CHAPTER 109

FIELD ANALYSIS OF WAVE ACTION ON BREAKWATER

Alessandro Muraca (*) - Vito Rossi (**)

Abstract

Field analysis of breakwater damage progression has been performed using monitoring programs which included both photographic and topographic surveying.
Reliable information on cover blocks displacement were obtained using a metric camera and a digitizer. Measured damage was compared with those estimated using empirical formulae.
A computer model, capable of predicting damage progression, has been also calibrated using in site collected data. Predicted damage has been satisfactory also for long time interval period.

Introduction

Field measurements have been carried out on a breakwater built up to protect a water intake dockyard for the power plant of Montalto di Castro (Tyrrhenian Sea, Italy).
Cover consists of two strata of rocks, randomly placed by land based equipment, whose average diameter is equal to about 1 meter. The weight of primary armour ranges from 2 to 4 tons and the seaward slope is 1:2. The water depth in front of the structure is about 5 m. The structure is faced by one Waverider Datawell and one Wave-Track directional Endeco: the first installed in 1978, the second in 1986. From December 1991 Wave Track Endeco was replaced by a directional wave rider Datawell .
A field analysis of breakwater behaviour is necessary to evaluate the capability of commonly used design formulae for predicting the damage level ,due to wave attacks, attained by mound structure. Photogrammetric techniques combined with adequate ground control represents a common method for monitoring breakwater damage progression (Ackers, 1983; Gebert, 1984; Kluger, 1982; Pope, 1983; CETN, 1984).

(*) Faculty of Engineering - Viale Ungheria, 43 - Udine, Italy
(**) ENEL-CRIS Servizio Idrologico - Mestre (Venice), Italy

 Accurate field investigations relied upon the use of photography, supported by topographic measurements .Both metric and non metric cameras were used to photograph the breakwater cover layer. Metric photographs were analysed using a stereoscope ; this allowed both a better evaluation of cover blocks movements and a good estimation of the rotation of visible stones.

An accurate time and frequency domain study was made on recorded wave climate; moreover wave grouping aspects, its statistical properties and possible affects on breakwater stability were analysed. Recorded wave parameters were introduced in four commonly used stability theories. Comparison between the empirical design methods and prototype behaviour were made and found to be satisfactory.

Analysis of wave records and results of field inspections were also used to calibrate a computer program for predicting breakwater damage progression. By this model damage progression can be estimated as a function of real sea state records.

Theoretical Damage Prediction

Breakwater stability analysis has been made over the past 30 years by using the Hudson formula (Hudson 1959). In recent years experiments in large wave flumes with irregular waves and careful analysis of prototype damage have led to the formulation of new theories which comprehend also random wave characteristic effects . Losada and Gimenez-Curto developed an exponential model as a function of surf similarity parameter to represent rubble-mound breakwater stability (Losada and Gimenez-Curto, 1980). This stability function is given by :

$$P = \frac{Hs^3 \cdot \gamma}{(S-1)^3} \cdot A(I - I_b) \cdot \exp[B(I - I_b)] \qquad (1)$$

A and B are coefficients whose value is the function of foreshore slope and type of cover layer block. In plane H, T expression (1) could be plotted as an "interaction curve", equal to a set of the points which produce the same value of armour unit weight (Losada, 1980).

More recently Sawaragi and Ryu (Sawaragi, 1983) have analyzed in detail group effects on mound stability. These authors have discovered that a strong correlation exists between Goda spectral peakedness parameter Qp and the energy sum of grouped waves Esumj (Sawaragi and Ryu, 1985).

This relationship is expressed as follows:

$$Esumj = Hs\ (0.042\ Qp + 0.125) \qquad (2)$$

For an exact significance of Esumj the reader is referred to Sawaragi, 1985. The linear relationship between sum energy of grouped waves (Esumj) and the spectrum peakedness parameter (Qp) has been verified using wave data recorded at Montalto di Castro. Both parameters have been evaluated at wave rider depth. Computed values of Esumj were very similar to those estimated using eq. 2. The comparison is reported in Fig. 1.

