

CHAPTER 151

MONITORING OF ZEEBRUGGE BREAKWATERS

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ABSTRACT

From the moment they are constructed, rubble-mound breakwaters are due to be damaged someday. Accepting damage is one of the basic principles of mound breakwaters design. Damage can take place either gradually in time or catastrophically after a major storm. Gradual deterioration of the armour layers or foundation may be unnoticed without the aid of a monitoring program and may ultimately result in the failure of the armour layer, in slope instability or in unacceptable large settlements. By comparison of measurements of the state of the structure at a number of points in time, a monitoring program allows these changes to be identified at an early stage, thus enabling the appropriate maintenance action to be carried out.

Several structural and environmental monitoring techniques are used in Zeebrugge. Three structural monitoring techniques are presented in more detail.

The emerged armour units of the Zeebrugge breakwaters are monitored using aerial remote sensing. An observation flight is made once a year. Each time, the position of over 15,000 armour units is very accurately retrieved by stereometric digitization. The coordinates are stored in a computer database. Several types of data visualization have been developed for a fast and efficient evaluation of the survey results.

For the underwater inspections of the breakwater two acoustic techniques are used. On the one hand, digital side-scan sonar recordings are used to produce high-resolution and contrasting images of the breakwaters' underwater armour layer. Such images allowed the detection of structure modifications in the breakwaters' toe protection.

On the other hand, high-frequent multibeam echosoundings, allow to exactly quantify the actual underwater armour unit movements in time.

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THE MONITORING PROGRAMME OF ZEEBRUGGE

The monitoring programme of Zeebrugge breakwaters is composed of the following parts : visual control of the armour layer, the crest of the breakwater and the filter construction next to the road; topographic survey, bathymetric soundings of the different zones around and in the harbour; aerial remote sensing of the armour units ; side scan sonar recordings of the underwater part of the armour layer and the wave breaking carpet and berms coupled to multibeam recordings; evaluation of the hydraulic design conditions on the basis of data collected by five measurement stations and seven waverider buoys in the neighbourhood of the harbour. The monitoring programme is now running for more than 10 years.

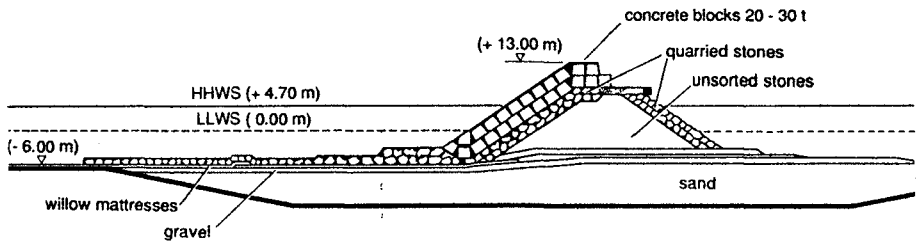


Figure 1 - Cross-section NW breakwater

Two parts of the monitoring programme will be treated in detail : aerial remote sensing of the armour units and the underwater inspections. Figure 1 is a typical cross-section of the Zeebrugge breakwaters. The toe of the breakwater is protected by a berm in 3-6 ton stones. The armour layer of the breakwater consists of antifer cubes 20 to 30 ton.

AERIAL REMOTE SENSING OF THE ZEEBRUGGE BREAKWATER ARMOUR LAYER

Several techniques are used for the survey of armour units. Soon after the construction of the Zeebrugge outer harbour breakwaters, an attempt was made to determine the position of the individual armour units, using land-based photographic recordings. This method was labourintensive and time-consuming, and posed serious problems in the areas that cannot be accessed on foot. Indeed, the vast majority of the armour units are inaccessible, or even out of sight for a land-based surveyor. Therefore, the use of aerial photography was proposed.

A survey based on this method offers the advantages proper to aerial photography: high accuracy, rapid (instantaneous) coverage of the complete breakwater length, recorded documents (photographs) allowing objective interpretation and verification, highly automated data handling and preparation for interpretation.

