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Assessment Methods for Sea-Related Hazards in Coastal Areas

C. C. GIARRUSSO[1], E. PUGLIESE CARRATELLI[1,⋆] and G. SPULSI[2]
[1]*Dipartimento di Ingegneria Civile, Via Ponte Don Melillo, 84084 Fisciano (Salerno), Italy;*
[2]*EtaBeta, Naples, Italy*

Abstract. Italian legislation provides for hazard contingency plans to be prepared by the regional, provincial and local authorities. Despite the extent of damage often caused on the Italian coasts by the action of the sea, sea related hazards have so far been usually ignored; only recently a limited budget in some provinces was allocated for the analysis of risks related to storm damage.

The present paper reports on the procedures and the techniques employed and tested within the framework of the provincial contingency plan on the coast of the Salerno province in Italy (Figure 1).

The work was mainly oriented to the evaluation of the potential damage that can be caused by the direct action of waves on coastal areas and on the preparation of hazard maps. The methods and the data that can be used to evaluate the risks are reviewed here, first by rapid examination of the wave field formation offshore and its transformation on shallow water and then by considering the run-up on beaches and infrastructures; the paper is focussed in particular on these latter problems, which – form some point of view – are original and specific to civil protection problems.

Key words: wave run-up, shore protection, coastal risk assessment, civil protection planning.

1. General Background

Civil protection activities can basically take two forms: the production of hazard maps and the setting up of a forecasting and alert system.

The first activity, which is referred to here as “static”, implies determining the probability of events (“scenarios”) which are more likely to produce damage and evaluating the effects they can have in different areas, thus supplying a once-and-for-all or static picture – hence the name – of the statistical risk level over a given area: in our case, the coast. This information can be used by the local authorities as a planning tool in order to identify the needs and the priorities of structural actions such as shore protection works.

Static Civil Protection measures border closely – and should be incorporated into – general planning and public works activities: thus in our case, for instance, beach management can be seen as a way of exploiting natural resources as well as providing protection to life and property.

⋆ Address for correspondence: fax: +39-89-964045; e-mail: eugliese@bridge.diima.unisa.it

Figure 1. Salerno province coastline.

Forecast and alert systems ("dynamic" Civil Protection) should provide the authorities with adequate forewarning of potentially dangerous storms and of their likely effects, the objective being thus of reducing the damage by alerting Emergency Services and – if possible – by taking pre-emptive measures such as interrupting train and road circulation and evacuating buildings and beaches.

The present paper is mainly focused on the static aspects, and therefore on risk mapping procedures. However, since both the static and the dynamic approaches of the Civil Protection planning imply a full understanding of the physical processes involved and some sort of modelling of such processes, some mention is also given to the possibilities of setting up a warning system.

2. Physical Process and Their Simulation

The physical processes leading to action of waves on the coast can be divided – somewhat arbitrarily, but conveniently for our purposes – into four blocks:

(a) Off shore wind field formation at sea level.
(b) Off shore wave field formation.
(c) Near shore wave field transformation.
(d) Run up and damage evaluation.

A civil protection plan must be based upon a set of procedures and models structured to represent the processes above: a dynamic forecast and early alert organisation will make use of real time data and modelling software, while a static plan will need statistical elaboration of the results supplied by models in order to produce hazard maps. In both cases, however, each subsystem can further be divided into sub-blocks while the complexity, accuracy and detail of the models to be employed will vary according to the time, budget and quality of available information. Besides, the whole system will have to be verified and calibrated over an adequate period of time so as to avoid false alarms and to make sure that a satisfactory performance is obtained during real emergencies.

The planners therefore have to provide, at the earliest phase of the programme, for a flexible and modular procedure in order to allow for periodic refinements and revisions. The operating experience will suggest changes and improvements which may vary from the calibration of parameters to the updating of maps and, as budgets increase, new and better technologies can be adopted.

It is worth noticing that the analyses of points (a) through (c) have much in common to coastal engineering problems such as harbour design and beach protection; they are therefore only briefly discussed in the following:

(a) Offshore wind field formation at sea level.
(b) Offshore wave field formation.

