was changed from 400 s to 7500 s, with more consistent results from then onwards.

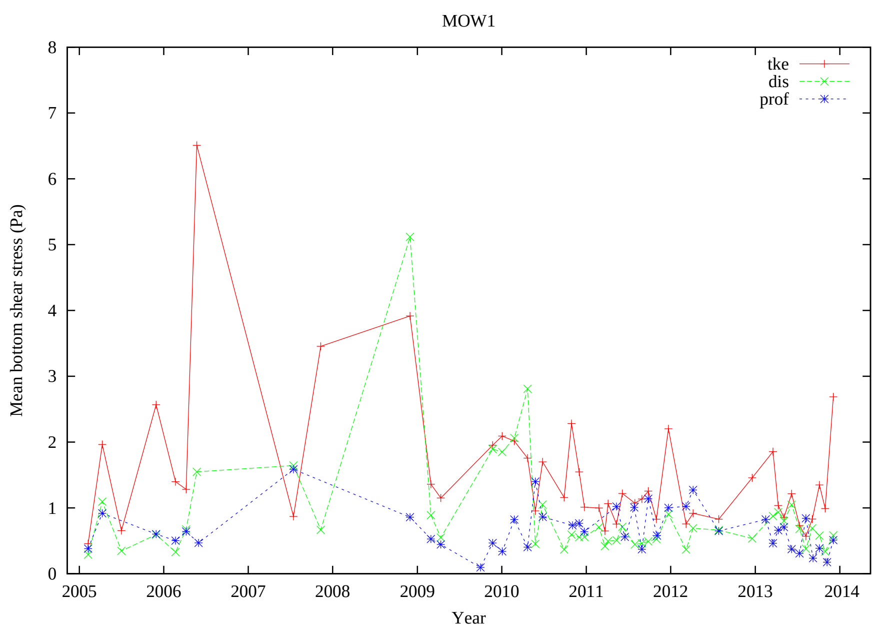

Figure 19: Mean (over deployment) bottom shear stress, measured using the turbulent kinetic energy method (tke), using the inertial dissipation method (dis) or from the current profile (prof) over the years, for the measurements in station MOW1.

Remark that the higher mean bottom shear stress in the measurements, using the turbulent kinetic energy method, is mainly due to the larger influence of the waves on the measured bottom shear stress. This is illustrated in Figure 20 where the mean bottom shear stress is plotted as a function of the mean significant wave height for the deployments from September 2010. It is clear that a good correlation exists between the mean significant wave height and the mean bottom stress, measured using the turbulent kinetic energy method, with a slope of 1.87 Pa/m and a correlation coefficient of 0.831. For the mean bottom stress, measured using the inertial dissipation method, of using the current profile, this relation is not clear. This could be an indication that the bottom shear stress, using the turbulent kinetic energy, could be the most reliable and should be used to validate the model results.

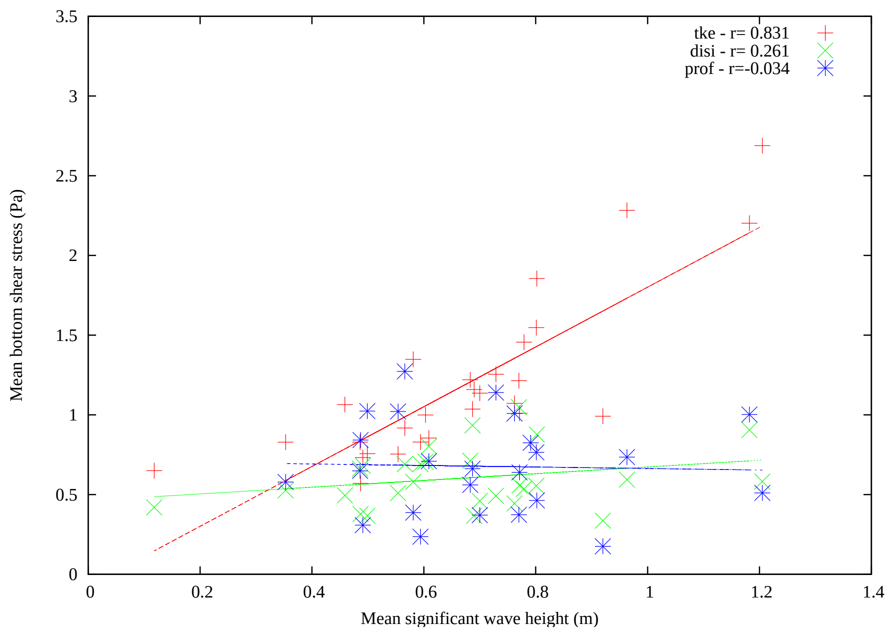

Figure 20: Correlation between the mean (over deployment) significant wave height and the mean (over deployment) bottom shear stress, measured using the turbulent kinetic energy method (tke), using the inertial dissipation method (dis) or from the current profile (prof) over the years, for the measurements in station MOW1.

5. Comparison of model results with measurements

5.1. *Introduction*

In this section the different models results will be compared with the measured bottom shear stresses. It is clear from the previous that, since the different measured bottom shear stresses are not similar, an important uncertainty exists in the "real" bottom stress that should be used to validate the model results. Since the measured bottom shear stress, using the turbulent kinetic energy method, has a clear relation with the mean significant wave height in the shallow waters of the coastal station MOW1, this seems to be the most reliable measurements. Remark that the burst length was increased from 400 s to 7500 s, from September 2010, to increase the reliability of the measurements. Therefore, the emphasis will be on the measurements from campaign 037 onwards.

In the next section, some model results will be discussed in more detail, for two deployments. For the deployment 025, there is a high correlation between the measured bottom shear stresses, using the different techniques. The deployment was executed in deeper offshore waters, at the Gootebank for a period of about 20 days, with low wave activities. The other campaign that will be discussed in more detail is the 078 deployment at MOW1, near the harbour of Zeebrugge, in a water depth of about 10 m. During this campaign of about 11 days, high waves occurred with a significant wave height up to 3 m.

In the last section, a more general discussion of the overall results is presented, investigating which model gives the best results, compared to the measurements. A difference is made between the model results, when a constant total bottom roughness is used, and the model results, where the bottom roughness is calculated by the model itself, based on empirical relations for the bottom roughness as a function of the bed load and of the bottom ripples.

Remark that to evaluate the agreement between the measurements and the model results, the root-mean-square error, the scatter index and the correlation coefficients can be used. These parameters are described in Appendix A. The lower the root-mean-square error or the scatter index, the better the agreement between the measured and the modelled bottom shear stresses. Remark that the scatter index is influenced by the magnitude of the measured bottom shear stresses.

The model simulations will be executed with a model with a constant total bottom roughness length and with the bottom roughness length, calculated in the model, using the different formulations for the bottom roughness length, as a function of the bed load and of the bottom ripples. For the constant total bottom roughness length, the values 0.004 m, 0.007 m, 0.01 m, 0.03 m, 0.07 m, 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, and 0.6 m are used.

5.2. *Selected deployments*

5.2.1. Deployment 025

5.2.1.1. *Currents and waves*

Campaign 025 was selected because for this deployment, the correlation between the measured bottom shear stress, using the turbulent kinetic energy method and the measured bottom shear stress, from the current profile was relatively high, i.e. 0.561. The deployment was executed at the Gootebank, in the offshore waters of about 23 m water depth over the period 23 June 2009 till 13 July 2009. The currents modelled by the OPTOS-model and the waves modelled by the WAM model are presented in Figure 21 and Figure 22, together with some measurements. For the currents the measurements by the ADP were multiplied by a factor 1.5, to obtain the depth averaged currents from the currents at only 1.83 m above the bottom. Remark that this factor 1.5 is relatively high, but the figure indicates that the currents behaviour is well modelled by the model. The correlation coefficient between the model and the measurements are 0.801. For the waves, measurements from the Meetnet Vlaamse Banken were used at the A2-buoy. The correlation between the modelled and measured waves is 0.89, the bias -0.013 m. Remark that the waves remain relatively small over the period, with a maximum of 1.5 m, in a water depth of 23 m. The influence of the waves will therefore be limited.

