Deltares

Enabling Delta Life

Environmental impact of tidal power in the Eastern Scheldt Storm Surge Barrier

Appendix A: Impact on tidal range due to tidal turbine installation

Prepared for:

OTP PROJ-00275, Stimulus: UP-16-01097
Deltares project: 11200444

Deltares

Impact on tidal range due to tidal turbine installation

Emiel Moerman

11200444-000

Deltares

Title
Impact on tidal range due to tidal turbine installation

Client	Project	Reference	Pages
OTP	11200444-000	11200444-000-HYE-0014	11

Keywords
Tidal energy, Tidal range, Eastern Scheldt

Summary
In this report the results are presented of the investigation to the impact of the tidal turbine operation on the tidal range in the Eastern Scheldt. The study is a continuation of a study conducted in 2014 in which the situation before installation was assessed based on the statistical dependency of the tidal range (i.e. the difference between consecutive high and low waters) between Roompot Buiten and Roompot Binnen. For individual years and relevant periods a (first-order, $y = ax + b$) linear fit between the tidal differences for the two stations was made. From the analysis the variation over the years was assessed. In this study the analysis was extended with the years 2014, 2015 (before installation) and a representative period for which an array of tidal turbines have been in operation.

The objective was to determine the possible effect of the operation of the tidal turbines in the Eastern Scheldt Barrier on the tidal range. For an operational period (June 2016 to May 2017) a remarkably lower mean value was found than for the year before operation. However, also for non-operational status during this period a comparable lower value was found. Furthermore looking at longer term trends and natural variability showed that the observed lower mean value for the operational period falls well within the long-term variation between the year averaged tidal difference for Roompot Buiten and Roompot Binnen. From the above it is concluded that at present no conclusions can be drawn on the effect of the tidal turbines on the tidal difference in the Eastern Scheldt. If there is an effect it seems to fall within the natural variation of the tidal difference. It is likely that the effect of the tidal turbines is generally lower than the natural variation of the water levels (including the 18.6 year tidal cycle, storminess, operation (opening and closing) and also other external forcing such as longer-term effects of the Eastern Scheldt Barrier construction and related morphological developments).

References
11200119-000-HYE-0006-r-Environmental impact of tidal energy plant in Eastern Scheldt Storm Surge Barrier – *Deltares Overall Report*
Oosterschelde Tidal Power PROJ-00275, Stimulus ref: UP-16-01097

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	Aug. 2018	Emiel Moerman	EM	Anton de Fockert	AdF	Bas van Vossen	BvV

State
final

Contents

1 Introduction

1.1 Background

In 2014, a study was conducted (ref [1]) in which the situation before the installation of the tidal turbines was investigated. For various years and periods between 1995 and 2013 statistical dependencies on the tidal differences between the various stations in the vicinity of the Eastern Scheldt Barrier were derived by means of linear regression on the data via a least squares method. Confidence intervals were assigned to account for the uncertainties in the estimates of the coefficients of the linear regression. As reference stations, the seaside stations *Roompot Buiten* and Westkapelle are selected. Stations in the Eastern Scheldt for which the dependencies are derived are the stations *Roompot Binnen*, *Stavenisse* and *Bergse Diepsluis west* (see Figure 1.1).

