CHAPTER 65

The effect of waves on surges in the North Sea

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Abstract

Three effects of surface gravity waves on storm surges in the North Sea are studied with numerical models. The enhancement of the effective sea surface roughness due to growing waves causes the storm surge to build up more quickly. The maximum effect on the waterlevel along the English and Dutch coast is about 5 % of the total waterlevel elevation due to the storm. The effect of the radiation stress is opposite: it slows down the building up of the surge in the beginning of the storm. The maximum effect of the radiation stress is about 2 %. The enhancement of the bottom drag by swell in shallow water can be considerable. The lack of detailed insight in the local bottom roughness and the turbulence near the bottom defies a quantitative analysis.

1 Introduction

Waves influence both the generation and the decay of storm surges. In this paper three effects of waves on storm surges are discussed: the enhancement of the surface stress due to growing waves, the contribution of radiation stress and the enhancement of the bottom stress by swell in shallow water. During their generation, surface waves subtract this momentum from the atmospheric boundary layer. Some 60 to 90 % of the momentum transfer from the atmosphere to the currents goes via waves on the surface. This changes the structure of the atmospheric boundary layer. Until recently, the roughness of the sea surface was thought to be a function of the friction velocity only (Charnock, 1955).

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This leads to a drag coefficient which is roughly proportional to the windspeed. In recent years it has been shown by experiments, numerical simulations and analytical models that the sea state plays an important role in the transfer of momentum to the sea. If the waves extract a large amount of momentum from the atmosphere, which happens in the case of growing waves, the apparent roughness of the surface is enhanced. If on the other hand the phase speed of the waves is comparable to the windspeed and the waves do not grow, the roughness of the sea is relatively small. Since the growth of waves is concentrated in the first part of a storm, the generation of a storm surge will be enhanced during this period.

The second consequence of waves carrying momentum is that they are capable moving it around. In the equation for the total momentum balance, this gives rise to an additional advection term: the so-called radiation stress. At places where waves break or dissipate otherwise, this term can give rise to a wave set-up of several decimeters (Bertotti and Cavaleri, 1985) and long- shore currents (Battjes, 1974). Though this effect can be large locally, in this paper we will argue that on the scale of several tens of kilometres or larger it is of little significance. On that scale, to a very good approximation momentum goes directly from the atmosphere to the currents. This is caused by the fact that the waves carrying most of the momentum are short and dissipate quickly. Swell, which is capable of travelling a long way, carries little momentum compared to the short waves generated in the same storm.

Waves can also influence a storm surge via the bottom. If the depth of the water is comparable to the dominant wavelength, orbital wave motions reach to the bottom. This enhances the turbulent mixing near the bottom, which in its turn enhances the bottom friction felt by currents. The effect is largest in shallow regions which can be reached by swell from the open sea and where strong currents are present. In the North Sea this includes for instance the English Channel and the Bristol Channel. A few problems arise if we want to model this effect. The layer near the bottom where the orbital motions of the waves and the current interact is typically a few centimetres wide. No current measurements are available this close to the sea bed. This makes it impossible to verify theory directly. Another problem is the large variation in roughness of the seabed on the continental shelf. Compared to the errors made in the assumptions of these roughnesses the effect of the waves may be insignificant.

In the following sections the influence of waves on storm surges in the North Sea will be studied by numerical simulation. In section 2 the effect of growing waves on the storm surge elevations is discussed. The effect of the redistribution of momentum by waves is the subject of the following section. The last section focuses on the bottom roughness enhancement by long waves.