Irregular wave experiments showed that the percentage of damage suffered by breakwater (D%) is a function of the above mentioned parameters according to the following expressions:

$$D\% = 153.8 \cdot \left[\frac{Esumj}{\gamma \cdot la^2} \cdot \frac{tg\,\alpha}{tg\,\varphi} \right] - 30.1 \qquad (3)$$

$$D\% = \left[\frac{\gamma_a \cdot Hs^2}{\gamma^{\frac{1}{3}}} \cdot \frac{tg\,\alpha}{tg\,\varphi} \cdot \frac{6.15\,Qp + 20}{P^{\frac{2}{3}}} \right] - 30.1 \qquad (4)$$

Sawaragi defines the degree of damage as the percentage of destroyed volume with respect to the total volume of cover layer. According to Sawaragi a displacement takes place when armour units are moved over a distance greater than the overall size of blocks (Sawaragi, 1983).

More than 300 experiments were done by Van der Meer to analyse the effect of storm duration, wave period, group characteristics and spectral shape(Van der Meer, 1987, 1988).The effect of cover layer and sub layer permeability were also carefully investigated. Surprisingly group effects were not found to have a significant effect. More recently, stone shape and layer thickness influence were also analyzed using an expression comparable with Van der Meer formulation (Bradbury, Lothan, Allsoy, 1990) and new stability formulae were found for both overtopped and submerged breakwaters (Van d. Meer 1991) . Van der Meer found two different relationships to determine stable rock block dimensions, for plunging and surging waves.

Plunging waves (I z < I c)

$$\frac{Hs}{\Delta \cdot D} \cdot \sqrt{Iz} = 6.2 \cdot p^{0.18} \cdot \left(\frac{d}{\sqrt{n}}\right)^{0.2} \tag{5}$$

Surging waves (I z ≥ I c)

$$\frac{Hs}{\Delta \cdot D} = p^{-0.13} \cdot \left(\frac{d}{\sqrt{n}}\right)^{0.2} \cdot \sqrt{\cot \alpha} \cdot (Iz)^p \tag{6}$$

Transition from plunging to surging is given by the following expression:

$$Ic = \left(6.2 \cdot p^{0.31} \cdot \sqrt{tg\alpha}\right)^{1/(p+0.5)} \tag{7}$$

Using Van der Meer theory a mathematical method capable of describing revetment damage progression has been calibrated.
This analysis is possible by introducing a parameter that can be referred to as "equivalent sea state". This is equal to a time parameter describing the duration of a fixed sea state capable of causing the same amount of damage of different wave climate conditions (Muraca, 1989). Rearranging formulas (5) and (6) "equivalent sea state" results equal to :

$$D_1 = a \cdot \left(\frac{d \cdot p^{0.9}}{Iz^5}\right)^2 \cdot \left(\frac{\Delta^5 \cdot D^5}{Hs}\right)^2 \cdot Tm \tag{8}$$

$$D_2 = b \cdot \left(\frac{d}{p^{0.65}} \right)^2 \cdot \left(\frac{Iz^p \cdot \cot \alpha}{Hs^2} \right)^5 \cdot \left(\Delta^2 \cdot D^2 \right)^5 \cdot Tm \qquad (9)$$

where D_1 and D_2 are for plunging and surging waves respectively and a and b are dimensional coefficients depending on the units used in the above formulas.

The following steps were used to implement the stability model:

1) Evaluation of data from gauge records and calculation of wave parameter at the front of the structure depth;

2) Computation of minimum sea state capable of causing significant damage to the structure, in order to attain a lower limit below which the wave data recorded can be disregarded;

3) Interpolation between sea states and computation of Van der Meer 's damage parameter with free interval time steps.

All these operations have been implemented on a Vax Digital Computer.

Superimposition of the effects of a sequence of sea states, such as those registered by wave gauges, and the damage description starting from whatever revetment condition is thus modelled.