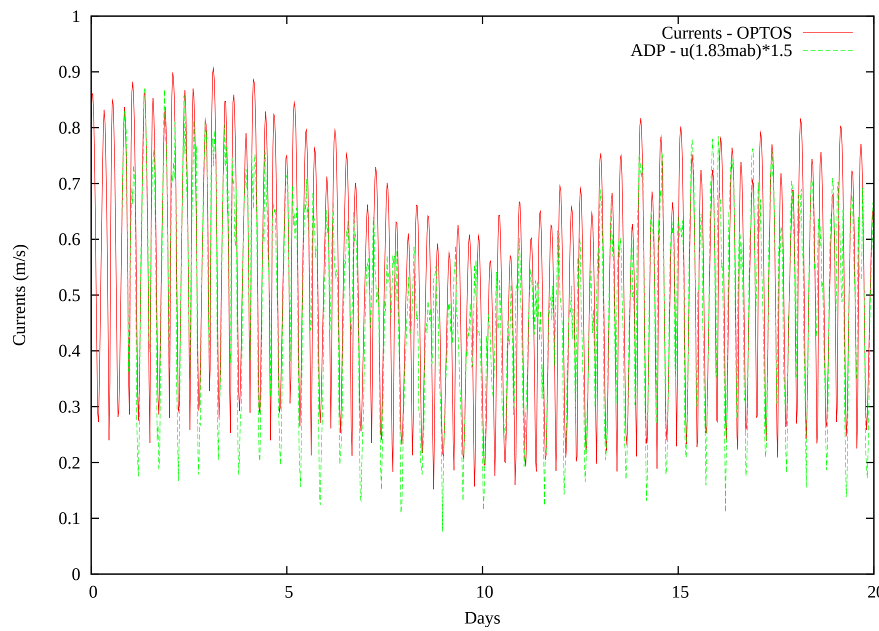

Figure 21: Currents modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009.

5.2.1.2. *Bottom shear stress with constant bottom roughness*

In the case the (total) bottom roughness is constant, good agreement between measured bottom stresses and model results is found for the bottom stress, derived from the current profile between 0.01 and 2.2 m, and the bottom stress, calculated using the Soulsby model with a constant total bottom roughness of 0.004 m. In this case, a bias is found of -0.052 Pa, a correlation coefficient of 0.748. This is shown in Figure 23 and Figure 24 (detail). For the measured bottom stress, using the turbulent kinetic energy method, the best agreement is found using the Soulsby model with a constant bottom roughness of 0.600 m (bias=-0.219 Pa, r=0.696 – see Figure 25). The measured bottom shear stresses are here much higher, resulting in a quite high bottom roughness. Also when the bottom shear stress is derived from the current profile between 0.15 m and

2.2 m (not taking into account the lowest more unreliable measured current value), the bottom shear stresses are much higher (as already mentioned in section 4.1).

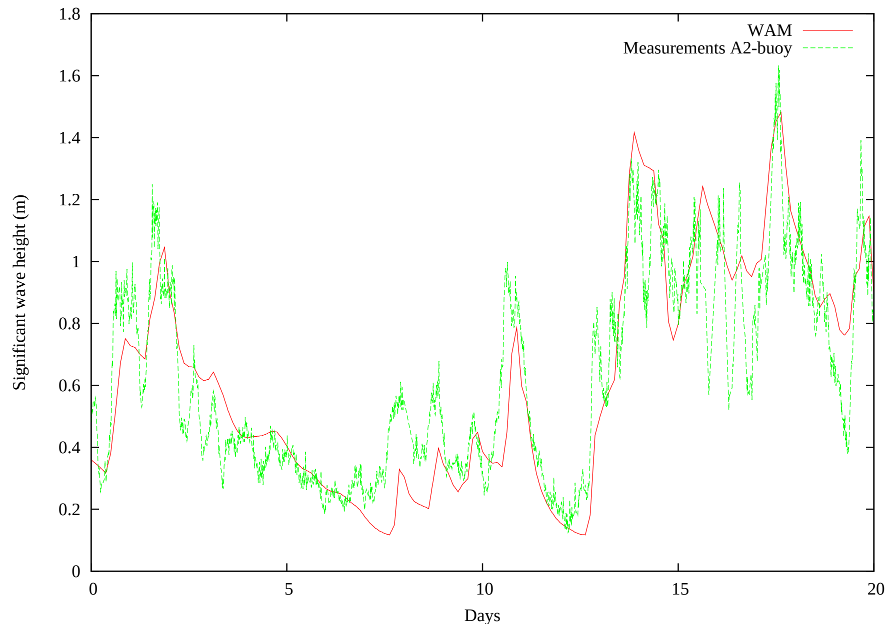

Figure 22: Waves modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009. Measurement at the A2-buoy from Meetnet Vlaamse Banken.

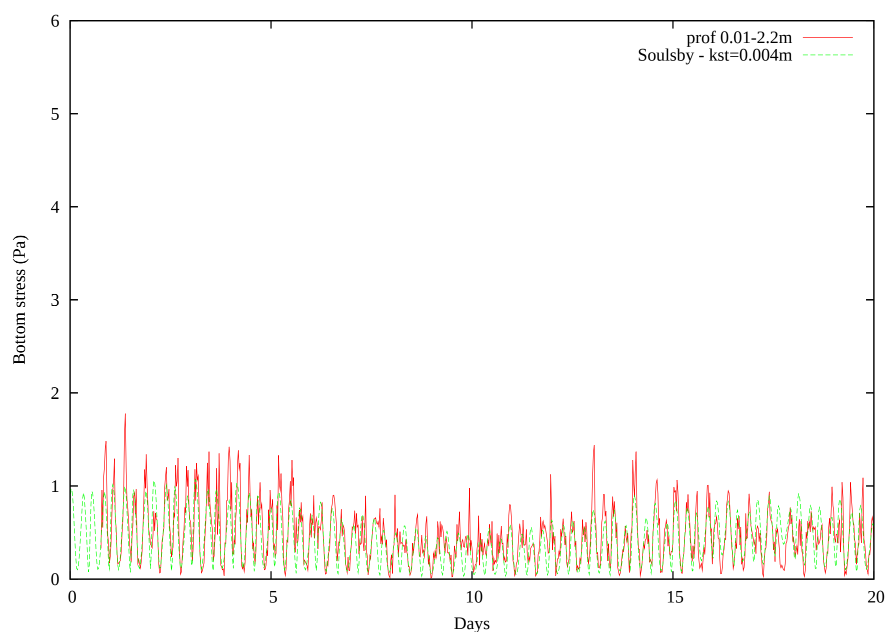

Figure 23: Bottom shear stress, modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: measurements: bottom stress from current profile 0.01-2.2m, model: Soulsby, bottom roughness length = 0.004 m.

