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# Run-up computation behind emerged breakwaters for marine storm risk assessment

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**ABSTRACT**

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Flood vulnerability assessment due to marine storms is very important for integrated coastal zone management. The case study site is a highly developed area (Rimini) along the Emilia Romagna coastline, facing the north Adriatic sea in Italy. This area is composed of low sandy beaches and is completely protected by emerged breakwaters. Rimini was chosen in order to assess the vulnerability of a very important tourist resort that represents one of the most significant revenue for the regional economy. For the vulnerability assessment it was decided to consider the worst scenarios, using a joint probability of occurrence for a 1, 10 and 100 years return period storm, happening at the same time as an atmospheric surge and with the maximum spring tidal level of +0.45 m above MSL (run-up + surge + tide). The beach slope of different profiles was calculated using the a 2004-DTM (Lidar-based). The attenuation effect of the breakwaters was considered inside the run-up formula using the following method: (i) a 1-d model was used to evaluate the wave height at the seaward foot of each structure; (ii) the Van der Meer formula was applied to calculate the wave height behind structures; (iii) the calculated wave height was transported back to deep water conditions using a 1-d model. Different damage categories were created. The results reveal that, even with the one year event, most of the infrastructures are damaged and the areas behind the beach are flooded.

**ADDITIONAL INDEX WORDS:** *Flooding, Vulnerability, Coastal Structures*

## INTRODUCTION

In the present scenario of climate variability many authors are debating about the impact of high energy events. In the aftermath of the Katrina disaster in New Orleans, the public opinion has become more aware of the vulnerability of highly developed area. Should a disaster occur, although not everywhere there is a risk to human lives, the impact on the economies can become significant and require considerable investment to recover it. Although from a public perception viewpoint the presence of coastal protection structures gives a false sense of “safety”, the failure of dykes during Katrina has proved that a concomitant occurrence of negative events can overcome design criteria. Additionally, the structures may be resist from a structural viewpoint, but there efficiency in preserving beach levels behind may be reduced during storms.

In order to estimate flooding probability of the area protected by the structures it is necessary to estimate wave run-up on the protected beaches. From a methodological perspective this requires to quantify wave dissipation over the structures, relating inshore wave height with offshore conditions, which are generally required by wave run-up formulas. The aim of this paper was to develop and test a computational protocol for estimating wave run-up in this conditions, applying to a case study site which is representative of most of the coastal zone in Emilia-Romagna, one of the wealthiest and most densely populated coastal areas in Italy.

## STUDY SITE

The Emilia Romagna coastline is composed of 130 Km of low sandy beaches, including the Goro spit. The 57% (80 km) of the coastline is protected by breakwaters (emerged and semi-submerged), groins, sea walls, etc. The dunes are almost disappeared but there are few places, inside natural parks, where they are preserved because of their natural value.

The main characteristic of the coastline is the massive presence of tourist activities. Tourism directly generates an yearly budget of 8 billion Euros, which corresponds to 7% of the Regional GDP. If the satellite activities are considered (e.g. services) this grows to 15% of the GDP.

During the summer season several millions of people go to the Romagna coast to spend their holidays. Most of the visitors are from Italy but there is a considerable amount of people from abroad. Between 1990 and 2007 the number of tourists is almost doubled: Italians have remained almost stable, while the number of foreigners has seen a two-fold increase.

The Rimini area (Figure 1) is one of the most popular and attractive touristic areas and shows the greater increase of population during the summer season among the four coastal

