EXAMPLES OF STORM SURCE PREDICTION MODELS

by

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ABSTRACT

For a given site, deterministic models may be applied to predict the tide level with a rather good accuracy. However, a difference is observed between the observed and predicted tide level under storm condition. This difference is called storm surge. Two different storm surges prediction models are presented for the site of Le Havre : an autoregressive model ; a model using wind and pressure local data.

The autoregressive model can be used for a prediction 5 hours in advance. The availability of accurate wind and pressure predictions by the Meteorological Service of Le Havre within 36 hours in advance makes the use of the second model of great interest because it provides the possibility of predictions within 39 hours in advance.

1. INTRODUCTION

For a given site, deterministic models based on harmonic analysis may be applied to predict the tide levels with a rather good accuracy. However, differences are observed between the real and predicted tide levels under storm conditions. These differences are called storm surges (fig. 1).

In many cases, prevision of theoretical tide levels is not sufficient and it is very useful to know the possible storm surges. For instance, in coastal projects, the design of structures is often influenced by the largest storm surges possible. In that case, exceptionnal storm surges associated with a prescribed risk level are needed. On another side it is also useful to predict storm surges a few hours in advance, either for navigation aid, or to protect coastal work in progress.

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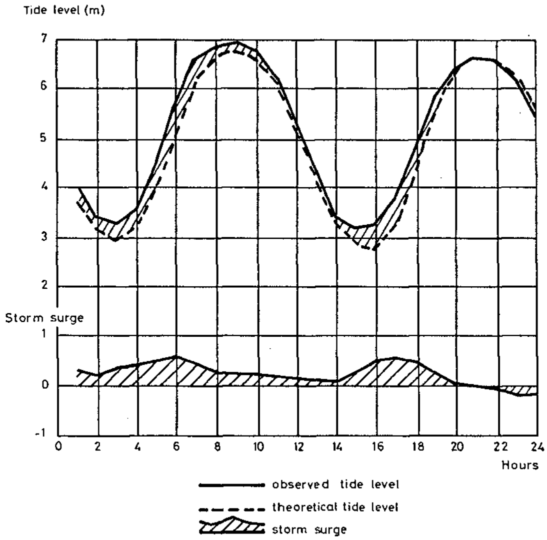

Fig.1_ DEFINITION OF A STORM SURGE

The present study is specially devoted to this second kind of prediction models, applied to the site of Le Havre (harbour of the Seine Estuary), but results obtained may be also used to predict exceptionnal storm surges by the mean of simulation.

The following steps of the study are described :

- analysis of storm surges, from the tide levels observed every hour on the site of Le Havre, from January 1976 to June 1978,
- elaboration of two storm surges prediction models :
  - . an autoregressive model, where the storm surge at the time t + k t is estimated knowing storm surges until the time t,
  - . a model using wind and pressure local data, these variables being available from Meteorological Services with 36 hours prediction.

2. ANALYSIS OF STORM SURGES RECORDED AT LE HAVRE

Storm surge is the algebraic difference between the real and predicted tide levels. The analyzed data set of storm surges resulted from tide levels recorded, every one hour, at Le Havre harbour from the 1/1/1976 to the 30/6/1978 and tide levels predicted by the S.H.O.M. (Marine Hydrological and Oceanographical Service), giving 21 888 values.

Graphic examination of storm surges and corresponding wind and pressure data, give the main tendancies of the phenomenon (fig. 2).

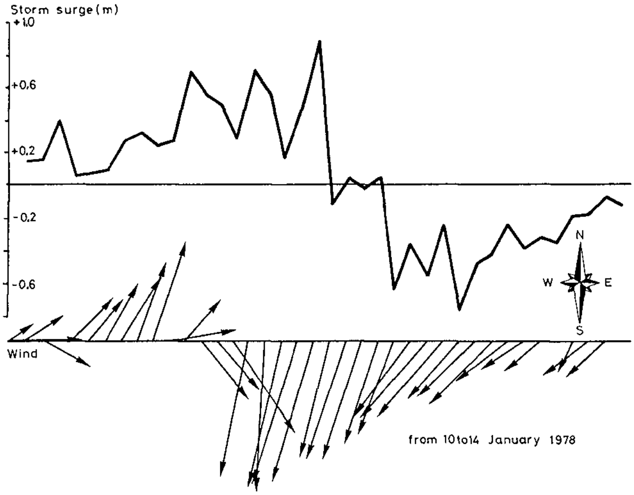

Fig.2_ COMPARISON BETWEEN STORM SURGE AND WIND

A quiet meteorological situation induces low storm surges. A low pressure and a strong intensity of wind raises high positive storm surges, with a 12 hours period (tide cycle). The maximum of the storm surge is generally situated around mean water level showing that the effect on tide may be seen as an increase (or decrease of mean water level) and a phase shift of the theoretical tide. To a high pressure corresponds negative storm surge.

