Geotechnical Prediction and Performance of Eastern Scheldt Storm Surge Barrier

J. Lindenberg
Ministry of Transport and Public Works, Department of Road and Hydraulic Engineering, Delft, The Netherlands

A. Plooster
Ministry of Transport and Public Works, Department of Road and Hydraulic Engineering, Delft, The Netherlands

J. P. F. M. Janssen
Ministry of Transport and Public Works, Department of Road and Hydraulic Engineering, Delft, The Netherlands

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J. Lindenberg, A. Plooster and J. P. F. M. Janssen
Research Managers, Ministry of Transport and Public Works, Department of Road and Hydraulic Engineering, Delft, The Netherlands

SYNOPSIS The construction of the Eastern Scheldt storm surge barrier was completed in 1986. The monitoring system meant to verify the functioning of the barrier during storm conditions became operational in 1988. Data concerning the geotechnical response was collected during the 4 days storm period between February 26 and March 2, 1990. In the paper some results are described. Conclusions with respect to the expected behaviour of the barrier during more extreme storms in future will be drawn in near future.

THE EASTERN SCHELDT STORM SURGE BARRIER

In the Eastern Scheldt, one of the sea arms of the south western part of the Netherlands, the construction of a storm surge barrier was completed in 1986 (see figure 1). The barrier allows normal tides to penetrate the estuary through the three main channels, but it prevents the penetration of extremely high water levels during storm conditions. In the middle of the channels the maximum depth is between 20 m and 38 m.

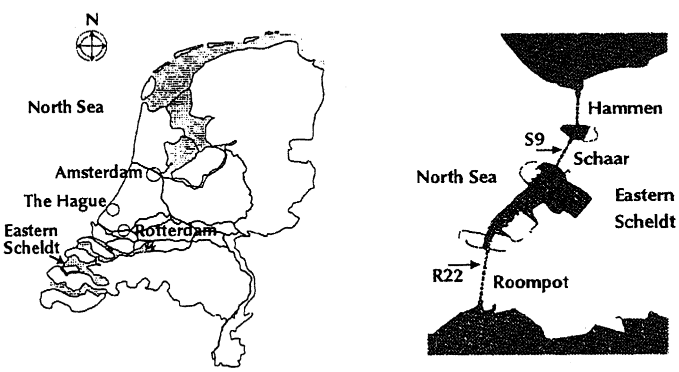

Figure 1: Location of the Eastern Scheldt storm surge barrier

The total length of the barrier is 4,500 m and the entrance aperture is 14,000 m^2. The barrier consists of 65 piers at distances of 45 m. The base dimensions of the piers are 25 x 50 m. the concrete piers were built in a construction dock, transported by vessel to the location in the channel and subsequently sunk on a prepared foundation covered by a prefabricated filter mattress. The movable steel gates are suspended between each two piers. During violent storm conditions the gates are closed and the hydraulic loads against the gates (static head loss and wave loading) are transferred to the piers by means of concrete beams above and below the gates (see figure 2).