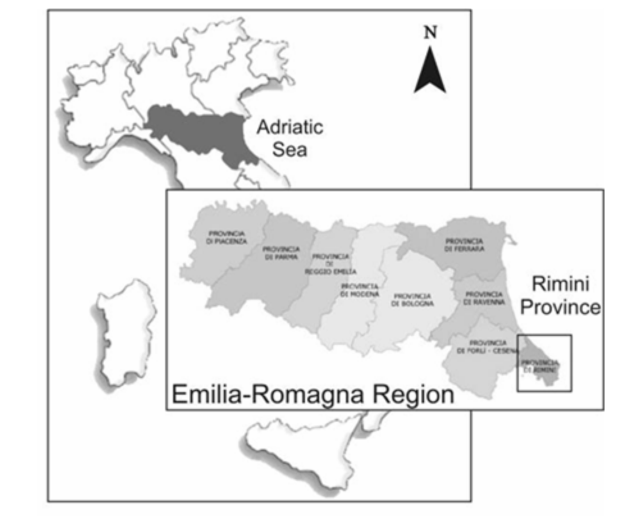


Figure 1. Study site location map.

provinces of the Emilia Romagna Region. The coastline is almost fully protected by coastal defences (60%: 22.7 over 35 km) that were built to prevent beach erosion starting from the end of the II World War (the coast was almost fully protected by the end of the 70s) . The Rimini coastal zone is covered by buildings both in a longshore and cross-shore direction for a few kilometres inland. There is no separation between the beach and the infrastructures behind it. The emerged beach is composed of fine sand (0.16 mm) and its mean slope is almost 3%. The present paper studies the vulnerability of the beaches located in the northern part of the Rimini Province (seaside villages of Bellaria, Igea Marina, Torre Pedrera, Viserbella, Viserba). The coastline is facing the north because it is rotated counter clockwise of an angle of almost 45° with respect to the north direction.

Coastal defences are emerged breakwaters (mean elevation 0.93 m above MSL) and groins. Between the shoreline and the structures there are several tombolos.

The area suffers from subsidence that somewhere reaches 2 cm /year (ARPA, 2006) confirmed by an extensive interferometric survey carried out by the regional government in 2007 (ARPA, 2007).

The wave climate is low energetic with modal wave height ≤ 1 m (65% of occurrence). Main storms are generated by NE and SE winds (Bora and Scirocco respectively). Storms coming from SE have a lower impact on the coast because of its orientation. Tides are asymmetric, with both diurnal and semi-diurnal components. The maximum spring tidal range is 0.7-0.8 m while the maximum neap tidal range is around 0.2-0.3 m.

## METHODS

For the vulnerability assessment it was decided to consider the worst scenarios of occurrence, using a joint probability of a 1, 10 and 100 years return period storm taking place at the same time as an atmospheric surge and with the maximum spring tidal level of +0.45 m above MSL (run-up + surge + tide).

The slope of the beach was calculated using Lidar data acquired in September 2004, in the form of Digital Surface Model (DSM) and Digital Terrain Model (DTM). The 2004 flight was performed by Instituto Topografico of Catalunia for the Geological Survey of the Emilia Romagna. A total of 24 cross-sections were extracted from the dataset, spaced almost 500 m, along a stretch of coastline 12 km long. Each profile was extracted from both DTM and DSM 2004. The first information (DTM) was used to calculate the beach slope while the second one (DSM) was used to find the location of buildings on or next to the beach. The upper limit for slope computation was chosen as the seaward location of man-made structures the lower limit is the location along the cross-section of the high water spring tidal level (+0.45 m; IDROSER, 1996). The 2004 Lidar flight vertical resolution is better than 10 cm; the planar resolution is 1 m.

Table 1: Characteristics of storm events. The surge value only considers atmospheric effects.

| Return Period (years) | Hs (m) | Ts (s) | Storm Surge (m) |
|---|---|---|---|
| T1 | 3.3 | 7.7 | 0.85 |
| T10 | 4.7 | 8.9 | 1.04 |
| T100 | 5.9 | 9.9 | 1.28 |

Once the slope for each section was available, to evaluate the run-up$_{2\%}$ elevation (elevation exceeded by 2% of the total data) the HOLMAN (1986) formula modified by KOMAR (1998) was used. To notice that this solution also includes the wave set-up:

$$R^{T}_{2\%} = 0.36 g^{1/2} S H_{\infty}^{1/2} T \qquad (1)$$

$H_{\infty}$ is the deep water significant wave height, T is the wave period S is the beach slope and g is the gravity acceleration.