Spectral analysis and autocorrelation functions of these storm surges (fig. 3 & 4) confirm the 12 hours period. Moreover three scales of time appear from the spectral analysis (6 hours, 12 hours and period greater than 24 hours). Autocorrelation functions show the high correlation between two values of storm surges separated by a short interval of time ; this is at origin of autoregressive model.

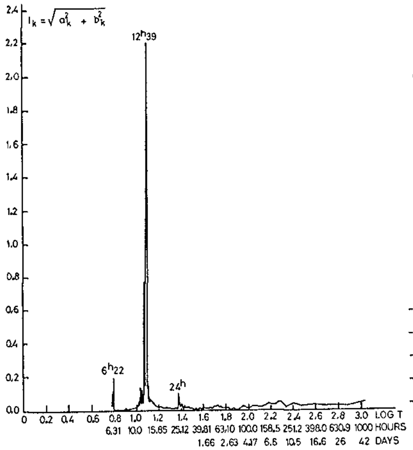

Fig.3_ SPECTRAL ANALYSIS OF STORM SURGES

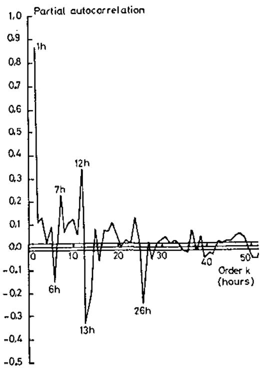

Fig.4_PARTIAL AUTOCORRELATION FUNCTION

3. <u>AUTORECRESSIVE MODELS</u>

In autoregressive models the storm surge at the time $t + k\Delta t$ is estimated knowing storm surges until the time t. The examination of autocorrelation function and partial autocorrelation allowed to retain the following regressive models :

$$\hat{S}\ (t + k\Delta t) = C_0\ (k\Delta t) + C_1\ (k\Delta t)\ S\ (t + k\Delta t - 12) + C_2\ (k\Delta t)\ S\ (t) \qquad (1)$$

where
- $\hat{S}$ predicted storm surge
- S observed storm surge
- $k\Delta t$ prediction time (1 to 12 hours)
- C_i model coefficient, function of $k\Delta t$, estimated from the totality of available observations (January 1976 to June 1978, 21 900 values), by least square method.

The multi correlation coefficient decreases when $k\Delta t$ increases. Four values of $k\Delta t$ were tried, respectively 1, 3, 6 and 12 hours. Multi correlation coefficients range between 0,89 with a 1 hour prediction and 0,68 with a 12 hours prediction.

The introduction of a Kalman filter was tried in this autoregressive model but did not give any better short term prediction.

Interest of Kalman filter is to use the last available observation to put model parameters straight. But autoregressive models also take into account this information and this can explain that for a short-range forecast model, Kalman filter does not improve results.

With or without Kalman filter multi correlation coefficient with a 1 hour prediction is 0,89. In 95 cases on 100, prediction error is $\pm$ 0,15 m. Figure 5 give a comparison between observed storm surges and predicted storm surges obtained by the autoregressive model with a 1 hour prediction.

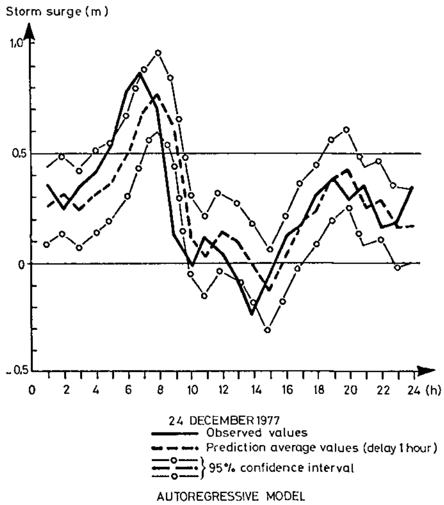

Fig.5. COMPARISON BETWEN OBSERVED AND PREDICTED STORM SURGES

4. MODEL USING WIND AND PRESSURE LOCAL DATA

Previous models cannot be really used with a prediction period greater than 12 hours.