Execution of the photoflight

The aerial photographic recordings are carried out at low water during spring tide, to ensure maximum coverage of the breakwaters, i.e. a maximal number of armour units is visible.

The flight axis is located above the seaward side of the breakwaters so that the breakwaters take a central position in the aerial photographs.

The flight altitude is a major key to the success and accuracy of the survey. First, the mean square error on height data, obtained by photogrammetric digitization, is directly proportional to flight altitude. As a rule of thumb, the error on altimetry is approximately 1/10,000 of the flight altitude. This clearly illustrates the advantage of low altitude recording.

Another advantage of very low flight altitudes is that recordings can be made under a cloud cover. The diffuse light favours the image quality of the objects surveyed (i.e. the individual armour units), as there are no deep shadows. This, however, is only possible using technical features to enhance the quality and contrast of pictures realized under such reduced light conditions. As a wide lens aperture ($f/4$) and a relatively long exposure time are needed, the use of forward-motion compensated (FMC) cameras is indispensable. The cameras are mounted in twin-prop aircraft of the STOL (short take off and landing) type, so as to realize the best stability at low flight altitude and low speeds.

At low-altitudes, the speed of the aircraft in relation to the reloading of the cameras determines the stereoscopic coverage of the area. As a minimum photographic overlap of 60 % in the flight direction is needed for adequate stereoscopic vision, a coupled system of two alternating photogrammetric cameras is used.

A first survey flight took place on 2 July 1988 ; a second flight was carried out on 18 October 1989. Each time, the flight altitude was situated between 150 and 200 m. About 7 km of the seaward sides of the breakwaters were covered. The recordings allowed the survey of over 15,000 concrete blocks from the upper layer of the breakwater armour layer.

Photogrammetric digitization of the armour units

The orientation of the photogrammetric couples in the stereoplotter poses a special problem. For the relative and absolute orientation of each stereocouple, use is normally made of six control points. The control points should be distributed equally over the area which is covered by the stereocouple. If the condition of aerial distribution is not met, inadmissible errors in the accuracy will occur as a result of the orientation procedure.

Aerial photographs of breakwaters, however, show large surfaces of water that do not allow the determination of fixed calibration points.

The breakwaters take up only the central portion of the aerial photographs, and so, no calibration points along the sides are available. The orientation problem was overcome by the use of a specially developed software orientation programme. After mounting the two aerial photographs that constitute a stereocouple into an analogous stereoplotter, the position is measured in stereoplotter coordinates of six arbitrarily chosen field points that can be recognized on both photographs and are sufficiently well distributed over the area. Also, the centre point of each photograph is determined. The computer program then calculates the parameters needed for the relative orientation of the stereocouple. The operator manually sets the stereoplotter using these parameters. Afterwards, use is made of field control points (situated on the breakwater), to perform the absolute orientation (i.e. relative to the known standard grid "Lambert"). This operation has to be performed on an analogous stereoplotter, because analytical stereoplotters have a built-in orientation program that continuously recalculates the orientation and repositions the photographs.

The digitization of the armour units is also performed using a non-standard procedure. Of every armour unit, a minimum of four well-defined points are digitized.

These points determine the exact position of each armour unit with sufficient redundancy. A computer program controls and corrects the digitization of the armour units, given that the exact dimensions of each type of armour unit are known. This operation minimizes operator-induced uncertainties. The high quality of the aerial photography recordings, the efficiency of the dedicated software and the skill and experience of the stereogrammetric digitization operators combined reduce the error on the altimetry of the armour units to below 5 cm. The accuracy was confirmed on a special occasion. In October 1989, some 20 armour units had to be displaced in order to improve the cover. Before the operation, their position was measured using classical, land-based methods. The position of those blocks that could be accessed was measured with high precision. Table 1 compares the centre point coordinates with those retrieved from the 1988 observation flight. It is clear that the differences in position are completely within the accuracy range stated above. Thus, the position of each armour unit is known with the utmost precision, as required to detect slight variations in position between consecutive flights.

