Ground water level measurements in Flemish sea dikes

Mertens Tina[1], Van de Walle Björn[2], Wildemeersch Koen[2]

[1] Agency for Maritime Services and Coast – Division Coast, Vrijhavenstraat 3, B-8400 Oostende
[2] KHBO, Department of Industrial Sciences, Construction Division, Zeedijk 101, B-8400 Oostende

The Flemish coast measures 66 km long (figure 1). More than 38 km of the coast is protected by dikes. The other part of the coast is protected by dunes. The protection of the coast is a major concern of the Flemish government as not whole of the coast can yet withstand a design storm with a return period of 1000 years.

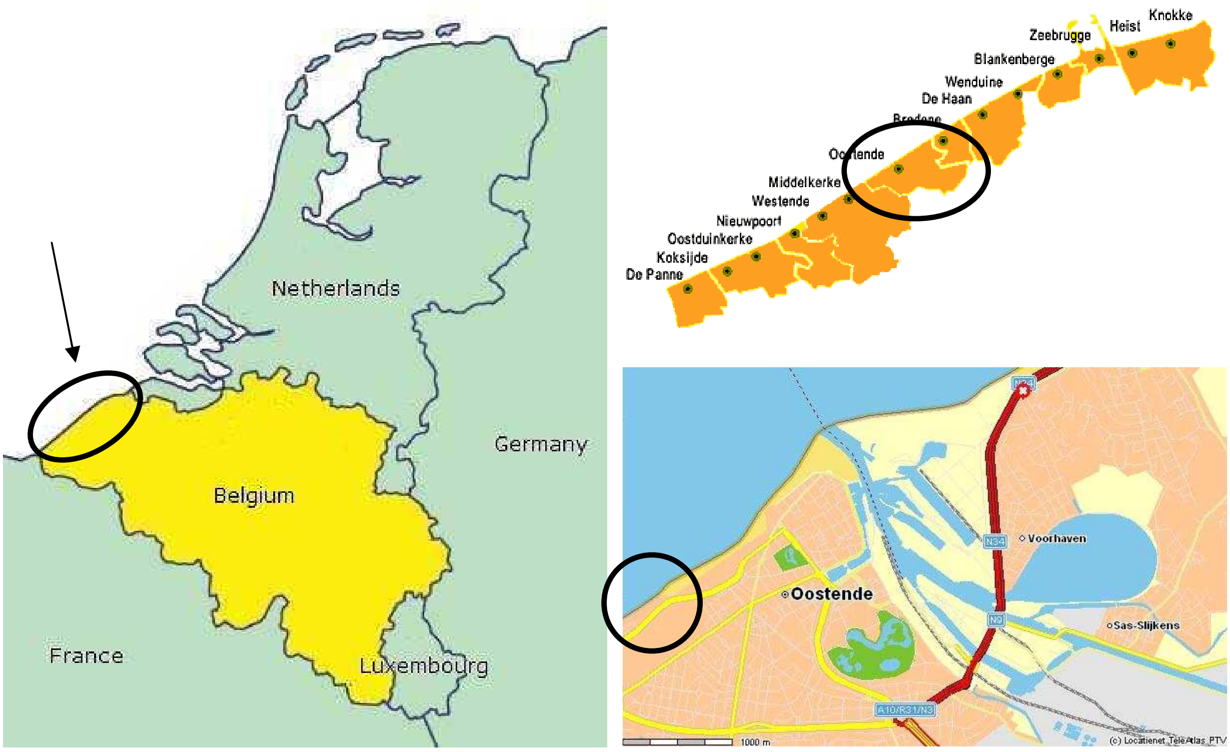

Figure 1: Situation of the measuring site along the Flemish coast.

In the night of 31 January to 1 February 1953, a severe north western storm attacked the Belgian and Dutch coast. The storm caused a lot of damage: in the Netherlands 1835 people were killed and about 141000 hectares were flooded. In Belgium along the coastline, a number of dikes in Knokke, Heist and Oostende bursted and the inner city of Oostende flooded: 7 people were killed. The dike in Oostende has been a weak link in the coastal protection of the Flemish coast for a long period. The dike of Oostende was not able to withstand a similar storm like the 1953-storm. In 2000 and 2001, pressure measurements have been carried on the dike in Oostende. Both wave pressures on the dike revetment and water pressure under the dike revetment have been measured. Boone et al. (2001) found upward water pressures acting on the bottom side of the dike revetment up to 2.64 mwc for a significant wave height of H_s = 3.00 m, which corresponds to water forces which are larger than the weight of the stones of the dike revetment. The upward water pressures are the largest at the toe of the dike.
A team of coastal experts have studied the dike and came to the conclusions that the crest height of the sea dike is too low and that the stability of the dike revetment is not guaranteed.
In order to increase the safety level of the dike, a beach nourishment was carried out in 2004: 718300 m³ sea sand have been dumped on the beach. Large infrastructure works (a.o. construction of breakwaters,…) are planned in near future to deal with this problem

definitely. When these works are finished, Oostende will be protected to withstand a design storm with a return period of 1000 year.