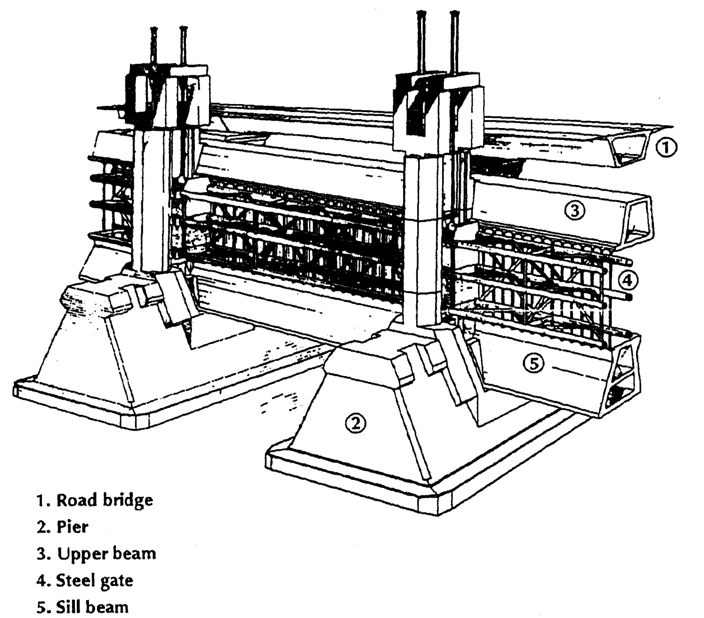

Figure 2: Some parts of the Eastern Scheldt storm surge barrier

At the location of the barrier the natural bed in the three channels of the Eastern Scheldt generally consists of fine sands. Below about 25 to 35 m - MSL (minus Mean Sea Level) the sand is of pleistocene origin and densely packed. Above this level the bed consists of holocene sand and is often loosely packed. In many locations the holocene layers are silty or include thin clay clayers. The existence of these upper layers (mainly present in the shallow northern channels and along the edges of the channel Roompot), appeared to be unacceptable. Displacements during design conditions would exceed the prescribed criteria. In addition uncertainties existed with respect to displacements and wave induced cyclic pore pressure build up. Therefore the upper meters below the barrier were dredged and replaced by a sand fill top layer consisting of coarser sand. Moreover the upper 15 meter has been compacted succesfully to an average relative density of about 75%. On top of this densified layer a prefabricated filter mattress was placed to create drainage of excess pore pressure from the sand and to guarantee a completely sand tight solution around the piers. The piers have been sunk on this filter mattress which extends far outside the pier base dimensions.

THE MONITORING SYSTEM

The design of a complicated structure, such as the Eastern Scheldt storm surge barrier, always includes a number of uncertainties with respect to the actual forces during extreme storm conditions, the strength of the structure and the bearing capacity of the subsoil. Although these uncertainties have been estimated and introduced in the probabilistic design as good as possible, the importance of a monitoring system with which the design criteria could be verified, has been strongly recognized. In 1985 the decision was made to install a large number of measuring instruments in front of, against and underneath two piers of the barrier.

In principle the intention was to carry out verification measurements during the first period of the lifetime of the structure: the first five to thirty years of an estimated lifetime of 200 years. Also of importance is the fact that the design conditions of the barrier are very extreme and related to a storm with an average return period of 4000 years. This meant that only relatively mild storms could be expected during the verification period and that very accurate measuring devices were needed. It also meant that the expected response of the structure would be mainly elastic and recoverable.

The behaviour of the structure is determined by the forces against the structure, the response of the structure itself and the reaction of the subsoil. Therefore, the measurements can be divided into three main elements: hydraulic boundary conditions, the reaction of the structure and the reactions of the subsoil. In addition, priorities had to be set with respect to costs, reliability and relevance in relation to the calculations used in the design stage. For the same reasons the measurements are only carried out during selected storm conditions and at only two pier locations in the channels Schaar (S9) and Roompot (R22). R22 is one of the most exposed piers with a relative deep foundation level (pier base at 29.0 m - MSL).

HYDRAULIC BOUNDARY CONDITIONS

To determine the forces against the structure, the instantaneous water level is measured in front of and behind the barrier. From these measurements the static load caused by the water level difference and the wave forces can be deduced. The wave spectrum showing the wave energy in frequencies is determined at two locations: just in front of the steel gates and at 800 m distance in North Sea direction. Also the wave direction is measured at the location 800 m in front of the barrier. The wave reflection and also the wave direction can be derived from three dimensional acoustic velocity meters just in front of the gates.