The setting up of a meteorological (level a) and offshore sea state forecasting system (level b) is quite beyond the competence and the resources of local authorities; moreover, weather data are also required for other aspects of the Civil Protection, for instance for flood and landslide damage mitigation. These tasks have to be carried out by pooling resources between Provinces or even Regions and by making full use of existing National or European data sources, such as for instance the European Centre for Medium Range Weather Forecasting (ECMWF). This paper does therefore not deal with this problem.

As far as the static approach is concerned, these two points can be dealt with separately or together, according to the available data and procedures: statistical analyses of the sea state require long records of wave heights; wind records are also useful, since a wealth of models is available for the computation of sea state from the wind field, ranging from the elementary SMB (Shore Protection Manual 1973), which supplies reliable results for reasonably constant wind velocities, to the second and third generation spectral model run by Meteorological Offices.

For the south and central Tyrrhenian Sea – where the area considered here is located – available wave data include some years of records from buoys located by the Italian Network (RON) off the island of Ponza, and by the IUN (Istituto Universitario Navale) off the city of Sorrento, (Benassai and Sansone, 1993, Pugliese *et al.*, 1987) in the Bay of Naples. Other possibilities include the NKMI and UKMO wave data observations, and the historical synthetic data sets produced by the ECMWF which also constitute a good reference.

Long historical series of wind measurements are provided by Italian Air Force weather stations; the recent anemometer network around the Bay of Naples (Pugliese Carratelli *et al.*, 1998) can also provide some.

The literature on the estimation of extreme wave probability is enormous and no attempt will be made here to review it. However, it is worth mentioning the method produced by Cavaleri *et al.* (1986) within the STONE project for its sound meteorological approach.

The STONE method distinguishes between four different kinds of weather perturbations on the Tyrrenian Sea, thus individuating four different classes of storms over which statistical parameter are evaluated. For a set of geographical points diagrams are supplied to yield the significant height to be expected with a given probability along a given direction.

Other possible approaches, such as the use of wave meter data or Weather Office synthetic data suffer form the same drawback as the STONE procedure, i.e., the small number of storms on which statistics are drawn upon, which hinders the reliability of extreme events which would be of interest to Civil Protection applications. Methods based on very long – but local wind records and visual wave observation data, on the other hand, do not offer the reliability of modern methods. The final answer lies probably in integrating all the data and the procedures available.

Whatever procedure is followed, however, the result must be a function which links the significant wave height and the average period of a storm in deep water to its probability (or to its return time). The waves considered in the examples reported in the following have a return time of 50 years.

The wave climate in any case must be evaluated for a number of points on deep water (i.e., more than 100 m) along the coast, specially along indented coastlines, where the fetch along some directions is completely cut off by headlands or promontories. These data can be used as a basis for wave analysis for any point on the shore.

(c) Wave field transformation and wave shoaling.

Wave conditions on deep water are different from conditions on the coast because waves undergo important changes as they proceed towards the coast into shallower water depths.

Taking these aspects into full account may lead to the use of models as complicated and expensive as those used to calculate the offshore wave fields which were mentioned in the previous paragraph. However, since the objective here is only the protection of coasts during extreme events, the only directions which are of interest for the wind and the waves are those towards the shore, so the problems are somewhat limited. The inverse ray tracing technique was therefore adopted (Figure 2) as a wave transformation tool from offshore down to a given depth in shallow water. The inverse procedure, as opposed to the direct one, also allows the offshore directional probability distribution to be transformed into the local near shore distribution.

After that point the transformation is either taken into account through empirical formulas or carried out with a Non Linear Shallow Water model. Both approaches will be dealt with below, together with the run up calculation.

(d) Run up and overtopping.

