DATA ANALYSIS AND INTERPRETATION FROM GPS MONITORING OF A BREAKWATER

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Abstract

A long-term settlement monitoring of an old classic rubble-mound breakwater has been performed in the Port of Genoa during refurbishment works aimed at transforming it into a dynamically stable berm type. Monitoring has been based on a network of GPS stations positioned on the breakwater crest plus two reference stations located on firm ground. After the first phase of the refurbishment of the sea-side jetty, a comprehensive data analysis and interpretation of the measured displacements was performed in order to infer the actual and expected stability conditions of the structure under wave actions and seepage. Based on known geotechnical parameters of the underlying sea-bed, several finite element models have been run, enabling interesting interpretations of the settlement phenomena that appear to have been produced both during the operational life of the structure and during the refurbishment works. Results from the interpretation of GPS data have also been compared with information derived from SAR satellite images.

The paper will briefly summarize the characteristics of the GPS monitoring system and its features, and will focus on the methods that have been used to interpret the data. Some considerations on the efficiency and utility of performing a long-term monitoring of breakwaters with the considered tools as a standard practice in port infrastructure management will be drawn.

INTRODUCTION

Breakwater stability analysis has attracted the interest of engineering researchers for a long time. The design and service life performance of breakwaters are the main issues because the type, weight and placement technique of breakwaters’ armour layer units need to be designed considering the damage ratio, which will occur under the estimated wave climate conditions [1,2].

Classic breakwater design includes a single slope jetty and an overlaying superstructure. The jetty is usually realized with armour stones from selected quarry sites or with concrete cover blocks. In cases where not enough large cover stones for a classical rubble-mound breakwater can be provided, a berm rubble-mound breakwater may thus be an interesting alternative to classical rubble-mound breakwaters with concrete cover blocks. The main advantage is related to the smaller armour stone mass required. Recently, attention has shifted from statically stable rubble-mound breakwaters to dynamically stable berm breakwaters [3,4]. The profiles of statically stable structures are not
permitted to change under severe wave conditions, whereas the profiles of dynamically stable structures (such as berm breakwaters) may change according to the wave climate.

Berms breakwaters have been successfully constructed at several locations throughout the world during the last 20 years. A berm breakwater has traditionally been constructed with a berm that has been allowed to reshape instead of constructing it with the reshaped profile directly.

Berm breakwaters can be divided into three categories:

- In the static non-reshaping condition, only a few stones are allowed to move under wave actions (similar to conventional rubble mound breakwater).
- In the static reshaped condition [5], the profile is allowed to reshape into a profile, which is statically stable and where the individual stones are also stable (S-shaped equilibrium profile).
- In the dynamical stable condition, the profile is reshaped into a stable profile, but the single stones may move up and down the slope [6].

The question of allowing reshaping or not obviously has to do with the stone quality and the ability of the stones to withstand crushing and/or abrasion when rolling on the berm [7]. During the past 15–20 years much research has been carried out on the reshaping and stability of berm breakwaters, especially through the EU MAST I and II research programs. A PIANC Working Group has compiled all the research and practical experience into practical guidelines [8].

Most of the stability research on berm breakwaters has dealt with the stability of homogenous berms. However, homogenous berms may lead to a less economical use of the quarry material and the core can be easily uncovered [9]. To be able to utilise as much as possible of the quarry yield and reduce the damage ratio, it may be beneficial to build the berm as a multilayer berm. Some authors [10] show that it is very useful to sort out the larger stones and place them in layers on top of the berm. As a consequence, some recent breakwaters have been designed as a multilayer berm breakwater [11, 12, and 13].

The main components of a berm breakwater are the core, the armour layers and the superstructure. A berm breakwater can fail due to longshore transport of the armour elements; a failure is defined as the event at which the stones of the armour layer have been displaced to such a degree that the core is unstable and needs to be reconstructed. The main modes of failure of a rubble-mound breakwater are also the overtopping failure and the superstructure sliding failure. Other important modes of failure are for example the armour structural integrity, the toe instability and the geotechnical failure due to excessive settlements of the structure. A more detailed description of the failure modes can be found in [14]. Some of these modes are usually correlated, but interaction between modes of failure is complex and poorly understood. A new method for engineering design that allows controlling safety factors and failure probabilities with respect to different modes of failure has been recently proposed by [15].

Due to the high risk of failure induced by severe wave actions, berm breakwaters have to be regularly inspected to reveal possible longshore transport of stones and other instabilities of the composite structure. Gradual deterioration of the armour layers may be unnoticed without the aid of a monitoring programme, and may ultimately result in the failure of the armour layers or in unacceptably large deformations of the structure. Comparison of measurements of the state of the structure at regular time intervals allows changes to be identified at an early stage, thus enabling the appropriate maintenance and repair actions to be carried out [16].