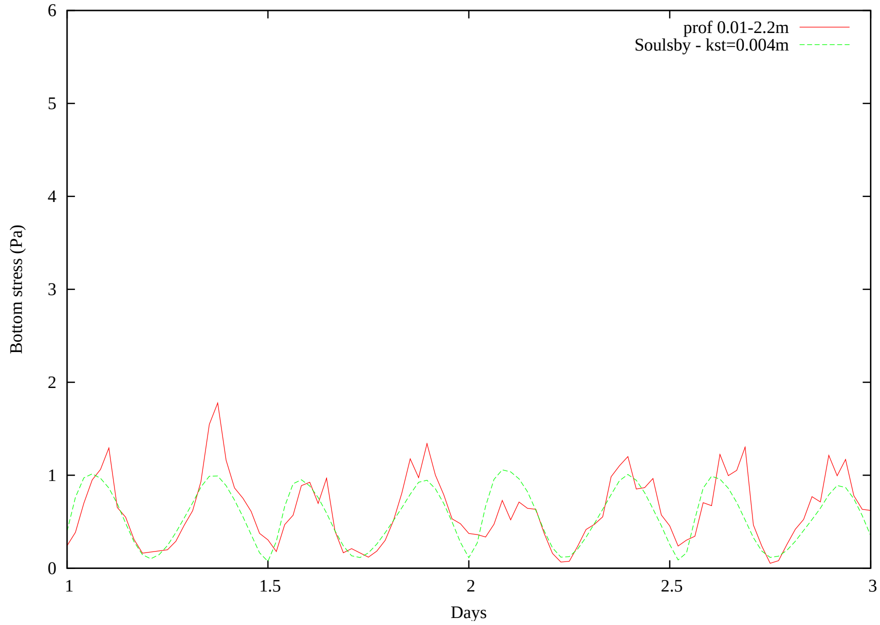

Figure 24: Bottom shear stress, modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: measurements: bottom stress form current profile 0.01-2.2m, model: Soulsby, bottom roughness length = 0.004 m (detail).

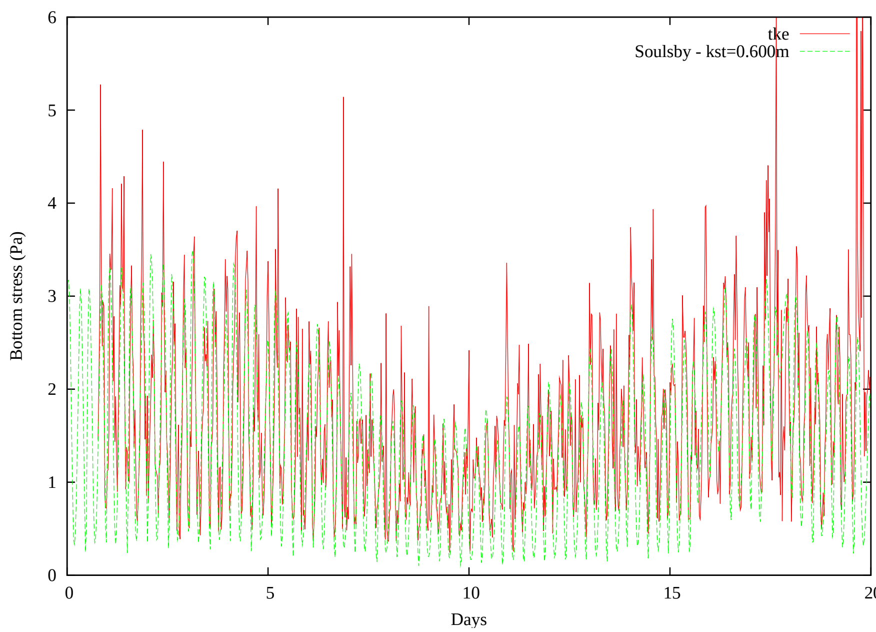

Figure 25: Bottom shear stress, modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: measurements: bottom stress from turbulent kinetic energy, model: Soulsby, bottom roughness length = 0.600 m.

Also for the other bottom stress models, good agreement can be found, when an appropriate constant bottom shear stress is selected. Remark that for the Malarkey model, in general a lower bottom roughness is used. This is probably due to the larger non-linearity included in the model and the resulting higher bottom stresses.

5.2.1.3. *Bottom shear stress with bottom roughness calculated*

As mentioned in section 3.3.4, the bottom roughness can be calculated in the model itself, accounting for skin bottom roughness, bottom roughness from bed load and from bottom ripples. When comparing the result with the bottom roughness, calculated from the current profile between 0.01 and 2.2 m, the modelled results seems to be too high (see Figure 26). The bias is 0.324 Pa, with a correlation coefficient of 0.678. For the bottom stress, calculated from the current profile between 0.15 and 2.2 m and for the bottom stress, using the turbulent kinetic energy model, on the other hand, the modelled bottom shear stresses are too low (not shown).

Remark that the bottom roughness length in this case is mainly driven by the bottom roughness, caused by the bottom ripples. Both the skin bottom roughness as the bottom roughness, caused by the bed load is an order of magnitude lower. When the Soulsby-Grant&Madsen model is used, the bottom roughness length varies around 0.1 m, while for the Soulsby-Whitehouse model, the bottom roughness length varies around 0.06 m (see Figure 27).

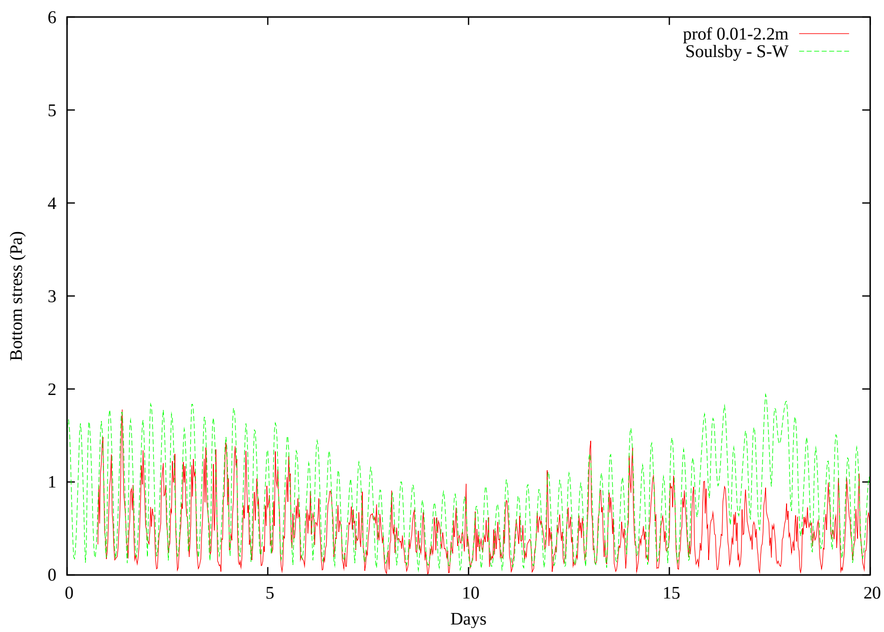

Figure 26: Bottom shear stress, modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: measurements: bottom stress from current profile 0.01-2.2m, model: Soulsby, ripples calculated with Soulsby-Whitehouse model.

It is clear that there results are less good than the results with a constant bottom roughness, but in that case, there was an additional freedom in choosing a good value for the bottom roughness. Therefore, this additional freedom was included in the model as well, by multiplying the calculated total bottom roughness with an independent factor *convkst*. In this case, the total bottom roughness can be scaled, but the roughness can vary over time, dependent on the bed load and the bottom ripples. Simulations were executed with 10 possible scaling factors, varying from 0.0001 to 10. Good results are obtained when comparing the bottom shear stress from the current profile between 0.01 and 2.2 m, with the bottom stress calculated by the Soulsby model, using the Soulsby-Whitehouse ripple model and multiplying the total bottom roughness with 0.1 (see Figure 28). In that case a bias of -0.013 Pa is obtained, a RMSE of 0.209 Pa and a correlation coefficient of 0.743. One must observe that these values are comparable with the results obtained with a constant bottom roughness. Since the bottom roughness doesn't really vary a lot over time (see Figure 27), this could be expected.

