CHAPTER 145

HYDRAULIC AND MATHEMATICAL MODELLING OF HISTORICAL AND MODERN SEAWALLS FOR THE DEFENCE OF VENICE LAGOON

Leopoldo Franco[1] and Giuseppe R.Tomasicchio[2]

Abstract

This paper gives an overview of the development of design and construction of coastal defence works in Venice. In fact shore protection is one of the tasks of the present large project for the safeguard of Venice lagoon. A brief description is given of the most interesting steps of the new design supported by extensive field measurements and interactive model testing. An introductory review of the old historical structures for the defence of the lidos (in part still existing) is also given to underline the important links with the past experience and the unusual constraints of the present designs.

Introduction

The lagoon of Venice is connected to the Adriatic Sea by three tidal inlets (the port entrances of Lido, Malamocco and Chioggia) which divide a system of barrier islands and sand beaches (Fig.1). These thin strips of land, named "lidi", extend for some 40 km and have long since been representing vital natural barriers to defend the physical integrity of the lagoon and even the military safety of Venice. Therefore, the protection of the littorals has always been a fundamental issue for Venetian Authorities and has been dealt with by a special Water Committee (Magistrato alle Acque) managed since 1501 by elected hydraulic experts. Despite their efforts, progressive shore erosion has been taking place after the diversion of the river mouths to avoid the lagoon siltation and after construction of the inlet jetties to ease navigation.

1 Professor of Coastal Engineering,Department of Hydraulic,Environmental and Surveying Engineering, Politecnico di Milano, P.Leonardo da Vinci 32, Milan