**MONITORING OF BREAKWATERS**

The performance of breakwaters can be significantly enhanced by a long-term monitoring to have information on their stability and to determine causes of failure. The measurements of stability parameters due to severe wave events and a subsequent physical model investigation can be useful to quantify the performance of the breakwater system and to assess solutions for breakwater improvements and repair. A global monitoring program can include the breakwater itself but also sea-state conditions and the effects the structure has on the total environment in terms of wave attenuation, wave transmission by overtopping, wave run-up and coastal erosion. Some programs to monitor completed coastal projects have been developed in the last years [17,18,19]. Different approaches and techniques have been followed for both structural and environmental monitoring and in the present section a brief summary of the methodologies is provided.
Coastal Erosion
Breakwaters influence the local hydrodynamic field which in turn affects the sediment transport processes in the local vicinity of the structure. Physical and numerical modelling techniques are used in many studies on the effects of breakwaters in shoreline changes [20]. Field measurements are usually carried out using Light Detection and Ranging (LiDAR) systems, colour infrared aerial photography, topographic and bathymetric data and also sediment control. LiDAR has the spatial density and the vertical precision required to map coastal areas at risk of flooding from water levels typically 1-2 m higher than predicted tides during storm surges [21]. Aerial photography has to be considered as a very useful technique which should be applied within every monitoring programme. Topographic and bathymetric surveys are used to document volumetric changes associated with the movement of sediments. Geographic Information System (GIS) and Remote Sensing techniques have also been used in numerous natural-resource applications; changes in the coastal shoreline can be captured from the imageries using overlay analysis techniques of GIS applications [22,23].

Overtopping
The complex process of wave overtopping at breakwater structures and related design criteria are generally being studied with small-scale hydraulic model tests. Two European rubble-mound breakwaters have been recently instrumented for field measurements and subsequent reproduction in laboratory models: the rock armoured breakwater in shallow water at Ostia, Italy [24] and the cubes armoured breakwater at Zeebrugge, Belgium [25]. Overtopping has to be related to wave characteristics and water level in front of the breakwater.

Wave Attenuation and Water-Level Measurements
Wave parameters before and after the interaction with the jetty need to be measured and correlated with measurements of the structural response. A conventional wave rider buoy located seaside near the breakwater can provide wave height and wave period of the incident waves. The water level at the toe of the structure can be measured by an infrared wave height meter (IR meter). The breakwater can be instrumented with pressure sensors to measure wave-induced pore pressures inside the breakwater core and wave run-up on the breakwater slope. The run-up height is one of the most important parameters associated with wave loading on the structure and its stability. The highest still water level determines the necessary crest level of the breakwater. A set of vertically placed stepgauges can be used to measure the water level variation. These instruments have been installed at the Zeebrugge rubble-mound breakwater for a prototype monitoring programme [18].

Breakwater Stability
Several monitoring techniques used for the control of the shoreline changes can be used to monitor also the armour stability. Topographic survey on slope, comparative and aerial photography and bathymetry on slope are used for monitoring the armour layers; they are useful when the emerged and submerged parts of the slope are large enough. The accuracy is rather limited and only significant changes can be observed. Some advanced techniques used for the observation of the submerged part are the underwater video recordings, the side-scan sonar and the multi beam recording. Underwater video recording is usually used as a support for observations done by divers but only local investigations are possible. A possible widening can be the recording of cross-profile at regular time intervals by means of an Autonomous Underwater Vehicle [26]. Side-scan sonar allows a ‘general picture’ of the submerged part of the breakwater but only qualitative information is obtained. Multibeam recording coupled with above water topographic information and supported by Digital Terrain models (DTM) allows comprehensive project data bases [27]. The monitoring programme of Zeebrugge also includes multibeam recording to measure the position of each armour unit of the submerged part.

Breakwater Settlements
If settlements stay within the expected values, the settlement of the structure is not a real failure mechanism. Measurement of settlements is usually necessary starting immediately after construction and going on for a few years. Settlement control can be also useful to follow the behaviour of the structure during maintenance or repair works. The technique to be used is known is topography survey of the breakwater crest and any other significant fixed points. Conventional surveys however require a ‘line of sight’, don’t lend themselves to continuous field operations and they are also limited in range. For these reasons, different engineered structures have recently been monitored using GPS. Continuous data recording from the GPS satellites, using ground-based receivers and robust telemetry, have been used for monitoring the settlements of breakwater structures, as described in the present work for the Duca di Galliera monitoring system [28].
MONITORING OF THE ‘DUCA DI GALLIERA’ BREAKWATER

The ‘Duca di Galliera’ breakwater was constructed between 1877 and 1888 to protect the enlargement of the Port of Genoa. It is an old rubble mound, crest walled structure that has suffered significant damage because of the storms and seepage that occurred during its life. The breakwater was certainly designed with little knowledge of the local wave climate and experienced a settlement of about 1 m after its construction. During the years, the breakwater became unstable, so that very significant changes occurred: the total removal of the rocks of protection layer, partial displacements of the crest wall and the total destruction of wide sections of the jetty are some of the damage states suffered by the structure. After the severe storm of 1955 that uncovered even the core at some locations, the breakwater was urgently restored with the placement of armour concrete cubes of more than 40 tons, on the original damaged profile, without the realization of a proper filter layer. Also this intervention showed not to be useful because the concrete rocks collapsed into the core.