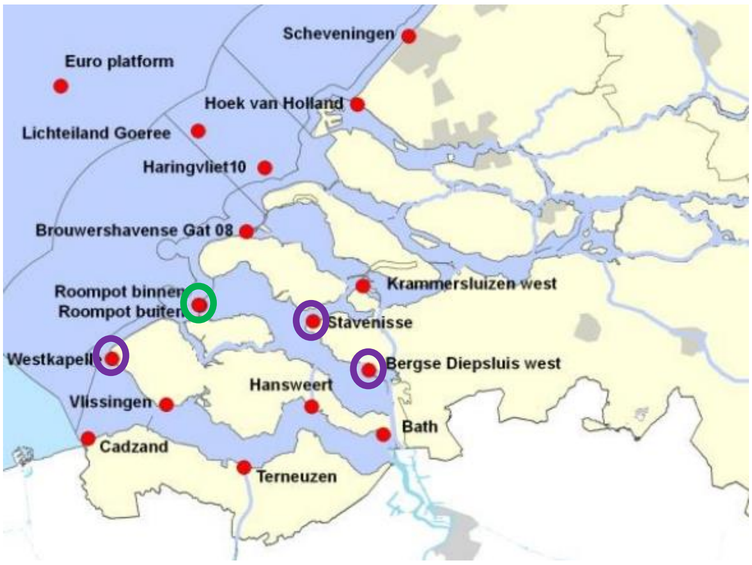

Figure 1.1 Measurement stations in vicinity of Eastern Scheldt Barrier (source Rijkswaterstaat), relevant stations highlighted in green and purple.

The analysis ref [1] showed that there is quite some variation of the tidal differences between the *Roompot Buiten* station and the inner stations from year to year. In this study the analysis is extended with the years 2014, 2015 and a representative period for which the tidal turbines have been in operation to investigate the possible effect of the operation of an array of tidal turbines in the Eastern Scheldt Barrier on the tidal range

In addition, a more general analysis looking at more overall longer-term variations is performed of the water levels and tidal differences at the Eastern Scheldt to better quantify any observed possible effects.

1.2 Objective and approach

The objective of this study is to investigate the possible effect of the operation of an array of tidal turbines in the Eastern Scheldt Barrier on the tidal range.

In the analysis, the variation in tidal range is investigated based on the long term water level data at the Eastern Scheldt Barrier, including one year of data in which the turbines have been in operation. The results of this analysis is compared against the natural variation of the water levels.

1.3 Research framework

The Eastern Scheldt Tidal Power project (OTP) consists of a consortium of 6 partners researching the effect of the tidal turbines on the environment. This research is part of the OTP project - Task 1, which is led by Deltares. Research Task 1 aims to investigate the environmental effects of the tidal turbines. Part of this task is to investigate the effect of the tidal turbines on the changes in tidal range.

2 Analysis

2.1 Continued analysis, statistical dependency 2014, 2015 and year of operation

In ref [1] an analysis was conducted to try and determine the statistical dependency of the tidal range (i.e. the difference between consecutive high and low waters) between *Roompot Buiten* and *Roompot Binnen*. For individual years and relevant periods for the years 1995-2013 a (first-order, y = ax + b) linear fit was derived for the difference in tidal range for the two stations. Figure 2.1 present the comparison of the tidal range and linear fit for the full 1993-2015 period data. The linear fit was used to derive a mean value (y) at *Roompot Binnen* based on the linear fit (y=ax+b) at a reference water level at *Roompot Buiten* (x) of 285 cm (= Slotgemiddelde). From the analysis the variation over the years was assessed.