2 Researcher, Hydraulic Institute, University of Perugia, Pian di Massiano, 06100 Perugia, Italy

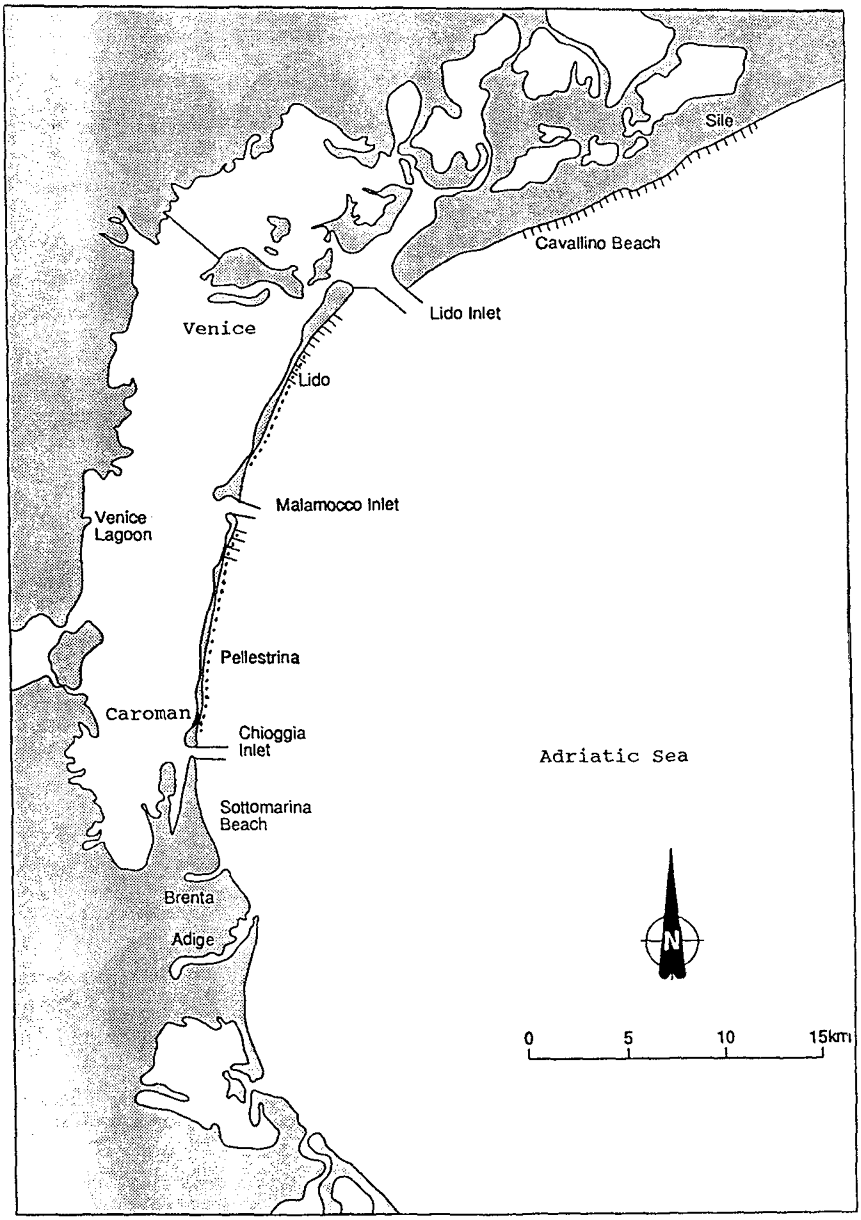

Fig. 1 Map of Venice lagoon and littorals including location of the existing "murazzi" (denoted by dots) and groynes.

Historical evolution of sea defence works in Venice

Interesting information on historical sea defences in Venice can be found in a nice book by Grillo (1989). Written reports of local shore protection works date back as early as 537 a.C., when wicker faggots were used to hold the earth dykes reinforcing the sandy dunes formed from river supply, wind and wave action.

Strict environmental regulations were issued since the 13th century to preserve the littoral defences, such as prohibiting the transit of cattle upon the dykes, the removal of sand or vegetation and the export of materials useful for shore protection. These were mainly timber and rock, often combined in a sort of cribwork.

The typical seawall in the 17th century was made by rows of longitudinal fences of timber piles half embedded along the dyke outer slope and at the toe which contained a few layers of stones (as shown in fig.2 in the drawing of 1692 by M.Alberti in comparison with the Dutch standards). The timber piles however had only few years lifetime and excessive maintenance work was needed.

Therefore the Authorities, around 1700, seeked for innovative designs: various technical solutions were experimented at the own risk of consultants and contractors (who might get paid only after the proved effectiveness of the work!). Coastal protection works included either seawalls and revetments (made with riprap, gabions, smooth marble blocks linked with mortar and steel, flexible steel strips, regularly placed stepped limestone blocks and various elements to increase the slope roughness) or groynes (made with timber and steel piles, often filled with rock).

Finally around 1740 a durable monolithic seawall structure was proposed by the mathematician B. Zendrini which worked successfully until today (Fig.3): the so called "murazzi" are composed by a smooth white flagstone revetment supported at toe and crest by massive walls. The innovative technology was in fact represented by the effective block bonding with "pozzolana" mortar (a lavatic powder hardening in water, shipped from Naples). The "murazzi" have been maintained and repaired in the last 250 years: the existing structure was reinforced in the middle of past century with a toe rock revetment and recently even with diaphragms and anchor piles (Fig. 4).

Rock groynes have also been built along the beaches of Lido, Cavallino and Pellestrina even in front of the "murazzi". The construction of the inlet jetties (Malamocco 1856, Lido 1887 and Chioggia 1914) and the dredging of navigation channels changed the sediment transport conditions along the littoral. Sand has been trapped by the long end jetties with accretion taking place in the lee areas (especially against the jetties at north Lido and south Chioggia), whereas strong erosion kept occurring in central Lido and Pellestrina beaches. Shoreline retreat has been enhanced in the last 40 years due to sea level rise (mainly because of subsidence) and to the reduction of river sediment supply, partly lost offshore during ebb tidal flows.

