

## ARTIFICIAL ROUGHNESS IN PHYSICAL MODELS OF ESTUARIES FOR STORM SURGE INVESTIGATIONS

BY

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### 1. INTRODUCTION

One of the characteristics of the North Sea between the British Isles, the Netherlands, Germany and Denmark is the occurrence of heavy storm surges especially in autumn and winter with heights of about 4 m above spring highwater. Coastal areas and especially the estuaries of the tidal rivers are hit by these storm surge events. The mean tidal range at the German coast comes to about 3 m with relatively low daily and semimonthly inequalities of less than 0.5m.

Within the framework of long-term developments of the navigation channels of the estuaries as well as of the storm surge protection works, physical model tests had to be carried out in order to predict the influences of such measures on the storm surge heights to be expected.

### 2. GENERAL REMARKS ON THE SIMULATION OF TIDES IN PHYSICAL MODELS

In connection with these model tests the question as to the artificial roughness pattern in distorted tide models necessary for simulating different types of storm surges had to be investigated. The simulation of unsteady alternating currents and water level elevations of a mean tide in a physical model of an estuary can be attained by a roughness pattern of artificial elements fixed over the total tidal cycle. For mean tides, determined as the mean of a long-term sequence of tides in an estuary which is morphologically in a state of equilibrium (morphology of the model), a roughness pattern denoted as "similar to prototype" can be defined. In principle, a roughness pattern different from the "similar to prototype" roughness should be neces-

sary for the simulation of other tides in this particular morphological state of the model.

It must certainly be taken into account that the "similar to prototype" roughness will be more and more restricted to the calibration tide and to the corresponding morphological situation with increasing distortion of the model.

Storm tides can only be reproduced incompletely in long models of estuaries when conventional methods are used, i.e. appropriate tide generation without reproducing wind effects and fixing the roughness pattern in the model. Specific current distributions basically different from current distributions of mean tides must be considered.

### 3. INVESTIGATIONS ON THE INFLUENCE OF TIDAL FLAT ROUGHNESS

The results of several tests within the framework of basic investigations at the University of Hannover as well as in the Laboratories of the Federal Government in Hamburg will show the influence of the roughness pattern in a model and especially its importance on the success of each investigation.

The subject of the investigations were storm surges in the Elbe Estuary in Germany. The Outer Elbe is characterised by wide tidal flats on both sides of the navigation channel. Upstream of the real coastline the dominant portion of the cross section of the Elbe River is the navigation channel accompanied by more or less wide smaller flats partly higher than mean highwater. For this case a physical tidal model with a distortion of 5, that means 1:500 for the lengths and 1:100 for the depths, of the Elbe Estuary was constructed (Fig. 1). The overall length of the part of the Elbe reproduced in the model is about 170 km from the seaward boundary up to the tidal boundary fixed by a weir.

Figure 2 shows schematically a longitudinal section of high-water elevations of a special type of storm surge in the Elbe Estuary.

The black line shows the storm surge highwaters actually measured along the estuary.

The dashed line represents the highwaters found in the model which had been equipped with conventional roughness elements such as barbed wire or small concrete blocks. In this model it was not possible to achieve a course of storm surges really similar to prototype. In the downstream area of the estuary with wide tidal flats the water level elevations do not follow the real highwater line well-known from the event in the nature. Only in that region where the cross sections of the estuary are reduced, are the model line and the nature line at least parallel to each other.

In order to raise the model highwaters up to the natural highwaters the storm surge curve of the control station was

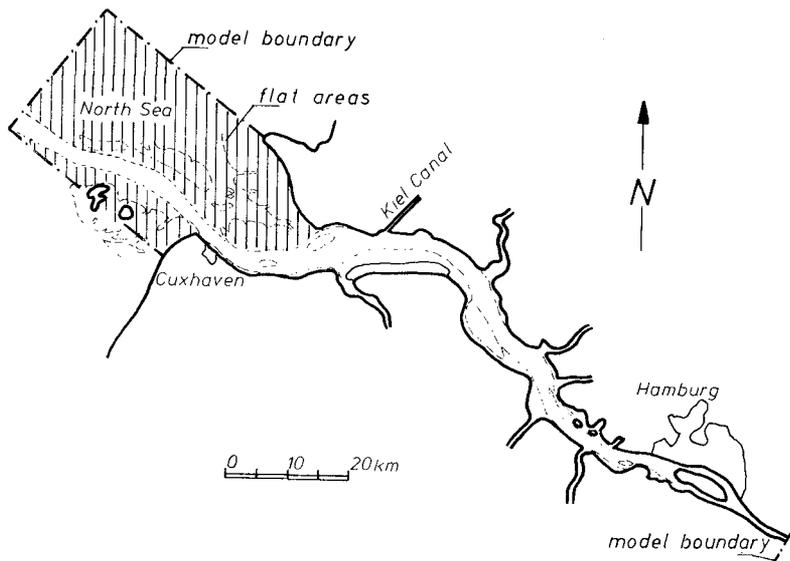


Fig. 1

General map of the Elbe Estuary and model boundaries

raised to a certain height above the real height. The result is demonstrated with the dotted line. It is obvious that the highwater line in the model was only raised nearly parallel to the dashed highwater line. So this measure was not successful in obtaining a highwater line similar to prototype.