Site investigation

The investigated breakwater is provisional and undergoes large damage during severe storms. From autumn 1984 the structure has been regularly surveyed by contractors. An accurate zonation of cover layer according to the degree of suffered damage and the number of blocks necessary to rebuild the original sections have been registered at the end of each major event. From 1988, a more accurate survey of damage has been programmed. Two stretches measuring about 15 meters of the structures have been delimited by permanent rods and more visible blocks at different levels have been marked by water resistant paints . Once in two months three pictures were taken of each of the selected parts and the exact position of marked blocks was surveyed using topographical instruments. These operations were also repeated at the end of storms, when the structure was subjected to significant damage.

Cover layer photographs have been analyzed using direct linear transformation, a method developed by Abdel Aziz and Marzan and Karara at Illinois University (Abdel, 1971, 1974; Marzan, 1975). This technique is applicable after measurement by topographic instruments of the position of seven marked blocks, visible in each picture. Using a computer program and a digitizer has allowed a satisfactory precision in the estimation of the movement of cover layer blocks.

The computer program was based on direct linear transform method of Marzan. The lowest movements estimated with this technique were within the range of five to ten

centimetres and the possible errors in predicted position only seldom were over 0.5 meter. From autumn 1989 metric camera and digital photogrammetric stereo workstation was also applied for inspection. The photographs have also been viewed in pairs under a stereoscope: this provided a three dimensional image of the breakwater primary layer and good estimation of rotation of all visible blocks. A higher degree of accuracy in cover blocks displacements estimation was possible by using the photogrammetric workstation ; this was an appreciable advantage for the evaluation of global damage.

 Since no underwater inspection was scheduled the following considerations refer only to the above water level part of the structure. However it is believed that this information provide a reasonable indication of the general condition of the breakwater cover layer.

Field survey were made on the following dates:

Topographic	**Photographic**
June 21 1988	June 21 1988
July 14 1988	July 14 1988
Sept 23 1988	Aug. 25 1988
Nov. 02 1988	Nov. 05 1988
Jan. 11 1989	Jan. 27 1989
Mar. 06 1989	Mar. 15 1989
May 02 1989	May 02 1989
June 12 1989	
July 06 1989	July 07 1989
Nov. 15 1989	Oct. 21 1989
Jan. 10 1990	Jan. 10 1990
June 26 1990	
July 09 1991	July 20 1991
July 16 1992	July 18 1992

The strongest storms were recorded in January and November 1987 and at the end of March 1988. The cover layer, which was seriously damaged, was repaired at the end of these storms.

Frequency and zero up-crossing time domain analysis of wave gauge records were made. An accurate study was also carried out to analyse wave grouping aspects registered by Datawell Waverider.

The length of runs were determined for two threshold values: the significant wave heights and average heights of the highest one-tenth waves. Possible resonance conditions were analyzed according to Sawaragi and Bruun and Gunbak theories (Sawaragi, 1985; Bruun Gunbak, 1978). Thus a continuous knowledge of structure behaviour and wave regime was available.

Results and Discussion

The sea state characteristic of the major storms registered have been treated with the above mentioned methodology. Bathimetry is regular in front of the structure and bottom slope is equal to 1:80. Goda technique for random sea waves was applied for transforming Waverider information from deep to shallow water (Goda, 1975, 1985). A comparison between predicted and measured damage was done for the major storms registered. Hudson, Losada, Sawaragi and Van der Meer theories has been applied to compute theoretical damage level. Two severe events were registered in January 1987 and March 1988. The results of analysis of wave records, for March 1988 storm, are shown in Tab.1.