The safety of the whole Flemish coast is checked on a regular basis. Within the COMRISK project (2002-2005) a risk assessment of the Flemish coast and the coast of Zeeland-Flanders has been carried out. Within this risk assessment a number of failure modes of sea dikes have been investigated: erosion of dike revetment on the outer slope by wave action, wave overtopping and overtopping of water by excessive water level and consequently erosion of inner slope, piping and heave, loss of stability by overall sliding of the inner slope and/or the outer slope. It was concluded that for a storm with a return period of 1000 years no failure is to be expected. For a storm with a return period of 4000 years, four locations along the eastern part of the Flemish coast can suffer breach formation. Due to the residual strength of the sand core of the dikes, all locations could survive the first peak of the storm, but all fail within the second peak of the design storm.

However, a major problem in determining the overall stability of the dikes is the knowledge of the soil conditions and the water level. The stratification of the subsoil was, due to a lack of sounding and drilling information, not known. Whereas the sea water level in front of the dike was known, a number of assumptions had to be made to define the phreatic (and in occurring case artesian) water level in the dike core. It is this water level which can make the difference between stability and instability: a higher water level (higher pore water pressures) implies lower effective stresses and thus lower shear resistance.

From 2004 on about 200 soundings and 40 drillings have been carried out along the Belgian coast in order to get to know more about the subsoil conditions of the Flemish dikes.

In 2007 and 2008 a large measuring campaign has been set up to monitor ground water level in the sea dikes. In the boreholes, divers have been suspended and measured ground water level variations in the core of the dikes. In several boreholes more than one diver was installed because of two reasons. Firstly, a diver is an instrument which measures pressure and temperature and when the diver is submerged, it measures both water and atmospheric pressure. To eliminate the atmospheric pressure, a second diver is suspended in the borehole above the water level. Secondly, to measure not only water level variations in the upper sand layer, but also in the deeper artesian sand layers, more than one submerged diver is used.

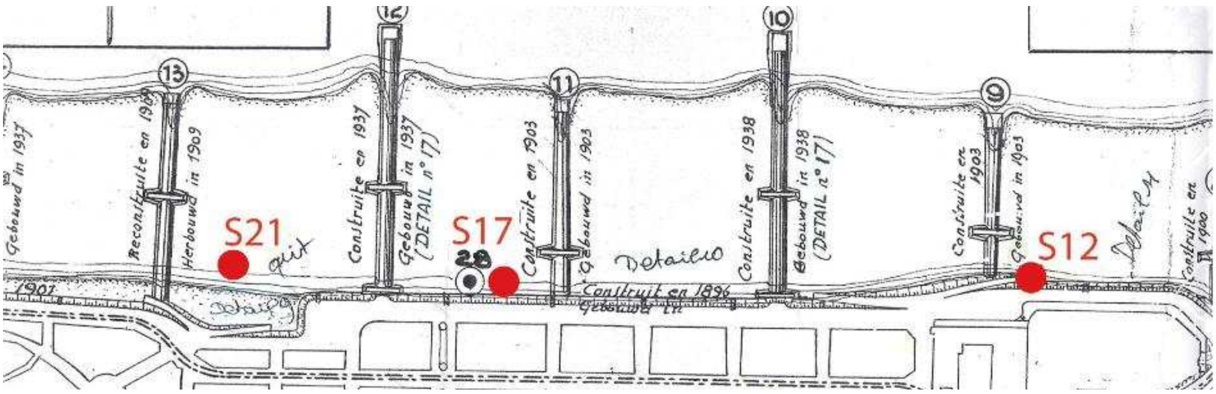

Figure 1: Plan view of dike and beach with groynes in Oostende with indication of selected locations S12, S17 and S21.

Though interesting information is obtained with this instrument, no information is found about the spatial variations of the ground water level in the sea dike.

Three locations in Oostende have been selected for detailed data analysis: S12, S17 and S21. Figure 2 shows the location of S12, S17 and S21 on a map.

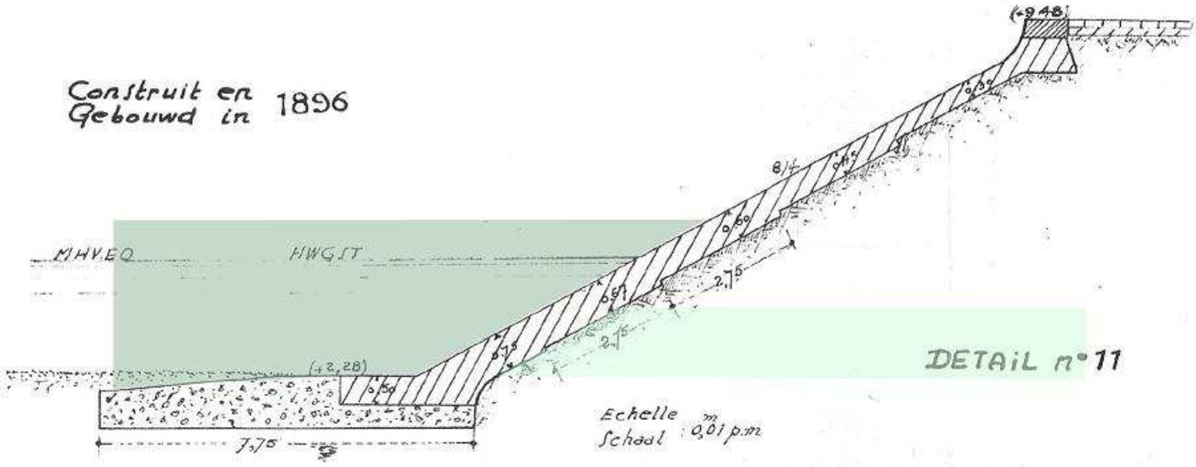

Figure 3: Cross section of dike at location S12 in Oostende.