In 1995 the Genoa Port Authority started a large-scale refurbishment of the outer jetty for a length of about 820 m. The works were aimed at reducing the action of the waves by transformation of the actual breakwater into a quasi-dynamically stable berm breakwater: the wave motion should model the jetty for achieving a balance configuration [9]. The design profile was defined on the basis of physical model tests. The reshaping berm breakwater typology had never been previously considered in Italy and for this particular case it can be considered an experimental structure. Work started in January 2001 and is still ongoing.

In order to monitor the settlements of the structure during this extensive refurbishment and the potential movements subsequently induced by wave action and seepage, the Authority decided to perform long-term monitoring before, during and after the reinforcing works. The project aim is to monitor the breakwater to control the settlements in the three directions (East, North, Vertical) to document all the unexpected structural movements. In collaboration with the Department of Structural and Geotechnical Engineering of the University of Genoa, the Port Authority has decided to install a network of GPS antennas on the crest wall. A GPS based monitoring system called MMS (Movement Monitoring System) has been selected for this application.

The GPS Monitoring Network
The Global Positioning System (GPS) technology can provide position information with precision to a few millimeters in near real-time [29]. The system consists of a number of small mobile GPS receiver units (sensors) installed on the object to be monitored, plus one or more reference receivers installed at fixed, possibly surveyed locations around the object. The control station provides for data collection, post-processing and supervision of the network; it is remotely accessible through a dedicated communication channel. The post-processing results are the relative position of the various mobile measuring stations with respect to the reference stations. As a few minutes are needed before yielding each final measurement, this monitoring system is used for the static approach.

The breakwater has been equipped with 10 GPS antennas and 2 reference antennas, located on firm ground, that are used for displacement calculation (Figure 1). The system is remotely operated via GSM telephone links. The instrumentation was installed on the breakwater in February 2002, but the system was fully operational in May 2002. The set up phase was rather complicated because of the environmental conditions and the extension of the network [28].

Figure 1. Top view of the 12 measurement stations network for the breakwater.
**Monitoring Results and Interpretation**

After about four years of continuous monitoring, data analysis has shown a strong correlation between the progress of work and the slow displacement of the structure. The crest wall shows a progressive sinking (between 2 and 17 cm), in particular in the middle-sections of the breakwater (sections from G to M), while the external parts of the structure (sections C, D and N) are relatively stable (Figure 2). The horizontal displacements in the North-East direction show also a little rotation of the crest wall towards landside. The tilting and sinking of the structure coincide with the starting of activities during June 2002; in that period a great amount of stone material was temporarily dumped on the landside of the breakwater, so to justify the observed rotation towards landside of the structure.

![Vertical Displacement, mm](image)

**Figure 2.** Vertical displacements (in mm) measured in the 10 sections from February 2002 to January 2005.

The data deriving from the GPS have been compared with available datasets derived from Permanent Scatterers (PS), a satellite technique which utilizes the images reflected by a series of points on the surface (used as radar points) to measure their absolute position [30]. PS vertical data has been plotted and compared with the vertical displacements measured with MMS in Figure 3. PS data shows a slight tendency of the breakwater to settle also before refurbishment works. The instability is more evident for the middle-sections of the breakwater and it is probably related to a consolidation occurrence due to the nature of the soil below the breakwater. MMS measurements show a great increasing of the deformation rate, probably due to the consolidation occurrence strictly related to the beginning of the refurbishment works. This fact is confirmed by observing that the vertical ditching tends to become stable in time starting from temporary interruption of work (October 2003).

From the comparison of the two satellite techniques some considerations can be done. GPS system has the advantage to have a vertical precision of 5-10 mm and to give 3D displacements in near real-time; the precision is independent from environmental conditions but strictly related to the good transmission of the satellite signal. On the other side, PS analysis is necessary for the monitoring of great and densely urbanized areas and can give a long historical data base of deformation. Vertical displacements can be measured with a precision of 1-3 mm but only long-period movements can be measured. As a conclusion, the combined utilization of both satellite systems has demonstrated to be a valid alternative to traditional surveys.

To better interpret the measurements, a finite element model of the breakwater has been studied [31]. The geological conditions and the characteristics of the soil underlying the breakwater have been properly modelled. A sequence of loading conditions has been analyzed starting from the construction phases of the breakwater in the 1880s (Figure 4). The consolidation of marine deposits under applied loads has been reproduced till the starting of the refurbishment program in 2001. Today, about the 80% of the total stone material needed for the intervention has been dumped on the breakwater. The various phases of dumping have been simulated on the FE model, reproducing the observed and the future movements. The model demonstrates that a rotation towards the seaside of the breakwater is forecasted for the final configuration of the project. On the contrary the failure of the structure will be eventually due to a landside rotation of the inner jetty. The results from the simulated model are in good agreement with the measured deformations.
Figure 3. Comparison between the PS data (circles) and MMS measurements (continuous line) for the L central section.

Figure 4. Section of the final configuration with the completed loading sequence.

ACKNOWLEDGEMENT

The Authors are grateful to Mrs. L. Cabona and S. Pampolini for their contribution in the preparation of the present paper.

REFERENCES