DATE	HOUR	H1/10 (cm)	T1/10 (s)	H1/3 (cm)	T1/3 (s)	Qp
30-03-88	18	307	6.8	253	6.9	2.2
	21	356	8.1	302	7.8	2.9
31-03-88	0	396	7.5	310	7.5	2.9
	3	537	8.0	415	8.0	2.4
	6	642	8.9	501	8.9	2.9
	9	508	8.9	405	8.8	2.4
	12	426	7.6	351	8.0	2.5
	15	425	7.8	312	7.5	2.5
	18	394	7.7	310	7.5	2.7
	21	344	7.3	268	7.5	2.5
01-04-88	0	265	7.0	206	6.6	2.6

Tab.1 Wave statistics from Waverider data - 30 March through 1 April 1988 (significant wave heights below 2.5 m are disregarded).

In both cases the structure suffered very severe damage.
Run lengths of groups exceeding significant and average of highest one-tenth waves were analyzed. During the March 1988 storm nearly all groups with heights over significant ones were within Sawaragi critical region and the breakwater suffered the highest observed damage: part of the filter was discovered and large portions of cover blocks were carried away. Tab. 2 shows damage estimations according to Hudson, Sawaragi and Van der Meer theories.

	Measured damage			Predicted damage		
EVENT	Hudson	V.d.Meer	Sawar.	Hudson	V.d.Meer	Sawar.
Jan.87	20	6.5-7	60	15-20	6.8	46
Mar.88	30	8	100	20-30	7.8	87
PERIOD						
Ja.-Ap.89		2.5			3	
Jul.90-92		4			5.2	

Tab. 2 Comparison of measure and predicted damage in selected events.

In June 1987 the damages were, in the same order mentioned previously, 20, 60 and 7 (Tab. 2). The maximum significant wave height and average height of the highest one-tenth waves, both computed in front of the structure, were introduced using Hudson formula. Predicted damage was closer to measured one using significant wave height.

Interaction and breaking limit curves for the Montalto breakwater have been plotted and compared with wave characteristic estimated in front of the structure. Interaction curve separates on plane (H, T) stability and instability zones (Losada, 1980). Significant wave characteristics, estimated at structure depth, for the March 1988 storm were compared with interaction curve . All significant waves were found to fall inside the stability area. To attain the instability region the average height of one tenth of waves should be used .

In shallow water this wave parameter seems more suitable for comparison between wave attacks and Losada stability function. For Sawaragi theory the maximum value of D% parameter has been considered. For each wave gauge record significant wave heights at structure depth were computed with the theory of Goda while Qp was estimated directly from Waverider records (eq. 4). No theory is available to transfer Qp parameter at different depths (Mansard, 1987, 1988). However, because of the complexity of the shoaling mechanism, an exact transfer of wave data, expecially those referred to wave grouping, from deep to shallow water depth is not possible through the existing theories (Mansard and Funke, 1988; Nelson, 1988).

Recently an application based on the TMA and Doneland models was used to transfer wave frequency spectrum from deep to shallow water, and results seem promising (Rebaudengo, 1992).

However all these methods are not applicable if there are significant non linearities. Since the variability of Qp is not predictable, the peakedness value introduced in Sawaragi formula was estimated at wave rider depth. This could explain the higher differences between measured and predicted damage levels (Tab. 2). However

bathimetry is regular in front of the structure and bottom slope lower than 1:80 ; as a consequence Qp computed at the Waverider depth is believed to be comparable with that in front of the structure (Rye, 1982).

To find out the degree of variability of Qp parameter with water depth, some wave records at different depths were carefully analyzed. Data are referred to different Italian sites where two or more wave-riders are located at different depths, but aligned orthogonally to the coastline.

As shown in Fig. 2 the range of Qp variability seems to be not significant in the range 13 to 50 meters of depths. An attempt to transfer the Esumj parameter from deep to shallow water was made using different shoaling theories for a single wave registered in time domain ; however results were not satisfactory.

The stability model was applied to determine the damage using the Van der Meer theory. Significant wave heights below 2.5 m were disregarded. After many computer trials and in site measurements to calibrate the program, this value of wave height value was found to be the minimum below which the estimated damage using the Van der Meer method, for a three hours wave attack, is negligible (Muraca, 1989).