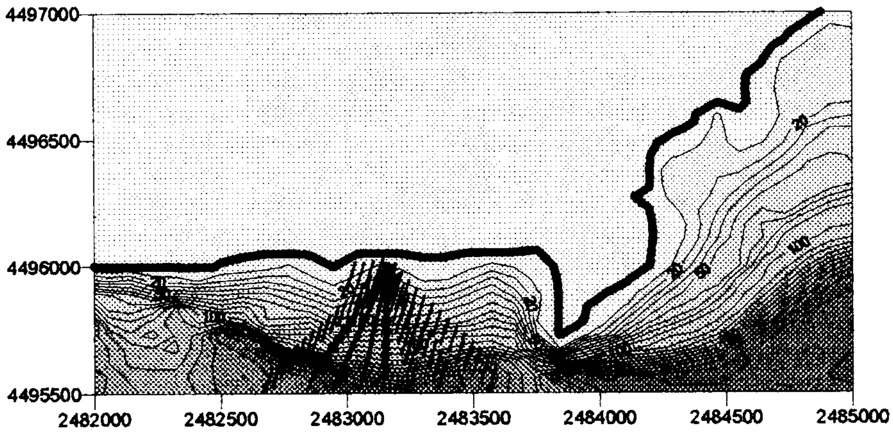


Figure 2. Inverse ray tracing.

The risk level associated with wave storms depends on the number of waves which reach or overtop the structure and thus on the run up of the waves. An irregular wave train is a very complex phenomenon, mainly because the behaviour of each wave is strongly influenced by the effects of the preceding ones, so the main tool to understand and forecast its effects has been so far the laboratory experiment.

The run up on beaches and structures has been indeed the object of many experiences, and extensive results are available for the shapes normally associated with dykes and breakwaters. Some of these experiences have led to simple formulas which yield the run up length, as a function of the significant wave height; other experiments yield more complex parameters such as the number of overtopping waves or the flow rate (Owen, 1980; Franco *et al.*, 1994; De Waal and Van der Meer, 1992). All the formulas necessarily refer to a simple geometry, such as a sea wall or a beach without obstructions.

In this first draft of the Civil Protection Plan, simple formulas are used to supply the run up length. For instance, according to a simplified method (Van Der Meer, 1994), the run up Ru is given as a function of the significant wave height Hs and of the breaking parameter ξ:

$$\mathrm{Ru} = 1.6 * \mathrm{Hs} * \xi.$$

The breaking parameter is in turn given by

$$\xi = \tan\alpha / \sqrt{2\Pi H_s / g T_p^2},$$

where α is the beach slope and Tp the spectral peak time.

The first part of the wave transformation is carried out by making use of a linear procedure. The bottom slope and depths needed to perform these calculations are obtained either by working on available bathymetric maps, or – when possible – from field measurements.

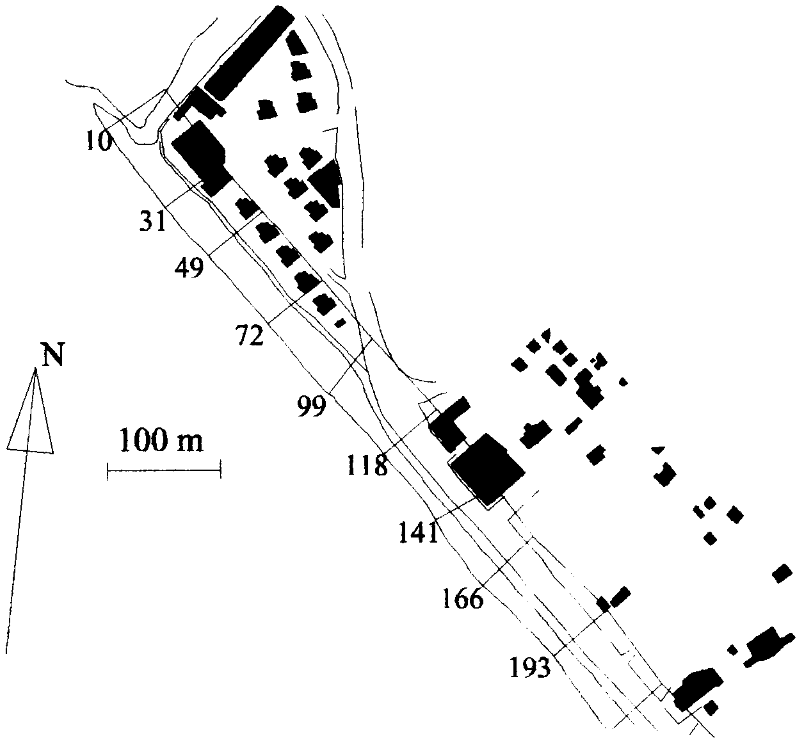


Figure 3a. Maps of flooded areas.

