CHAPTER 127

RUBBLE-MOUND BREAKWATER STABILITY : RESULTS OF IN-SITU MEASUREMENTS

ir. L. Van Damme [1]
dr. ir. J. De Rouck [2]
ir. D. Vermeir [3]

ABSTRACT

When the construction of the Zeebrugge Outer Harbour was finished a full scale monitoring system was realized as a part of the global monitoring and inspection programme.

The monitoring system was designed to follow the water level- and the water pressure fluctuation inside and in front of the breakwater.

A general description is given of the instrumentation of a section of the NW-breakwater followed by a global overview of the data-acquisition system and off-line data processing.

Results from the primary analysis of the raw data of relevant storm measuring sessions are presented.

1. INTRODUCTION

In 1989 the construction of the breakwaters of the Zeebrugge Outer Harbour was finished. The breakwaters are of the rubble-mound type with open crest (without a concrete parapet wall). Figure 1 shows a typical cross-section. Some quantities involved in the construction of the breakwaters are approximately : willow mattresses : 1.1 Mm^2 ; quarry stones : 11 Mtons ;

[1] Ministry of Public Works, Coastal Department, Ostend, Belgium
[2] Harbour and Engineering Consultants HAECON N.V., Ghent - Ghent University, Belgium
[3] Harbour and Engineering Consultants HAECON N.V., Ghent, Belgium

concrete cubes 25 t - 30 t : 60,000 units ; Haros® 15 ton : 11,000 units.

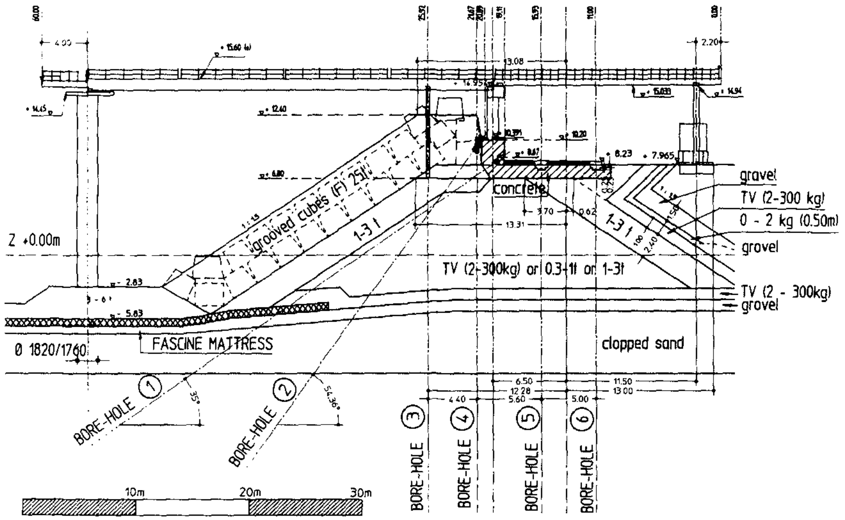

Figure 1. Cross-section of the breakwater

Once the construction of the breakwaters was finished, the principal organized an inspection, monitoring and maintenance programme of the new breakwaters. Such a programme is a standard rule in the management policy of the Ministry of the Flemish Community regarding major infrastructure works.

The monitoring and inspection programme is based on a complete design file and is composed of the following parts :

(a) visual control of the armour layer, the crest of the breakwater and the filter construction next to the road ;
(b) topographic measurements ;
(c) bathymetric soundings of the different zones surrounding and inside the harbour ;
(d) aerial remote sensing of the armour units ;
(e) side scan sonar recordings of the underwater armour layer and the wave breaking carpet and berms ;
(f) evaluation of the hydraulic design conditions on the basis of data collected by five measurement

stations and seven wave-buoys in the surroundings of the harbour ;
(g) evalation of some design hypothesis by means of an instrumentation of a section of the NW-breakwater.

The last item of this programme, the NW-breakwater instrumentation, makes it possible to collect reliable prototype measurement-data. As such, it is an important step forward to a more reliable design of rubble-mound breakwaters.