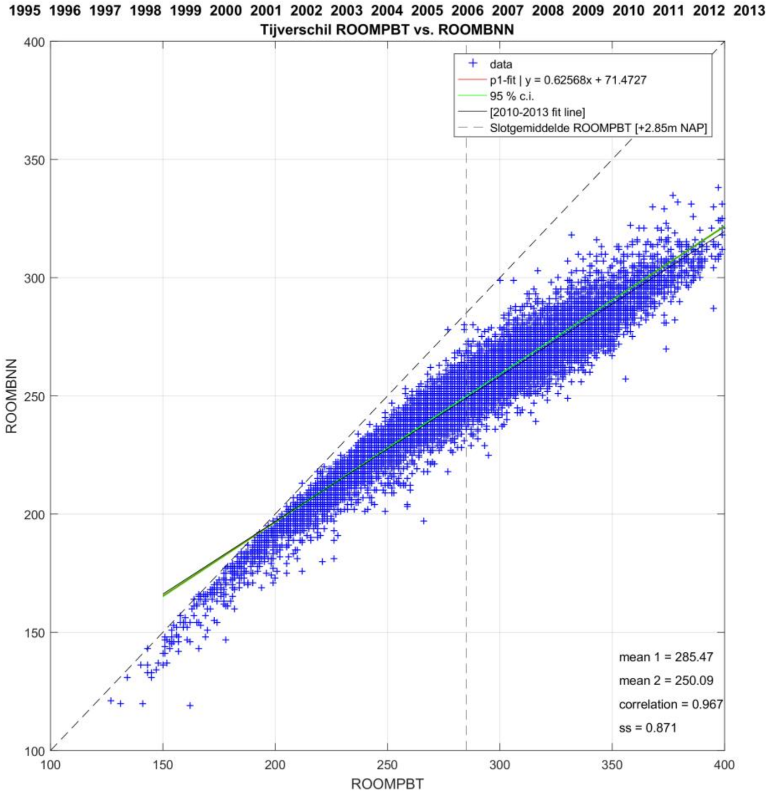

Figure 2.1 Comprison tidal range (difference between consecutive high and low waters) Roompot Buiten (x-axis) and Roompot Binnen (y-axis) for 1995-2013 period, including linear fit (y =0.62568x + 71.4727)

In this study the analysis has been extended with the years 2014, 2015 (before installation) and a representative period for which an array of tidal turbines have been in operation in order to determine the possible effect of the operation of the tidal turbines in the Eastern Scheldt Barrier on the tidal range.

The tidal turbines have been in operation since January 1, 2016. For the period up to the start of this study, hourly data is available of the status of the tidal turbines: *production*, *parked* or *no data.* Table 2.1 provides an overview of the operational status in percentages per month. For the period January to May 2016 insufficient applicable data is available. The period from June 2016 to May 2017 therefore has been selected as reference year in which the tidal turbines have been in more consistent operation.

Table 2.1 Overview operational status tidal turbines (representing selected months)*

Period	production	parked	no data
Jan '16	46%	37%	18%
Feb '16	27%	73%	0%
Mar '16	0%	100%	0%
Apr '16	0%	97%	3%
May '16	0%	100%	0%
Jun '16*	36%	64%	0%
Jul '16*	43%	53%	4%
Aug '16*	2%	65%	33%
Sep '16*	39%	52%	8%
Oct '16*	83%	17%	0%
Nov '16*	51%	49%	0%
Dec '16*	57%	43%	0%
Jan '17*	1%	96%	3%
Feb '17*	70%	30%	0%
Mar '17*	73%	26%	0%
Apr '17*	48%	17%	35%
May '17*	53%	43%	4%

The relation of the tidal range (i.e. the difference between consecutive high and low waters) for *Roompot Binnen* and *Roompot Buiten* for the years 2014 and 2015 are given in Figure 2.2. Figure 2.3 presents the relation of the tidal differences for the selected ‘operational’ period, mid 2016 – mid 2017.