The parameterisation was obtained from the literature using the statistical analysis of YU *et al.* (1998), who calculated surge levels for events with return periods of 1, 10 and 100 years. The work of these authors is considered reliable as it used a wind circulation and barometric model for the whole northern Adriatic. Significant wave height ($H_s$) and significant wave period ($T_s$) are taken from IDROSER (1996) that statistically computed them using empirical relationships that were calibrated with long-term wave data recorded by gauges mounted on oil platforms (25 m below MSL) in front of Lido di Dante, a small seaside village close to Ravenna several kilometres to the north of the study area. The characteristics of the events are presented in Table 1.

The presence of coastal defences has to be considered together with their capability of lowering the wave height and consequently to decrease the impact of the waves on the beach. In this case the main modification of the method described above is the computation of the wave height behind structures. The VAN DER MEER (1990) formula was used to calculate the transmission coefficient ($K_t$) and to compute the wave height behind breakwaters.

$$K_t = \frac{H_t}{H_i} \qquad (2)$$

Where

$$K_t = 0.46 - 0.3\left(\frac{R_c}{H_i}\right) \qquad (3)$$

$H_t$ is the transmitted wave height, $H_i$ is the incident wave height, $R_c$ is the freeboard elevation. The VAN DER MEER (1990) formula was chosen because the only information available on the structures is the freeboard elevation. The first step is to know the wave height at the seaward limit of each structure ($H_i$). A 1-d

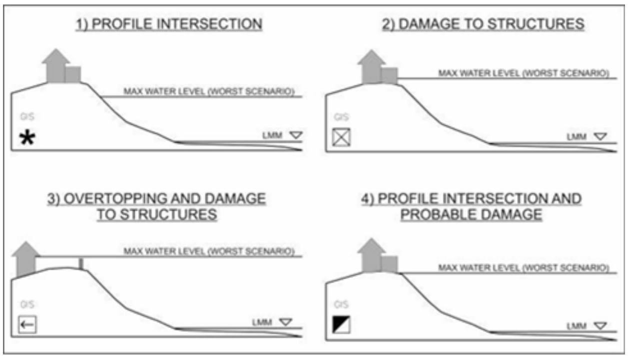


Figure 2. Four vulnerability classes for built up areas. 1) Safe condition, profile intersection; 2) Hazardous condition, damage to structures; 3) Hazardous condition; overtopping and damage; 4) boundary between "safety" and "hazard", intersection and probable damage to structures.

model (linear wave theory) was used to bring the waves from the depth of 25 m (location of the wave gauge, as described above) to the seaward foot of each structure. The same procedure was applied for every return period (1, 10, 100 years) to find three different values of $H_i$. The slope of the seafloor, that is used in the 1-d model, was extracted from cross-shore bathymetric profiles performed in 2000 by ARPA (Agenzia Regionale Protezione Ambiente, Environment Conservation Regional Agency) for the whole regional coastline and spaced 500 m. The same transects were used to estimate the depth of the seafloor at the seaward limit of each structure. Once the wave height outside the barriers is known ($H_i$), it is possible to apply the Van der Meer formula. The freeboard elevation was extracted from 2004 Lidar data. It was decided to use only one freeboard value for all cases because the structures are quite homogeneous and their elevation is similar over the whole study area. The $R_c$ value used inside the formula is the mean value (0.93 m above MSL) and was corrected, as follows, to consider the three worst selected scenarios.

$$R_{cT_{1,10,100}} = R_c - 0.45 - surge_{T_{1,10,100}} \quad (4)$$

where 0.45 is the tidal level (spring tides), $R_c$ is the freeboard (0.93 m) and $surge_{T1,10,100}$ are the values listed in Table 1.