GEOTECHNICAL INSTRUMENTATION AND DATA ACQUISITION

The aim of the measurements is the determination of the forces that are exerted by the piers to the subsoil and the corresponding reaction of the subsoil. The piers transfer the following load components to the subsoil:

- dead weight of the pier structure;
- horizontal static load and moment loading due to the water level difference and reduction of effective dead weight due to the storm surge at the front side
- cyclic horizontal force and a cyclic moment due to fluctuating wave forces.

The periodic movements of the piers due to the wave loading are measured by accelerometers fixed to the footing of the piers at two locations. The periodic displacements in the foundation bed below the piers can be derived from accelerometers placed at several locations up to a depth of 15 meters below the foundation level (Nelissen et al., 1985). The permanent displacements of the two monitoring piers are perodically measured by using accurate geodetic instruments. During a storm the pore pressures in the bottom below the piers are measured in 28 locations up to max. 9 m depth below the foundation level. The instruments are included in casing tubes which have been pushed after placing of the piers through shafts in the pier floor. In figure 3 the top view of the base of the pier including instrumentation probes is shown together with a cross section (Nelissen et al., 1985). As can be seen from figure 3, most measuring gauges are located below the front and back side of the pier. In these regions the highest pore pressures may be expected due to the dominant moment loading during extreme wave attack.

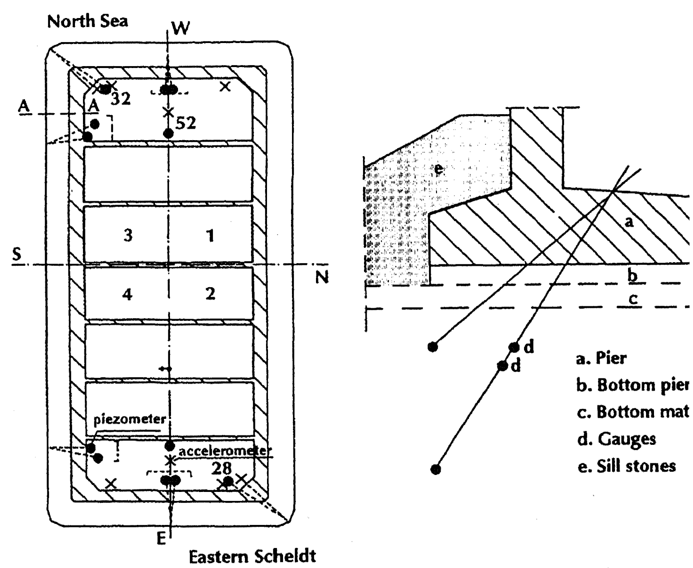

Figure 3: Top view of pier base with measuring devices (left)
Cross section A-A (right)

During a storm in total about two times 30(electronic signals (including measurements o structural elements) are recorded during ; measuring campaign.

To control this amount of data an acquisition system has been designed and installed for data storage and pre-processing. The monitoring system which was installed in the period 1986 to 1988, became available in 1988. After completion of some final inspections under daily conditions and during some minor storms the entire system is stand-by since 1989 and operational in case the weather and hydraulic conditions exceed the prescribed criteria. In this paper attention is focused on the measured data obtained during the storm period February 26 - March 2, 1990.

MEASUREMENTS DURING STORM PERIOD FEBRUARY 26 TO MARCH 2, 1990

The storm period can be characterised by its extreme long duration of about 4 days with continuous strong wind from dominating west direction. The maximum recorded wind-velocities and storm-intensity were not very extreme.