2 Effect of Waves on the Surface Stress

To simulate the elevations due to the tide and the storm a barotropic storm surge model of the continental shelf is used (Verboom et al, 1992). This numerical model solves the depth averaged Reynolds equation and the continuity equation with a resolution of 16 km. The waterlevels on the open boundaries, located in deep (> 200 m) water, are prescribed by 10 tidal constituents. The surface stress is derived from the wind at 10 meter calculated by a regional meteorological model. In the standard version the wind is related to stress using the Charnock relation: $z_0 u_*^2/g = \alpha$, where z_0 is the roughness length which determines the wind profile, u_* is the friction velocity, g is the gravitational acceleration and $\alpha = 0.032$ is a constant found by tuning the model. The windprofile is assumed to be logarithmic:

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

where $u(z)$ is the windspeed at height z and $\kappa = 0.4$ is the von Karman constant. For given windspeed at a certain height these two equations yield u_* and z_0. The definition $u_* = \sqrt{\tau/\rho_a}$ gives the windstress τ.

To model the effect of waves on the momentum transfer the theory described by Janssen (1992) was used. In this theory, Janssen assumes that the momentum is transferred to the water by the turbulence and via the waves. To calculate the contribution of the waves a wave model is needed. In this research a regional implementation of the third generation WAM model was used (WAMDI, 1988). In fig. 1 an overview is given of the three models involved: the meteorological model, the wave model and the storm surge model. In the theory of Janssen, waves act to increase the effective roughness of the surface in the following way:

$$z_e = \frac{z_0}{\sqrt{1 - \tau_w/\tau}}, \tag{2}$$

where the roughness length z_0 is given by the Charnock relation: $z_0 = \tilde{\alpha} u_*^2/g$ with $\tilde{\alpha} = 0.01$. The windprofile is given by:

$$u(z) = \frac{u_*}{\kappa} \ln(\frac{z + z_e - z_0}{z_e}). \tag{3}$$

The total stress is now calculated in the following way. First, the wind at 10 meters u_{10} is obtained from a meteorological model. Using a wave model, the flow of momentum τ_w to the waves is calculated with this wind. The equations (2), (3) and the Charnock relation give an implicit set of equations from which τ (or u_*), z_0 and z_e can be obtained. Sometimes it is necessary to repeat this procedure, since the wave stress τ_w depends on u_*. However, it converges very quickly and in practice no more than two iterations are required.

The coupled storm surge model has been compared with the standard version for several recent storm periods (Mastenbroek et al, 1992). Results from both versions have been compared with waterlevel measurements along the English and Dutch coast. It is found that the elevations calculated with the coupled model are in good agreement with measurements. This is important because it means that the description of the flow of momentum according to Janssen is consistent with the momentum balance of the waves. A more detailed analysis reveals that the drag coefficient, defined as $C_d = u_*^2/u_{10}^2$, can vary a factor two depending on the sea state. Growing waves, dominant during the first part of the storm, enhance the drag considerably. This is illustrated in fig. 3. Due to this enhancement of the momentum transfer in the first part of the storm, the storm surge builds up more quickly. The maximum difference between elevations calculated with the coupled model and the reference model is about 10 cm, which is about 5 % of the total elevation due to the storm. This small difference disappears in the noise caused by measurement uncertainties and errors in the numerical model.

3 Transportation of Momentum by Waves

Due to the fact that propagating waves carry some momentum with them, an additional advection term arises in the balance equation for the total momentum, the so-called radiation stress term. The total momentum is the sum of the momentum of the depth averaged current and the momentum associated with waves. In terms of the wave spectrum $F(f,\theta)$, where f is the frequency and θ the propagation direction, the radiation stress τ_i in deep water is given by:

$$\tau_i = \rho g \nabla_j \int_{-\pi}^{\pi} \int_0^{\infty} \{\frac{c_g}{c}\frac{k_i k_j}{k^2} + (\frac{c_g}{c} - \frac{1}{2}\delta_{ij}\} F(f,\theta) df d\theta. \tag{4}$$