On the other hand, similar problems did not arise in reproducing storm surges in another physical tide model of the Elbe Estuary with the same scales but with a seaward boundary upstream of the flat areas.

#### 4. IMPORTANCE OF REAL SIMULATION OF TIDAL FLAT ROUGHNESS

The outstanding result of the tests described above was the realization of the importance of the flat areas in the downstream areas of the model. The flat areas, even in a model with a distortion of 5, seem to be hydraulically too rough, and this is caused by the shallow water depths and a model bottom surface with a relative roughness which is too great. The influence of roughness in the flat areas must not be neglected. It is a serious mistake to accept a storm tide in a model under the assumption that the model tide which occurs accidentally is only one of a great number of different possible storm surge tides. In order to show the

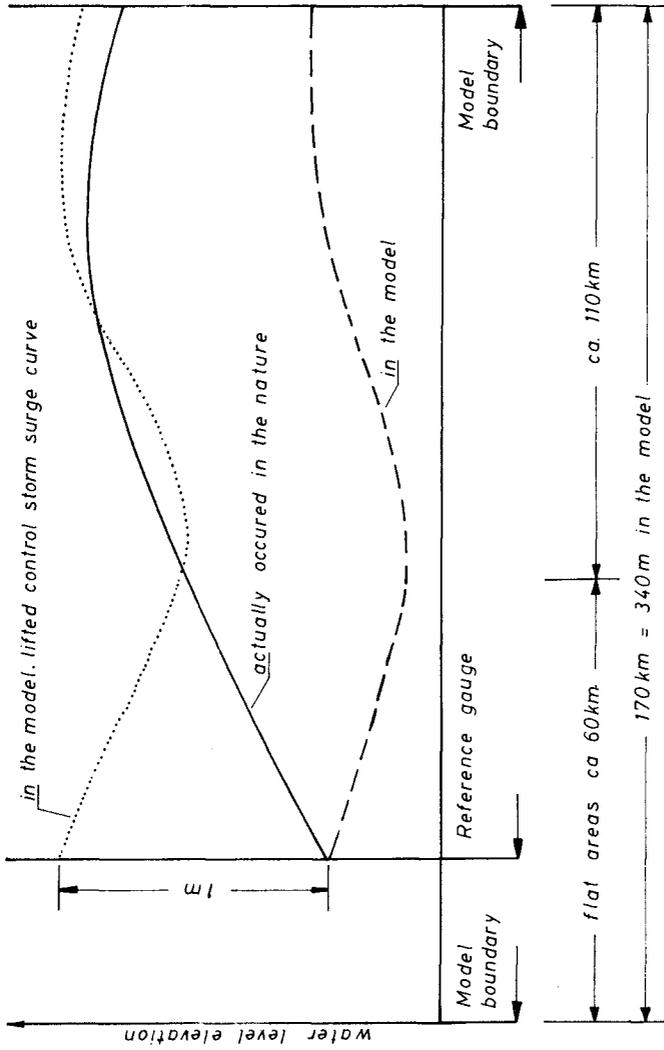


Fig. 2  
Storm surge highwaters in the prototype and in the model  
(schematically)

importance of the demand for the real simulation of the roughness pattern on the flats, that means a smoothing of the relative roughness, some tasks of storm surge investigations are to be briefly mentioned.

Model investigations of storm surges in general refer to the prediction of storm surge heights to be expected after more or less serious artificial changes of the morphological situation of an estuary (Fig. 3). Basically two types of changes can be imagined.