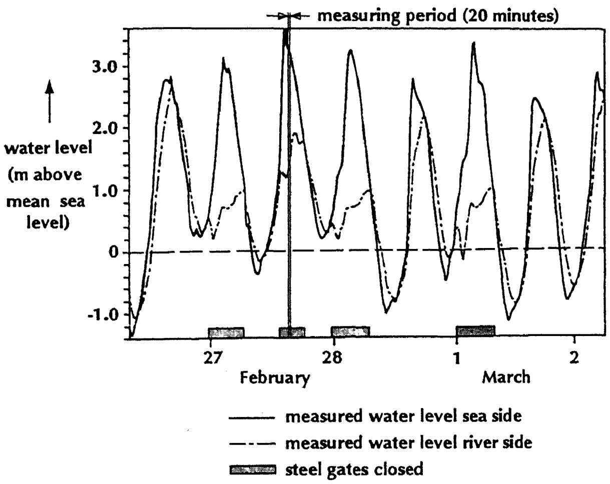

Figure 4: Measured water level as a function of time at sea side and Eastern Scheldt side of storm surge barrier during the 4 days storm period.

In figure 4 the sea side water level is presented with the level measured at the Eastern Scheldt side of the storm surge barrier. Also indicated are the four times of barrier closure during the 4 days period. From this figure it can be observed that the maximum water level difference over the closed barrier has been about 2.5 m (design value for static head difference amounts 6 m).

The water level at sea side includes the astronomic tide (which corresponds to rather extreme spring tide) and the storm surge set up. The maximum storm surge set up was about 1.8 m (design about 5 m). The highest water level occurred at February 27 at 15.15 h and amounts 3.60 m + MSL. As an average the exceedance frequency of this water level amounts 4 times in 100 years (average return period 25 years). The second highest water level (3.35 m + MSL at 4.00 h on March 1) corresponds with an average return period of about 7 years.

Monitoring measurements were carried out during the periods that the barrier was closed on February 27 only. The total duration of the two concerned periods of the measuring campaign amounted about 8 hours.

Until now, only the measured geotechnical data gathered during the 20 minutes period 15.00 - 15.20 hours (so including the maximum water level at 15.15 h, February 27) have been processed and interpreted. In this paper these data will be presented and discussed. Furthermore only some results of the measurements obtained from pier R22 will be described. The data for the second instrumented pier S9 in general show identical results.

Wave characteristics

Waves have been measured by wave recorder buoys (Wavec) at a distance of about 800 m in front of the barrier. Wave height, wave period and wave direction (direction in which wave crest propagates) could be derived from these measurements. The significant wave height during the period between 15.00 h and 15.20 h appeared to be 2.28 m, dominant wave periods between 5 and 8 second. The wave direction was 292 degrees which correspond roughly with the barrier direction in the main channel Roompot (see figure 1).

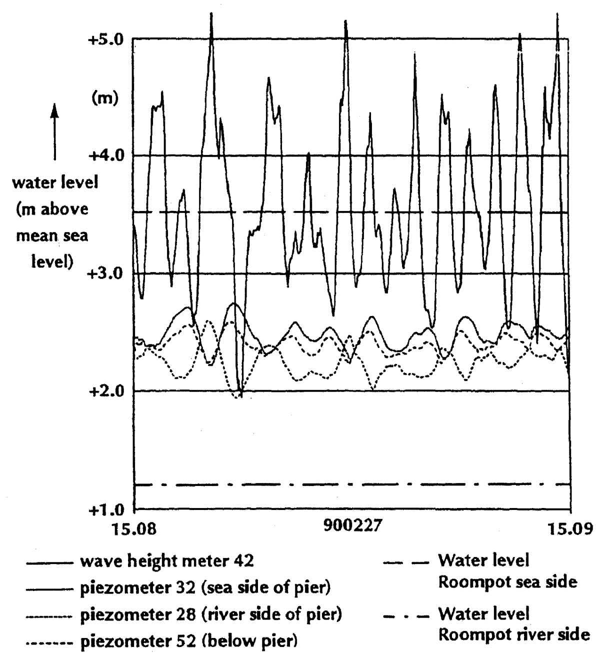

Figure 5: Recordings of wave instrument 42 and piezometers 32, 28 and 52 during 60 seconds