Following these simplified procedures large scale maps of potential hazard can be produced in a reasonably short time: Figures 3(a) and (b) show some typical results: flooded or potentially hazardous areas are given for the 50 year return time offshore wave ($H_s = 4$ m, $T_p = 9.88$ s).

These maps, however, should only be used as a first approximation tool in order to identify areas or infrastructures which should be the object of more careful analysis; when dealing with complex coastal sections, the ordinary run-up formulas are inadequate and more complex wave simulation techniques have to be used.

A test programme was therefore undertaken in order to verify the possibility and the convenience of using Non Linear Shallow Water 1-d Equation integration procedures (NLSW) in this context.

The "Anemon" software (Dodd, 1998; Giarrusso and Dodd, 1997; Dodd *et al.*, 1998; Giarrusso, 1998) was therefore employed to compute numerically the wave evolution from an intermediate depth to the shoreline, including run-up and overtopping. By making use of these procedures, the bottom profile can be specified with any degree of accuracy, and wave trains of any length with a given spectrum can be considered; the result is a full time history of the water height and of the flow rate, thus providing a statistical estimate of the risk level.

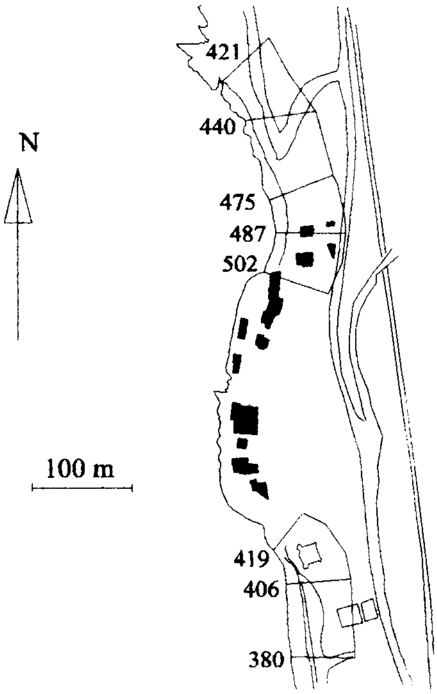


Figure 3b.

NLSW based software only simulates the effect of amplitude dispersion and ultimately wave breaking, so that it must be run from a very near shore location, near the breaking point. Offshore conditions have therefore to be transformed into near shore ones, where waves are depth-limited; this is made by using a linear wave transformation model (Southgate and Nairn, 1993; Wallace, 1994).

There is no standard method for determining where the offshore boundary should be located; based on significant wave heights and periods, it was decided to run the NLSW model from water depths D of about 5.0 m, so that the order of magnitude of the ratio D/L between the depth and the wave length L is about 0.05, typical of the intermediate-shallow water regions (Dean and Dalrymple, 1984). The results shown refer to numerically generated pseudo-random time series of the free surface elevation with a standard JONSWAP spectrum. A model run duration of 1000 s representative of about 100 waves was found to be a satisfactory compromise between accuracy and statistical consistence. The wave direction was assumed to be perpendicular to the shoreline since in most cases waves were normal or nearly normal to the shore because of the refraction effect.

The definition of tolerable limits for overtopping is still an open question, given the high irregularity of the phenomenon and the difficulty of measuring it and its consequences. When calculating the run-up, the 3% highest values of the time series are considered; however, according to recent, if not fully consistent published