In the numerical experiment discussed here, the radiation stress is calculated from the wave spectrum of the regional WAM model mentioned above. It is then subtracted from the wind stress. The calculations show that the waves transport away less than 5 % of the total stress applied by the atmosphere. The rest either goes directly to the currents by means of a tangential turbulent stress or via waves that dissipate within one time interval (3 hours) between to consecutive windfields in the same gridbox where they were generated. In the case of the storm of 12/13 December 1990, dissipating waves exert a force on the water of up to 0.15 N/m^2 for a period as long as 12 hours on the Doggerbank. This corresponds to a windspeed of more than 10 m/s. This leads, in the case this storm, to an extra current of 3 cm/s to the South West on the Doggerbank and to an increase in the waterlevel along the English South East coast and the Dutch coast of 5 cm. During the storm of 13/14 February 1989, when the maximum winds were directed more to the East, the maximum force exerted by dissipating waves on the watercolumn occurred in the German Bight, raising the waterlevel a few centimetres along the German coast. Unfortunately these differences are small compared to the accuracy of the surge model and the measurements. The comparison of waterlevel measurements and calculations does not lead to conclusive evidence in favour or against the phenomenon discussed here.

4 Effect of Waves on the Bottom Stress

In most 2D storm surge models the bottom stress τ_b is parametrised like $\tau_b = \rho_w f_c \bar{u}^2$, where $\bar{u}$ is the depth averaged current. The bottom friction coefficient $f_c \simeq 0.0025$ is constant. From recent experiments (Gross et al, 1992) it is known that waves have an important influence on this coefficient. A theoretical model of the effect of the orbital motions of waves on the turbulence near the bottom is given by Christoffersen and Jonssen (1985). For typical values for the North Sea, this theory predicts a significant variation of the bottom stress depending on the sea state. To model the effect of waves on the turbulence near the bottom, first an assumption has to be made for the turbulence in absence of waves. A convenient assumption is to parametrise the vertical exchange of horizontal momentum with an eddy viscosity μ:

$$\tau = \rho_w \mu \frac{\partial u}{\partial z}. \tag{5}$$

The assumption that this eddy viscosity is proportional to the distance to the bottom $\mu = \kappa u_* z$ leads to a logarithmic velocity profile $u(z) = (u_*/\kappa)\ln(z/z_0)$. The profile depends on an integration constant z_0 which is usually associated with the roughness of the bottom. If the profile is integrated over the depth h, it can be found that the bottom friction coefficient equals:

$$f_c = \frac{\kappa^2}{(\ln(h/z_0) - 1)^2}. \tag{6}$$

Note that the assumption f_c =*constant* implies that the bottom roughness z_0 is proportional to the water depth. The amplitude of the orbital motions at the bottom of a wave with amplitude a are $u_w = (a\omega)/\sinh(kh)$, where ω is the angular frequency and k the wavenumber. This periodic motion causes an enhancement of the turbulent viscosity near the bottom in a region (the so-called *wave boundary layer*) which is typically a few centimetres wide. The apparent roughness felt by the current will be enhanced, leading to an enhancement in the bottom friction coefficient. In fig. 2 the bottom friction is given as a function of the wave height for a set of parameters which are typical for the North Sea.

In order to study the sensitivity of a storm surge model to a wave dependent bottom drag, a storm surge model (Flather, 1984) has been coupled to a wave model. If the results of this coupled model are to be compared with results from the conventional model, we have to assume that the roughness z_0 is proportional to the depth. This is not based on a physical consideration, but it is implied by taking the bottom drag coefficient f_c constant in the conventional model. The calculations were performed for the storm surge which occurred 1 February 1983. Two regions on the continental shelf seem to be specifically sensitive to a wave dependent bottom drag: the English Channel and the Bristol Channel. Both of these regions are relatively shallow, have an open connection to the sea and sustain large currents. On the Doggerbank, which is shallow and experiences large waves from the North, the drag coefficient is affected considerably. But on this location the currents are small, so the extra energy loss to the bottom due to the waves is small.

To make a quantitative analysis rather than a qualitative, several problems should be solved. First of all the modelling of the turbulence in the watercolumn in absence of waves should be made more sophisticated, specifically near the bottom. This will require a three dimensional model. Second, to test and calibrate theories such as the one discussed above, turbulence measurements near the bottom are needed. The interaction with ripples and other features on the bottom should be examined. Finally a bottom roughness map should be compiled for all relevant shallow areas.