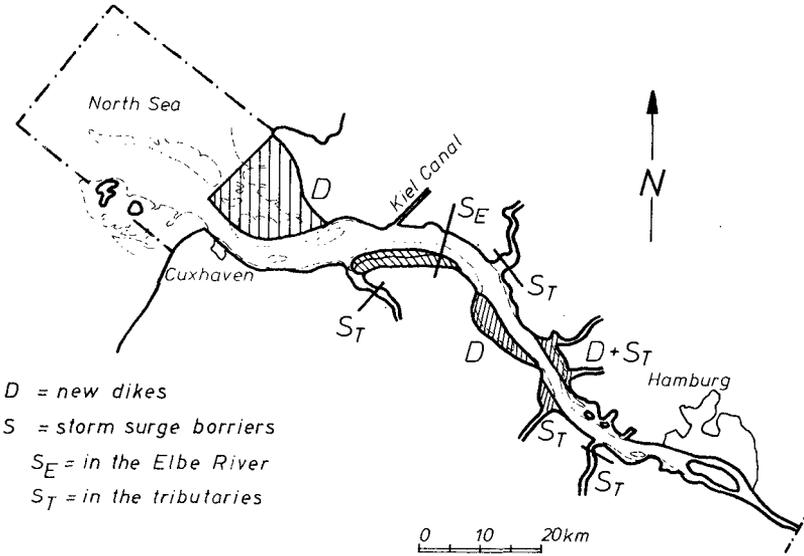


Fig. 3

Storm surge protection works in the Elbe Estuary

1. Because of the development of a harbour in the upper region of an estuary, such as Hamburg on the Elbe River about 100 km upstream of the point where the Elbe flows into the North Sea, deepenings of about 4 m as well as enlargements of the width of the navigation channel in several steps over a couple of decades became necessary.

In this case the deepening will result in an increase of the amplitude of a storm surge wave, which results in higher highwaters.

In addition, basic considerations confirmed by SIEFERT (1) led to the conclusion that with the increasing depths of the navigation channel the efficiency of the discharge in the deepened portion of the estuary increases. From

the MANNING-STRICKLER formula it can be derived that, assuming certain simplifications, the efficiency is increased by nearly the square of the additional water depth. When the main channel of the estuary is deepened the remaining efficiency of the flat areas becomes less and less important for the course of the storm surge.

2. In order to minimize the risk of flooding in lower regions on both sides of the estuary, existing storm surge protection facilities have to be reinforced or new structures such as dikes in front of newly reclaimed areas for human and industrial settlements have to be planned. This means that certain portions of the cross sections, in general with low efficiency of the discharge, will not yet be available for the filling and emptying of the upper estuary. The effect on the storm surge heights is dependent on the importance of these portions of the cross sections for the discharge. The resulting effect on the storm surge in an estuary caused by reducing the cross section by means of dikes is, in any case, an increase of roughness, which leads to higher partial reflections of the tidal wave downstream of the construction measure and to corresponding reductions of the amplitude of the tidal wave upstream.

## 5. DEVELOPMENT OF EFFECTIVE ROUGHNESS ELEMENTS

### 5.1 GENERAL REMARKS

A method therefore had to be found for overcoming the roughness effect of the tidal flat areas including the effect of winds blowing in the direction of the floodstream which cannot be reproduced directly in a physical model. The rise of storm surges had to be accelerated in order to obtain higher peak water elevations in the lower region of the estuary. On the other hand, the fall of the storm surges in the lower regions had to be decelerated in order to postpone the turn of the flood currents in the upper region of the estuary.

### 5.2 MOMENTUM JETS

On the basis of an idea being developed in the Hydraulics Laboratories of the Federal Government in Hamburg, momentum jets were used to achieve the required effect.

This new method was proved in pretests in a plume with a width of 1 m. 8 jets of about 4 up to 8 cm<sup>3</sup>/s each were pressed out of nozzles with diameters of 3 mm, located in horizontal tubes arranged at a distance of about 2 m across the plume (Fig. 4). Jets were injected in the direction of the plume flow as well as against the plume flow. The discharge of the plume came to about 16 l/s with a water depth of about 20 cm.