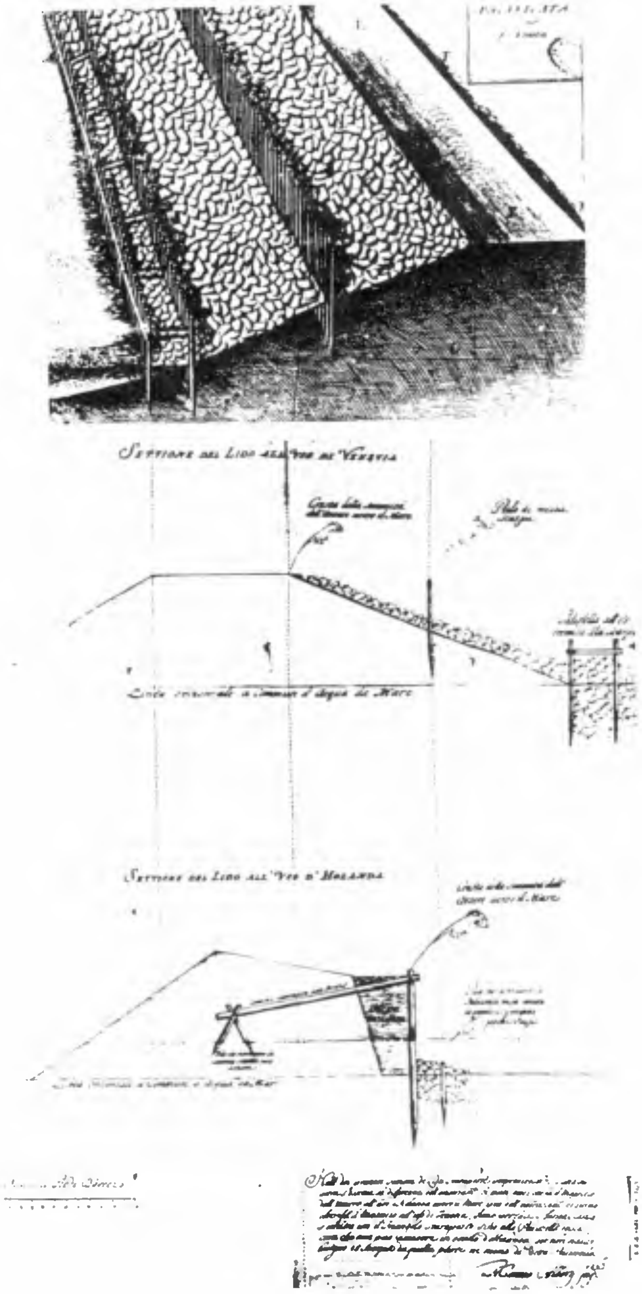

Fig. 2 Ancient drawings of typical coastal dykes in Venice (with "paleselle") in the 17th century, in comparison with the Dutch technique (bottom) (Grillo,1989)

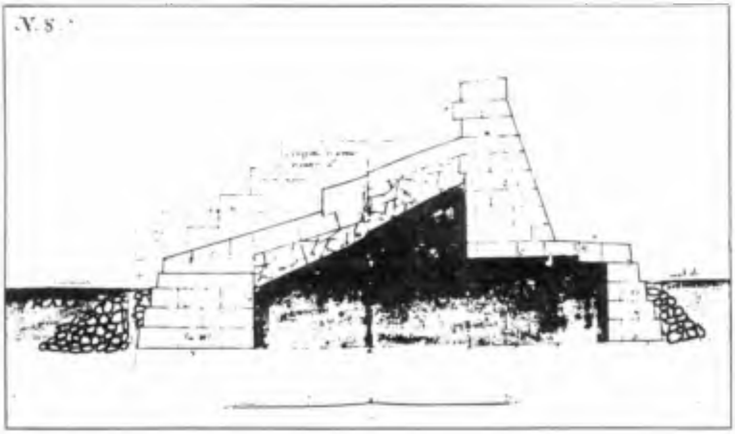

Fig.3 The original "murazzi" seawall at Caroman in a drawing by B.Zendrini (1743) (Grillo,1989)

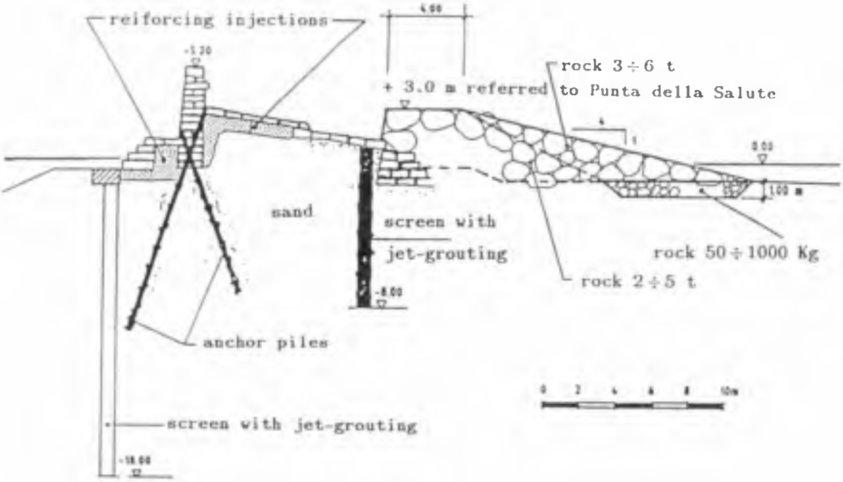

Fig.4 The present reinforced murazzi seawall at Caroman

The disappearance of the emerged beach and the erosion of the submerged seabed profile (with deposition occurring at depths below -8 m), results in larger waves reaching the seawall with increased overtopping and reduced stability of the rock protection. Infact a large breaching took place during the severe storm of 4 November 1966, when an extreme water level of nearly +2.0 m M.S.L. was recorded.