2. AIM OF THE NW-BREAKWATER INSTRUMENTATION PROGRAMME

The whole infrastructure was designed to measure, to follow the water level- and water pressure fluctuation inside and in front of the breakwater. Knowledge of these phenomena are important on the one hand with regard to the stability of the armour layer and on the other hand with regard to the overall slope stability of the breakwater.

At several occasions the importance of water pressures inside the armour layer on the hydraulic stability of the armour units has been emphasized. To our knowledge less attention has been paid to the influence of the water pressure fluctuation on the overall slope stability. We will focus our attention to this item.

With regard to the water level fluctuation and especially the influence on the slope stability one has to distinguish between two loading situations :
A. slope only subjected to tides (e.g. inner slope of a breakwater)
B. slope subjected to tides and waves.

For case A one can assume that the pore pressure is hydrostatic with regard to the still water level (S.W.L.). Regarding the high permeability of the breakwater material the S.W.L. in the core will be the same as in front of the breakwater. The low water situation is the most critical one.

For case B (tide and waves) the water level in front of the breakwater varies over several meters in a few seconds. As a result hydrodynamic pore-pressures will be generated in the armour layer, under-layer and breakwater core. Harlow E.H. (1980), Barends F.B.J. et al. (1983) and others state that these hydrodynamic pressures played an important role in the destruction of some bigger rubble-mound breakwaters (such as Sines, Bilbao, Tripoli, Arzew, ...).

Literature review revealed only limited information with regard to research work on the water pressure fluctuation inside the breakwater : some researchers have tried to solve the problem using mathematical modelling, others worked on physical models.

Before discussing in more detail the results of the modelling we draw the attention on the set-up which occurs in the breakwater core (fig. 2). This set-up is predominantly caused by the geometry of the slope : inflow of water through AC (at maximum run-up), outflow through AB (at maximum run-down). This difference in surface, together with the longer way which has to be passed through by the water particles during outflow cause a surplus of water with an internal set-up of the water level as a consequence.

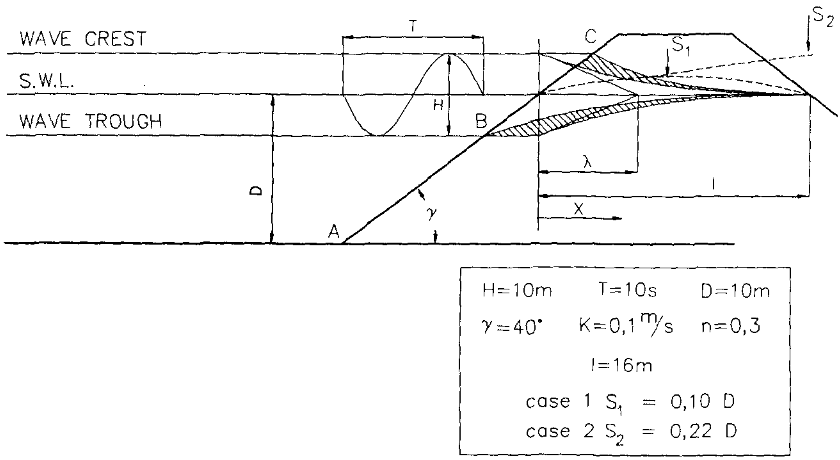

Figure 2. Internal set-up due to wave action (Barends, 1985)

a) Mathematical models

The water level fluctuation inside a breakwater is determined by the still water level S.W.L., the internal set-up and an internal wave. The S.W.L. is defined by the design conditions.
The internal set-up depends on the permeability of the materials and the width of the breakwater at the S.W.L. Barends F.B.J. (1985) finds a set-up up to 0.25 D (D = water depth in front of the breakwater). The set-up becomes important, especially when a sand fill has been placed at the inner side of the breakwater. Barends F. B.J. et al. (1983 and 1985) and Hannoura A.A. et al.