5 Conclusions

- Growing wind sea enhances the wind stress in the beginning of the storm considerably. After a few hours this enhancement disappears. In the case of the North Sea, the maximum effect on the water level is about 5 % of total elevation due to the storm.
- In a growing sea, the radiation stress modifies the wind stress no more than 5 %. When swell generated in the Norwegian Sea reaches the shallow parts of the North Sea a radiation stress can be as large as 0.15 N/m^2. The maximum effect on the waterlevel along the English and Dutch coast is about 2 % of the total elevation due to the storm.
- The modification of the bottom stress by waves is important in shallow regions which can be reached by swell and which sustain large currents. Specific knowledge about the local bottom roughness and turbulence near the bottom is needed to make quantitative statements.

References

[1] Battjes, J.A. (1974) Computation of set-up, longshore currents, run-up and overtopping due to wind-generated waves, *Comm. on Hydraulics, Dept. of Civil Eng., Delft Univ. of Techn.*, No. 74-2.

[2] Bertotti, L. and L. Cavaleri (1985) Coastal set-up and wave breaking. *Ocean. Acta*, **8**, No. 2, 237-242.

[3] Christoffersen, J.B. and I.G. Jonsson (1985) Bed friction and dissipation in a combined current and wave motion. *Ocean Engng*, **12**, No 5, 387-423.

[4] Flather, R.A. (1984) A numerical model investigation of the storm surge of 31 January and 1 February 1953 in the North Sea. *Quart. J. of the Royal Met. Soc.*, **110**, 591-612.

[5] Gross, T.F. et al (1992) Estimation of stress and bed roughness during storms on the Northern California Shelf. *Cont. Shelf Res.*, **12**, No. 2/3, 389-413.

[6] Janssen, P.A.E.M. (1992) Quasi-linear theory of wind wave generation applied to wave forecasting. *J. Phys. Oceanogr.*, **21**, 1631-1642.

[7] Mastenbroek, C., G. Burgers and P.A.E.M. Janssen (1992) The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer. *accepted for publication in J. Phys. Oceanogr.*

[8] Verboom, G.K., J.G. de Ronde and R.P. van Dijk (1992) A fine grid flow and storm surge model of the North Sea. *Cont. Shelf Res.*, **12**, No 2/3, 213-233.

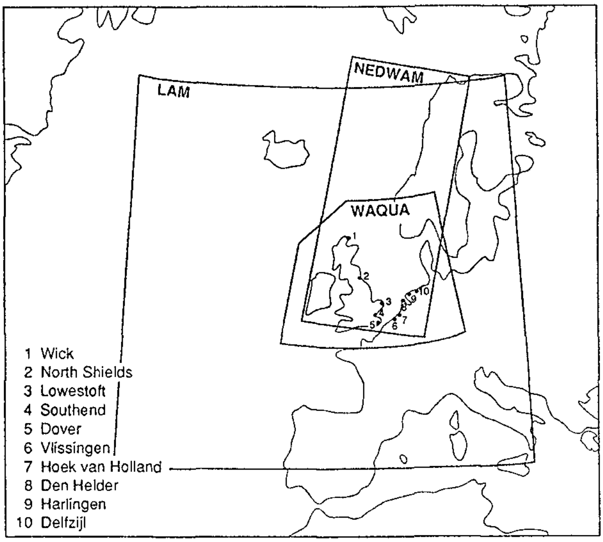


Figure 1: An overview of the areas covered by the meteorological model LAM, the wave model NEDWAM and the surge model WAQUA.