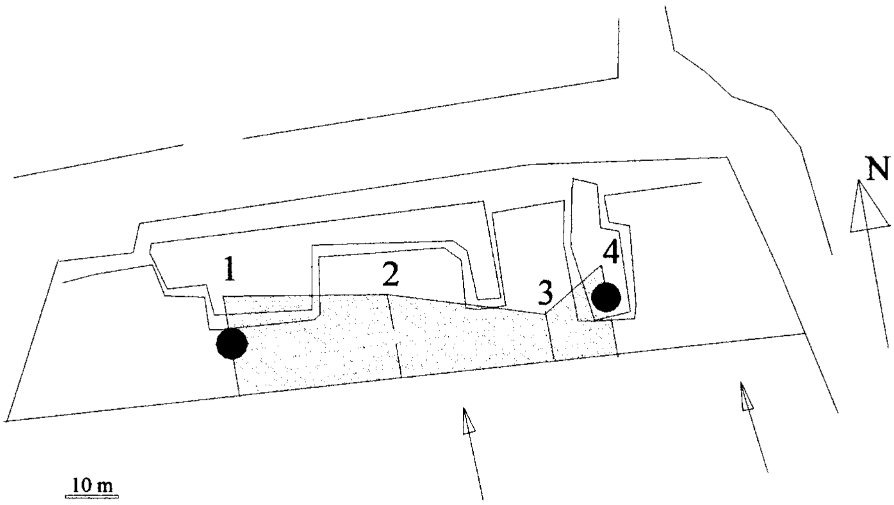


Figure 4a. Amalfi peak flow 0.05 m^3/m, H_s = 4 m.

data (Goda, 1985; Franco *et al.*, 1994; Smith *et al.*, 1994) the risk of a storm event for buildings, vehicles and pedestrian is in fact linked to the peak and to the average flow rate.

An example of results obtained by making use of these calculations is given in the following. The potential risk for a person standing in a given position is shown in Figures 4(a), 4(b) and Figures 5(a), 5(b), respectively, for two different locations, assuming the peak flow rate of 0.05 m^3/s (Franco *et al.*, 1994) as a threshold, for a significant wave height of $H_s = 4$ m and $H_s = 6$ m. A black spot means risk, while a white spot means no risk.

Figures 4(c), 4(d) and Figures 5(c), 5(d) show, for the same locations and wave heights, the potential (minor) damage to buildings, evaluated as a threshold of 0.001 m^3/s for the average flow rate; again shadowed buildings are at risk, while white ones are not.

All the pictures also indicate the flooded areas which were calculated by the simplified formulas; as it can be seen, the results are different, and the more complex the coast cross section is, the bigger the difference is likely to be.

The use of NLSW should therefore be recommended for coastal storm risk assessment; such complex calculation procedures, however, are useless without a precise description of both the bottom and the surface topography. Ordinary maps are often either too old or not accurate enough for this purpose, so field surveys are needed in order to supply adequate data for all potentially dangerous situations. Since this is likely to be a costly and complex procedure, it should be reserved to areas which have been shown to be damage prone according to the simplified procedure.

Finally, it is worth remarking that NLSW procedures are particularly suited to gentle slopes (where the one-d approximation is more likely to hold true) while

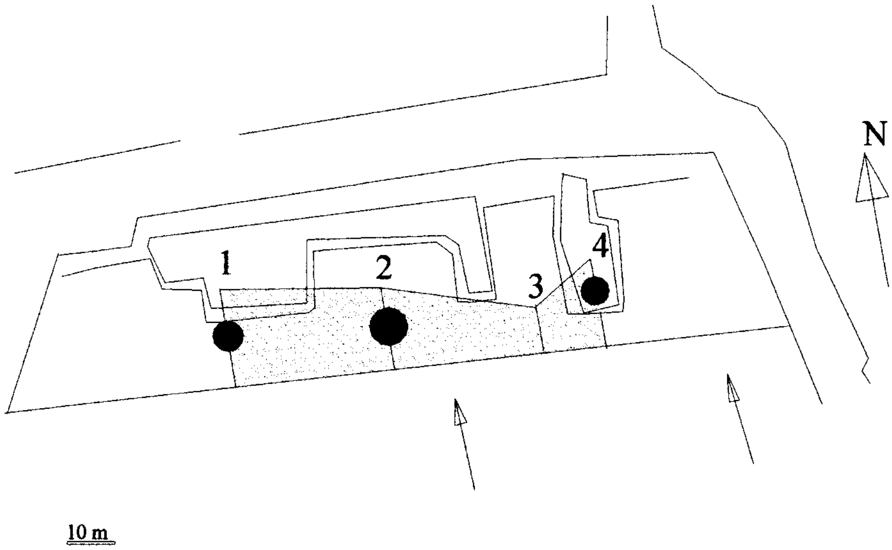


Figure 4b. Amalfi peak flow 0.05 m^3/m, H_S.