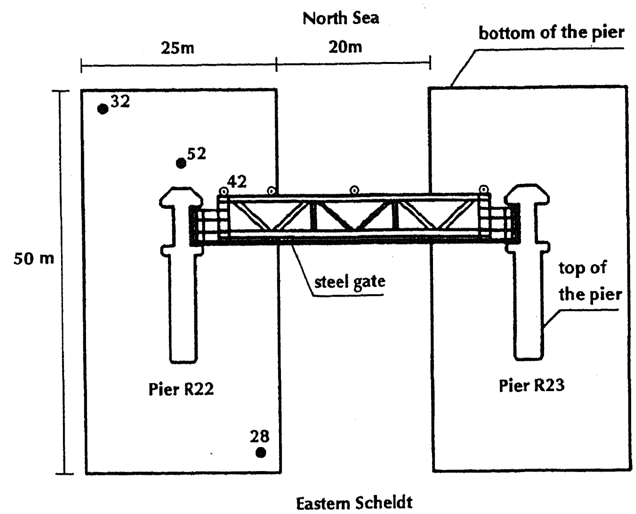

Figure 6: Position of wave measuring instrument 42 and piezometers 32, 28 and 52 in plan view

Figure 5 shows the water level changes (wave heights) and the response of two piezometers during 1 minute. The water level changes (instrument 42) are measured at 7 m in front of the gate directly north of the instrumented pier R22. The position of the piezometers and the water level measuring instrument is indicated in figure 6.

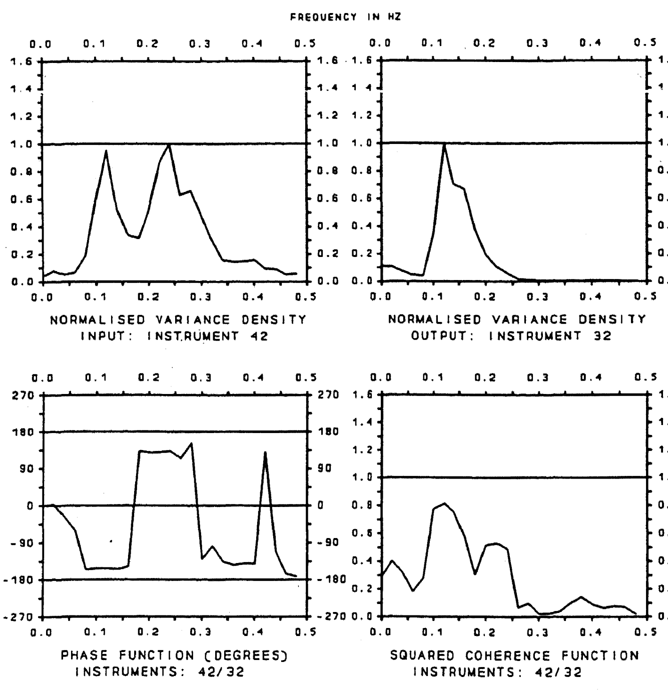

Figure 7: Energy density spectra of wave instrument 42 and piezometer 32, and interrelated phase function and squared coherence function

In figure 7 the energy density spectrum of the waves is given (instrument 42). Clearly visible is the separation of energy grouped around the frequencies 0.12 and 0.24 Hz and due to reflection, the energy around frequency 0.18 Hz is missing.

For this frequency, at 7 m in front of the gate, a nodal point is present (wave length roughly 30 m), sothat the energy is not present in vertical changes of the water level. Reflection coefficients between 0.6 and 0.9 have been derived, among others depending on wave period. From the recording of wave instrument 42 a significant wave height of 2.55 m has been found (sample period 15.00 h to 15.20 h). So somewhat higher than the incoming significant wave height measured at sea, 800 m in front of the barrier. The increase must be assigned to the effect of reflection.
Although the dominating wave direction corresponds to the barrier direction, compared with the wave instrument 42 (closest to pier R22) the neighbouring wave instruments in front of the gate (at larger distance from pier R22) show a rather capricious response as a function of time. Or, even if significant wave height and energy density spectrum are identical, the points of time of wave impact may differ considerably along the gate. This means that the relation between significant wave height in front of the barrier and pore pressure amplitude at a certain depth in the bed below the pier is not as simple as supposed in the design stage of the barrier and this relation may be rather poor.