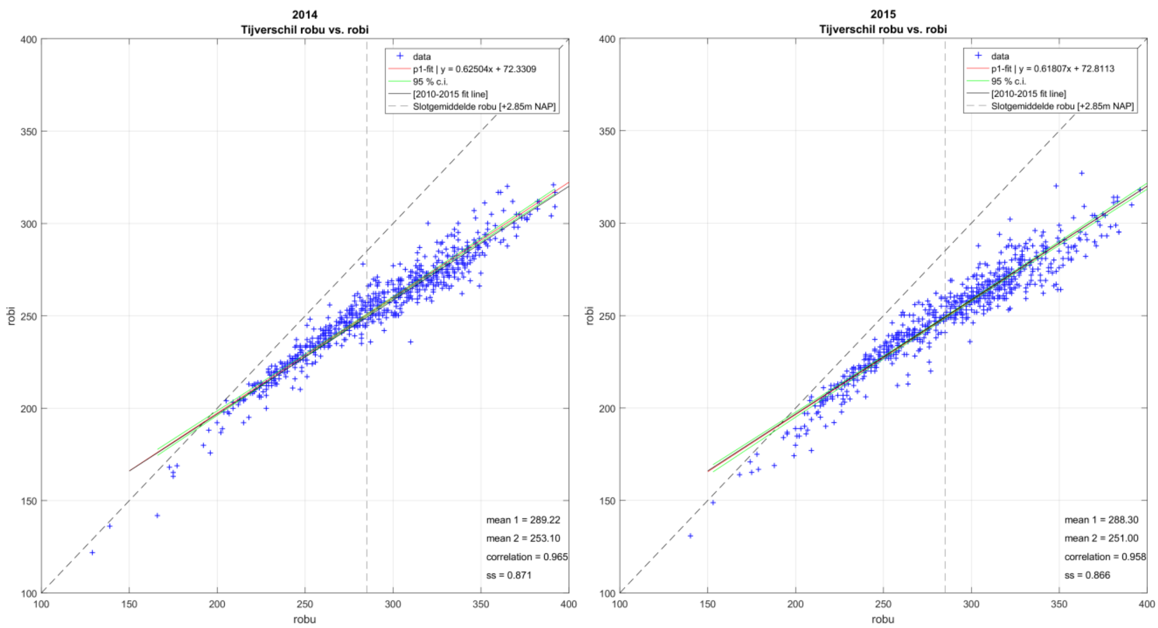

Figure 2.2 Relation tidal difference (difference between consecutive high and low waters) Roompot Binnen and Roompot Buiten, 2014 (left) and 2015 (right)

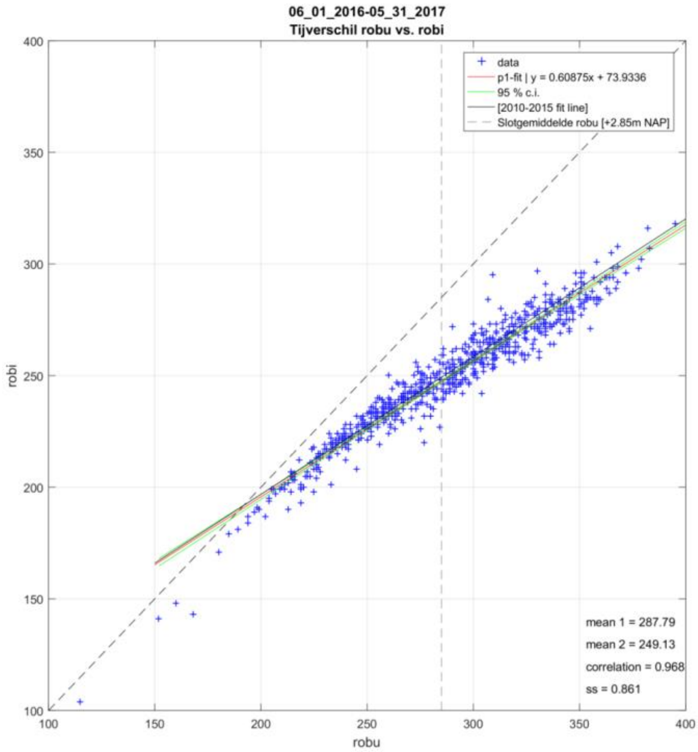

Figure 2.3 Relation tidal differences (difference between consecutive high and low waters) Roompot Binnen and Roompot Buiten, 06/01/2016 – 05/31/2017

Table 2.2 gives an overview of the derived variables of the linear fit for the years 2010-2015 (before installation of the tidal turbines) and for the selected periods from June 2016 to May 2017 and June 2017 to May 2018 (after installation of the tidal turbines) for the tidal differences between *Roompot Buiten* and *Roompot Binnen*. A distinction has been made here in moments where the tidal turbines are actually in operation (*production*) and where they are not (either *parked* or *no data*). Apart from the individual years given in the table also multi-year periods: 2010-2013 (as in ref [1]) and 2010-2015 have been analysed.

Table 2.2 Results regression analysis for the relation between the tidal differences of Roompot Binnen with Roompot Buiten (grey representing ref [1] results, black the continued analysis).