A data analysis has shown that wind and local pressure data are able to explain the storm surges. The main interest to predict storm surges using these meteorological factors is that these variables can be given by Meteorological Services with a 36 hours prediction. Models based on wind and pressure data were then developped.

Spectral analysis of storm surges, pressure and wind at Le Havre was made. We considered the two components of wind, projected on rectangular axis ; E-W - 30° and N-S - 30°, these directions allowing the best correlation between wind and storm surge.

In this prediction model, the storm surge S has been splitted in 3 parts, according to spectral analysis and graphic examination of storm surges and concomitant meteorological data

$$S = S_1 + S_2 + S_3$$

S storm surge

S_1 storm surge corresponding to periods greater than 24 hours highly depending on recent meteorological events (wind, pressure)

S_2 storm surge corresponding to periods between 6 and 24 hours corresponding to tide periodicity. This cycle comes from a phase shift on tide theoretical cycle induced under some meteorological conditions (low pressure)

S_3 storm surge corresponding to periods smaller than 6 hours.

Standard deviations are respectively :

$\sigma(S) = 0{,}17$ m

$\sigma(S_1) = 0{,}14$ m $\quad \sigma(S_2) = 0{,}08$ m and $\sigma(S_3) = 0{,}05$ m

the most important part comes from S_1.

Each component is separatedly examinated.

4.1. <u>Component S_1</u> (period greater than 24 hours)

For a given class of wind direction, S_1 is computed from wind intensity and pressure by the following regression model :

$$\hat{S}_1(t) = a_o(\alpha) + a_1(\alpha)\ V(t-3) + a_2(\alpha)\ V^2(t-3) + a^3(\alpha)\ P(t-3) \tag{2}$$

where :

α	wind direction (18 classes of 20°)
$V(t-3)$	wind mean intensity at the time t - 3 hours
$P(t-3)$	pressure at the time t - 3 hours, zero pressure level corresponding to 1 013 mbars
a_i	model coefficients, functions of wind direction.

The mean wind is determinated on 12 hours ; the two mean components EW and NS are computed as :

$$\overline{V}_{EW} = \frac{1}{5} \sum_{j=-2}^{2} V_{i-j} \cos \alpha_{i-j}$$

$$\overline{V}_{NS} = \frac{1}{5} \sum_{j=-2}^{2} V_{i-j} \sin \alpha_{i-j}$$

and the wind mean intensity

$$V(t) = \sqrt{\overline{V}^2_{EW} + \overline{V}^2_{NS}}$$

and its direction

$$\alpha(t) = \text{arc tg} \frac{\overline{V}_{NS}}{\overline{V}_{EW}}$$

Correlation coefficients between S_1 and P are highly significant and negative (this means S_1 increases while pressure decreases). Wind introduction allows increasing of multiple correlation coefficients.

Residue values, difference between real and estimated values of S_1 are biassed so that the model overvalues S_1 if S_1 is small and undervalues S_1 if S_1 is great. This is corrected by an empirical factor C

$$S = \hat{S}_1 + C$$

where :

$\hat{S}_1$ is given by regression model (2)

$C = 0,1\ (\sqrt{1 + 5\ \hat{S}_1} - 1)$ if $\hat{S}_1 > -\ 0,2$ m

$C = 0,1$ if $\hat{S}_1 < -\ 0,2$ m

In 95 cases on 100, the real value S_1 appears to be in the range of predicted $S_1 \pm 0,18$ m.

4.2. Component S_2 (periods between 6 and 24 hours)

Modelisation of S_2 is based on the time phase shift observed between real and predicted tide levels which can be detected from the presence in storm surges evolution of the tide periodicity. That induced cycle has zero value at high and low tide, extremum occuring during increasing or decreasing tide level.

This shape of the cycle of S_2 is confirmed if we consider the average of S_2 during a tide cycle in function of the pressure level (see fig. 6).