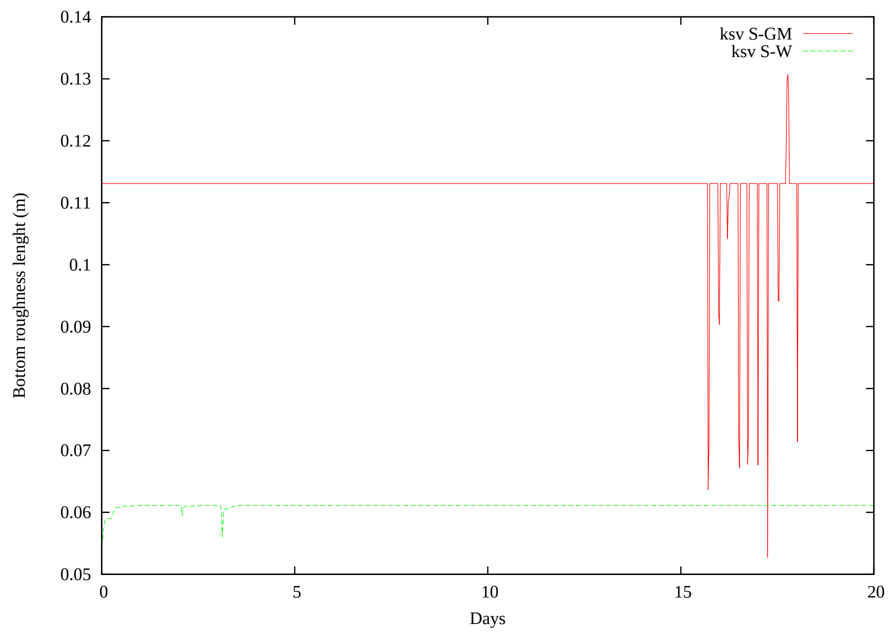

Figure 27: Variation of the bottom roughness length, due to the bottom ripples for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: S-GM: Soulsby-Grant&Madsen model; S-W: Soulsby-Whitehouse model.

5.2.2. Deployment 078

5.2.2.1. Currents and waves

Deployment 078 was a deployment at the station MOW1, were almost 70 % of the deployments have been executed. The station is in a near shore area, near the harbour of Zeebrugge, in a water depth of about 10 m. During the campaign, which was executed from 28 November 2013 till 9 December 2013, high waves occurred with a significant wave height up to 3 m.

The currents modelled by the OPTOS-BCZ model and the waves modelled by the WAM model are presented in Figure 29 and Figure 30 respectively, together with some measurements. For the currents, the measurements by the ADP were multiplied by a factor 1.1, to obtain the depth averaged currents from the currents at only 1.9 m above the bottom. The currents are well modelled by the model, with a correlation coefficient between the model and the measurements of 0.761. For the waves, measurements from the Meetnet Vlaamse Banken were used at the A2-buoy (see Figure 30). The correlation between the modelled and measured waves is 0.972, the bias is 0.093 m.

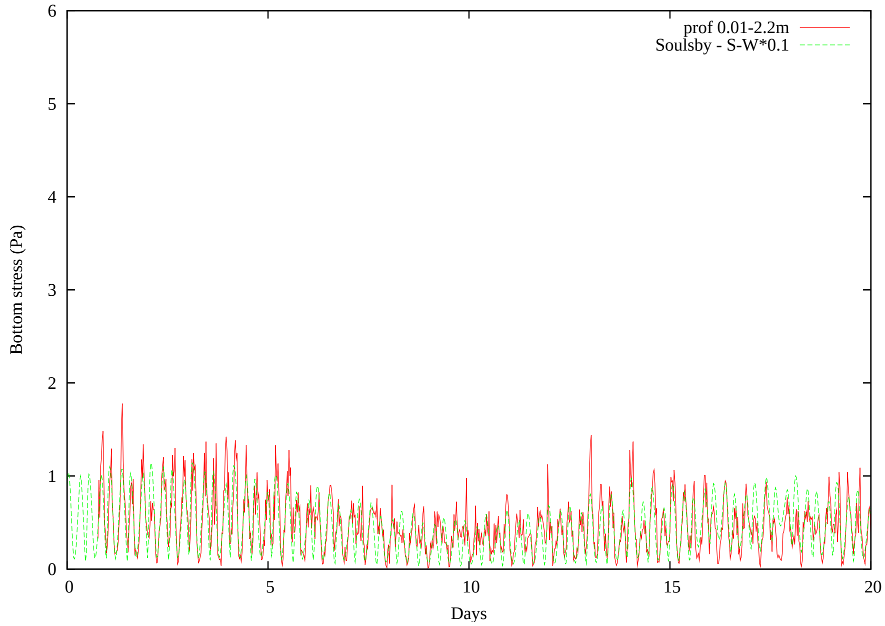

Figure 28: Bottom shear stress, modelled and measured for campaign 025 at the Gootebank for the period 23 June 2009 till 13 July 2009: measurements: bottom stress from current profile 0.01-2.2m, model: Soulsby, ripples calculated with Soulsby-Whitehouse model, total bottom roughness *0.1.

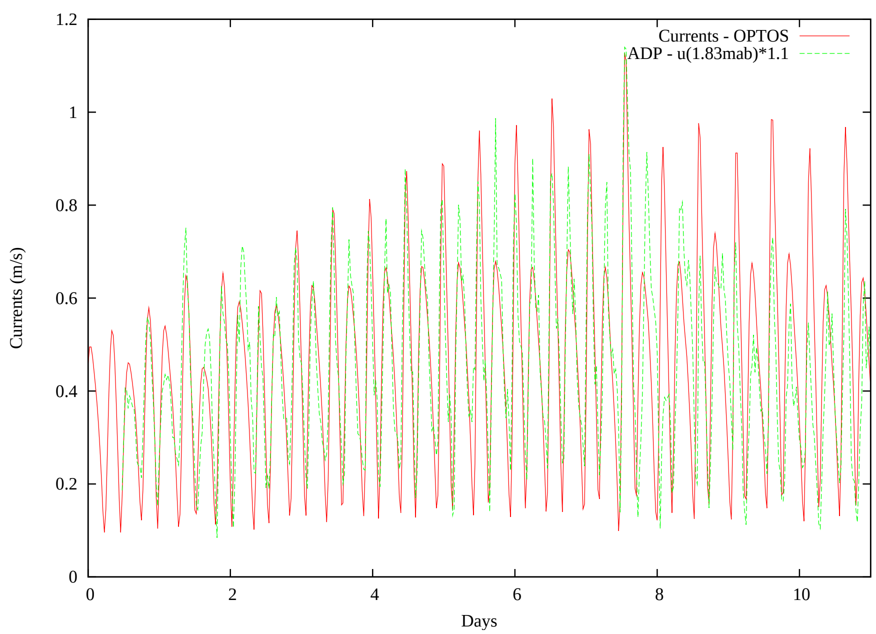

Figure 29: Currents modelled and measured for campaign 078 at MOW1 for the period 28 November 2013 till 9 December 2013.