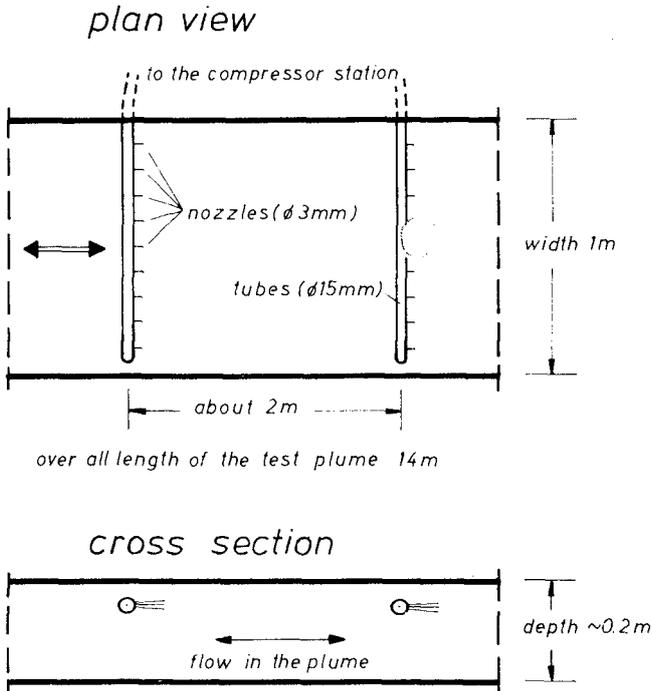


Fig. 4  
Test facilities for momentum jets

The results of the pretests showed a remarkable decrease of the longitudinal gradient of water level elevations, which means an increase of the roughness coefficient of MANNING-STRICKLER. In this case increasing the roughness coefficient means increasing smoothness.

The momentum jets were found to be even still more effective when directed against the flow. It was possible to achieve remarkable roughness effect which led to an increase of the gradient, for instance, from 1 $\text{‰}$  to 6 $\text{‰}$ .

Dependent on the distribution of momentum jets in the model as well as on the control of the jet intensity, the desired gradients of the flow can be achieved in a limited range.

The use of the jets in the flat areas of the downstream region of the estuary (Fig. 5) was as successful as expected.

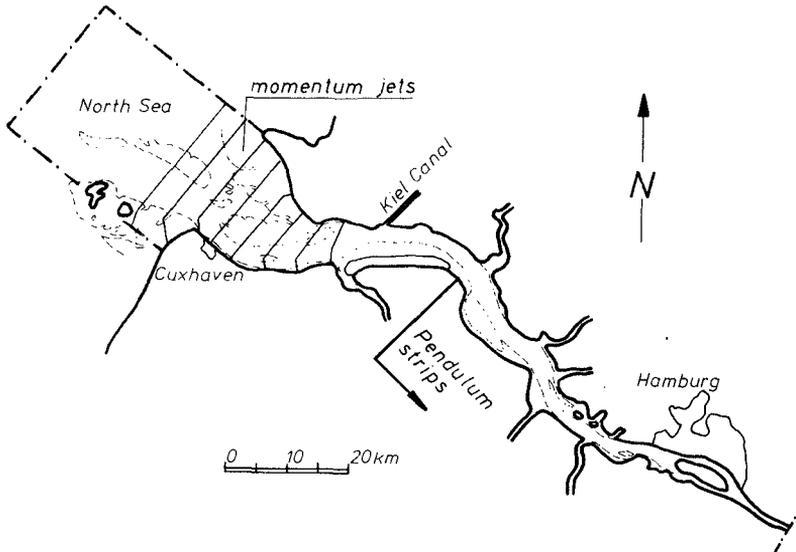


Fig. 5  
Location of momentum jets in the model

The course of the storm surge over the whole estuary was in almost good agreement with the natural course.

### 5.3 PENDULUM STRIPS

However, the fall of the storm tide after highest highwater had to be corrected by additional roughness elements effective only in the ebbstream phase. Fixed roughness elements for the simulation of mean tides are thus modified by flexible roughness elements in the form of pendulum strips (Fig. 6). These strips are raised by flood currents and placed in a vertical position by ebb currents, which causes increased friction in the flow direction, while the flood currents are not influenced by this kind of roughness element. The use of flexible roughness elements yielded a still better agreement between model and prototype storm surges.

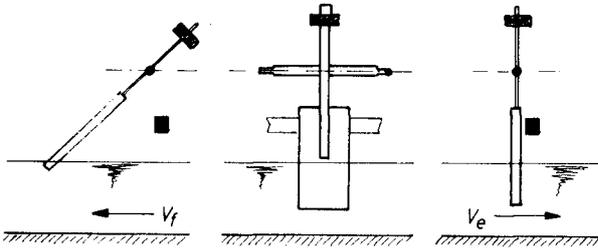


Fig. 6  
Pendulum strips

## 6. CONCLUSION

It was possible to find out the reason for the difficulties in reproducing storm surge events in physical models of estuaries with wide flat areas. The importance of the necessity of not underestimating the influence of flat areas on the simulation of storm tides was pointed out.

On this basis a new method for such investigations including the consideration of the influence of local winds was developed and successfully applied. By means of momentum jets and pendulum strips it was possible to achieve a good agreement with natural courses of storm surges.

Finally it should be pointed out that up to now the idea for this new method and its application exists for one physical tide model after some basic tests in a plume. However, further research is needed, in particular to modify the facilities of this new development.

## 7. REFERENCE

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