Period	**Obs [#]**	**y(x=285) [cm]**	**a [-]**	**b [-]**
2010	704	249.6	0.61	76.0
2011	704	248.7	0.62	73.6
2012	706	248.9	0.61	73.9
2013	703	248.8	0.62	73.5
2014	704	250.5	0.63	72.3
2015	703	249.0	0.62	72.8
2010-2013	2821	249.0	0.61	74.2
2010-2015	4231	249.2	0.62	73.5
With tidal turbine installation				
01/06/2016 – 31/05/2017	701	247.4	0.61	73.9
01/06/2016 – 31/05/2017 <u>*production*</u>	333	247.2	0.60	75.1
01/06/2016 – 31/05/2017 <u>*parked*</u>	368	247.1	0.62	71.9

For the selected periods after installation of the tidal turbines the derived mean value of the tidal difference at *Roompot Binnen* is 1.3 – 3.1 cm lower with an y(x=285cm) of 247.4 cm versus 248.7 - 250.5 cm values in earlier years. Because of the expected relatively large natural variation through all kinds of effects, e.g. meteorological conditions, the number of storms per year, operation of the storm surge barriers (closures) and other maybe more long-term (morphological) trends, an overview is given of the mean, min and max values of the derived tidal differences for more long-term periods: 2010-2015 and 1995-2015 in Table 2.3 as reference. From the table it shows that the minimum year value for the period of 1995-2015 is 248.7 cm and that the selected period after installation of the tidal turbines shows a 1.3 cm lower value (247.4 cm).

It is noted however that when solely taking into account the tidal registrations when the status is parked, with the tidal turbines out of the water (non-operational), also these lower values are obtained. Furthermore for the year 2015 also a decrease of 1.5 cm was observed in reference to 2014. Therefore no direct relation to the operation of the tidal turbines and derived lower tidal differences for the selected period can found.

Table 2.3 Mean, minimum, maximum year values and standard deviations of the derived tidal differences at Roompot for various periods.

Period	Mean [cm]	Minimum [cm]	Maximum [cm]	Standard deviation [cm]
1995-2015	249.8	248.7	251.2	0.71
2010-2015	249.2	248.7	250.5	0.68

In Table 2.4 an overview is given of all the derived variables of the linear fit for the tidal differences between *Roompot Buiten* and *Stavenisse* for the years from 2010-2015 (before installation of the tidal turbines) and for the selected period of June 2016 till May 2017 (after installation of the tidal turbines). A similar pattern is observed with 4.2-5.9 cm lower values of y(x=285cm) for the period after installation of the tidal turbines, 288.1 cm in comparison to 292.3 – 294.0 cm.

Table 2.4 Results regression analysis for the relation between the tidal differences of Stavenisse with Roompot Buiten.

Period	y(x=285) [cm]	A [-]	B [-]
2010	292.4	0.68	97.2
2011	292.3	0.69	95.9
2012	292.6	0.70	94.4
2013	292.4	0.70	93.3
2014	294.0	0.70	93.9
2015	292.3	0.70	92.7
2010-2013	292.4	0.69	95.2
2010-2015	292.7	0.70	94.4
With tidal turbine installation			
01/06/2016 – 31/05/2017	288.1	0.67	95.9
01/06/2016 – 31/05/2017 *production*	288.4	0.68	94.8
01/06/2016 – 31/05/2017 *parked*	287.8	0.69	92.7

Despite the fact that the above uniformly applied method of linear regression analysis shows that for the selected period after installation of the tidal turbines the derived value is lower than before, it is not possible to draw a direct conclusion to the relationship of the effect of the tidal turbines from this. For the non-operational period 2014-2015 also a downward signal was observed. Furthermore, when solely taking into account the tidal registrations when the status is parked, with the tidal turbines out of the water (non-operational), the same lower values are obtained.

2.2 Long-term water level signal

In the previous analysis relative relationships of the tidal differences between the inner stations of *Roompot Binnen* and *Stavenisse* and the outer station of *Roompot Buiten* have been derived for various individual years and multi-year periods. With these relations averaged values for the inner stations were derived on the basis of the published averaged value ("Slotgemiddelde") for Roompot Buiten of 285 cm and the linear relations (y = ax + b). It showed that natural variations over the years and uncertainties in the derived regression lines hamper the possibility to draw hard conclusions on the possible effect of the tidal turbines on the observed trends in the tidal range. In relation to this and to get a better feeling for the natural variation of the tidal differences over the years the year averaged tidal ranges per station are analysed as well.