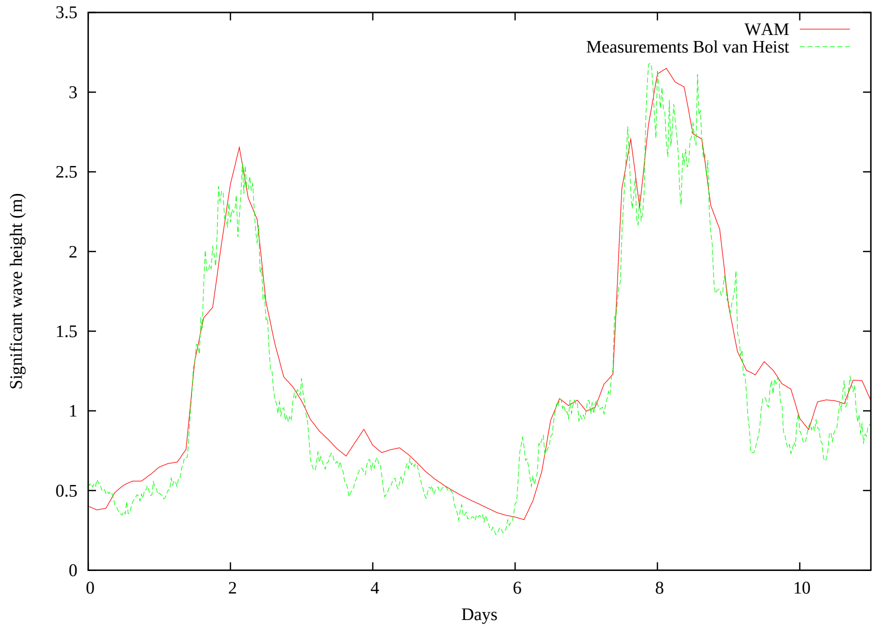

Figure 30: Waves modelled and measured for campaign 078 at MOW1 for the period 28 November 2013 till 9 December 2013. Measurements from the station Bol van Heist are from the Meetnet Vlaamse Banken.

5.2.2.2. *Bottom shear stress with constant bottom roughness*

Where for the campaign 025, with low waves, good agreement could be found between the model results and the bottom shear stress, derived from the measured current profile, this is not the case for campaign 078. Good agreement is only found between the model results and the bottom shear stress, derived from the turbulent kinetic energy. This is shown in Figure 31 and Figure 32. The bottom shear stress, derived from the turbulent kinetic energy is well modelled by the models. In both results the influence of the waves on the bottom shear stress in shallow waters is very clear. For the Soulsby-Clarke model with a bottom roughness length of 0.01 m, a bias of -0.22 Pa is found, and a correlation coefficient of 0.931. The constant bottom roughness length is in this case much lower that for the results of the campaign 025.

The bottom stresses, derived from the current profile or derived using the inertial dissipation method, are much lower and don't show a very clear influence of the waves. It is unclear at the moment why these measurements seem less reliable. This should be investigated in the future.

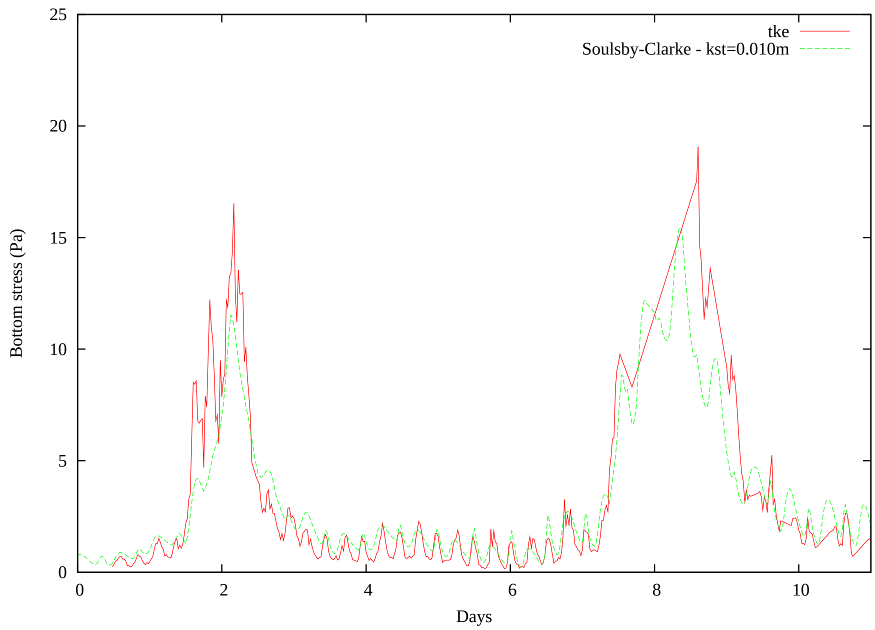

Figure 31: Bottom shear stress, modelled and measured for campaign 078 at MOW1 for the period 28 November 2013 till 9 December 2013: measurements: bottom stress from turbulent kinetic energy, model: Soulsby-Clarke, bottom roughness length = 0.010 m.

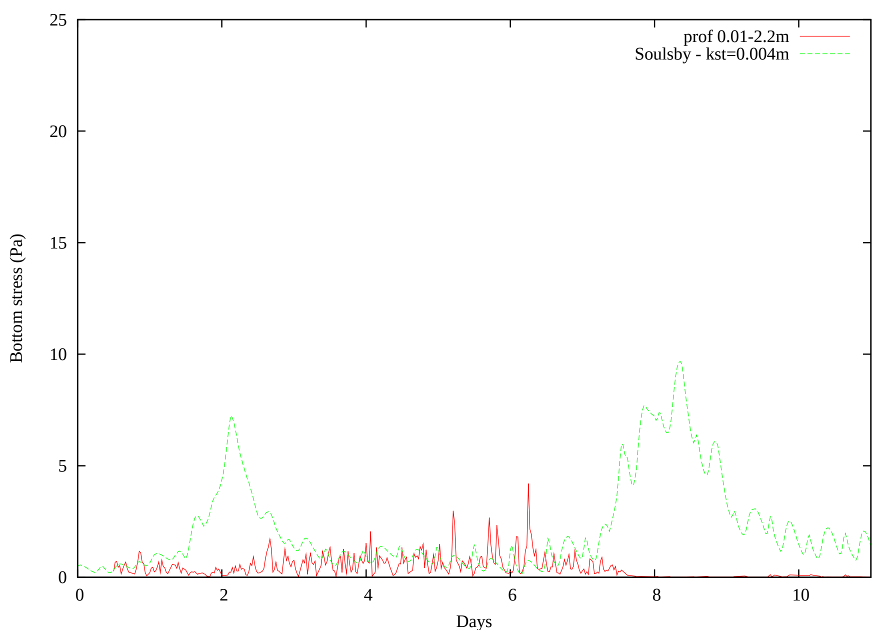

Figure 32: Bottom shear stress, modelled and measured for campaign 078 at MOW1 for the period 28 November 2013 till 9 December 2013: measurements: bottom stress from current profile between 0.01 and 2.2 m, model: Soulsby-Clarke, bottom roughness length =0.004 m.

5.2.2.3. Bottom shear stress with bottom roughness calculated

Also for campaign 078, the modelled bottom shear stresses are much too high, when the bottom roughness length is used, as calculated by the model itself. However, when the calculated bottom roughness length is again multiplied with a scaling factor, good results are obtained, comparing the model results with the bottom shear stress, derived from the turbulent kinetic energy. This is shown in Figure 33 for the Soulsby-Clarke model, when the calculated bottom roughness length is multiplied with a factor 0.1. In this case the bias is only -0.02 Pa and the correlation coefficient 0.910. Also the RMSE of 1.44 Pa is lower in this case than the RMSE, obtained with a constant bottom roughness length (of 0.01 m).