Furthermore, if armour units are damaged, the entire cleavage area is digitized. The volume percent of the armour unit lost by breakage is calculated accordingly. If an armour block is broken up into several, almost equally large pieces, then these pieces are digitized separately.

The armour unit database

Each flight results in the creation of three data files, containing all the information for further data handling and visualization, which are incorporated in the overall breakwater database.

The main data file, the so-called master file, contains an identification number, the absolute position of the centre point of the upper plane and the relative coordinates of the corner points of all the armour units measured. The absolute position is specified by the planimetric coordinates (with respect to the national grid Lambert '72) and by the altimetric coordinate (with respect to the level datum "Z" of the Ministry of Public Works). A second data file, called pointer file, contains the armour unit type and links the block identification number of the current survey to the reference breakwater survey (i.e. the first survey, performed on 18 October 1989). In the third output file, called cleavage file the information regarding the damaged armour units is stored, i.e. the armour unit identification number, and the absolute coordinates of the cleavage line.

The displacement of the centre point of the armour units is calculated for each inspection flight. This data, together with the information on breakage, is represented in an updated report table.

In the table 1 the measurement some results of the 1989 and 1991 surveys of a selected area of the Westdam (between the P2810 and P2910 marks) are listed.

Block Number	Block Type	Top Plane Centre at Reference			Displacement (cm)			Breakage (%)
		X(Lambert)	Y	Z	dX	dY	dZ	
3925	25TP	66594,840	227772,352	10,181	0	-11	-21	1,1
3926	25TP	66590,628	227772,288	7,957	5	-1	-15	
3927	25TP	66592,556	227773,504	8,381	15	0	-2	
3928	25TP	66590,904	227774,560	6,774	2	1	-14	

Table 1 - Armour Unit Data table

This table consist of five primary columns, containing the following information:

1. The armour unit ID number : a unique number allotted to each armour unit at the photogrammetrical digitization of the 18 October 1989 reference survey. The position of the armour units can be found in the armour unit location plan.
2. The armour unit type : 20TP, 25TP, 25T or 30T.
3. The coordinates (respectively Lambert-72 X and Y (in metres), and Z (in metres as well) with respect to the Z datum of the Ministry of Public Work) of the centre of the armour unit's upper face, as measured at the 18 October 1989 survey.
4. The displacement of the armour unit's centre, in centimetres, i.e. the difference in position between the reference survey and the present survey.

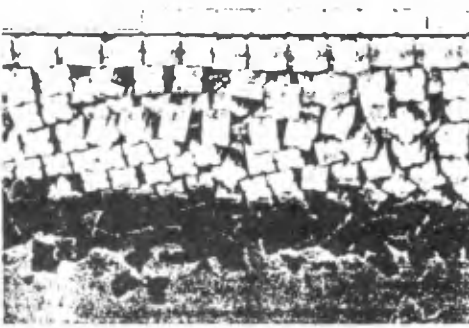
The displacement is calculated by defining the difference between the reference survey coordinates and the present coordinates along each coordinate axis (X, Y, Z).

5. The breakage volume rate. The rate of volume loss due to breakage is calculated for each armour unit that has suffered breakage.

From the table (with armour unit identification numbers identical to those of the armour unit location plan) it can be quickly determined which armour units have undergone a displacement with respect to the reference survey, how large the displacement is, and in which direction it has occurred. This gives a quantitative overview of the displacements between the different surveys.

It can also be seen which armour units have suffered breakage, and how important the damage is. The armour unit displacement plans visualize the block's displacements.

VISUAL REPRESENTATION OF THE BREAKWATER SURVEYS



In order to allow a quick and accurate interpretation of the vast amount of data involved in the breakwater armour survey and several cartographic representations were developed. The definition and the main characteristics of the different ways of representation are briefly outlined below.