To include inside the Komar formula the attenuation effect generated by the structures on the wave height it is necessary to transport the transmitted $H_t$ back to deep water conditions in order to obtain $H_\infty$. The same 1-d model, that uses linear wave theory, was applied to $H_t$ transmitted to find its value in deep water. With this method it is possible to calculate the run-up and set-up behind breakwaters using the Komar formula that contains the deep water wave height. The wave period was not modified because the presence of the structures does not affect $T_s$.

## RESULTS

The new values of $H_\infty$, modified by the presence of the structures, obtained with the calculation described above are: 1.55 m for T1; 2.22 m for T10 and 2.78 m for T100. Comparing these values with the "original" ones extracted form literature, the attenuation effect lowers $H_\infty$ of 47% for each return period.

The maximum water elevation (worst scenario) found with the methodology described above was compared with the maximum beach elevation along each cross-section. Five vulnerability categories were created in order to define which are the forcing thresholds (waves, surge and tide) that favour damage. The study area is included inside four hazard-groups (Figure 2) plus one for inundation only that occurs where there are no buildings on the beach and the water is free to inundate the areas that are behind the shore: 1) profile intersection (safe condition, when the water elevation intersects the beach away from human infrastructures and/or buildings); 2) direct damage (hazardous condition, when the max water elevation crosses infrastructures and buildings); 3) overtopping and direct damage (hazardous condition, when the water overtops low structures (concrete walls, fences, etc.) placed on the beach and can possibly damage buildings that are located behind them); 4) intersection and probable damage (boundary condition between "safety" and "hazard", when the water elevation intersects the beach at a location that is very close to the seaward limit of buildings located on the beach). To underline that "safety" and "hazard" for built up areas are related only with the absence/presence of hazards for human structures. The beach itself is only considered as a natural element able to absorb the energy of a storm. The damages produced on the beach by extreme events were not included in this analysis.

Table 2: Number of profiles for each category of damage (Figure 2) for every return period.

| Hazard-groups | T1 | T10 | T100 |
|---|---|---|---|
| Profile intersection | 1 | 0 | 0 |
| Damage to structures | 20 | 16 | 13 |
| Overtopping and damage to structures | 0 | 6 | 9 |
| Profile intersection and probable damage to structures | 1 | 0 | 0 |
| Inundation | 2 | 2 | 2 |

In Table 2 the number of profiles is indicated for each vulnerability category that was observed along the 24 cross-sections analysed. The number of profiles that are inundated remains stable for the three scenarios because there are only two transects crossing an area without buildings. In fact the Rimini site is almost fully built and there are hundreds of hotels, beach huts, etc. all over the beach and behind it. There is only one safe profile for the T1 event that becomes vulnerable for the T10 and T100 scenarios.

The results were put inside a GIS (Geographical Information System) to map the vulnerability of the coastline (Figure 3). In Figure 2 each category is associated to a symbol (lower left corner of each schematization inside the figure) used to represent the effect of the worst case scenario on the beach. Each symbol is associated to several information: profile name, brief description of the main characteristics of the profile (protected by structures, natural or built up, etc.), the return period event associated to the symbol, max water elevation (run-up + surge + tide), effect of the worst case scenario on the cross-section

## DISCUSSION

As it is possible to see in Table 2, even for the T1 event, the majority of the profiles is vulnerable (damage to structures, profile intersection and probable damage, inundation). The mean maximum elevation of the analysed profiles is 1.38 m. Comparing this elevation with the sum of the surge level plus the tide (= 1.30 m) for the T1 event, it is clear that the vulnerability of the area is mainly due to its low elevation with respect to the MSL. Clearly