(1985) present the model HADEER : this model calculates the horizontal water movement in and through the coarse core-material, caused by regular waves acting on the seaward slope of the breakwater. The main results of the published data are :

- the finer the core material, the higher the set-up and the higher the damping (= the lower the wave amplitude at the leeside) ;
- the higher the incoming wave, the higher the set-up ; the damping is not influenced by the magnitude of the incident wave.

b) Physical models

Depending on the scale of the physical model one can distinguish models with normally applied scale (scale model less than 1,0 m high) and the so-called big scale models.

Considering scale models with normally applied scale, the most relevant results were found in Günbak A.R. (1976) and Simm J.D. et al. (1988).

The main results of Günbak's experiments are :

- mean water level inside the breakwater core is clearly higher than S.W.L. .
- the water level fluctuation decreases while moving to the centre of the core;
- the water pressure inside the core increases when finer core material has been used.

Simm J.D. et al. find :

- the set-up is proportional to H^2T, so closely related to the wave energy ;
- the damping of the fluctuation inside the core ;
- the pore pressure in the middle of the breakwater varies almost hydrostatically.

Considering the so-called big scale models, Burger W. et al. (1988 and 1990) report the results of tests carried out in the Groszen Wellen Kanal (G.W.K.) at Hannover. In the G.W.K. they have built a breakwater of ca. 4.00 m high on a sandbed of ca. 1,50 m thick.

When analyzing into detail one finds that the results of Burger et al. confirm some results of Simm et al. : the water pressure varies almost hydrostatically in the centre of the breakwater core.

To our knowledge only few attempts have been made to measure the pore water pressure fluctuation in a breakwater on site, e.g. Hakimi et.al. (1984) describe the instrumented breakwater at Jorf Lasfar (Morocco).

Only preliminary results are available. They find a rather high damping even in the seaward borehole, which is located close to the axis of the breakwater. However they have used open pipes instead of pressure transducers.

The foregoing emphasizes the lack of results, especially full-scale results, with regard to the water level and pore water pressure fluctuation inside a breakwater. By reviewing some literature we focussed on data which are useful to analyze the overall slope stability. We assume that a review focussed on the armour layer stability will lead to a comparable conclusion.

Yet, in 1983, at the opening session of the "Coastal Structures Conference" held in Washington D.C., A.W. Price stated that the common approach for the design of rubble mound breakwaters (based on mathematical and physical modelling) was not sufficiently funded on measurements on full scale operational breakwaters and that there was a serious lack of knowledge about the real phenomena of energy dissipation inside the different parts of the rubble-mound breakwater.

The main final objectives of the herein presented instrumentation programme are :

1) Acquire a better understanding of the geo-hydraulic phenomena and parameters affecting the overall stability and behaviour of the armour layer of rubble-mound breakwaters subjected to random wave attack.
2) Development of simulation techniques of these phenomena on physical models, leading to higher reliability in model tests.
3) Particular attention will be paid to the determination of the real forces acting on the amour units and the real hydraulic pressure set-up in the breakwater core and foundation layers.

These goals can't be achieved all at once. So in a first phase, we intend to collect data, interprete and implement these data in order to be able to provide basic full scale data for :

- the calibration of mathematical models ;
- the elaboration of a more comprehensive and adequate scaling method in physical modelling.

3. INFRASTRUCTURE

A measurement jetty of ca. 70 m long has been built on a steel pile at the toe of the breakwater and on a support on top of the breakwater (fig. 1).

Six boreholes have been drilled : four vertical boreholes (3, 4, 5 and 6) in the core and partially in the armour layer and two oblique boreholes (1 and 2) in the core, underneath the armour layer. Galvanized steel casings are placed in these boreholes. These casings are perforated in order not to disturb the overall permeability. In these casings part of the instruments are placed.

The casings reach the clapped sand. Doing this way it is possible to place pore water pressure transducers in the clapped sand underneath the breakwater toe. Knowledge of the variation of the pore water pressure in this area is very important for the overall slope stability.
The results of a measurement campaign and an evaluation of their influence on the overall slope stability can be found in De Rouck (1991).