Therefore, within the present large project for the safeguard of Venice, new sea defence works have been designed in order to preserve not only the valuable coastal strips, but also the existing monumental old defence works themselves, without any negative aesthetical impact.

New design of coastal defence works with model studies

An accurate design process has been undertaken by TECHNITAL on behalf of the CONSORZIO VENEZIA NUOVA. The main design efforts have been devoted to the most vulnerable Pellestrina littoral and included detailed field investigations on the coastal morphology and dynamics and a large set of advanced physical and mathematical model studies for the design optimization.

At the basic design stage an extensive series of small scale (1:30) model tests was carried out in the 42.5 m long random wave flume at the hydraulic laboratory of the Magistrato alle Acque in Voltabarozzo (Padua). The tests were conducted and reported by PROTECNO (1990) with the assistance of DHI (Denmark) for the weakest "murazzi" sections at Pellestrina (first phase) and Caroman (second phase).

The following measurements were made in each test of 6 hours duration (prototype) with five Jonswap wave spectra (up to Hs=4.5 m and Tp=11.0 s) and four water levels (0,+1.0,+1.5,+2.0 m MSL) : wave heights and reflection coefficient, wave overtopping discharge, rock armour stability (by counting the coloured displaced stones), forces on the old vertical wall (by a strain gauge), pressures inside the rubble mound (by two transducers), toe scour of the mobile seabed (Fig.5). The beach profile, with a slope of 1:100, was modelled to a depth of -8 m MSL.

Initial testing of the existing structure showed unacceptable overtopping rates and damage of the 2-5 t rock armour under the design conditions (sea level +2.0 m).

For the "murazzi" at Caroman (the area at the southern border of Pellestrina strip) four alternative defense schemes with submerged berms with variable width and elevation were tested. The design choice was to extend the rubble mound toe underwater to avoid any visual impact, whereas a beach nourishment was not regarded as a cost-effective option due to the particular convex coastline planshape. The model tests showed that a satisfactory reduction of wave forces on the old vertical wall, overtopping discharge, and armour damage was obtained with a berm crest at -0.5 m to m.s.l. extending offshore for 30 m, whilst no further benefits related to the forces on the wall were found by increasing the berm width to 40 m. The scheme shown in fig. 6 (together with the local existing section) was then adopted for