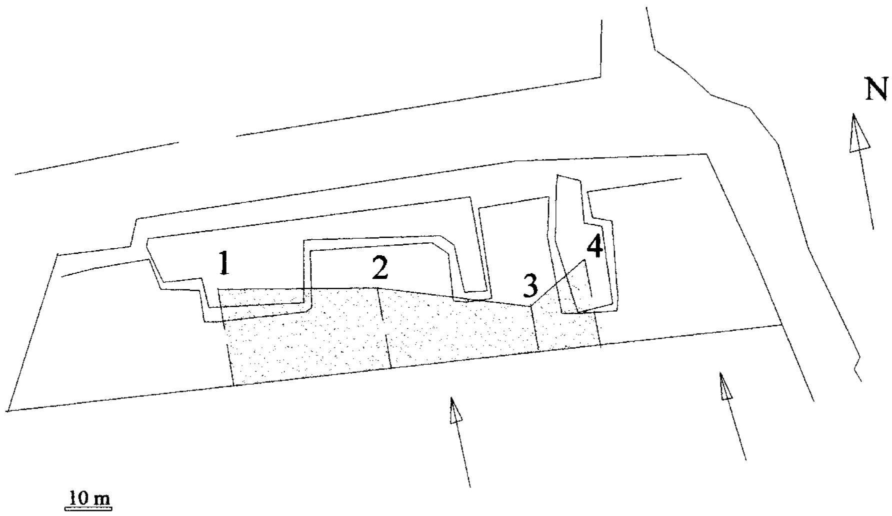


Figure 4c. Amalfi average flow 0.001 m^3/m, H_S = 4 m.

current research is extending their application to irregular or complex geometries (Hu *et al.*, 1999; Giarrusso *et al.*, 2000). For nearly vertical wall problems, full Navier-Stokes numerical integration with free surface (Beale *et al.*, 1996) could be a promising candidate, even though many problems still have to be solved before this technique can be considered mature for operational needs. In this sector the need for specialised research is most acute.

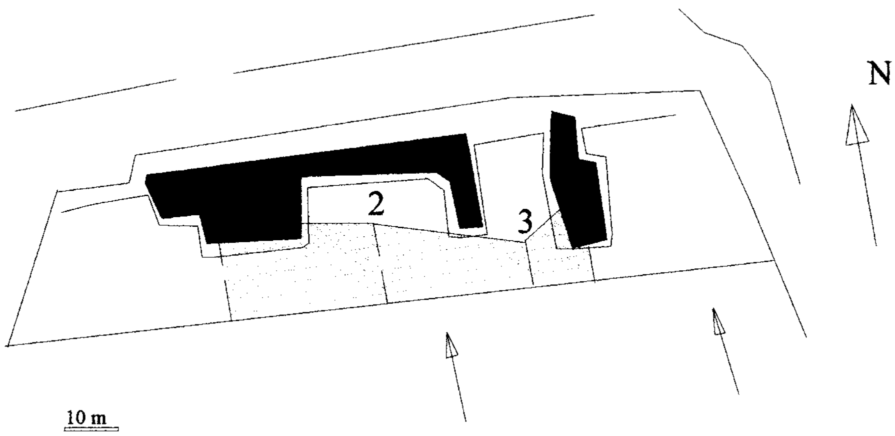


Figure 4d. Amalfi average flow 0.001 m^3/m, $H_s = 6$ m.

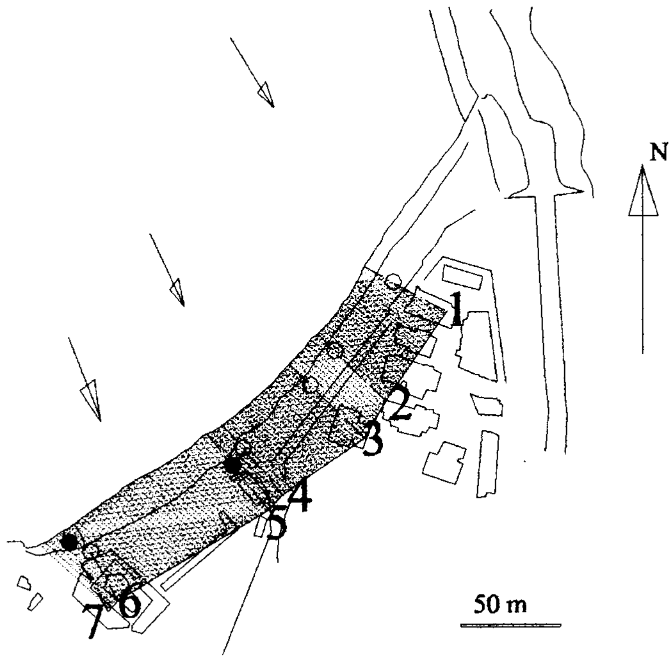


Figure 5a. Agropoli peak flow 0.05 m^3/m, $H_s = 4$ m.