A data acquisition system confined in an airconditioned 20' container is placed on the lee-side of the jetty at the landward side of the service road.

The steel pile and the bridge over the armour layer, is used to install measuring equipment.

4. MEASURING EQUIPMENT

The main considerations kept in mind during the selection of instrument layout and instruments themselves were :
- good reliability to marine environment and wave action ;
- good accessibility for instrument installation and maintenance ;
- provision of reliable power supply.

The instrumentation was directed to the measurement and observation of the following phenomena :
- wave characteristics in front of the breakwater up to 250 m seaward, and at greater distances (ca. 3 km) ;
- tidal currents and orbital velocity (3 axes) at the toe of the armour layer ;
- water level and water pressure fluctuation at several points in front of the breakwater, in the armour layer and in the core ;
- air pressure in the upper part of the boreholes underneath the service road of the breakwater ;
- impact pressure on all faces of armour units ;
- video observation of the uprush and downruch of the waves on the armour layer.

The following equipment has been installed :

- wave-rider buoys : 2
- infra-red wave height sensor : 1
- pressure transducers : 11
- electrical analog step-gauge : 3
- electrical digital step-gauge : 1
- video camera : 2
- 3D ultrasonic current meter : 1
- temperature meter : 1

The location of the sensors is indicated on fig. 3.

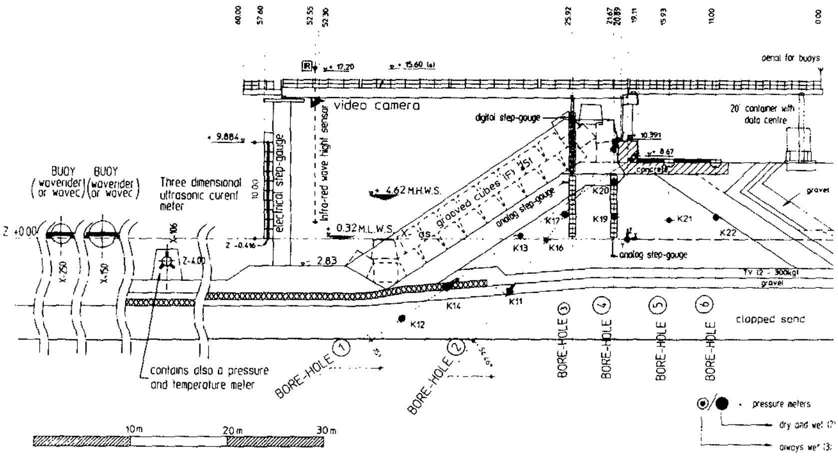

Figure 3. Location of the sensors in the measurement jetty

All instruments are controlled by a data acquisition system and scanned at variable frequencies, with a maximum of 50 for the dynamic wave impact on the armour units. The system permits a visual control of the signals and dumps the accumulated data into a hard disc memory. After a measuring session the data are transferred to tape cassettes for further off-line data processing.

Fig. 4 is giving a global overview of the data-acquisition system and the off-line data processing.