In ref [2] an analysis was done to determine the average sea levels in the Dutch coastal waters for time-series up to 2010. The stations *Roompot Buiten* and *Roompot Binnen Westkapelle*, *Stavenisse*, *Bergse Diepsluis West* are part of this (see Figure 1.1). *Westkapelle* is used as an additional reference stations outside and *Bergse Diepsluis West* as an additional station inside the Eastern Scheldt.

From ref [2] it also showed that the yearly averaged tidal differences vary, from 280-294 cm for *Roompot Buiten* and 246-255 voor *Roompot Binnen*. The analysis has been extended here with the years 2011-2015 and for the selected period of June 2016 to May 2017. The yearly averaged tidal levels have been extended for the reference stations *Roompot Buiten* outside the Eastern Scheldt and for the stations *Roompot Binnen*, *Stavenisse* and *Bergse Diepsluis* west inside. An additional station outside the Eastern Scheldt barrier: *Westkapelle* was selected for which really long term water level data was available, back to the year 1880. Results are presented in Figure 2.4. In which the value for the selected period of tidal turbine operation is presented with the red marker.

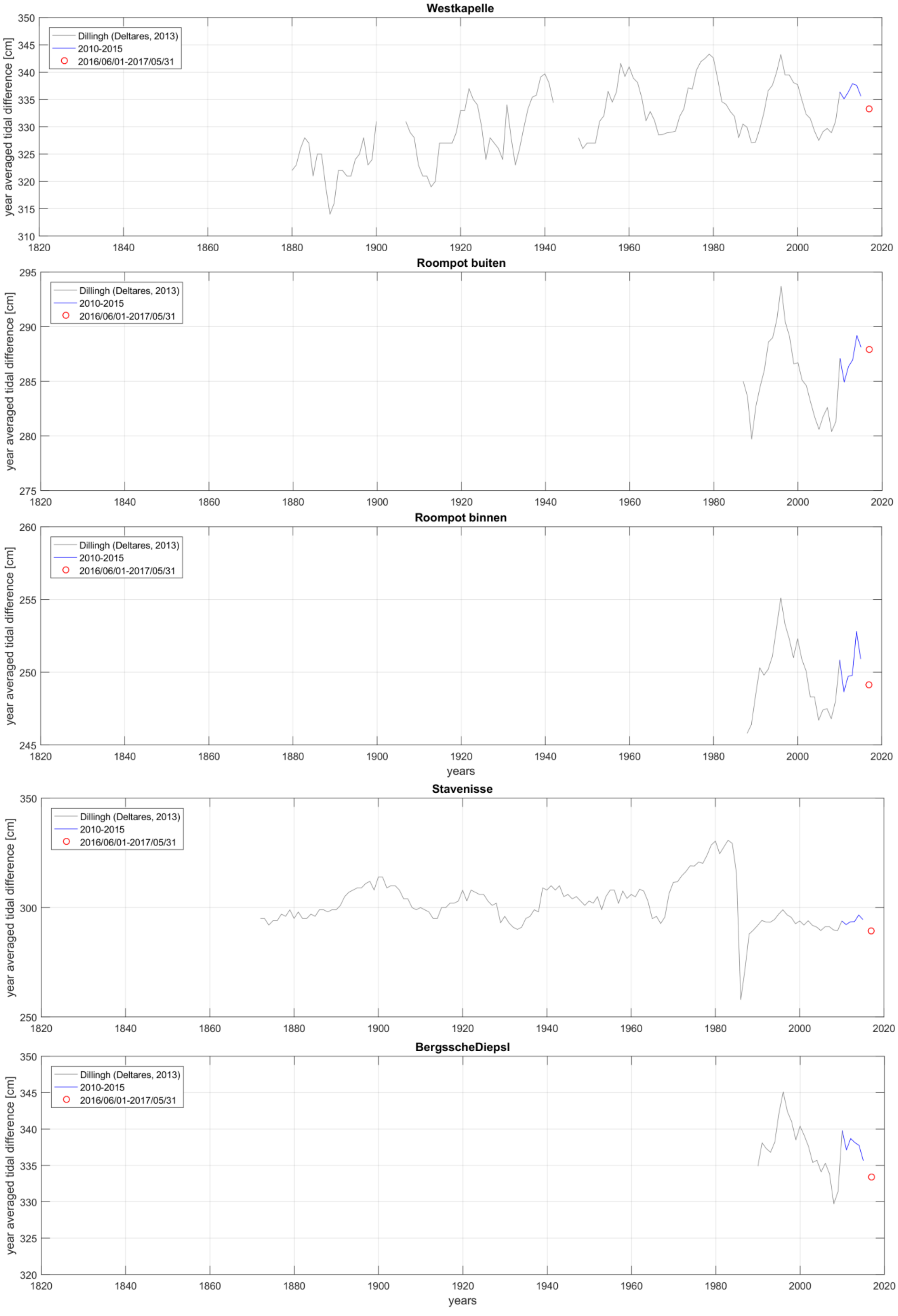