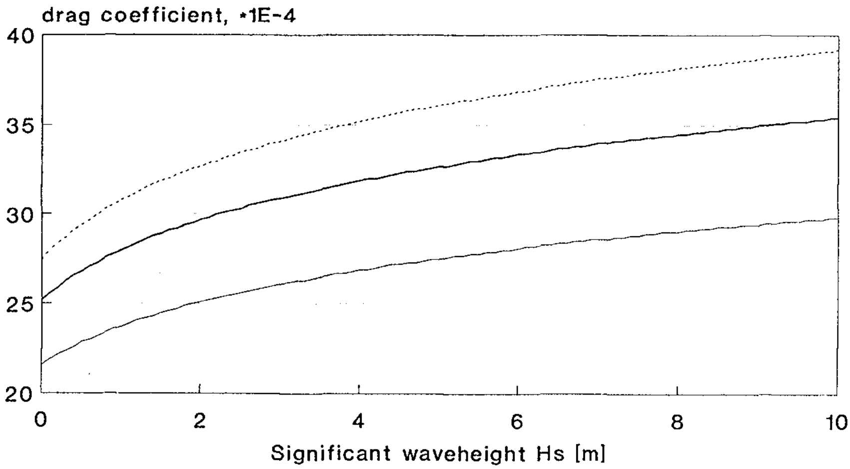
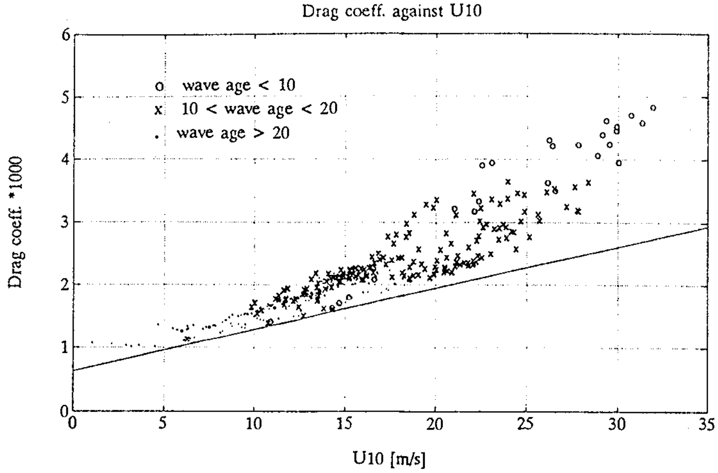


Fig. 3. Bottom drag coefficient f_c as a function of significant wave height for a typical North Sea case (depth is 40 m, wave period is 8 sec). The three line represent different sea bed roughnesses: z_0 is 5, 3.3 and 1.7 mm from top to bottom.



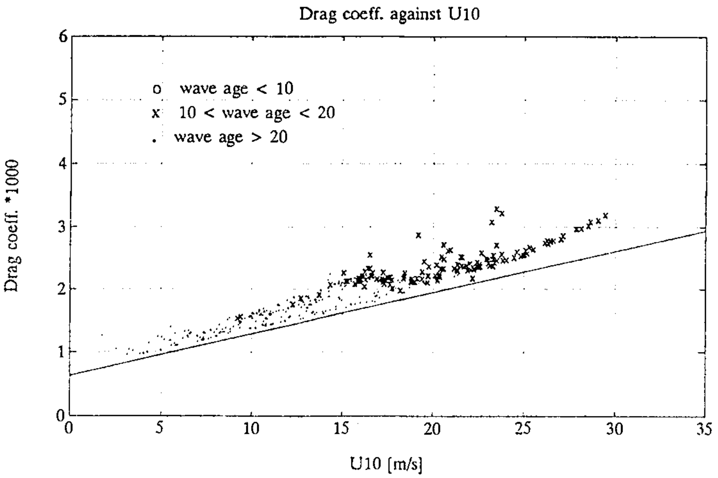


Figure 2: Scatter plots of the drag coefficient against windspeed at two different stages in the storm of 12 December 1990. Above, at the beginning of the storm, a lot of young sea is present. Below, 9 hours later, the waves are older. The wave age is defined as the phase velocity of the peak frequency divided by the friction velocity: c_p/u_*.