Armour unit location plan



The armour unit location plans show the position of each armour unit in the upper layer. The slope plane, as defined above, is taken as the projection plane. All upper surfaces are shown in projection.

It follows that the upper surfaces of all regularly-positioned blocks of the slope plane are shown as squares in an optimal projection.

Irregularly positioned or tilted units are represented by flat parallelograms.



Figure 2 - Unit location plan

The central part of Fig. 2 is an extract of the 1989 armour unit location plan corresponding to the part of the breakwater shown in the upper aerial photograph.

On the armour unit location plan, three digits identifying each block are indicated. Areas of tilted blocks or regularly-positioned blocks can immediately be recognized. Also, a qualitative picture is provided of the density of the breakwater cover. Furthermore, the blocks affected by breakage are hatched.

Armour unit occupation plans

Different ways of visualizing the positioning density of the armour units on the breakwater slopes have been established. Each method emphasizes one particular aspect with respect to the protective function of the armour layer:

- the mean occupation plan highlights the positioning density of the armour units as a function of their spacing and orientation. The plan shows the values of the "mean occupation density", calculated for each point of the slope plane. The mean occupation density assumes high values when armour unit spacing is smaller than originally designed (i.e. the units clump together), while low values indicate a poor block density.

Low values are also achieved when the armour units are irregularly oriented (i.e. the basal surface of the block is at angles to the slope plane). Therefore, a low mean occupation density always indicates a poorer protection of the breakwater at the location considered ; either the blocks make irregular angles with respect to the slope plane, or their spacing is too high ;

- the differential mean occupation plan compares the mean occupation density as calculated for a specific observation flight with the design mean occupation density. As different types of armour units and patterns of positioning were applied, part of the variation of the mean occupation density is due to the design. The differential mean occupation plan singles out this part of the variation and only shows discrepancies in occupation between the current survey and the design situation. Of course, this technique can be applied to any two surveys;
- the porosity plan regards the occupation density as an inverse function of the occurrence of hollows and spaces between the armour units of the upper layer. The plan represents the real porosity of the outer armour layer, such as calculated for a given observation flight. It does not conform with the design porosity, as the latter is calculated over the two armour layers, in which all armour units have the same orientation.

The values, represented in each type of plan are, respectively, the mean occupation density, the relative mean occupation density and the porosity.

These values are calculated for each point of the slope plane.

For computational reasons, these points are positioned on a rectangular grid.

The unit spacing of the calculation grid can be chosen according to local conditions. For the Zeebrugge breakwaters, a 1-m spacing was adopted. All values determined are averages calculated over a unit surface, of which the centre is located successively in each grid point. In Zeebrugge, a unit surface of $6 \times 12 \text{ m}^2$ was found to provide the most relevant areal detail after some preliminary tests. The long axis of the unit surface is oriented parallel to the long axis of the breakwater. The rectangular shape of the unit surface provides a better sensitivity to density variations in the slope direction.

The dimensions of the unit surface were chosen so that it contains 15 to 20 armour units at a time. The values calculated in each grid point therefore represent the point itself and its immediate environment.

The armour unit occupation plans are produced in colour. In each of the three approaches, red corresponds to a poor condition, yellow represents the ideal or mean situation and green is used for a too close armour. The use of this colour representation of the occupation values described, enables a very precise and fast overview of the condition of the breakwater armour layer. The lower part of Fig. 3 is an extract of the porosity plan of the section shown above.

Though the figure is in black and white, the relation to the aerial photograph and the location plan above is still clear. Parts of the breakwater having a dense occupation of armour units are characterized by a low porosity, and vice versa.

Armour unit displacement plans

An essential indication of breakwater instability is the movement of the individual armour units. In order to detect such movements and their rate, inspection flights are carried out every year. As the aerial photography, the photogrammetric digitization and the subsequent computer processing are carried out with utmost care, absolute shifts in position of armour units can be traced once they exceed about 5 cm.