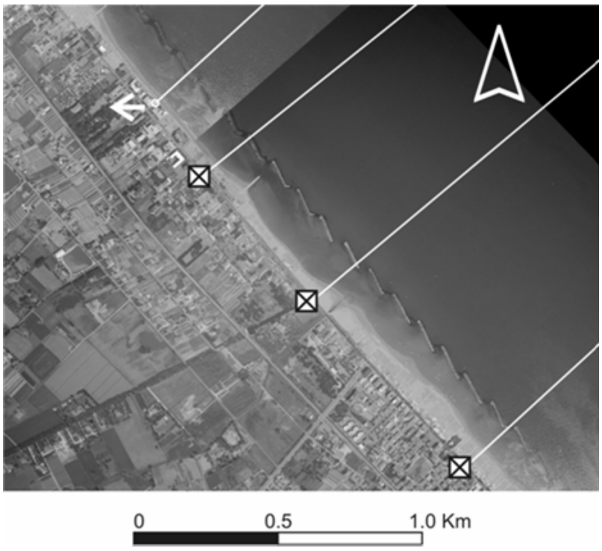


Figure 3. Example of vulnerability symbols placed along four cross-section (white lines) inside a GIS: three profiles represent "damage to structures"; one profile represents "inundation". To notice the continuous presence of coastal defences and the massive urbanization of the site. Rimini area, 2005 Flight (Regione Emilia Romagna).

the same conclusion is reached if we consider the T10 and T100 events. However the contribution of the run-up and set-up to the vulnerability of the area is important. This is clear if we analyse the maximum topographic elevation of each cross-section. This elevation was used to find the effect of the worst case scenario on the site through the direct comparison of the max profiles height and the max water elevation. If we consider the T1 event (because the same considerations are valid for the T10 and T100) and the number of cross-sections that are affected by the T1 scenario (23; Table 2), the number of profiles among them that have a maximum elevation (mean value = 1.20 m) that is below the sum of surge and tide only, without the run-up, (1.30 m, see above) are 11. Along these profiles the run-up and set-up are not influencing the effect of the storm on the beach. The remaining 12 profiles have an elevation (mean value = 1.50 m) that is above 1.30 m, meaning that the hazardous condition is generated by the run-up.

The attenuation effect of the breakwaters lowers the deep water wave height and consequently the run-up elevation on the beach. Clearly the consequences of the three different scenarios would have been much greater if the breakwaters were not included inside the computation because they are able to lower $H_\infty$ of almost a half. In fact, if we consider the only safe section and we recalculate the maximum water elevation without including the attenuation effect, this profile shows a greater vulnerability and becomes "damaged".

## CONCLUSIONS

The vulnerability of the coastline to marine storms is one of the most important issues that coastal managers will face in the future. In the present paper three worst case scenarios were presented (spring high tide + T1, T10 and T100 surge + run-up) in order to create different damage categories able to define the vulnerability of several cross-sections along the study site. Moreover, in order to include the contribution to water levels of the run-up and set-up the KOMAR (1998) formula was applied. The methodology described is able to include inside the formula the attenuation of the wave height generated by breakwaters. The computation of this reduction is very important for the study area (Rimini Province) but also for the whole Regional coastline (Emilia Romagna) because the 57% it is protected by structures. Not including the attenuation means to produce wrong results and consequently to develop incorrect plans of mitigation of the impact of storms. The Rimini area is composed of low sandy beaches that have a low elevation above MSL. The combined effect of high tides and surges plus run-up and set-up is able to deeply damage the beach and the buildings also for the T1 event. The three scenarios that were analysed can be defined as a snapshot of the current situation because they do not include subsidence, infiltration of marine water inside beach sediments, roughness of the terrain and friction generated by the vegetation. Further development should include more detailed analysis and 3-d modelling for selected cases. It is important to underline that the results achieved are a first step to find "hot spots" of vulnerability in order to effectively concentrate scientific and management efforts.

The same procedure is being applied to the whole Regional coastline along built up areas and natural sites with dunes. This is done to develop a vulnerability cartography that will be made available for costal managers. The cartography will be displayed for public access inside the web-GIS of the Emilia Romagna Region (http://www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/web_gis_costa.htm).

This kind of representation is very useful for coastal managers in order to have an overview of the possible damages on the coast due to extreme events and where to act if a storm occurs (CIAVOLA *et al.*, 2008). Moreover, for coastal planning it is very important to know which are the most vulnerable areas in order to use the resources where there is an actual need of restoring the beach and to guarantee safety for goods and people living and working along the coastline.

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