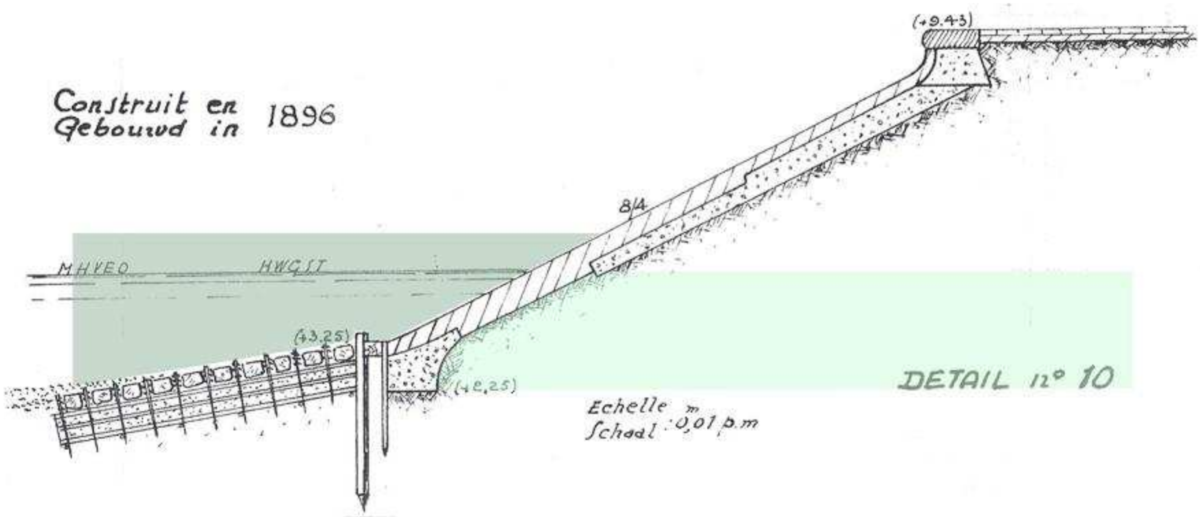

Figure 4: Cross section of dike at location S17 in Oostende.

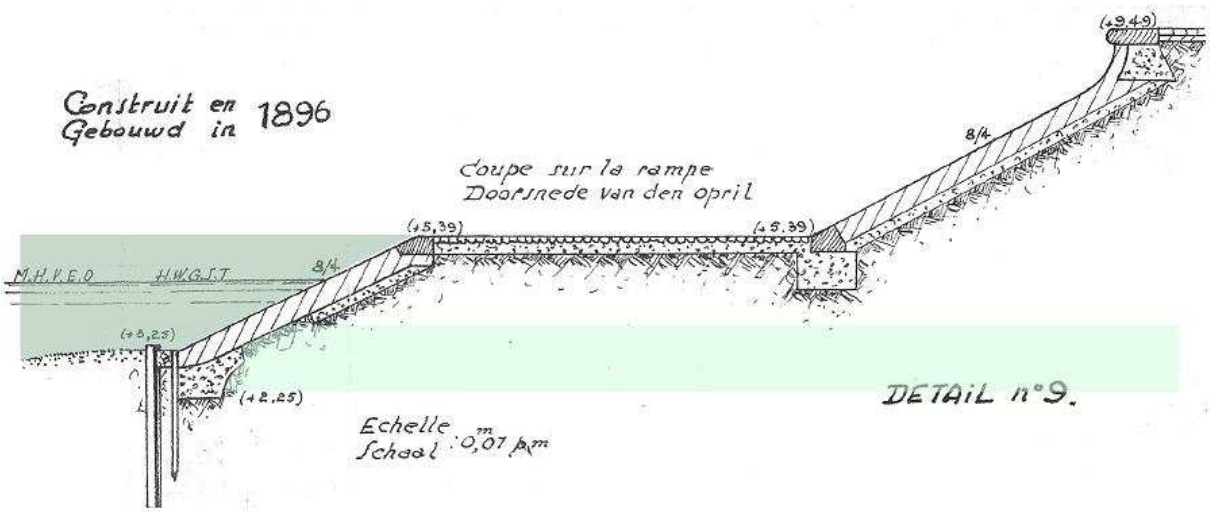

Figure 5: Cross section of dike at location S21 in Oostende.

Dike cross section
Figures 3, 4 and 5 show the cross section of the old dikes (19^{th} century) at the selected locations S12, S17 and S21. The dike revetment at all locations consists of regular stones on a slope of 1:2. The total height of the dike is 7,20 m at S12, 6,18 m at S17 and 6,24 m at S21. At location S21 a slibway has been constructed. Under the present conditions, beach sand is put against the dike revetment.