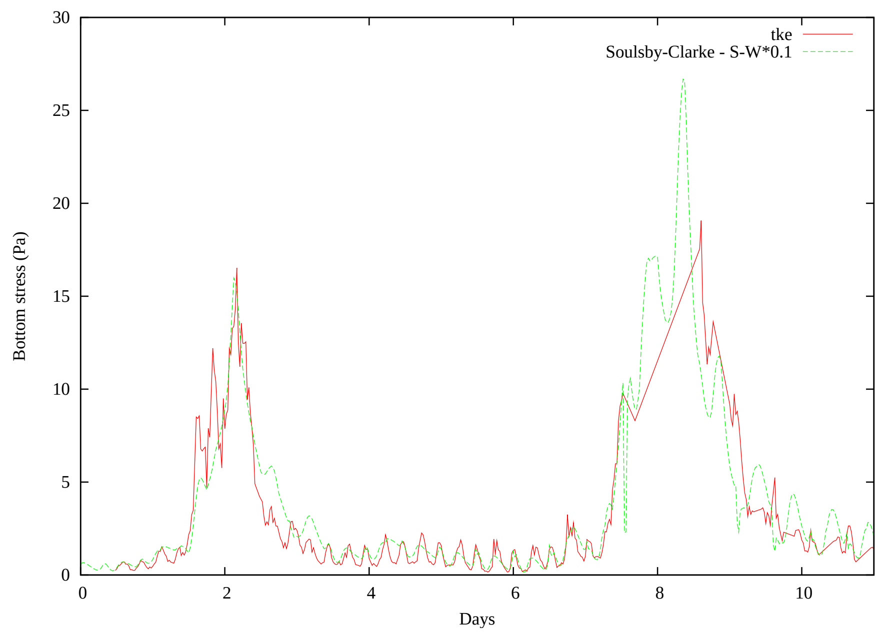

Figure 33: Bottom shear stress, modelled and measured for campaign 078 at MOW1 for the period 28 November 2013 till 9 December 2013: measurements: bottom stress from turbulent kinetic energy, model: Soulsby-Clarke, ripples calculated with Soulsby-Whitehouse model, total bottom roughness *0.1.

Remark that in this case the bottom roughness, due to bed load can be higher and comparable in magnitude as the bottom roughness, due to the ripples. In the case of high waves, the wave ripples are washed out and the bottom roughness, due to the bed load becomes more important. This is illustrated in Figure 34. The bottom roughness, due to ripples, calculated by the Soulsby-Grand&Madsen model and by the Soulsby-Whitehouse model have some differences, but have the same order of magnitude and show more or less the same behaviour (Figure 35).

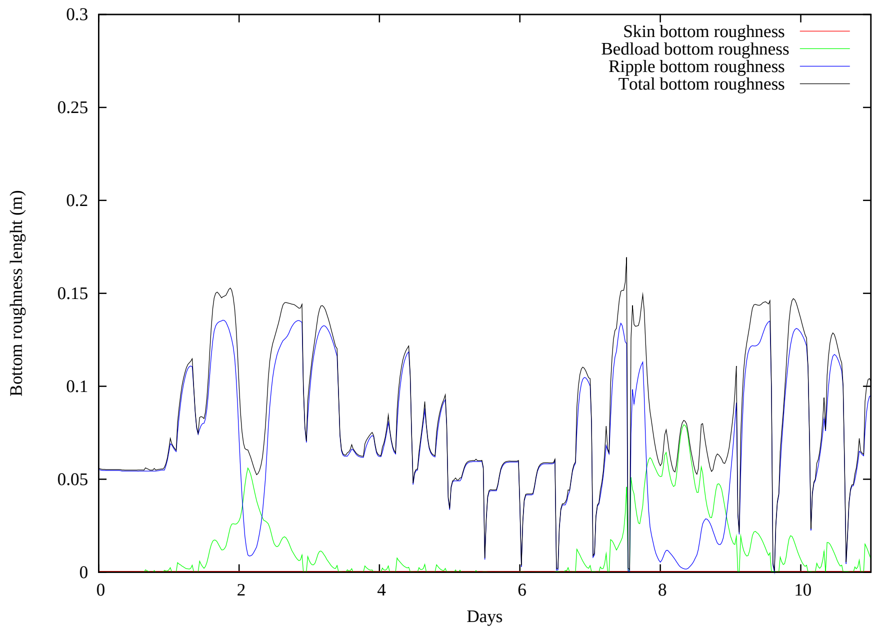

Figure 34: Variation of the skin, bed load, ripple and total bottom roughness length for campaign 078 at the station MOW1 for the period 28 November 2013 till 9 December 2013 for the Soulsby-Clarke model. Bed load roughness by Grant-Madsen, k=1; ripple roughness calculated with Soulsby-Whitehouse model.

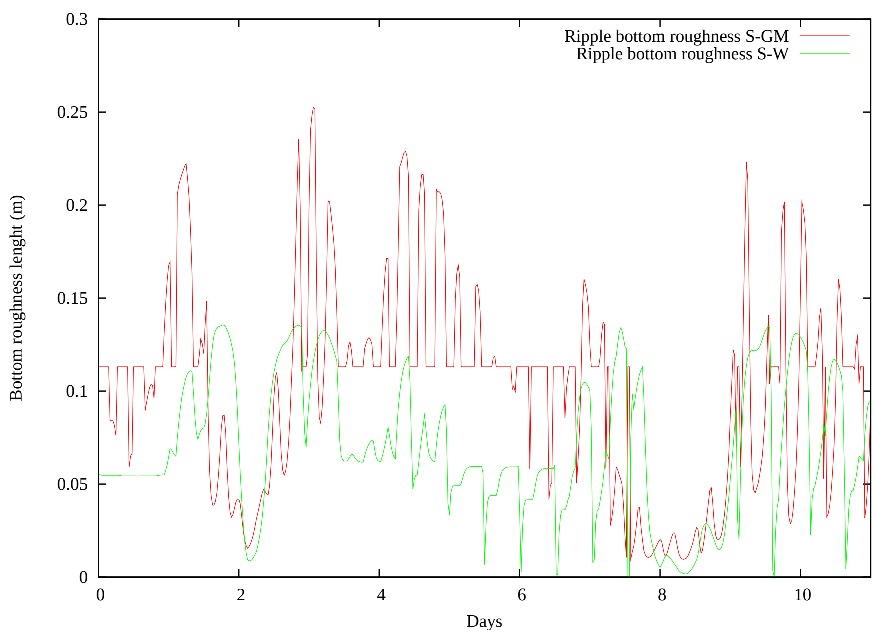

Figure 35: Variation of the bottom roughness length, due to the bottom ripples for campaign 078 at the station MOW1 for the period 28 November 2013 till 9 December 2013: S-GM: Soulsby-Grant&Madsen model; S-W: Soulsby-Whitehouse model.

5.2.3. Conclusions

For two deployments the comparison between the measurements and the model results were evaluated more in detail. The first deployment was executed offshore in deeper waters, with low wave activity, while the second deployment was executed more near shore in a water depth of only 10 m and with waves up to 3 m.

First of all, it was shown that the bottom shear stresses, measured with different techniques didn't show at all similar results. It is therefore difficult to assess what bottom shear stress the model results should be compared to, which of course makes the comparison difficult and the results ambiguous.

However, for the campaign with the low wave activity, when comparing the modelled bottom stress with the bottom stress, derived from the current profile 0.01-2.2 m, good results were obtained with a constant bottom roughness length of about 0.004 m. When using the bottom roughness length, calculated in the model, the bottom roughness length should be multiplied with a factor 0.1 to get good results. When comparing the model results with the bottom roughness, derived from the current profile 0.15-2.2 m, or with the bottom roughness, derived from the turbulent kinetic energy, very high bottom roughness lengths have to be used, due to the fact that the measured bottom stresses are much higher.

