CHAPTER 117

Monitoring hydraulic loads on the Eastern Scheldt Storm Surge Barrier

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1. Abstract

The paper describes the monitoring program that has been set up for the hydraulic loads on the Eastern Scheldt Barrier. The strategy for the measurements will be discussed in detail. The results of the measurements, that have been performed yet, will be presented. These results are discussed only briefly, because the evaluation of the results has not been completed yet.

2. Introduction

The Eastern Scheldt Barrier is located in the mouth of the Eastern Scheldt and is built across the three main channels; Hammen and Schaar both one kilometer wide and Roompot two kilometers wide (See figure 1). The barrier consists of 62 basic sections. Such a basic section is 45 m wide and is built up as following (See figure 2):

The sandbed is covered by a filtermat. On these mat concrete piers are placed. The final flow opening is framed by a concrete sill beam and an concrete upper beam. A steel gate driven by hydraulic cylinders can close the flow opening. On top of the piers a motorway bridge is located. The piers and sill beams are packed in by a rubble sill structure.

All structural elements were prefabricated at a remote construction site, and have been placed by heavy floating equipment.

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Figure 1: Location of the Eastern Scheldt Barrier



Figure 2: Elements in the Eastern Scheldt Barrier

3. The monitoring system

In an early stage of the design of the barrier it was decided to set up a monitoring program for the entire barrier project (See van Westen, 1990 for the effects of the barrier on environmental aspects). This paper describes the monitoring system for the hydraulic loads on the barrier itself. The need for this monitoring system is dictated by the following reasons: - The innovative design concept called for extrapolation of existing techniques and development of new techniques. - The probabilistic design coupled the design loads and the rules for operating the barrier. Incertainties in the design are "balanced" against each other. - The design concept with large prefabricated elements placed on a sand bed foundation made construction tolerances and later deformations critical items. - The design lifetime of the barrier of 200 years made evaluation of subjects as fatigue of the steel gates and life time expection of geotextiles necessary. A monitoring system has been designed by the Dutch Rijkswaterstaat and its contractors, in close cooperation with Delft Hydraulics and Delft Geotechnics. The following items are monitored: - The hydraulic boundary conditions; waves, waterlevels and currents. - The loads on the structural elements with special attention for: steel gates; effect of wave impacts, stress variations and response of the gates. upper beam; wave impacts and the response of the beam. - Foundation aspects (van Heteren et al, 1988). The measurement system is set up to enable a trace back of the forces (by waves and waterlevel difference) through the structure and the response of the foundation; pore pressures and deformations of the subsoil. - Concrete technological items. - The behaviour of the rubble sill, bedprotection and scour holes.

It is obvious that it is impossible to measure every item at every pier location. The following strategy has been chosen: extensive measurements are performed at selected locations. In the Schaar-channel at gate S13 and pier S9, in the Roompot-channel around pier R22, gate R21 and upper beam R20 (See figure 3).



Figure 3: Measurement locations

At all pier locations the overall displacements are measured once a year.

Most of the measurements are concentrated during storm closures the of the barrier, with additional campaigns for example to determine natural frequences of the gates.

All measured data are gathered by a data aquisition system (DAS). The large number of sensors, over 250, with frequences ranging from 10 - 1000 Hz made a powerfull computer system necessary. The DAS is located in the operating post (figure 3).

Before results of the measurements will be presented, attention will be paid to the difference between field measurements and model tests:

- In model tests the boundary conditions that are applied, are mostly even more extreme than the design conditions. Field measurements howerver are likely to take place under rather moderate conditions.
- Model tests are these days performed in conditioned, sheltered areas while field conditions are relatively rough.
 - This is important for the selection of the instruments.
- Model tests are planned operations. Field measurements are occasional operations and the conditions for the measurements are more or less a surprise.
- Model tests are relatively cheap compared to field measurements.
- Model tests can be repeated. I field measurements, of say once a 10 years conditions, fale, one has to wait for another 10 years (statisticaly) before these measurements can be repeated.

Because of the items mentioned above, translation problems will occur when interpreting field measurements: To evaluate the design, the level of the field measurements has to be translated to the design level, with the complication that the design level of the structure, as built, may differ from the theoretical design level.

The results of the measurements are valid at the measuring locations only. So the results have to be translated to other locations or well, for a complete evaluation of the design of the barrier. When one compares the results of the field measurements with those from model tests, again a translation to another level and/or other location has to be performed. The translation problems, related to the evaluation of the design with results of field measurements have to be considered thoroughly for the design of a monitoring system.

4. Measurements performed

Since the barrier has been completed in 1986, it still took some time to overcome problems encountered, mainly with the data aquisition system. By the end of 1988 the system became operational. In december 1988 the first real measurements were performed. These were measuring campaigns were the single gates, R21 and S13 were closed to measure wave impacts and the response of the gates.

In February 1989 the first storm closure of the barrier was performed, and a complete measurement campaign has been performed then (see figure 4).



Figure 4: Storm report 13th - 14th February 1989 Westerly winds, with windspeeds between 15 and 20 m/s, caused a maximum waterlevel of 3.08 m above mean sea

level. The maximum waterlevel difference, with the barrier closed was 2 m, with wave heights of over 2 m (significant wave height).

In Oktober 1989 a special measuring campaign was performed to measure the natural frequences of the gate S13. These are important for the interpretation of the dynamic response of the gates.