The computer model allowed, in all examined events, a reliable prediction of breakwater damage due to wave attack (see Tab. 2 for January 1987 and March 1988 storms).

In 1988 the breakwater cover layer was repaired. During the first four months of 1989 the structure suffered only a slight damage. At the end of April 1989 the measured damage according to Van der Meer theory was equal to 2.5.

To test the capability of computer program in reproducing damage evolution, wave data of January-April 1989 were inserted as input. The test result was completely satisfactory since the final predicted damage was very close to the measured damage (Fig. 3).

A lengthy duration test was made inserting recorded wave data from July 1990 till June 1992. Also for the two year period the predicted damage was very closed to the measured damage (Fig. 4).

A continuous description of damage level evolution, based on Van der Meer's theory, then seems possible with satisfactory approximation. Nevertheless, some indetermination remains in estimation of wave parameter at shallow water depth, although the site measurements and wave data were carefully analysed.

Conclusion

Photographic and topographic surveying have been applied for monitoring the stability of a rubble mound breakwater. Reliable estimation of cover blocks displacements can be obtained using non metric camera and direct linear transform method of analysis.

The use of a metric camera and digital photogrammetric workstation has allowed a high degree of accuracy.

A comparison between in site measured and predicted damage for a prototype breakwater has been made applying four different theories. A mathematical model for continuous damage description, based on Van der Meer stability analysis, has been calibrated with in site measured data.

This model describes superimposition of different sea states and evaluates the damage starting from different structure conditions. Predicted damage with stability model has been satisfactory also for very long simulation period.

A knowledge of the response of the structure for a real or project sequence of sea states can be helpful in programming maintenance or to decide if damage attained can be critical for the whole stability of the structure.

LIST OF SYMBOLS

d   = Van der Meer damage level
D   = median diameter of stones of armour layer
D%   = Sawaragi damage index
Esumj   = Energy sum of grouped waves
H   = wave height
Hs   = significant wave height
I   = Iribarren number
Ic   = transition Iribarren number
Ib   = Iribarren number for breaking condition
Iz   = Iribarren number using Rice average wave period and Hs
la   = average dimension of armour stone
m_n = spectral moment of n order
n   = number of waves
Qp   = Goda spectral peakedness parameter
p   = Van der Meer permeability parameter
P   = weight of stable stone
S   = specific gravity of armour rock (γ / γ_a)

Tm   = average wave period ($\sqrt{m_0 / m_2}$)
α = angle of seaward slope of the structure
γ = specific weight of stone
γ_a = specific weight of water
φ = natural angle of repose of stone
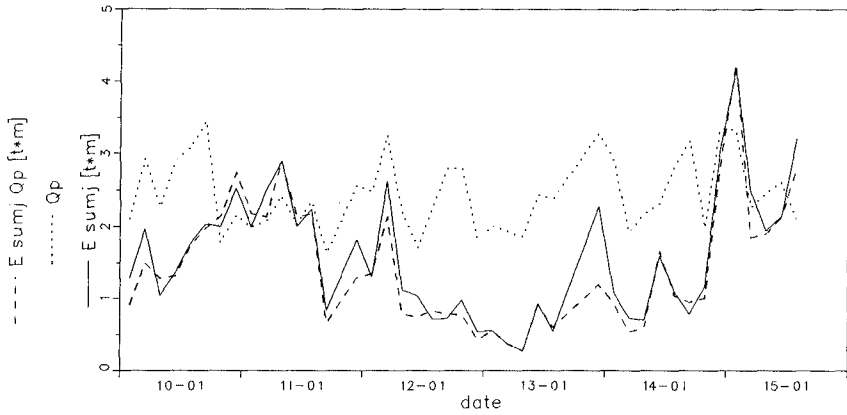Δ = relative mass density (S - 1)