For the deployment with high waves, clearly the best measurement are obtained using the turbulent kinetic energy method. In this case, the model results agree well with the measurements, including the strong increase in bottom stress during high wave activity. The best results are obtained using a bottom roughness length of 0.01 m. When using the bottom roughness length, calculated by the model, again a scaling factor of 0.1 should be used. In this case the bottom stresses, calculated from the current profile, or using the inertial dissipation method, give much too low values.

5.3. Overall results for all campaigns

5.3.1. Introduction

In this section, results for all deployments will be evaluated in general. For all deployments, the measurements for which the best agreement exists, between measurements and model results, will be selected. For those measurements, first the optimal bottom roughness length is selected for the different campaigns, when a constant bottom roughness is used in the bottom shear stress models. In this way, a first estimate can be made for the optimal bottom roughness length to be used. The same can be done for the model results, when the bottom roughness is calculated in the model itself, taking into account the scaling factor.

To decide which model gives the best agreement with measured values, a new quality parameter is defined, which combines the effect of the bias, to be as low as possible, and the correlation coefficient, that has to be as high as possible. The quality parameter is thus defined as:

$$QP = \frac{\text{abs}(bias)}{r^2}$$

with	*bias*	bias between the measurements and the observations
	r	correlation coefficient

In this case the best agreement is determined by the lowest value of the QP. It is clear that using other parameters, like the RMSE, to define the best agreement could influence the results. However, the overall conclusions will not be changed drastically.

Remark that the model predictions are not executed for all deployments. As described above, emphasis was given to the deployments, starting from deployment 037, from September 2010, since from that moment, the burst length was increased, giving more reliable estimations of the bottom stress, using the turbulent kinetic energy method or the inertial dissipation method. Also for the deployments 015 and 025 model simulations were executed, since for these deployments, relatively high correlations were found between the bottom stresses, using different measurements techniques. Furthermore also deployment 26 was included, which was for the same period as deployment 025 and was a more offshore station. Finally all the other deployments from 2010 were included in the study. In total, model calculations were performed for 45 deployments. The deployments for which model simulations were executed are indicated in Table 1.

5.3.2. Bottom stress with constant bottom roughness length

For the models with a constant bottom roughness, the best agreement between the model results and the measured bottom stresses were obtained when the measured bottom stress, was derived from the turbulent kinetic energy. For the 45 deployments, for which the comparison was made, for 30 deployments, this was the case. Remark furthermore that 6 of the deployments for which better agreement was found with the bottom shear stress, derived from the current profile, were before deployment 037, where the bottom stresses derived from the turbulent kinetic energy were less reliable, due to too short burst lengths. Furthermore, for 3 deployments (059, 066 and 068), the ADV was not available. It is therefore clear that in this study, the best results are obtained by comparing the model results with the bottom stress, derived using the turbulent kinetic energy method.

When the bottom shear stress, measured using the turbulent kinetic energy method, is used as the measured bottom shear stress, one can investigate the best model to simulate the bottom shear stress, using a constant bottom roughness length. The results for the mean bias, RMSE and correlation (over all deployments) using the different models is presented in Table 2. The best results (lowest bias and RMSE, highest correlation) was found for the Soulsby model, followed closely by the Soulsby-Clarke model. For the Soulsby model the constant bottom roughness length that was most used to obtain the best results was 0.010 m. For the Soulsby-Clarke, the bottom roughness length that was most used was 0.007 m (16 deployments) or 0.01 m (13 deployments). As remarked earlier, when using the Malarkey-Davies model, lower bottom shear stresses should be used.

When the results of the Soulby model, with a constant bottom roughness length of 0.01 m are compared with the bottom shear stress, derived from the turbulent kinetic energy, for all deployments, a mean bias is found of 0.25 Pa, a RMSE of 1.21 Pa and a correlation coefficient of 0.72. In more the 88 % of the campaigns, the correlation is higher than 0.5. This is clearly satisfactory.

Table 2: The mean (over all campaigns) bias, RMSE and correlation coefficient for the different model results, when comparing the model results, using a constant bottom roughness length, to the measured bottom shear stress, using the turbulent kinetic energy method. Kst: the bottom roughness length that was most used to obtain the best results.

Model	Bias	RMSE	Correlation	Kst
Bijker	0.16	1.20	0.70	0.010 m
Soulsby	0.09	1.14	0.72	0.010 m
Soulsby-Cl.	0.10	1.16	0.72	0.007 m
Malarkey-D.	0.12	1.19	0.70	0.004 m

5.3.3. Bottom shear stress with bottom roughness length calculated

Also in the case the bottom roughness length is calculated by the model itself, taking into account the bottom roughness, due to bed load and bottom ripples, the bottom stress models have the best agreement with the measured bottom shear stress, using the turbulent kinetic energy method. Again in 30 of the 45 campaigns, the best results are obtained using that measured bottom shear stress. However the bias and the RMSE are much higher in this case, due to an over prediction of the bottom roughness length in the model. This was already shown in the two deployments, discussed in more detail in the previous section.

Therefore, also here the scaling factor is applied, to scale the calculated bottom roughness length, but allowing it to vary over time.

For the four different models, the best model results, compared to the bottom stress, derived from the turbulent kinetic energy, were selected. The results are presented in Table 3, where the Quality Parameter, calculated using the overall bias and correlation coefficient, together with the overall bias, RMSE and correlation coefficient are given. Furthermore also the best models to calculate the bottom roughness, due to bed load and bottom ripples, are given in the table. One can again conclude that the best results are given by the Soulsby model. It can be mentioned that, although the Raudkivi model to calculate the bottom roughness, due to bed load, gives non-realistic results is some cases (see 3.3.4), the model gives the best results for the Soulsby model. The bottom ripples roughness is best predicted by the model of Soulsby-Whitehouse. Remark however that the differences between the results of the different models for the bottom roughness length due to bed load and bottom ripples, is very small. Finally the scaling factor that is used to obtain the best results is a factor of 0.1.

Finally, the results are calculated for all deployments when comparing the measured bottom shear stress, using the turbulent kinetic energy method with the bottom stress, calculated using the Soulsby model with bottom roughness length, due to bed load, calculated with the Raudkivi model, the bottom roughness length, due to bottom ripples, with the Soulsby-Whitehouse model and with a scaling factor of 0.1. The overall bias is 0.27 Pa, with a RMSE of 1.28 Pa and a correlation of 0.72. These results are comparable with the results using a constant bottom roughness length, but are not better. At the moment, it is therefore recommended to use a constant bottom roughness length of 0.01 m.

Table 3: The QP, the mean (over all campaigns) bias, RMSE and correlation coefficient for the different model results, when comparing the modelled bottom stress, using the bottom roughness length calculated by the model and a scaling parameter, to the measured bottom shear stress, using the turbulent kinetic energy method. BRM: bottom roughness model that was used to obtain the best results: Raud: Raudkivi, Souls: Soulsby for bottom roughness from bed load; S-W: Soulsby-Whitehouse for bottom roughness from bottom ripples. Convkst: the scaling parameter that was most used to obtain the best results.

Model	QP	Bias	RMSE	Correlation	BRM	*convkst*
Bijker	0.33	0.17	1.20	0.71	Raud/S-W	0.1
Soulsby	0.24	0.12	1.20	0.72	Raud/S-W	0.1
Soulsby-Cl.	0.26	0.13	1.19	0.72	Raud/S-W	0.1
Malarkey-D.	0.31	0.15	1.17	0.71	Souls/S-W	0.1

6. Conclusions

The bottom shear stress is an important parameter for the calculation of the sediment transport. The erosion and deposition of the material is determined by the bottom shear stress. It is therefore important to have an accurate calculation of the bottom shear stress under the influence of the currents and the waves and to compare the model results with bottom shear stress measurements.