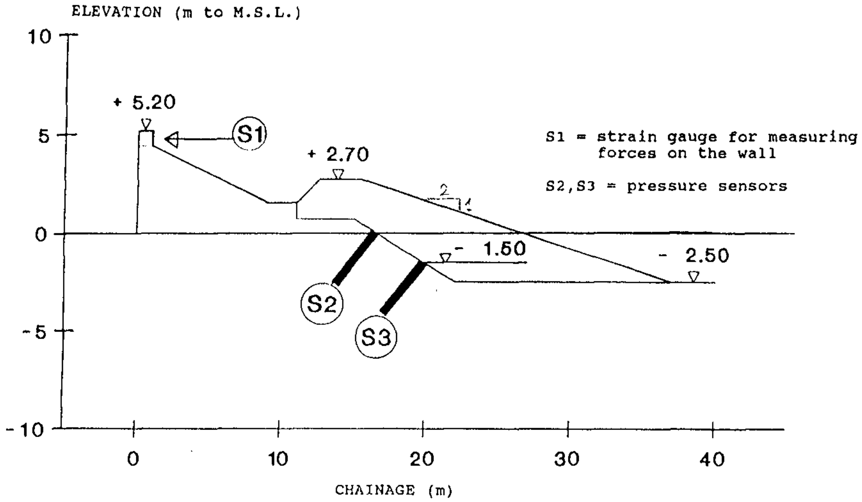

Fig. 5 Model set-up of existing "murazzi" at Pellestrina

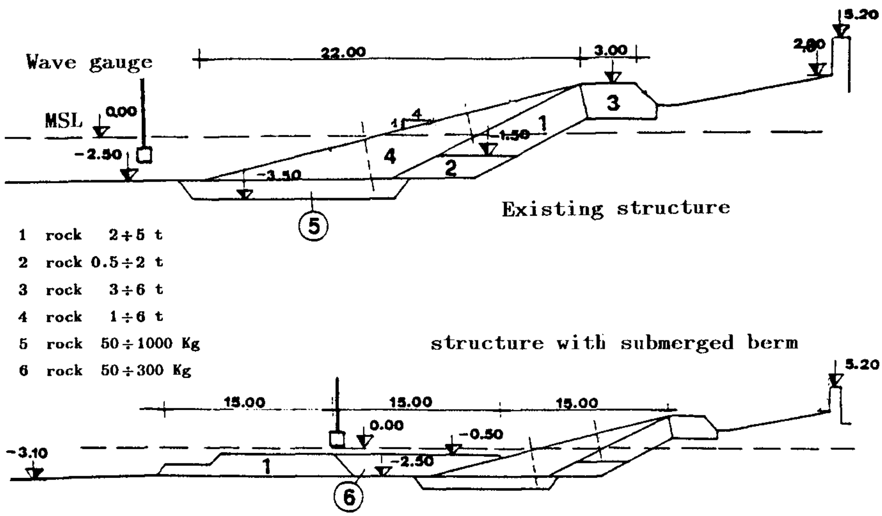

Fig.6 Model test sections for the Caroman murazzi

the final protection design at Caroman. The stability of the submerged rock berm was also checked by profiling along two longitudinal axes after each test.

For the "murazzi" at Pellestrina several alternative reinforced structures have been tested, following the "environmental requirement" that crest elevations could not be increased. The remedial works mainly consisted in larger and heavier rock revetments (even including proper underlayers) and beach nourishment. The results showed a significant decrease of the overtopping discharge and of the cumulated damage of the main armour (always reduced below 2%). The most effective solution turned up to be a combination of a larger rubble seawall and a beach nourishment protected by submerged rock barriers.

The final design of the protection scheme for Pellestrina was recently optimized with the support of an interactive system of both 2-D and 3-D mathematical and hydraulic mobile-bed models performed by HR, Wallingford (1992). The main conclusions of the study allowed an inshore displacement of the submerged rock sill and a larger spacing of the rock groynes, partly submerged, which confine the artificial beach with just a 2-3% yearly volume loss of sand (provided a borrow fill material with D50 in excess of 0.1 mm). The final and optimized design schemes are shown in fig. 7 .

At present detailed geophysical surveys and vibrocore sampling are being undertaken to verify the exploitation of ancient sand deposits in depths of 17-22 m off the Malamocco inlet, to be dredged and pumped ashore. It may be interesting to remark that even this "modern" scheme of artificial beach nourishment was among the shore protection solutions proposed three centuries ago, when primitive dredgers were in use to excavate the channels of Venice lagoon!

Comparison of model results with formulae of static stability

The above studies demonstrate the great efficiency of a combined use of physical and mathematical models to verify the complex sea-structure interactions in the coastal zone. Generally the laboratory tests can be used to study small scale processes and to calibrate the numerical model tests, which in turn can be quickly repeated to investigate the influence of many parameters and extend the analysis to a larger temporal-spatial scale. Model tests can also be useful to calibrate practical empirical design formulae which can then be easily applied for a greater number of hydraulic and geometric conditions.

It was then believed useful to make a comparison between the results obtained from the application of some well known formulae of armour stability against the observed damage of the existing murazzi rock revetment. The count of the displaced stones at the end of each test enables to determine the numerical value of the damage parameter $S = A_e/D_{n50}^2$, where A_e is the erosion area in a cross section, D_{n50} is the nominal diameter of the stones. The damage parameter S is physically the number of cubic stones with a side of D_{n50} eroded within a D_{n50} wide strip of the structure.