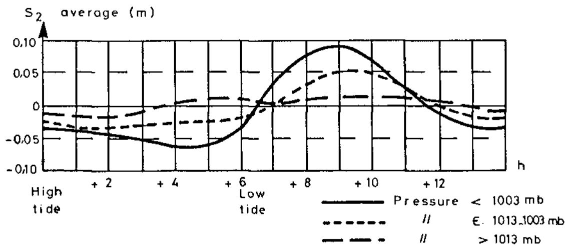

Fig.6. AVERAGE CYCLE OF S_2 FUNCTION OF THE PRESSURE LEVEL

Cycle is especially important for low pressures ; in opposite when pressure is greater than 1 013 mb, average of S_2 has pratically zero values.

The amplitude A of this cycle is computed in function of the pressure level, according to 3 classes, by the following relations :

- Low pressure P < 1 003 mb
  the amplitude A is function of mean wind (V_M, α_M), as previously defined

$$A = 0,153 + 0,014\ V_M \cos \alpha_M$$

  however if A < 0,15 m A = 0,15 m

- Mean pressure 1 003 < P < 1 013 mb
  the amplitude A is constant A = 0,14 m

- High pressure P > 1 013 mb
  in this case S_2 = 0

4.3. Component S_3 (periods smaller than 6 hours)

S_3 represents a white noise which is difficult to explain from wind and pressure, though its variability must be function of wind.

S_3 has been neglected in prediction.

4.4. Results

From comparison between real and predicted storm surges at the same time we can say, in 95 cases on 100, prediction error is :

$\pm$ 0,20 m if storm surge value is smaller than 0,20 m
$\pm$ 0,30 m if " " " " greater " "

Storm surges range being included between - 0,50 m and 1 m, this error can appear important, but evolution in the course of time is well reproduced (fig. 7).

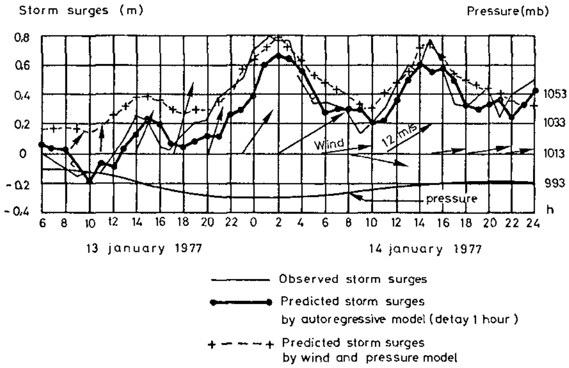

Fig.7. COMPARISON BETWEEN OBSERVED AND PREDICTED STORM SURGES

This model predict storm surges at the instant t, knowing pressure and wind (intensity and direction computed over 12 hours) at the instant t - 3 h. Correlation coefficient between observation and the 3 hours prediction is 0,75, slightly smaller than the value obtained by autoregressive model.

For the case where only storm surge prediction corresponding to high or low tide is needed, component S_1 gives directly the prediction of storm surge. In that case prediction error is limited to $\pm$ 0,18 m for 95 cases over 100.

It must be noticed that knowing a large sample of wind and pressures, it is possible, using this kind of model, to generate storm surges values which allow to predict exceptionnal storm surges of low probability.

5. CONCLUSION

The present study has shown that in the case of Le Havre an autoregressive model can be used for a prediction up to 5 hours in advance with a reasonable accuracy. For a more extended forecast, it is better to use models based on meteorology. The availability of accurate wind and pressure predictions by Meteorological Services of Le Havre within 36 hours in advance makes the use of the second model of great interest as it provides the possibility of prediction within 39 hours in advance.

When the interest is restricted to storm surges predictions high and low tides, the model based on meteorology appears to be especially easy to handle and reasonably accurate.

However, it is clear that local wind and pressure data are not enough to explain the totality of some storm surges. Such occurences cannot be predicted without knowing more on the interaction between large scale meteorological patterns and the tide propagation over the domain of interest.

This problem will be investigated by using a tide propagation deterministic model of the whole English channel, based on Saint-Venant equations. The results of interaction between typical meteorological patterns and the tide propagation should lead to a deeper understanding of the physical phenomena involved and allow the choice of adequate parameters for future prediction models.