Therefore, a link is provided between the block coordinate lists of the reference flight and the last flight performed. Using a dedicated software program, the armour units of the last flight are automatically linked with the corresponding armour unit of the reference flight. The link method is based on the position of the centre of gravity of each block. Once this identification procedure has been carried out, the displacement of the individual armour units is readily established. The armour unit displacement plan represents, by the same projection method as the one used for the location plans, the displacement of all individual armour units between two surveys by means of colour coding.

DIGITAL SIDE-SCAN SONAR RECORDINGS

Side-scan sonar is basically an imaging technique whereby sound pulses are transmitted at both sides of a towed 'fish'. The pulses are sent perpendicular to the track of the vessel under approx. 90° , allowing a full coverage of the sea bottom on both sides of the vessel from the water surface to below the survey vessel. As the ship advances, a complete image of the seabottom along-track the survey vessel is created.

The strength and delay of the returned signals are measured and presented to the user on an analog thermal paper output. The returned signals are indicated by black dots on white thermal paper. As the initial sound pulse covers an angle of 90° , return signals from within this entire lookangle are received. The darkness of the dot corresponds to the strength of the returned signal. Usually, 16 or 64 discrete levels of black can be shown. The dot is positioned away from the centre of the paper roll proportional to the time delay of the returned signal. With each new emitted sound pulse, the time delays of the returned signals are measured with respect to the new trigger point (i.e. the new pulse). This provides information about the distance from the source the reflecting substance can be found, not however on the direction in which to search for this distance.

The maximum time allowed to wait for a returned pulse is a measure for and proportional with the distance the sidescan sonar is allowed to 'look' under the water. The thermal paper of the analog output is advanced at regular speed, which can be set manually or automatically to reflect, as much as possible, the speed of the survey vessel. By doing so, as one line of information is written with each emitted and returned pulse and consecutive pulses create consecutive lines in the output, an image of the seabottom is created.

However, because exact directional information (from where the return signal is coming) is missing, side-scan sonar measurements do not provide absolute positioning of the recorded features. This is the main difference with the other measuring technique used, multibeam (see below).

All objects under water, when hit by the sound pulse, will reflect part or whole of the incident energy back to the source. Some objects, such as stone, are much better reflectors than others, e.g. silt. The strength of the return signal, duly amplified because of the attenuation of the signal with distance from the source creates an image, that gives an impression of the kind of materials detected under water. Also, objects by returning the sound pulse create a shadow zone behind them, effectively hiding part of the seabottom or underwater part of the breakwaters from detection by the side-scan sonar.

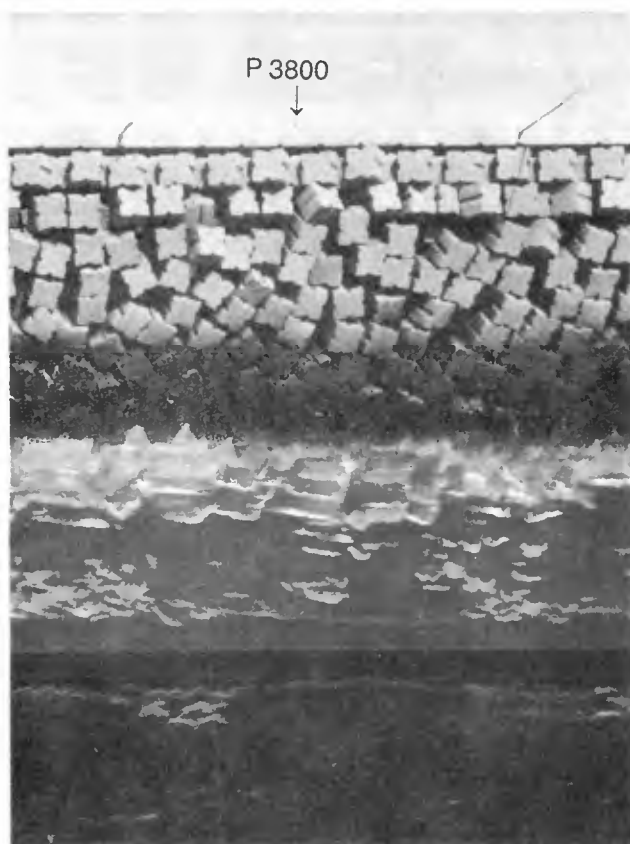
Such shadow areas are normally indicated as white - blank areas on the visualisation output.