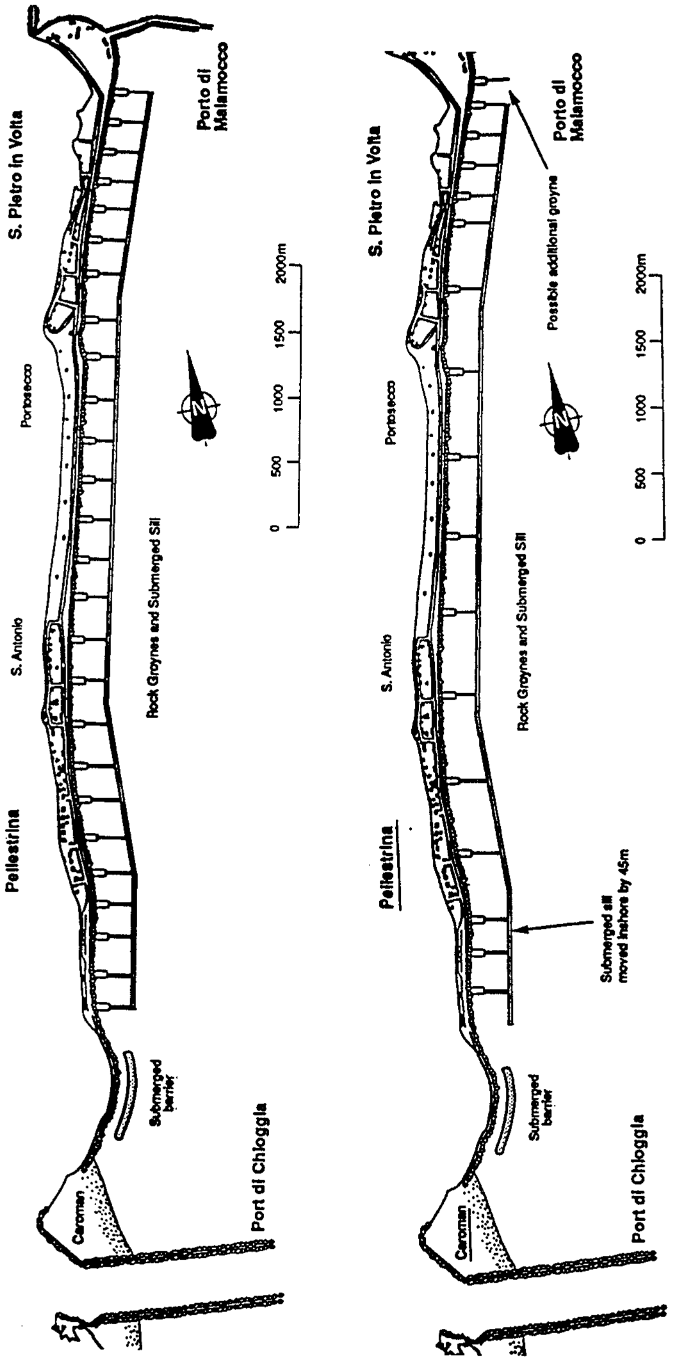

Fig. 7 New defence of Pellestrina littoral: basic design plan and final optimized design

The parameter S can be related to the actual number of displaced stones (N_d):

$S = N_d * D_{n50}/[B * (1-n_v)]$ where:

B = length of modelled seawall;
n_v = porosity of the mound.
S = 2 signifies start of damage, S = 8 means that the underlayer is visible (slope 1:2).

Two well known equations for static stability have been considered: the one proposed by Van der Meer (1988) for plunging waves :

$$H_s/\Delta D_{n50} * \sqrt{\xi_m} = 6.2\ P^{0.18}\ (S/\sqrt{N})^{0.2} \qquad (1)$$

and the Hudson formula given in SPM (1984) and modified by Van der Meer (1988):

$$H_s/\Delta D_{n50} = 0.70\ (K_D \cot\alpha)^{1/3}\ s^{0.15} \qquad (2)$$

N = 2500-4000 is the number of waves in the various test series.
P = 0.4 is the assumed value of the permeability factor
Tm = Tp/1.25 is the assumed average wave period in each test.

Eq. (1) and (2) were obtained for not overtopped structures. The test conditions and some results are given in tabs.1, 2 for the two slopes and in figs. 8, 9. The high rate of wave overtopping on the "murazzi" influences the observed damage. The results may also be affected by the depth limited wave conditions at the seawall. This analysis enables to verify the reliability of the two proposed formulae for static stability when predicting the rock armour damage of the existing "murazzi" seawalls. Van der Meer's formula was used to predict the cumulated damage for all the considered water level conditions and the results show a good agreement with the observed damage up to a water level of +1.5 m MSL, with a slight expected overestimation (see Fig.8 for the 1:2 slope). The application of the modified Hudson formula (with K_D = 2 for breaking waves) does not describe the cumulated damage and produces unreliable results for both slopes of the "murazzi". A stability factor K_D=5 should be used in this case to match the experimental results.

