Abstract for the 18$^{\mathrm{th}}$ Physics of Estuaries and Coastal Seas Conference, 2016

In the footsteps of Lorentz: extending the network model of the Wadden Sea

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Keywords: Network models, Wadden Sea, Tide-surge modelling

Introduction Between 1918 and 1926 the State Committee on the Zuiderzee investigated the hydrodynamic effects of damming the Dutch Zuiderzee ahead of the prospected construction of the so-called Afsluitdijk. The State Committee, chaired by physicist and Nobel laureate H.A. Lorentz, developed a network model based on the governing equations of fluid flow, rather than on empirical relationships in order to assess the effects of the closure dam on the water motions in the Wadden Sea, due to both tide and storms. It was Lorentz' conviction that a thorough theoretical investigation was necessary for such a large-scale coastal engineering work (e.g. Mazure, 1963 and Kox, 2007) The limitations of the computing capabilities of the time forced a number of schematizations:

- the network approach, where only the flow in the gullies was considered;
- the water depth is represented by the mean water depth as the setup is assumed to be small in comparison to the mean water depth ($\zeta \ll h$), as a result also advective terms can be neglected;
- the bottom friction term , usually quadratic, was linearised giving a linear friction coefficient $r = \frac{8}{3\pi} c_D U$ (known as Lorentz' linearisation).

Beside a baseline model for the tidal motion, an even simpler storm surge model was developed that could only account for the equilibrium (steady-state) response to a steady wind forcing. The transient phase towards this equilibrium was thus ignored. Despite such simplifications the model results showed good agreement with measurements in consideration of the standards of the time.

The aim of this study is to extend the original model applied by the State Committee by including non-stationary wind forcing and non-linear dynamics in a network system. It is ascertained to which extent this modelling strategy provides useful insights in the transient behaviour of storm surges.

Reproducing the results of the State Committee First the original model is rebuilt and the results found by the State Committee are reproduced. The left hand side of figure 1 shows the amplitude that the model predicts for the semi-diurnal lunar tide (M_2). One can see that the tidal amplitude is lower in the western part of the Wadden Sea and higher in the north-eastern part.

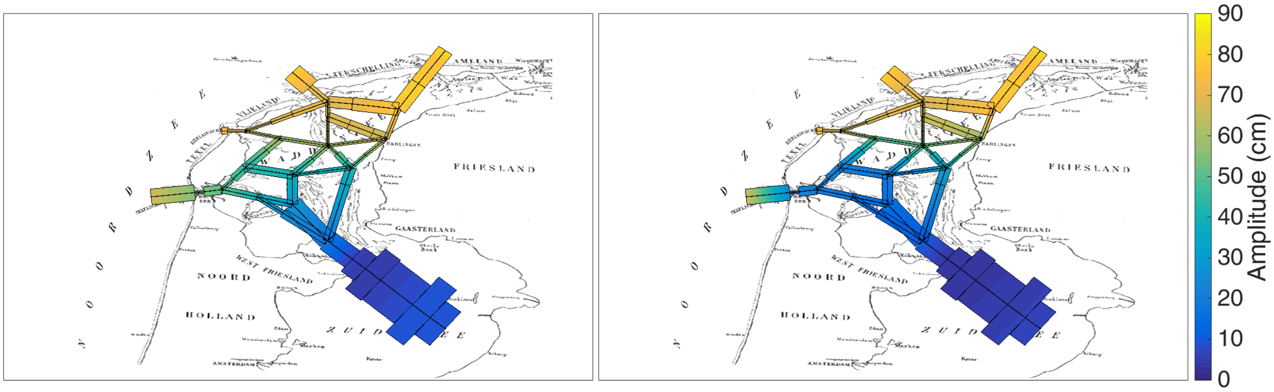

Figure 1: Modelled amplitude of the semi-diurnal lunar tide (M_2) computed with a linear friction coefficient r that is based on guesses of the velocity scale (left) and determined iteratively (right).