The measurements of the bottom shear stress have been executed during a series of 70 deployments going from 2005 to 2013, during which the current profile near the bottom and the high frequency velocities near the bottom were recorded. Three different techniques were used to determine the bottom shear stress. A first method uses the measured current profile near the bottom, which is assumed to be a logarithmic profile, governed by the bottom shear stress and the bottom roughness length. Further, the turbulent kinetic energy, which can be derived from the high frequency variations of the currents, is assumed to be linearly related to the bottom shear stress. Finally, the bottom shear stress can be derived using the inertial dissipation method. In this method, the velocity spectrum, and more specifically, the high frequency part of the spectrum, that is showing a decay with the wave number following a characteristic -5/3 power, is related to the turbulent kinetic energy dissipation and further to the bottom shear stress.

To model the bottom shear stress, four different models were implemented and tested. Normally, a constant bottom roughness length can be applied. However, the bottom roughness length also can be modelled as a function of the currents and the waves. In the framework of this report, different new models were implemented for the calculation of the bottom roughness length, under the influence of the bed load and two models for the calculation of the bottom roughness length, as a function of the bottom ripples. The model results were compared with bottom shear stress measurements to validate the model results.

When comparing the measurements for the bottom shear stress, using the different techniques, it was clear that no correlation between the different measurements of the bottom shear stress was found. Furthermore, it was clear that the bottom shear stress, calculated from the current profile, was highly dependent on the number of current measurements that were taken into account. Since the measurements were not correlating and sometimes had large differences in their values occurred, it was not clear which measured bottom shear stress was the best approximation of reality and should be used to validate the model results. However, the fact that the bottom shear stress, derived from the turbulent kinetic energy, clearly was influenced by the wave height, while the other bottom shear stresses had no correlation with the significant wave height, gave some indication that this technique gave the best results and should be used to validate the model results. Furthermore, it was shown that the most reliable results were obtained from deployment 037 from September 2010, since the burst length seemed to be too short before that date.

The validation of the model results first was executed more in detail for two specific deployments, i.e. deployment 025, on the Gootebank in a water depth of 23 m, over a period with low wave activity, and deployment 078, near the station MOW1 in a water depth of about 10 m and during a period of high wave activity with waves with a significant wave height up to 3 m.

It was first shown that the hydrodynamic and the wave models gave good results for the two deployment periods. For the deployment 025, a large difference was found between the bottom shear stress, derived from the current profile between 0.01 m and 2.2 m, and the bottom shear stress, derived from the turbulent kinetic energy or derived from the current profile between 0.15 and 2.2 m. A quite low constant bottom roughness length of 0.004 m was used to have a good agreement between the model results and the bottom shear stress, derived from the current profile between 0.01 and 2.2 m. In the other case, a very high bottom roughness length of 0.6 m had to be used to give a good agreement between the model results and the measured bottom shear stress. When the bottom roughness was calculated in the model itself, it was observed that the calculated bottom roughness length was a factor 10 too high, to give good agreement with the bottom shear stress, derived from the current profile between 0.01 and 2.2 m.

For the deployment 078, clearly the best results were obtained when comparing the model results with the bottom shear stress, derived from the turbulent kinetic energy. When using the Soulsby-Clarke model and a constant bottom roughness length of 0.01 m, a small bias was found of -0.22 Pa, and a correlation coefficient of 0.93. When using the bottom roughness, calculated in the model, good results were obtained when the total bottom roughness length was again multiplied by a factor 0.1. In this case the results were better than the results with a constant bottom roughness length.

When looking at the best agreement between the model results and the measured bottom shear stress for all deployments, more or less the same conclusions could be put forward. The best results are when comparing the model results with the bottom shear stress, derived from the turbulent kinetic energy. Furthermore, overall the Soulsby model gives the best results, when using a constant bottom roughness length of 0.01 m. When using the bottom roughness, calculated by the model, a scaling factor of 0.1 should be used to lower the calculated bottom roughness. The Soulsby or the Soulsby-Clarke or model gives the best results, when the Soulsby-Whitehouse formulation is used to calculate the bottom roughness length, due to bottom ripples. Remark that the model results with the calculation of the bottom roughness in the model doesn't give necessarily better results than using a constant total bottom roughness. It is, for now, therefore recommended to use in the sediment transport model a constant bottom roughness length.

Overall, one can conclude that using these parameters, good results can be obtained, modelling the bottom shear stress, for most of the deployments. However, one has to take into account that the fact that the measured bottom shear stress, using different techniques doesn't correlate at all with each other, does make the results of this study still uncertain. It is clear that more research has to be done to evaluate the measurements and to obtain in the future high quality measurements of the bottom shear stress. Only in this way, a solid validation of the model results can be achieved.

In the future, the results of the different deployments will be analysed in more detail. Furthermore, an analysis will be made on the dependency of the best bottom roughness length on the water depth, the maximum current or the significant wave height. Unfortunately, all measurements since September 2010 were executed in shallow, near shore waters (MOW1 and WZ-buoy). It could be useful to obtain new, high quality, measurements in deeper waters. Finally, one must remark that apart from the ADV and ADP measurements, also some ADCP measurements are available. An analysis of these results is foreseen.

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8. Appendix A: Statistical parameters

For the validation, the statistical parameters bias, root mean square error (RMSE), the systematical and unsystematical RMSE and the correlation coefficient can be be calculated.

Hereafter, the measurements series will be presented as x and the model results (that is subject to the test) as y.

The mean values of the time series are represented by $\bar{x}$ (reference) and $\bar{y}$ (subject to test):

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

$$\overline{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$

where N is the length of the time series.

The bias is the difference between the mean of the modelled and the measured time series:

$$bias = \overline{y} - \overline{x}$$

The closer the bias is to zero, the better both time series correspond. A positive bias value means that the modelled time series are an overestimation of the observed time series. A negative bias value means that the modelled time series are an underestimation of the observed time series.

The root mean square error (RMSE) is a measure for the absolute error and is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - x_i\right)^2}{N}}$$

Corresponding time series will result in RMSE values close to zero.

Furthermore, a systematical RMSE ($RMSE_s$) and an unsystematical RMSE ($RMSE_u$) can be defined, that evaluate respectively, the (absolute) error, which is generated by the deviation from the linear regression of the modelled time series from the measurements, and the error that is generated by the deviation from the individual model results from the linear regression itself. While the systematical RMSE could be reduced by applying a correction, using the linear regression, the unsystemical RMSE is the error which is inherent from the variation from the results themselves. These parameters can be calculated as:

$$RMSE_s = \sqrt{\frac{\sum_{i=1}^{N}\left(\hat{y}_i - x_i\right)^2}{N}}$$

$$RMSE_u = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2}{N}}$$

with $\hat{y}_i$ is defined from the linear regression

$$\hat{y}_i = mx_i + b$$

with slope *m* and intercept *b* calculated from:

$$m = \frac{N\sum x_i y_i - \sum x_i \sum y_i}{N\sum x_i^{\ 2} - \left(\sum x_i\right)^2}$$

$$b = \overline{y} - m\overline{x}$$

The correlation between both signals is given by Pearson's correlation coefficient, defined as:

$$r = \frac{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)^2}}$$

The scatter index is a measure for the relative error and is defined by:

$$S.I. = \frac{RMSE}{\overline{x}}$$

COLOPHON

This report was issued by Operational Directorate Natural Environment in February 2015.

The reference code is ZAGRI-MOZ4/1/DVDE/201501/EN/TR2.

Status
☐ draft
☒ final version
☐ revised version of document
☐ confidential

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