Subsoil
The subsoil at the three selected locations is made up based on the soundings and drillings at these locations (figure 6). These can be found on Databank Ondergrond Vlaanderen (DOV, http://dov.vlaanderen.be) which is a database with all data related to the Flemish subsoil (geology, geotechnics, hydrology,…). It is seen that at locations S12 and S17 the major component of the soil is fine sand. Other substances are shell grit and (little) clayey particles. At S17 a clay layer is found fine sand is found within the upper layers, whereas at location S21 a one meter thick clay layer is detected at a depth of 16 to 17 m. The subsoil at location S21 is completely different from the subsoil at S12 and S17, though S21 is only a couple of hundred of meters away from the other locations. A lot of clay is found in the subsoil.

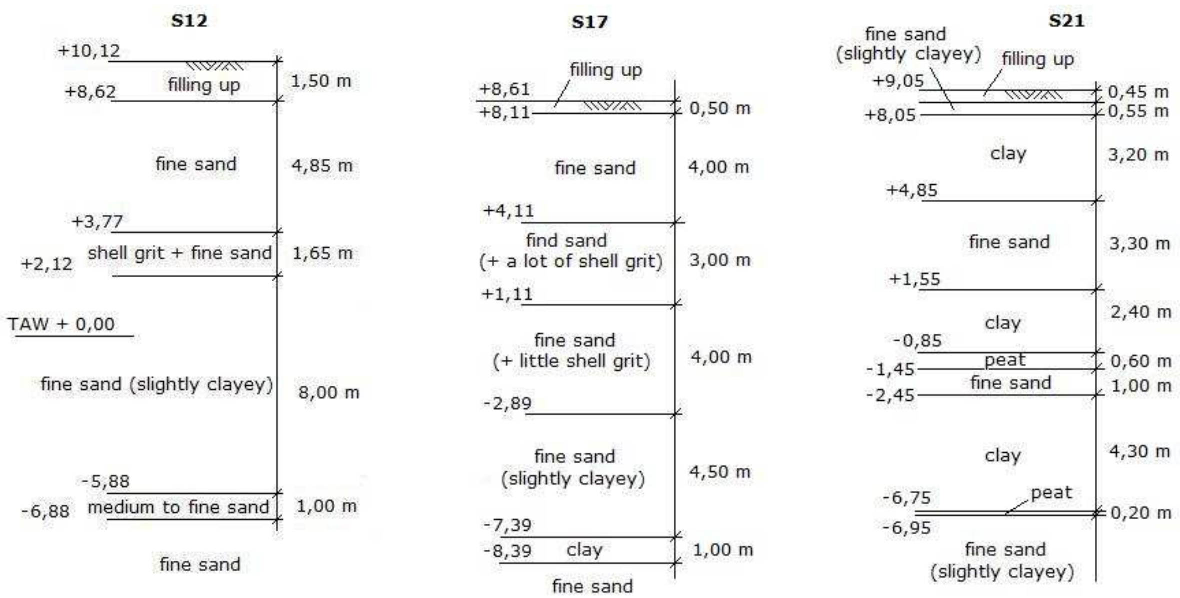

Figure 6: Subsoil at locations S12 (ground level at +10,12 m TAW), S17 (ground level at +8,61 m TAW), S21 (ground level at +9,05 m TAW).

Instrumentation
Sea level measurements (tide) are measured at fixed locations at sea in front of the coastline and in the harbour of Nieuwpoort, Oostende en Zeebrugge (figure 7).

Tide measurements are online available through the Flemish Monitoring Network. The Flemish Monitoring Network is set up for real-time data acquisition of oceanographic (waves, tide, current and water temperature) and meteorological (wind, air pressure, air temperature and precipitation) data along the Belgian coast and on the Belgian continental shelf. It consists of measuring pillars and wave data buoys fitted with hydro-meteo sensors.

The tide along the Flemish coast is a semidiurnal tide with a period of 12 hours and 25 minutes. The mean tidal difference in Oostende is 3.88 m and varies from 4.20 m at spring tide to 2.97 m at neap tide.

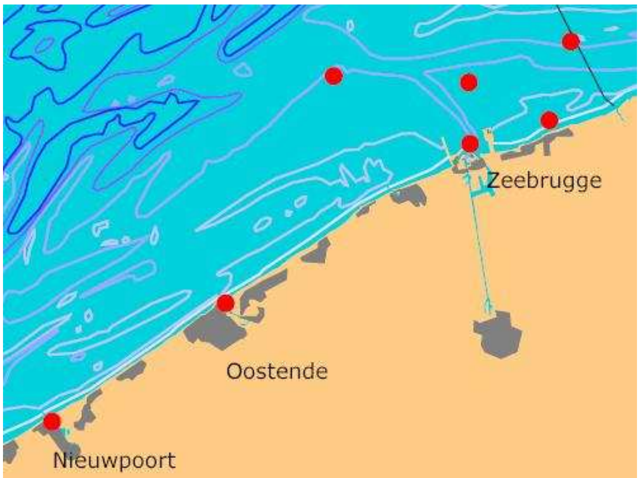

Figure 7: Location of tide measurement instrumentation along the Flemish coast.