Figure 2.4 Year averaged tidal differences for relevant water level stations (inside) following Deltares (2013)

In the figures a distinct multiyear sinusoidal signal is observed, attributed to the 18.6 year tidal cycle. The natural variation over this cycle is in the order of 15 cm, an order of magnitude larger than the values derived from the statistical dependency of the tidal difference described in Section 2.1. Another distinct feature that can be observed is the construction of the Eastern Scheldt barrier, visible in the *Stavenisse* averaged tidal signal around 1986.

Focussing on the the *Roompot Buiten* and *Roompot Binnen* stations, in Figure 2.4 the yearly averaged tidal ranges are presented again together with the relative tidal difference (red line) between the two stations (relative to the mean). From this it follows that the relative variation between the yearly averaged tidal difference for *Roompot Buiten* en *Roompot Binnen* ranges from –3 cm to +2.5 cm. A range the derived operational period falls well within.

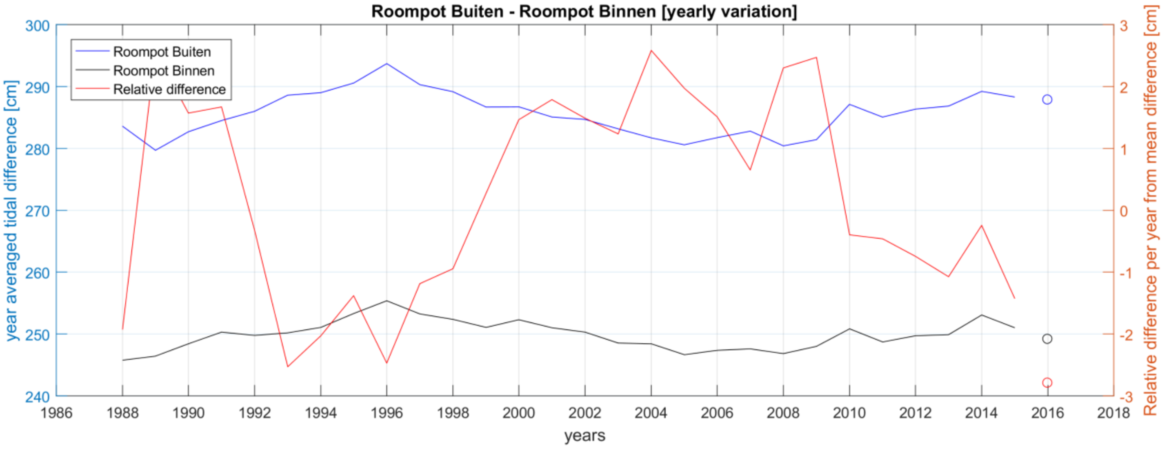

Figure 2.5 Yearly variation tidal differences Roompot Buiten and Roompot Binnen and relative difference (before installation).