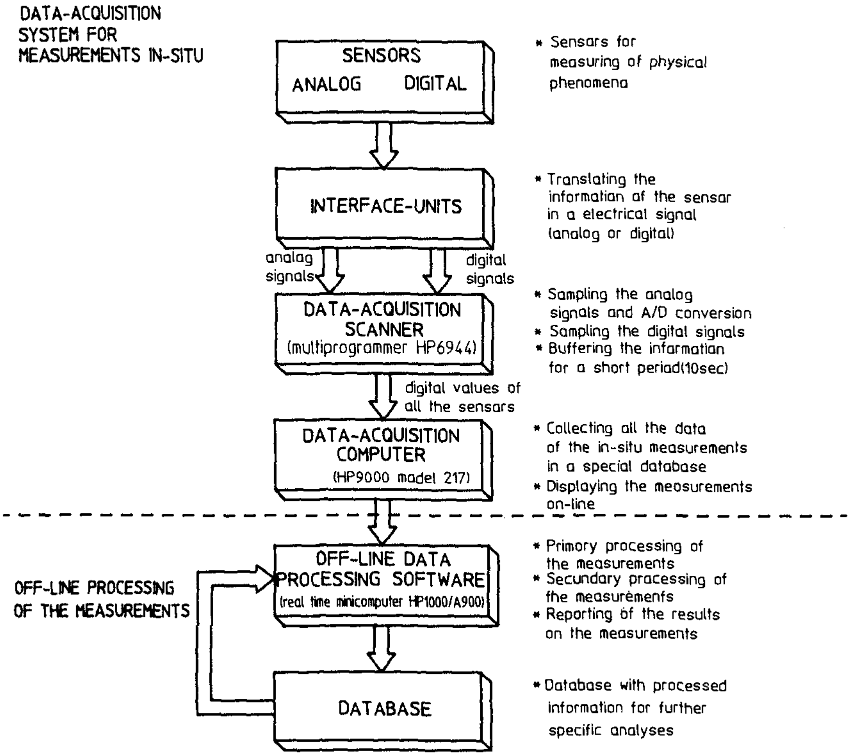

Figure 4. Global overview of the data-acquisition system and off-line processing

A basic software package has been established to reorganize the data in an appropriate database, to calibrate and scale the raw data, to produce graphical output (time plots and instant profiles) and to perform the specific analysis of some variations in selected significant time intervals. Experience has shown that this basic package has to be revised and upgraded continuously in parallel with the interpretation, further analysis of the results and orientation of the research.

In normal weather conditions a watch-dog programme is running continuously on the computer system to check all sensors. In order to be aware of major storm weather conditions a special prewarning procedure has been elaborated. The oceanographic hydro-meteo station at Zeebrugge is making special forecasts with a preavis (stand-by) of 48, 24, 12 and 6 hours to the responsible scientist. At this moment the decision is taken to measure or not. In the positive case the programme is loaded for the start of a continuous measuring session during maximum 17 hours.

5. RESULTS

Relevant storm measuring sessions were performed during the storm periods of March 1988, March-April 1989 and January-February 1990.

These sessions did provide the raw data for a primary analysis which revealed very promising results. All data and results were stored in a well structured database and are partially reported. A primary interpretation did reveal some interesting phenomena, e.g. about the components of the waves in front of the rubble-mound breakwater and the damping of these waves in the core.

As an example : on 26.01.1990 measurements were carried out for several hours during a storm. An excerpt of the measurements is given on fig. 5. The wave height of the incident wave was 3.30 m. From this figure it can be concluded that the incoming wave is propagated into the core of the breakwater at least to sensor K19 which is installed in borehole 4. Even the signals registered by sensor K21 (borehole 5) and K22 (borehole 6) show some damped wave action.

To detect any damping of the waves with increasing distance from the slope of the breakwater the double amplitudes A_{Ki} of the measured waves at each location are compared with the wave height of the incident wave $A_{inc.w}$. The mean results are given in table 1 and are represented on fig. 6.

Sensor	A_{Ki} (m)	$\frac{A_{Ki}}{A_{inc.w}}$
K13	1.90	0.58
K16	1.30	0.39
K17	1.27	0.38
K19	0.50	0.15
K21	ca. 0.30	0.09
K22	ca. 0.20	0.06