At location S12, in the borehole (ϕ = 168 mm) two piezometers (ϕ = 63 mm) have been installed (figure 8). The first piezometer has a filtering element with a length of 2 m between +1.12 m TAW and +3.12 m TAW which is approximately at the soil layer with a lot of shell grit. The diver (furtheron called the 'shallow' diver) was installed at the bottom side of the filtering element (at level +0,98 m TAW). The second piezometer has a filtering element at a larger depth, between -6.12 m TAW and -8.12 m TAW, which is located at the soil layer with medium to fine sand. The diver (furtheron called the 'deep' diver) has been suspended at the level -0.05 m TAW.

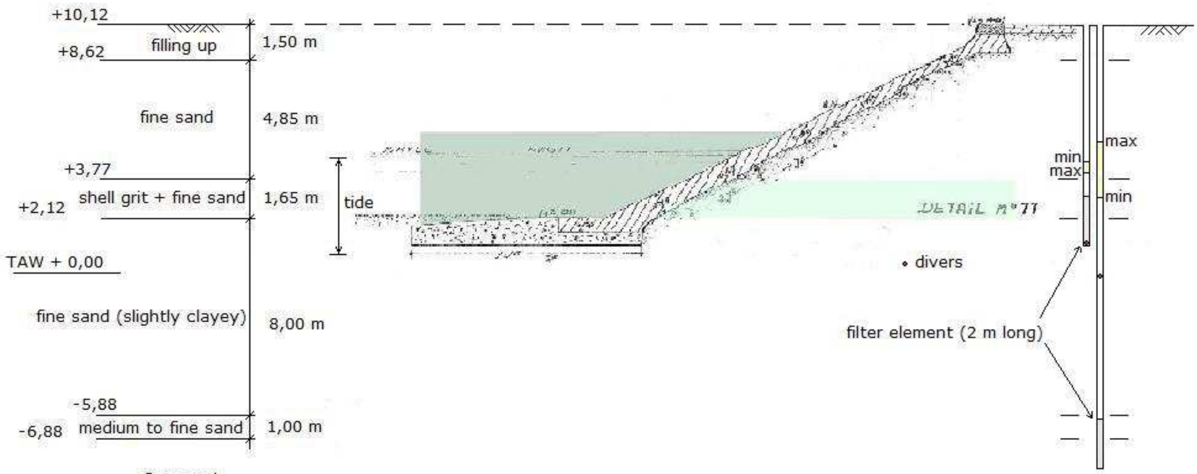

Figure 8: Subsoil at the selected locations S12, S17 and S21. Indications about maximum and minimum water level are based on observations from 5 February to 3 October 2007.

Measurement data

Figure 9 shows the measurement data of tide and both the deep and shallow divers at location S12 for the period from 3 to 14 March 2007. All time indications are referred to GMT. The deep diver at S12 measured a wave action in the ground water with the same period of the tide (i.e. 12h 25 min). At first sight, the hydraulic head in the dike core correspond to the hydraulic head at sea. But when we look closer to the data, it is seen that when water levels at sea are very high (peaking towards +5 m TAW), the hydraulic head in the dike is a little bit smaller than the hydraulic head at sea. When water levels at sea are rather small (about 3.5 m TAW), the hydraulic head in the dike are larger than the hydraulic head at sea. Furthermore it is noticed that when tide is out and water levels at sea are decreasing to +0,00 to +1,00 m TAW, the hydraulic head in the dike is not decreasing to the same level. The hydraulic head in the dike core always remain constant at (on average) +3,27 m TAW, there is some kind of 'rest' hydraulic head.

The shallow diver at S12 did not measure any wave action. The water pressure in the highly permeable soil layer (fine sand with a lot of shells) approximately remains constant at a level 4,29 m TAW and only varies between 4.20 m and 4.34 m.

The pressure wave measured by the deep diver in S12 was detected at a depth of (on average) 17 m below the surface level on the dike. The shallow diver in S12 did not measure a pressure wave at a depth of 8 m below the surface level on the dike. The soil between the two divers is fine sand. One should expect that water level variations in the upper soil layers also vary with tide. It is not clear yet what causes the 'rest' hydraulic head and why the level of this 'rest' hydraulic head is smaller than the level of the hydraulic head measured by the shallow diver in S12. At the level +3,27 m TAW there is no special soil layer.