MONTALTO DI CASTRO — WAVE DATA 1987

Fig. 1 — Comparison between energy sum of grouped waves calculated
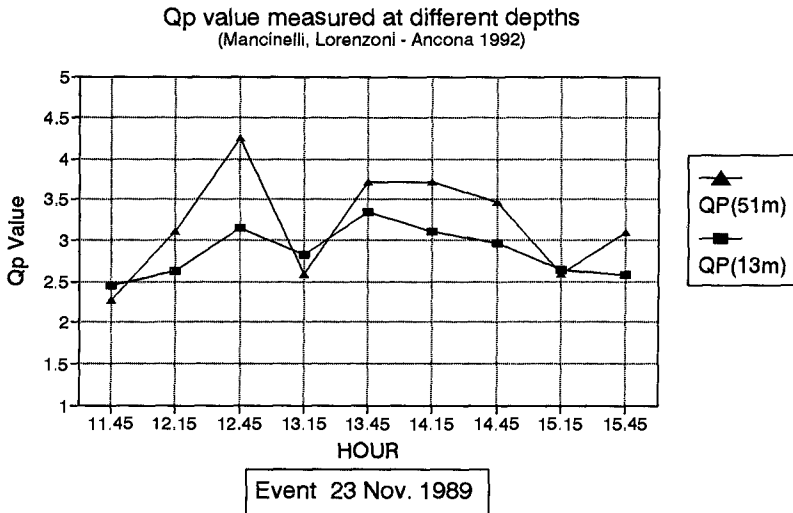   from Qp (Esumj(Qp)) and measured by waverider record(Esumj)

Qp value measured at different depths
(Mancinelli, Lorenzoni - Ancona 1992)

Event 23 Nov. 1989

Fig. 2 — Range of Qp variability at different depths.

MONTALTO — JAN. APRIL 89 — MEASURED AND PREDICTED DAMAGES
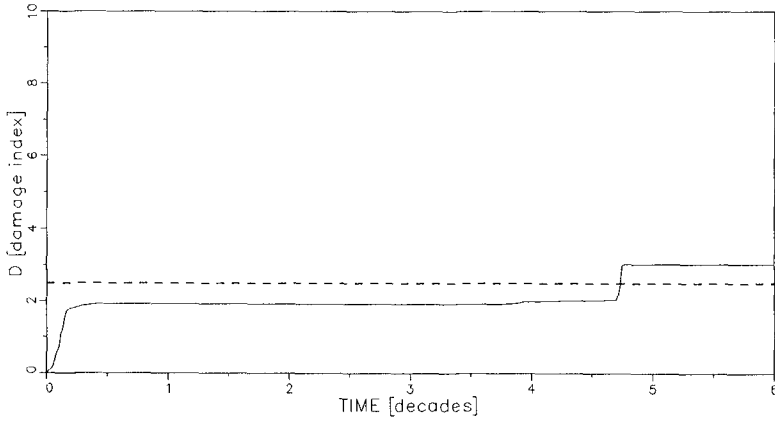
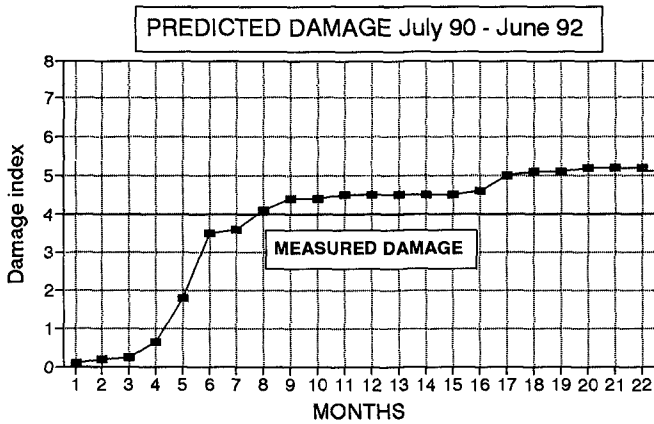Fig. 3 - Damage index evolution (period January-April 1992).

Fig. 4 - Damage index evolution (July 1990 - June 1992).

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