Table 1 : Damping ratio of sensors placed in the six boreholes

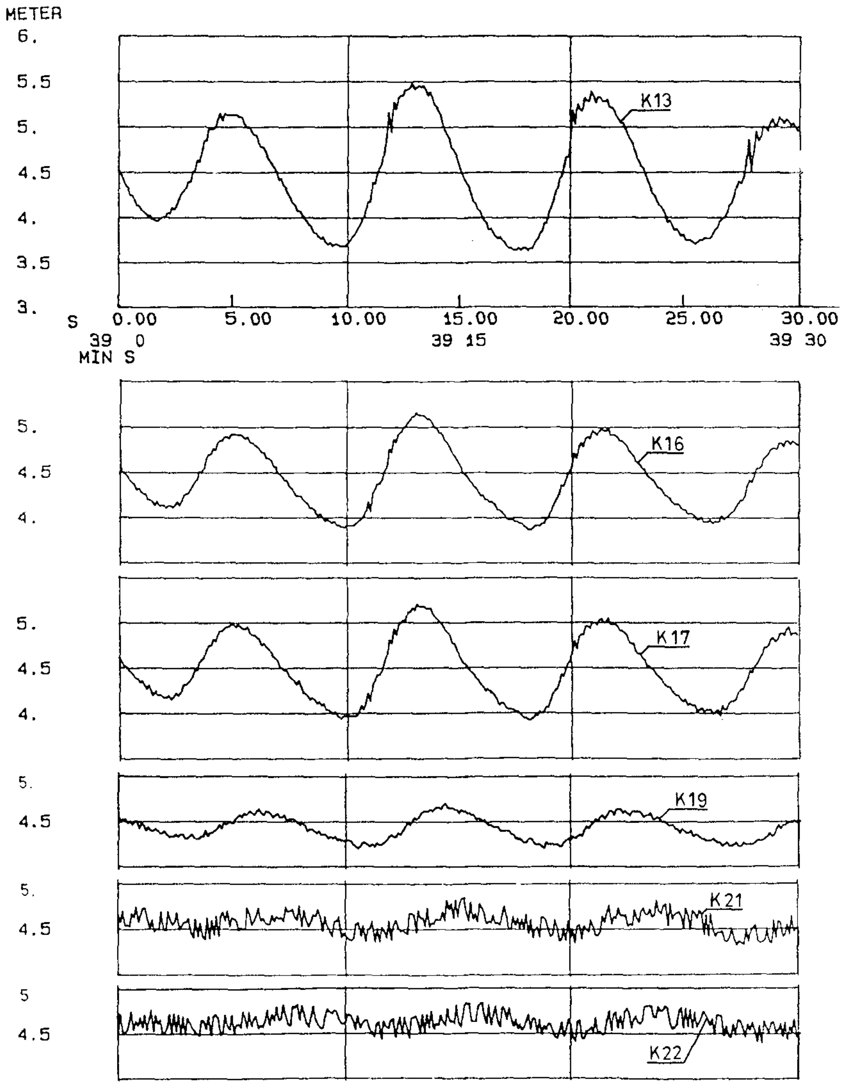

Figure 5. Example of propagation of an incident wave into the core of the breakwater

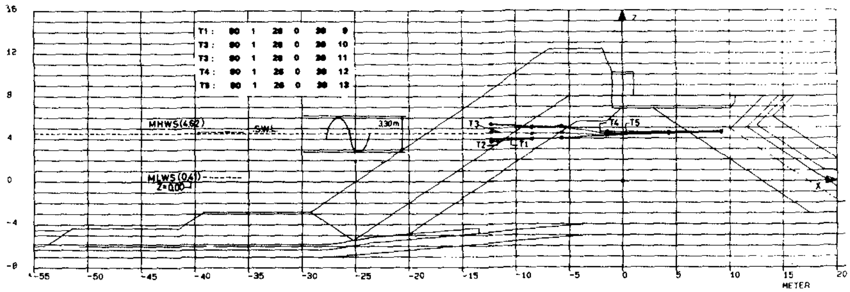

Figure 6. Cross-section of instrumented breakwater and example of wave damping

Pressure meter K13 is placed at the LW-level and approximately on the interface between the 1-3 ton filter layer and the core. At the location of K13 the amplitude has decreased to ca. 1.90 m, due to damping in the armour layer and underlayer.

6. CONCLUSIONS AND PERSPECTIVES

The first results of the breakwater instrumentation have proved the reliability of the system to collect full scale data. However more elaboration and interpretation is needed to clearly identify and extract the basic information.

The complexity of the phenomena and the considerable investments involved make it necessary to look for future international cooperation.

As the available infrastructure in Zeebrugge is unique, it can also be used for testing of marine instruments and measuring sensor packages actually under development.

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