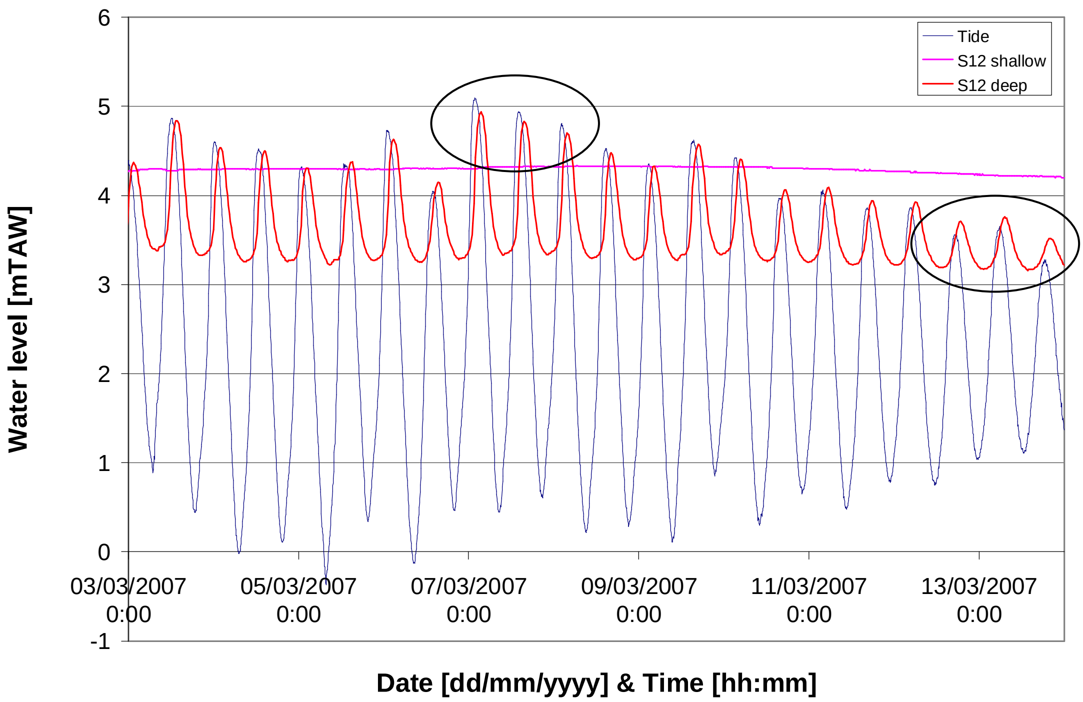

Figure 9: Tide and diver (deep and shallow) measurements at location S12 (3 to 14 March 2007).

Figure 10 shows a detailed example of the tide measurements (solid line) and the measurements of the (lower) diver in borehole S12. It is seen that there is an attenuation of the amplitude of the water level variation at sea to the water level variation in the dike. The time of maximal water level at sea does not correspond to the time of maximal water level in the dike: there is a phase shift. Maximal (resp. minimal) water level at sea always runs ahead maximal (resp. minimal) water level in the sea dike.

At the location S17, also two divers have been installed in two piezometers. The first piezometer has a filtering element between +2,11 m TAW and +4.11 m TAW (which is in the soil layer consisting of fine sand and shell grit). The level of the diver is +1,77 m TAW. The second piezometer has a filtering element between -9,39 m TAW and -11,39 m TAW (which is under the one meter thick clay layer). The level of the diver is -0,60 m TAW. Again, the hydraulic head measured by the deep diver is varying with tide (figure

11). Though the hydraulic head wave is somewhat damped compared to the tidal wave. Again, there is a threshold value for the hydraulic head: when sea level is decreasing, the hydraulic head in the soil does not drop below a certain level. It is also seen that when tidal variations at sea become small, the measurements of the shallow diver slightly decrease. This can also be noticed in the measurements of the shallow diver at location S12.

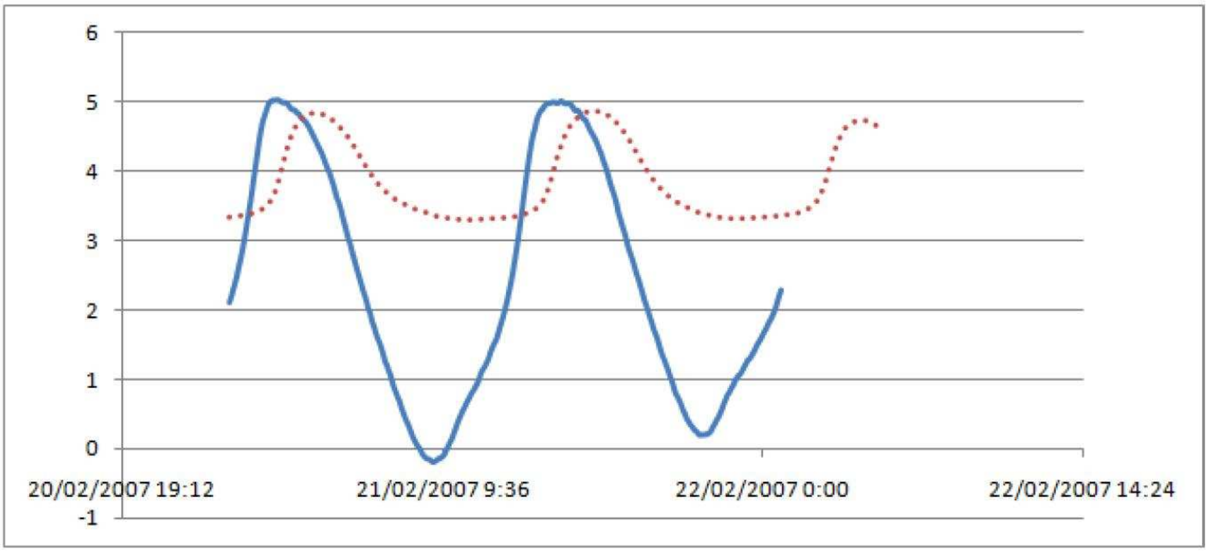

Figure 10: Detailed example of tide measurements (solid line) and diver measurements (dotted line) at location S12.