The description above applies to standard side-scan sonar. However in Zeebrugge the analog output of the side-scan sonar is systematically digitized, in real-time and this information is stored in digital form. That technique is therefore dubbed digital side-scan sonar.

The side scan sonar used is a dual-frequency instrument, with analog output and recording. The analog output is digitized in real-time and connected to a VME-computer for data logging. The VME-computer also records the GPS information as well as the information of the vessel's roll, pitch and heading, destined for geometric corrections later on.

The digital storage of the side-scan sonar output is in 12 bit, allowing 4096 distinct data values (or 'grey values' in terms of analog output), while normal analog output on thermal paper only allows 16 or 64 grey values. All subsequent data treatment is also performed digitally.

Processing of the digital side-scan recordings



First, geometric corrections are applied, together with a straightening of the sounded track. Geometric corrections are needed because the sounding vessel's speed nor behaviour (roll, pitch) are constant during the recording.

Also, the followed path is not a perfect straight line parallel to the breakwater. Corrections are based on the continuously stored positioning, heading, roll and pitch data.

A further data treatment arranges the sonar recordings into a straight strip parallel to the breakwater.

Figure 3 - SSS-recordings

Adequate along-track way-points ensure a uniform scale in this direction, to which the transversal scale is adapted. After the geometric corrections, a number of digital imaging techniques is applied to render the side-scan sonar image easy to read and interpret. This step is largely made possible by the great number of recorded grey levels. Figure 3 contains an example of enhanced side-scan sonar recordings, fit to aerial photographs showing the subaerial part of the breakwater. The armour units below and above water level are clearly detectable.

The aerial photographs are rectified grey-scale images of the breakwater, above the low-water line. Both types of recording are fitted together without transition break, so that a continuous image of the breakwaters is created, showing them from the breakwater crest till its toe. On the image, distance indications and other marks are added, so as to facilitate the interpretation.

MULTIBEAM RECORDINGS

With multibeam, as the name implies, a number of discrete sound pulses (or 'beams') are emitted and the returned signal is recorded within well specified angles. Basically the same information is thus collected as with side-scan sonar, only now because of the known direction of the returned signal, the exact distance and hence location of the underwater object can be determined. In multibeam, the output of the device is always in digital form, needing often not more than serial RS-232 connection to have access to the measured data. While, side-scan sonar can be considered an 'imaging' technique, multibeam is a real 'measuring' technique.

Multibeam principle and deployment geometry

Multibeam systems emit a number of discrete sound pulses and record the returned signal within well-specified angles. The system used in the Zeebrugge breakwater monitoring programme, emits 60 beams at a time in a profile, perpendicular to the track. The beams have an aperture angle of 1.5° so that a complete profile covers an angle of 90° . The basic geometry of the system deployment much resembles the one used in side-scan sonar surveying, only now, because both the delay time and the direction of the returned signal are known, the exact location of the reflecting underwater object with respect to the sensor head can be determined.

For the breakwater surveys, the sensor head is rigidly fixed to the vessel's starboard side in an angle of 45° from the vertical, so that the beams look sideward from the sea bottom over the toe protection and armour layer to the watersurface.