For all the tests with water levels up to +1.5 m MSL a good correlation was found between the measured overtopping discharge and the difference of the computed (S_{VdMcum}) and the observed (S_{obs}) damage as shown in fig. 9. Only for the highest water level , near to the seawall crest (+2.0 m), the data is more dispersed. In the figure data from both Pellestrina and Caroman test series is plotted.

This analysis confirms the correlation between the stability of the front armour and the overtopping rate of a low-crest coastal structure. It also shows that the Van der Meer formulae can give acceptable conservative results even for low seawalls in shallow waters.

murazzi at Pellestrina $W_{50} = 2.45$ t *slope 1:2*

Hs [m]	Ns	Tm [s]	S_{obs}	$S_{VdM\ cum}$	S_{Hudson}	Sea Level [m]	Q [$m^3/s/m$]
1.90	1.04	5.60	0.0	0.20	0.66	1.50	–
2.40	1.41	6.64	0.87	0.91	4.88	1.50	$1.46 \cdot 10^{-4}$
2.57	1.51	7.36	1.49	1.68	7.36	1.50	$7.21 \cdot 10^{-4}$
2.60	1.52	7.00	1.61	2.15	8.33	1.50	$1.56 \cdot 10^{-3}$
3.20	1.88	8.00	2.86	4.79	33.26	1.50	$7.08 \cdot 10^{-3}$
3.20	1.88	8.88	4.23	6.70	33.26	1.50	$5.82 \cdot 10^{-3}$
2.10	1.23	6.16	0.0	0.46	2.00	2.00	$3.63 \cdot 10^{-4}$
2.70	1.58	7.20	0.80	1.69	10.71	2.00	$5.26 \cdot 10^{-3}$
3.00	1.76	8.00	2.36	3.43	21.63	2.00	$2.16 \cdot 10^{-2}$
2.80	1.64	8.48	2.86	4.30	13.65	2.00	$1.63 \cdot 10^{-2}$
2.80	1.64	8.88	3.23	5.16	13.65	2.00	$2.99 \cdot 10^{-2}$
3.10	1.82	8.88	3.23	6.63	26.92	2.00	$4.38 \cdot 10^{-2}$
1.90	1.11	7.20	0.24	0.30	1.02	0.00	0.00
2.00	1.17	8.48	0.37	0.59	1.44	0.00	0.00

Table 1 *Sea level to msl*

S_{obs} = *observed damage*
$S_{VdM\ cum}$ = *cumulated damage calculated using BREAKWAT (Van der Meer, 1988)*
S_{Hudson} = *damage calculated using Hudson formula with* $K_D = 2$

murazzi at Caroman W_{50}=2.9t *slope1:4*

Hs [m]	Ns	Tm [s]	S_{obs}	$S_{VdM\ cum}$	S_{Hudson}	Sea Level [m]	Q [$m^3/s/m$]
2.53	1.49	7.20	0.0	0.34	2.48	1.00	$1.54 \cdot 10^{-5}$
2.57	1.51	8.00	0.0	0.56	2.76	1.00	$6.75 \cdot 10^{-5}$
2.47	1.45	8.88	0.0	0.73	2.11	1.00	$1.95 \cdot 10^{-4}$
2.70	1.59	7.20	0.13	0.43	3.88	1.50	$4.58 \cdot 10^{-4}$
2.70	1.59	8.00	0.17	0.69	3.83	1.50	$1.01 \cdot 10^{-3}$
2.75	1.62	8.88	0.24	0.99	4.33	1.50	$2.90 \cdot 10^{-3}$
2.79	1.64	7.20	0.55	0.49	4.77	2.00	$3.30 \cdot 10^{-3}$
3.07	1.81	8.00	0.68	1.01	9.03	2.00	$9.10 \cdot 10^{-3}$
3.24	1.91	8.88	0.92	1.65	12.94	2.00	$2.24 \cdot 10^{-2}$

Table 2 *Sea level to msl*

S_{obs} = *observed damage*
$S_{VdM\ cum}$ = *cumulated damage calculated using BREAKWAT (Van der Meer, 1988)*
S_{Hudson} = *damage calculated using Hudson formula with* $K_D = 2$

Tabs. 1-2 Comparison of observed and calculated armour damage
(Hs = significant wave height at the toe in depth of -2.5 m MSL)