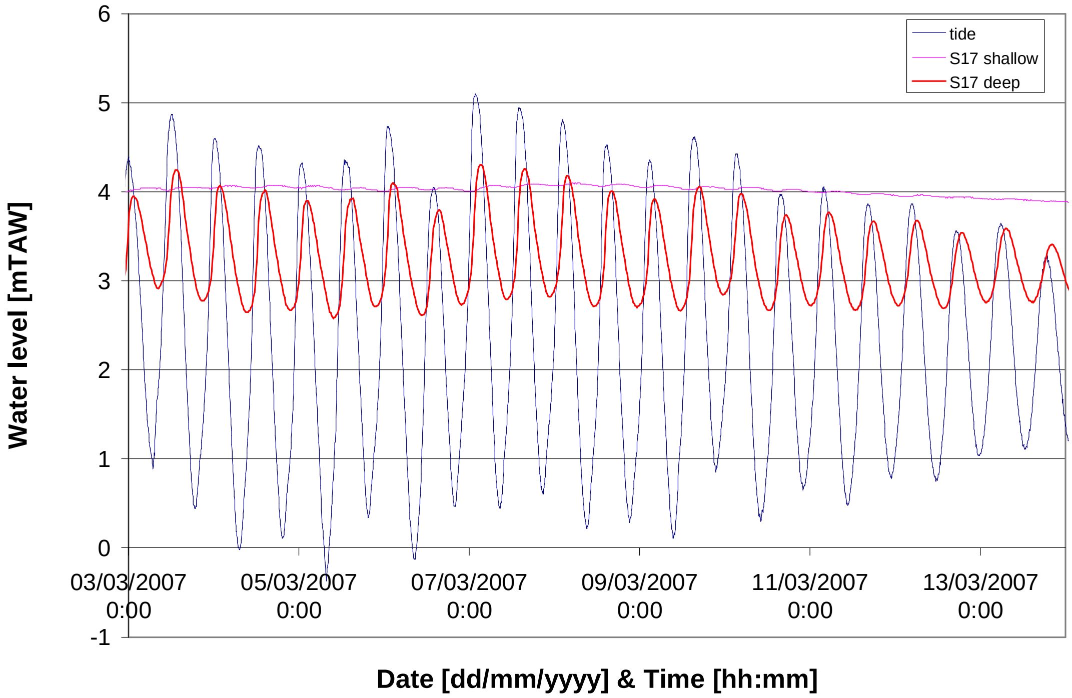

Figure 11: Tide and diver (deep and shallow) measurements at location S17 (3 to 14 March 2007).

The borehole at location S21 contains two piezometers. The first piezometer has a filtering element between +2,05 m TAW and +4,05 m TAW, which is in the artesian sand layer in between two clay layers (see figure 6). The (shallow) diver is located at the level +1,96 m TAW. The second piezometer has a filtering element between -8,95 m TAW and

-6,95 m TAW, which is the layer of fine sand underneath a clay layer (see figure 6). The (deep) diver is located at -0,66 m TAW. It is seen that the hydraulic head in the artesian sand layer is not affected by tidal variations, though tide varies between the boundary levels of this sand layer (figure 12). The hydraulic head measured in the lower sand layer shows tidal variations with a phase shift that is larger than observed at locations S12 and S17, though, the amplitude is much smaller. Again, hydraulic heads measured by the deeper diver do not underspend a certain level (~ +2.70 m TAW).