Pore pressures below the piers

During the processing and interpretation of the data collected on February 27, 1990 (3 years after installation of the monitoring system), it had to be concluded that almost 50% of the piezometers does not respond or does not function in a reliable way. At the moment of drawing up this paper this percentage (September 1992) has even been increased to about 60%. Therefore, with respect to pore pressures, it is doubtful that future measurements will yield useful results. It means that the conclusions that can be obtained from the 1990 measuring campaign might be even more important.

Figure 5 shows the response of the piezometers 32 and 28 together with the recording of the wave instrument 42. The position of piezometer 32 is below the south-west (sea) side of the pier base at a depth of 32.92 m - MSL (figure 6), so 3.9 m below the pier base and about 2.7 m below the filter mattress. Piezometer 28 is located below the north-east (river)side of the pier base at a depth of 33.53 m - MSL, 3.3 m below the filter mattress. The two horizontal lines at levels 1.2 m and 3.6 m water column + MSL correspond to the average water level at both sides of the barrier. The average vertical position of the two piezometer recordings is about 2.2 m and 2.45 m water column + MSL for instruments 28 and 32 respectively. Though the location of both piezometers in plan view differ very much (at the opposite sides below the pier bottom), the average pore pressure in the seabed below the filter mattress tends to adjust at the average of the head loss over the barrier. It may indicate that the filter mattress below the pier is more permeable than the sills against the pier. This could be caused by a reduction of permeability of the sills after 1986 due to sedimentation and penetration of sand into the sill stones and/or attachment of shell-fish, etc.

From figure 5 it is clear that the cyclic response of both piezometers is low frequent compared with the water level signal in front of the gate. It is clear that the higher frequencies are felt less by the piezometers. This might be caused by the irregularity of the wave loading against the steel gate. This effect will be stronger for high frequent and shorter waves. Another reason could be that the inertia effects for frequencies .2 and higher become more dominant.
In figure 7 the energy density spectra of the signals 42 (wave instrument) and 32 (piezometer at sea side) are presented together with the interrelated phase function and squared coherence function. The spectrum for piezometer 32 only shows only energy around the lower frequency 0.12 Hz. The phase function gives a roughly counter-phase response whereas the coherence is rather low. The counter-phase response has been predicted and can be explained by the dominating moment loading of the pier.

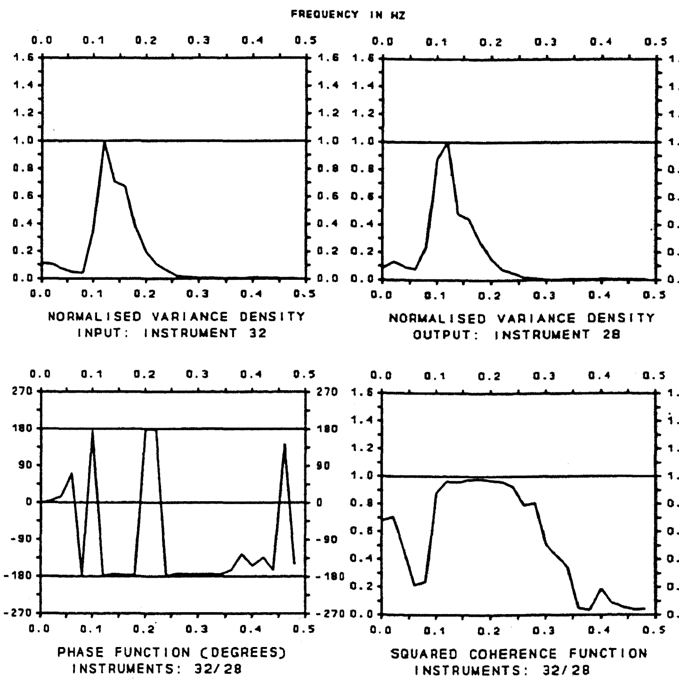

Figure 8: Energy density spectra of piezometers 32 and 28, and interrelated phase function and squared coherence function