Contrary to the side-scan sonar measurements however, with the used multibeam, only on one side of the track are measurements possible at any one time. As the survey operation takes place in very shallow water, a high beam update frequency can be obtained.

A high frequency is advantageous to increase the number of measured profiles, so that a high data density is achieved. In the Zeebrugge breakwater surveys, update frequencies in the order of 13.5 Hz yielded the best results. This rate corresponds to 810 measured points per second, or, at a survey speed of 1 to 1.5 m/s at least 100 measured points per armour unit.

Processing and interpretation of the survey results

The output of multibeam echosoundings is typically a map showing all measured points (on their true location x,y), together with an indication of the measured depth (z , with reference to the chart datum).

Such a basic visualization poses some difficulties, especially when one is interested in comparing the results of successive surveys. Two different approaches to this problem can be used, depending on the type of breakwater material.

For quarry stone layers, such as the toe protection of the Zeebrugge breakwaters, a digital terrain model (DTM) can be fitted through the measured points that are located on the top of the rubble mound surface.

When a second survey has been completed, e.g. one year later, a new DTM of the rubble mound slope can be established. The difference of both DTMs can then be represented in a map, displaying areas where changes in the rubble mound topography have occurred.

If the breakwater is protected by armour units, such as in Zeebrugge (grooved cubes), this method no longer applies. Here, the exact location of the armour units is needed to assess the breakwater's safety, so that displacements per unit can be calculated. The determination of the exact location of the underwater units is possible, as sufficient points are measured per armour unit, with an absolute accuracy of approx. 20 cm in all three axes. This is less than 1/10 the dimensions of the armour unit. Comparison of the same unit, measured at a later stage, e.g. a year later, at the same accuracy, allows the production of differential maps of the submerged armour units with an approximate precision better than 40 cm, 1/5 the dimensions of armour units. Considering that only displacements equal to the unit length are significant in breakwater stability rules and equations, it is evident that the measuring technique effectively and quantitatively allows the assessment of breakwaters' stability.

CONCLUSION

The measurement of the position and displacement of individual armour units of a rubble mound breakwater is the most straightforward method for early detection of breakwater changes.

Due to the difficult and dangerous access, aerial remote sensing is one of the most appropriate ways to obtain the position of those blocks of the outer armour layer that are emerged at low tide.

Aerial photography moreover adds the advantages of high accuracy, fast speed of observation and automated data acquisition and processing.

Appropriate tools have been developed to obtain and evaluate the volume of information. The unit data tables, armour unit location plans, occupation plans and displacement plans provide an effective and accurate picture of the actual condition of the armour layer and the movement of the armour units since a reference situation.

The use of digital side-scan sonar recordings allow qualitative assessment of the stability of the underwater part of breakwaters. Multibeam recordings are very useful when quantitative data are needed.

Since 1993, the determination of the exact position of the Zeebrugge breakwaters underwater armour units, as well as of the exact underwater topography of the breakwaters' toe protection, is based on high-accuracy multibeam echosounding. Successive surveys allow the movements of the armour units and changes in the toe protection topography to be mapped and analyzed.

These three structural monitoring techniques are excellent tools to organize adequate maintenance and to keep the breakwaters in optimum condition.

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References

- Van Damme L., De Wolf P., Fransaer D., Braet K., Van Rensbergen J. (1990).* Breakwater armour units monitored using aerial remote sensing. PIANC-Bulletin n° 70, pp 22-28.
- Van Damme L., Vandenbossche D. (1992).* Port of Zeebrugge breakwater monitoring. Coastal structures and breakwaters. Thomas Telford, London, pp. 165-170.
- De Putter B., Van Damme L., Fransaer D., Claeys F. (1996).* High-quality quantitative and qualitative underwater inspections of breakwaters. Proc of the 11th International Harbour Congress, Antwerp, Belgium.
- Eurosense NV (1995).* Zeebrugge breakwaters Survey. Overview report. Western Breakwater. P2810-P2910.