Iterative friction Secondly we investigated what results are obtained when the linearised friction coefficient r is determined iteratively. In the original calculations the linear friction coefficient is based on a velocity scale the value of which

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had to be guessed. Here we iterate to make sure that the velocity scale, used in the calculation of r, agrees with the velocity scale found in the actual solution. This was not feasible at the time.

The result of the tidal model with iterative friction is shown in the right panel of figure 1. This figure shows that the amplitude of the semi-diurnal lunar tide (M_2) differs especially in the western part of the network. Here the tidal amplitude resulting from iterative friction is several decimeters lower than the amplitude resulting from a constant friction. A similar but smaller effect can be seen in the southern part (representing the Zuiderzee) and eastern part (on the Frisian coast near Harlingen) of the network.

Non-stationary wind stress Next, a non-stationary model allows for a time dependent wind stress, whereby both wind speed and direction are allowed to vary in time. The solution method is based on Chen et al. (2015 & 2016) in which the time-dependent wind stress is written as a superposition of time-periodic signals at different frequencies using a discrete Fourier transformation. A solution is obtained for each frequency and, by linearity, a superposition of the solutions at all frequencies represents the actual storm surge in one channel. Following Lorentz, the Wadden Sea is represented as a channel network for which a system of linear equations is solved. Therefore the transient behaviour of storm surges can be studied through a combination of one-dimensional models. This is illustrated in figure 2, showing that the response exhibits characteristics of a relaxation phenomenon and tries to reach an equilibrium when wind forcing is applied. When the wind has vanished the water level gradually decays to a new equilibrium.

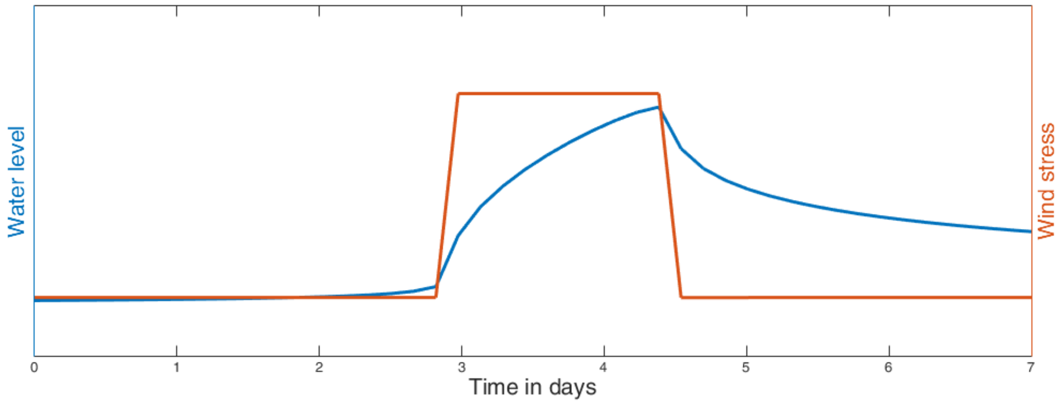

Figure 2: Transient response (blue line) to a steady wind pulse (red line).

Non-linear dynamics Finally we explore the role of non-linear effects using an expansion method similar to that in Alebregtse and de Swart (in press). This allows us to systematically investigate the internally generated overtides. The simplifications that the original model is based on are becoming less realistic under storm conditions — i.e. the water level elevation is not small in comparison to the mean water depth and linear friction becomes less accurate with higher flow velocities. Therefore a new model is formulated including non-linear dynamics thus avoiding the limitations mentioned previously. By including non-linear dynamics it becomes possible to investigate the effects of the simplifications that were made in the original model.

Conclusion We have revisited and extended the model that was used to investigate the hydrodynamic effects of damming the Zuiderzee. Iterative friction was shown to result in lower tidal amplitudes for the semi-diurnal lunar tide (M_2). Including non-stationary wind-forcing gave insights in the transient behaviour of storms, a relaxation phenomenon is encountered.

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