The pore pressure as a function of time (figure 5) for instruments 32 and 28 show also an almost perfect counter-phase response. This is illustrated in figure 8 in which in addition to the energy density spectrum for both recordings, also the interrelated phase function and the squared coherence function is presented. The phase difference in the dominating frequency range (between .08 and .25 Hz) is roughly 180 degrees, although the figure is somewhat confused by the sudden changes from +180 to -180 degrees. The squared coherence function shows a fairly good interrelation between both recordings. This combined response again demonstrates that the moment loading is the most important one for the cyclic pore pressures in the seabed below the piers.

The pore pressure amplitudes for piezometers 32 and 28 are 2.0 kN/m^2 and 2.2 kN/m^2 respectively. Both amplitudes can be understood as significant values corresponding to significant wave height. In figure 5 also the pore pressure - time function for piezometer 52 (depth just below the filter mattress, see also figure 6) is shown. A somewhat earlier response of piezometer 52 compared with piezometer 32, can be observed. The pore pressure amplitude recorded by piezometer 52 is about 1.3 kN/m^2. So considerably smaller than the amplitudes of the deeper piezometers 32 and 28. The reason probably is the drainage influence of the filter mattress just above piezometer 52. Furthermore the effect of direct wave pressure penetration into the bed at North Sea side can be neglected because of the strong damping of the waves through about 31 m water, sill stones and filter mattress.

The described tendencies are generally confirmed by all (15 reliable) piezometers below pier R22. An additional important conclusion is that no pore pressure generation effect has been found. This means that the measured cyclic pore pressures are completely caused by the recoverable pseudo-elastic properties of the sand. Possibly also the drainage capabilities play an important role.

VERIFICATION OF THE DESIGN

Additional geotechnical calculations were made in 1985 to support the design of the monitoring system and to enable interpretation and evaluation of the measured data (Van Heteren, Lindenberg and Nelissen, 1988). Here only some special results will be presented.
The following starting-points were chosen for these calculations:

- the same design methods and design procedures were used as for the real design;
- the hydraulic boundary conditions used for the design were scaled back to shorter return periods of loading up to the once in a year storm;
- to predict the response during less exceptional storm-conditions also best guess predictions were made in addition to the less probable response resulting from the "more safe" design calculations.

Pore pressure response

For each piezometer below the two instrumented piers the expected cyclic response due to wave attack has been calculated for a number of combinations of wave characteristics. These combinations are related rather arbitrarily to the average return periods of the storm surge levels. Figure 9 shows the results for the piezometer 32 at a depth of 2.7 m below the filter mattress below the bottom of pier R22. Two ranges for the amplitude of pore pressure response are indicated. The lower range refers to the significant wave height. The upper range refers to the maximum wave height. The upper line of the range for the response to the maximum wave roughly corresponds to the design procedure for the storm surge barrier. So for the design of pier R22 27 kN/m^2 has been assumed for the pore pressure amplitude.