February 1990 a heavy storm occurred. This most recent storm was a succesfull one from monitoring point of view; westerly winds, with wind speeds over 20 m/s lasted for more than two days (see figure 5).



Figure 5: Storm report 26th February - 1st March 1990

The barrier has been closed four times. A maximum water level of 3.61 above MSL was reached. The maximum waterlevel difference was approx 2.4 m with the barrier closed. The significant waveheight reached almost 2.5 m.



Figure 6: Registration WAVEC buoy

Figure 6 gives the spectral registration of the directional WAVEC buoy. The wave frequences are in the range of 10 to 3 seconds. The average wave period is 5 seconds.

Rather rough conditions with caused a lot of damage to the Dutch coast. However compared with the design conditions the storm conditions were rather moderate; see table below:

design values	February 1990
waterlevel 5.4 , above MSL	3.6 m
waterlevel difference 5 - 6 m (*)	2.4 m
wave height 5 - 6 m (*)	2.5 m

(*) Due to the probabilistic design an exact design level cannot be given

Until now most of the 1989 data have been processed. The 1990 data are still beiing processed. Interpretation is planned together for all data.

5. Results

The following paragraph gives a overview of the results of the measurements that were analysed until now. Most of the results are based on the 1989 data.

5.1 Wave impacts on upper beam



EASTERN SCHELDT



NORTH SEA

- Pressure gauge.
- Accelerometer.
- Force gauge.
- ▲ Waterlevel gauge.

Figure 7: Instrumentation upper beam

When te gate is open, wave impacts against the bottom of the beam can be expected when the waterlevel is in the vicinity of the bottom of the beam, which is at 1 m above MSL. The prestressed concrete beam is relatively light and is sensative to these loads.

The upper beam is instrumented with pressure gauges, accelerometers, a force gauge in one of the supports and a waterlevel gauge (See figure 7).

As an example of the results, the registration of four pressure gauges are presented in figure 8.

The maximum pressure in this registrations is approx. 30 kN/m^2 with 1 m significant wave height.





Figure 9 shows the registration the accelerometers in the middle of the beam and at the support, the registration of the force gauge in the support of the beam and the registration of the waterlevel under the beam. The interpretation and the evaluation of the design still have to be completed. Especially the area opposed to an impact is of importance here.



Figure 9: Registrations accelerometers, force gauge and water level gauge upper beam.

5.2 Wave forces on steel gates

The forces in the girder system of the gate are measured by strain gauges attached to the tubes of the girder system.

In this way the force distribution in a single node is measured by instrumenting all five connecting tubes. The horizontal and vertical lateral forces on the gate are measured indirectly by instrumenting six thruss girders close to the supports of the gate.

Figure 10 gives an example of one of stress signals related to the lateral force in the gate. The figure gives the stress signal and the exceeding percentage of the stress amplitude.



8.0 s 40,0 s

Figure 10: Registration stress signal (below) and exceeding percentage stress amplitude (top) of "lateral force gauge", gate S13.

Evaluation of these results is important, because the gates are constructed of a high strength type of steel that must be inspected on fatique cracks. The results will be used to evaluate the inspection strategy of the gates.

Wave impacts on the girder system of the gates occur when the girders cross the waterlevel. Impacts have been recorded during the 1990 storms and are under evaluation.

5.3 Boundary conditions

The evaluation of the boundary conditions has been concentrated on waterlevels en flow parameters, and the validation of the flow models that were used for the design (Klatter et al, 1989). Further the discharge coefficients of the barrier were determined. Still under evaluation are the result of wave models for reflection coefficient and effects of crest length of the waves.

5.4 Foundation aspects

To evaluate the geotechnical aspects, measurements were performed of pore pressure generation and dynamic deformation of the subsoil. To evaluate these aspects much more measuring data will be needed. The relatively low level of the loads, compared to the design conditions makes an evaluation of the results, especially of the accelerometer data very difficult.

5.5 Bed protection

The bed protection has been monitored by acoustic and visual inspections. These inspections were mainly used to trace damages in the bed protection due to the construction activities of the barrier. Additional field measurements were performed to determine the design load of the critical part of the bed protection close to the barrier. Herefore pilot locations were fitted up with relatively light stones. There locations were carefully monitored and in this way the critical waterlevel difference for initial damage to the bed protection could be determined effectively.

6. Conclusions

The items that have been evaluated so far showed that a monitoring program is highly valuable for:

- optimization of the rules for the barrier operations,
- the closure and opening strategies of the gates.
- optimization of the inspection program.
- evaluation of the design tools, for example the flow models that were used for the design of the barrier.

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Setting up a monitoring system requires much more than just rebuilding a scale model instrumentation at full scale.

- Certain phenomena can better be determined in model tests than in field measurements (eg. stability of rubble stone, liquefaction of the subsoil).
- A selection of a limited number of signals that are representative for the design problems is of vital importance.
- The measuring system should be redundant, critical sensors should be installed double.
- The translation of the measured signals to design conditions must be possible. One has to account for the relatively moderate conditions that can be expected in field measurements.
- The system must be an operational system. The latest high-tech, state of the art systems are likely to fale.
- Optimization is necessary, because the costs of a field monitoring system are extremely high. Not only the construction costs should be considered but also the maintenance costs and operational costs.

The experience is, that it is much easier to record a few gyga-bytes of data than to retieve, analyse and interpret these data.

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