For all stations it seems that at present the 18.6 year cycle is in a downward trend. The June 2016 to May 2017 period for which the tidal turbines have been in place and operable (red dots) seems to fit this trend. Again it is concluded that because of this natural variability from year to year no conclusions can be drawn on the individual effect of the tidal turbines on the tidal differences.

3 Summary and conclusions

In this report the results are presented of the investigation to the impact of the tidal turbine operation on the tidal range in the Eastern Scheldt. The study is a continuation of a study conducted in 2014 (ref [1]) in which the situation before installation was assessed based on the statistical dependency of the tidal range (i.e. the difference between consecutive high and low waters) between *Roompot Buiten* and *Roompot Binnen*. For individual years and relevant periods a (first-order, y= ax+b) linear fit between the tidal differences for the two stations was made. From the analysis the variation over the years was assessed.

In this study the analysis was extended with the years 2014, 2015 (before installation) and a representative period for which an array of tidal turbines have been in operation. The objective was to determine the possible effect of the operation of the tidal turbines in the Eastern Scheldt Barrier on the tidal range.

In Table 2.3 the results are presented of the derived mean value (y) at *Roompot Binnen* based on the linear fit (y=ax+b) at a reference water level at *Roompot Buiten* (x) of 285 cm (= Slotgemiddelde). Between 1995 and 2015 (before installation) the lowest observed value was +248.7 cm NAP and the highest observed value was 251.2 cm NAP, which is a range of 2.5 cm with a standard deviation of 0.71 cm. For a reference operational period (June 2016 to May 2017) a mean values of 247.4 cm was found, remarkably lower than for the previous years. To determine if there was a direct effect of the tidal turbines a separation was made into operational and non-operational conditions. From this analysis it showed that for both the operational and non-operational conditions the derived mean value fall outside (i.e. are lower than) the multiyear ranges. (247.2 and 247.1 cm respectively). Furthermore it showed that also for other non-operational periods (i.e. 2014-2015) a relative decrease of 1.5 cm was observed showing the order of the natural variation form year to year. From this it was concluded that no direct effect of the tidal turbines could be found from this analysis.

In relation to this and to get a better feeling for the natural variation of the tidal differences, the year averaged tidal differences per station were also analysed.

In the long-term data a clear trend was observed representing the 18.6 year tidal cycle. From the analysis it was found that the analysed operational period (June 2016 to May 2017) falls within the observed downward period of the cycle. The analysis furthermore showed that the variation in the tidal differences is about 15 cm, an order of magnitude larger than the values derived from the statistical dependency of the tidal difference. The relative variation between the year averaged tidal difference for *Roompot Buiten* en *Roompot Binnen* ranges from –3 cm to +2.5 cm (see Figure 2.4).

From the above it is concluded that at present no conclusions can be drawn on the effect of the tidal turbines on the tidal difference in the Eastern Scheldt. If there is an effect it seems to fall within the natural variation of the tidal difference for *Roompot Buiten* en *Roompot Binnen*. It is likely that the effect of the tidal turbines is generally lower than the natural variation of the water levels (including the 18.6 year tidal cycle, storminess, operation (opening and closing) and also other external forcing's such as for example longer-term effects of the Eastern Scheldt Barrier construction and related morphological developments).

4 References

[1] Bijlsma, A.C., de Ronde, J.G., Moerman, E.(2014), "*Monitoring effect getijturbines Oosterscheldekering op zandhonger*", Deltares ref: 1210208-000-HYE-0002, memo, 28 juli 2014

[2] Dillingh, D. (2013). "*Changes in mean tidal levels in the Dutch coastal waters*". Deltares report 1206182-000-ZKS-0003. (In Dutch: Veranderingen in gemiddelde zeeniveaus in de Nederlandse kustwateren). Commissioned by Rijkswaterstaat Waterdienst. Deltares, 2014

www.deltares.nl

Deltares