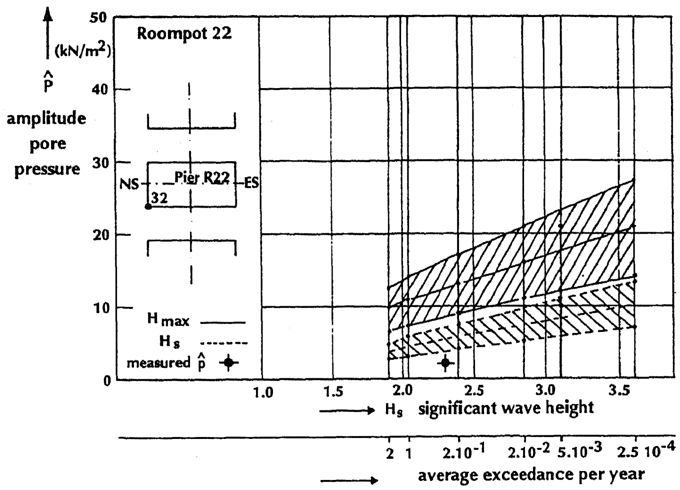

Figure 9: Predicted pore pressure amplitude as function of significant wave height and exceedance frequency of storm for piezometer 32 below pier R22 (position see figure 6)

The two middle lines within both ranges represent the most probable response.
In figure 9 the pore pressure amplitude of 2.0 kN/m^2 measured February 27, 1990 is plotted at the actual measured significant incoming wave height of 2.3 m. This measured pore pressure lies well below the lower predicted range. Comparison of prediction and measurement generally yields the same conclusion for all piezometers. Many reasons may be mentioned, partly related to the functioning of the instruments, partly to the assumptions made during the prediction analysis. From the recordings no real doubt with respect to the functioning of the piezometers could be observed. The deviation must therefore be explained by an over estimation in the prediction. One possible reason has been found from the wave measurements in front of the gate. Namely the fact that water level changes are very non-uniform whereas a purely two-dimensional wave loading has been assumed for the predictions. It will be clear that the pore pressure measurements are no reason at all for concern with respect to the expected response during more severe storm conditions.

Displacements

During the monitoring operations on February 27 accelerations have been measured to determine the cyclic displacements of the pier and the subsoil. However, the recordings never showed any significant deflection. The resolution of the instruments is in the order of 1.10^{-3} m/s^2 which means that a displacement amplitude of 1 to 2 mm should be measurable. No reason could be found for not adequate functioning of the instruments. Therefore, it has been concluded that the amplitudes of cyclic displacement remained below the mentioned limit value of 2 mm during the monitoring periods.
Based on the procedures used for the design of the barrier, calculations have been made to predict the cyclic displacements for less extreme loading conditions (Van Heteren, Lindenberg and Nelissen, 1988).

The predicted displacement amplitudes in horizontal and vertical direction are between 5 and 8 mm. As mentioned no cyclic displacements have been measured and it can thus be concluded that the displacement amplitudes did not exceed 2 mm. Therefore also with respect to cyclic displacements, there is no reason for concern.

After the storm period the permanent displacements of the piers have been measured. Also these measurements did not demonstrate significant movements. Identical results were found for the preceding regular displacement measurements. From the moments of pier placement in 1984 only significant movements have been measured during the construction period (ballasting, placing sill blocks, etc.). This applies for vertical settlement in particular. However the magnitude of this vertical movement was certainly not alarming.

CONCLUSIONS AND FUTURE ACTIVITIES

The monitoring system meant to verify the response of the storm surge barrier in the Eastern Scheldt was operational during some periods of the storm February 27, 1990.
After processing of only a minor part of the collected data and interpretation of the results, the following main (but rather preliminary) conclusions have been drawn:

- piezometers in the seabed below the piers do not reflect frequency above .2 Hz while these frequencies are clearly present in the external (wave) loading. This phenomenon could not be explained completely;
- measured pore pressure amplitudes are well below predicted values. It is believed that this difference is caused by conservative assumptions introduced in the prediction analyses;
- no cyclic displacements could be derived from the accelerometers in the seabed and against the pier floor. The calculations made in a earlier stage, however, demonstrated measurable displacements. Again, this most probably is due to rather conservative starting points in the analyses.

In near future some more data-sets will be treated and evaluated too. Main goal is to find confirmation of the above mentioned conclusions and to support decisions concerning future measuring campaigns.

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