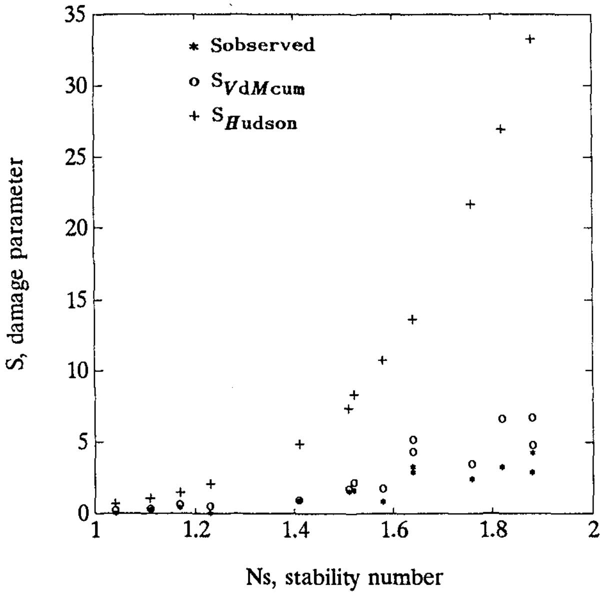

Fig.8 Comparison of observed and calculated armour damage for the murazzi at Pellestrina (Ns = Hs / delta D50)

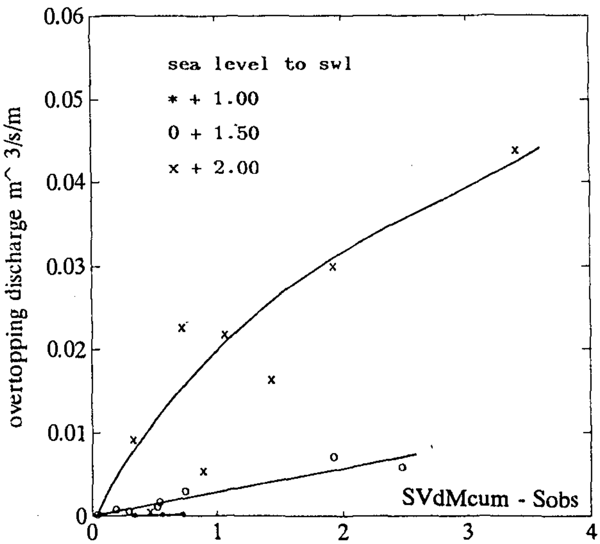

Fig.9 Correlation between damage and overtopping for the murazzi seawall

Final remarks

The development of an effective system of coastal defence works plays an important role within the present large project for the safeguard of Venice lagoon. Careful studies have been carried out to optimize a modern design in armony with the past experience, in order to ensure the required level of structural stability and environmental protection. The chosen solutions, a confined beach nourishment at Pellestrina and submerged berm at Caroman, are compatible with the conservation of the historical "murazzi" seawall and the former one also with the increasing touristic use of the beach. Since the sediment available for beach nourishment is very fine, the design of the longitudinal and transversal structures for the sand containment required extensive simulations with advanced interactive mathematical and physical models. Results from model tests have also been used to check the efficiency of two popular formulae for armour static stability in depth-limited wave conditions. The equations by Van der Meer seem to give reasonable conservative predictions in the case of the low crest "murazzi" seawall and the difference between the computed and observed damage is in fact fairly correlated with the overtopping discharge.

Acknowledgements

The authors wish to thank Mr P. Silva and Mr. F. Galante of TECHNITAL, Verona, design engineers of Venice coastal defences, and Mr A.Venuti of PROTECNO, Padua, model engineer, for the kind supply of useful information.
The model studies have been conducted for the Consorzio Venezia Nuova, concessionary for the studies and works related to the Venice project on behalf of Magistrato alle Acque.

References

Grillo, S., (1989). Venezia, le difese a mare. Arsenale Editrice, Venezia.

HR Wallingford, (1992). Model tests for the Pellestrina littoral. Report EX 2524.

Protecno,(1990). Prove su modello fisico dei Murazzi di Pellestrina, I e II fase, Padova.

U.S.Army CERC (1984). Shore Protection Manual, Washington

Technital, (1990). Interventi di difesa del litorale veneziano dal fiume Brenta al fiume Sile. Progetto di massima, Verona.

Van der Meer, J. (1988). Rock slopes and gravel beaches under wave attack., Ph.D. thesis, Delft

Photo 1-2 Views of the existing murazzi at Pellestrina
(in some areas with macro-roughness elements)

Photos 3-4 Views of the model section of the "murazzi" at Pellestrina with evidence of rock armour displacements