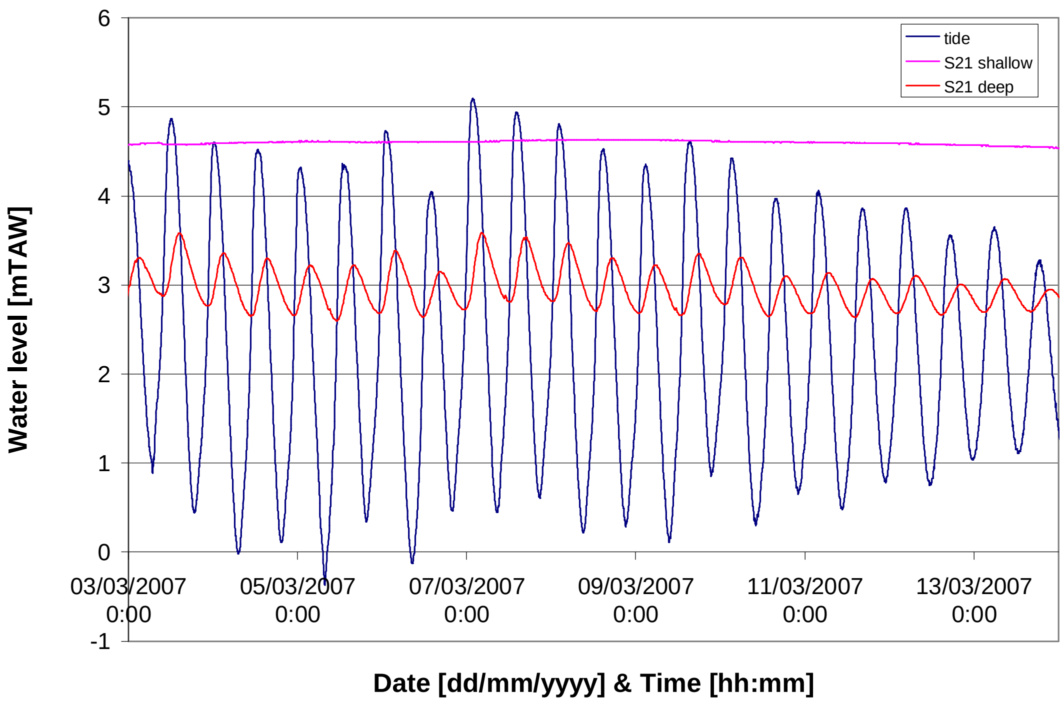

Figure 12: Tide and diver (deep and shallow) measurements at location S21 (3 to 14 March 2007).

Data analysis

Two parameters have been calculated: the attenuation and the phase shift. All analysis has been performed in time domain.

The attenuation A of one single wave in a wave train is defined as

$$A = 1 - \frac{a_s}{a_d}$$

with
- a_s [m] = (positive) amplitude of the tidal wave measured by the tide gauge
- a_d [m] = (positive) amplitude of the wave measured by the diver in the borehole in the dike

In the analysis all waves have been treated one by one. For every single wave event a value for A is obtained. The average of all A-values within a time series is $\overline{A}$. The standard deviation of the attenuation is σA.

The phase shift ϕ is defined as the difference in time between the moment of maximal water height at sea and the moment of maximal water height in the core of the dike. For every single wave event, a value of ϕ is calculated. The average of all ϕ-values within a time series is $\bar{\phi}$.

Analysis results
For a number diver measurements the relation between ground water level variation and tidal movements has been investigated through the attenuation and the phase shift. Tabel 1 shows the preliminary results of the analysis. It is seen that the tidal waves are transmitted in the dike core and that only little energy losses are noticed: the attenuation factors along the coast vary between 0,691 and 0,971. The values of the standard deviation are quite small (95% of the A-values is situated within the interval [$\bar{A}$-2σ, $\bar{A}$+2σ]).

The phase shift varies between 01h12'42" at Wenduine (S6) and 03h12'59" at Blankenberge (S6). Latter value indicates that when water level at sea starts decreasing from high water, pore water pressures in the dike are still increasing and reach their maximum value when water level at sea is already at mean sea level. This also occurs at Oostende in S21 and S33.

Table 1: Analysis results.

Location		$\bar{A}$ [-]	σ_A [-]	Phase shift φ [h/min/sec]	σ_φ [hh:mm:ss]
Nieuwpoort	H5	0,739	0,016	01h42'41"	00:14:29
Westende	S82	0,851	0,011	02h40'33"	00:32:36
Westende	S75	0,854	0,014	02h17'01"	00:42:02
Oostende	S33	0,881	0,008	03h03'42"	00:29:21
Oostende	**S21**	**0,854**	**0,011**	**03h07'31"**	**00:28:15**
Oostende	**S17**	**0,691**	**0,011**	**01h44'07"**	**00:21:50**
Oostende	**S12**	**0,728**	**0,035**	**01h38'21"**	**00:16:12**
Oostende	S1	0,921	0,005	02h26'33"	00:20:30
Wenduine	S8	0,835	0,010	01h26'21"	00:20:21
Wenduine	S6	0,869	0,008	01h12'42	00:14:05
Wenduine	S5	0,850	0,010	01h36'57"	00:22:34
Blankenberge	S9	0,918	0,014	01h48'11"	00:35:19
Blankenberge	S6	0,903	0,012	03h12'59"	00:44:33
Zeebrugge	S2	0,971	0,005	02h27'23"	00:38:35

Conclusions
Ground water level measurements have been carried out in Flemish sea dikes by means of divers. Diver data have been compared to tide measurements at sea. Two parameters have been used for comparison: the attenuation factor and the phase shift.

It is noticed that tidal waves at sea propagate into the dike core and affect the ground water level. Comparing tidal waves and ground water level variations, little difference is notice (little energy has disappeared): the parameter $\bar{A}$ varies between 0.691 and 0.971. The phase shift varies between approximately 1 hour and 3 hours (which is a quarter of a tide cycle).

More research is needed to investigate the influence of the ground water level discharge from the hinterland towards the sea and meteorological influences (such as rain) on the ground water level. A measurement technique to measure water level variations in a cross sections in multiple points is searched.

Numerical (and physical) modelling could give insight in the governing parameters in ground water level variations due to tidal variations at sea. Also permeability of the dike revetment en width of the beach in front of the sea dike can have an influence on the water level movements in the core of the dike.

The penetration of salt sea water into the dike and the interaction with the sweet ground water needs to be investigated.

Acknowledgement
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