3. Organization and Data Collection

The main product of the Civil Protection Plan is a set of maps (or a GIS sub-system) of the coastal zone where the sectors of potential damage and the areas flooded by the run-up are highlighted in accordance to storm intensity and direction.

The length of the coast to be considered amounts to tens or hundreds of kilometres (about 200 km in the case of the Salerno Province) which have to be care-

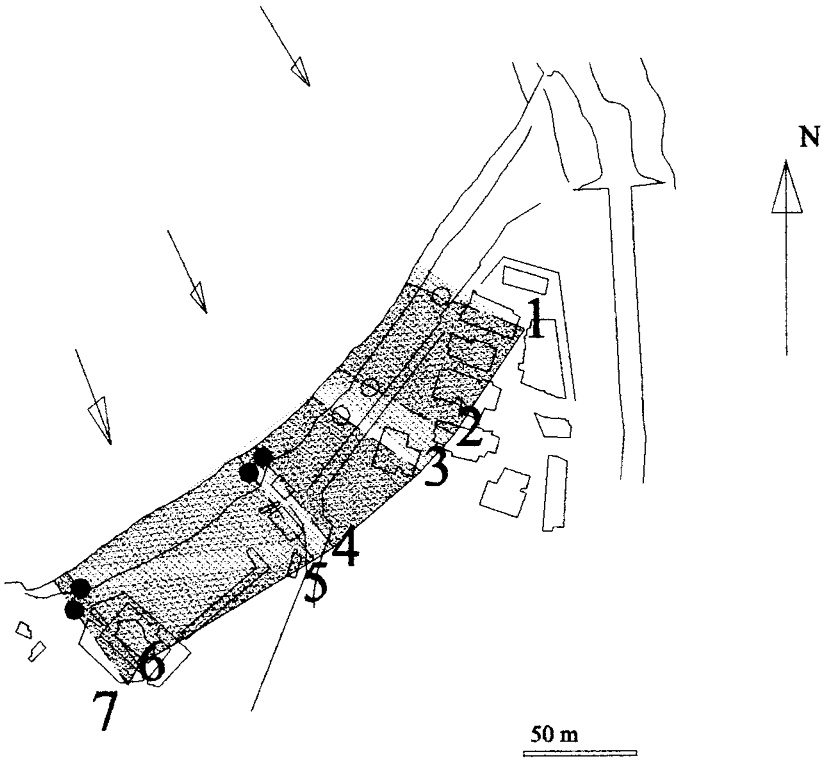


Figure 5b. Agropoli peak flow 0.05 m^3/m, H_s = 6 m.

fully mapped in order to carry out oceanographic, hydraulic and risk evaluation methods described in this paper; besides, man made structures such as harbours, marinas and coastal protection works cover a large percentage of the shoreline. Even by making use of highly simplified procedures, the amount of data handling and elaboration needed is enormous.

Fortunately, the nature of the problem, as has been presented here, allows for a largely decentralised organisation, since the various steps can be assigned to different authorities and offices. The Italian legislation, moreover, seems to provide for this type of hierarchical organisation by instructing each level of local authority (Regioni, Province, Comuni) to prepare its own contingency plan. So, one of the main tasks of the work described here was the appropriate sharing of activity and responsibility among the different authorities and technical bodies involved.

It seems reasonable that the steps (a) and (b) referred above (offshore wind field formation at sea level and wave field formation) should be handled by properly trained and equipped personnel in a regional centre, which should also establish connections and data links with National, European and International organisations. Lacking this, in the first approach to the production of the Civil Protection Plan a wave climate analysis has been carried out for five offshore points, which

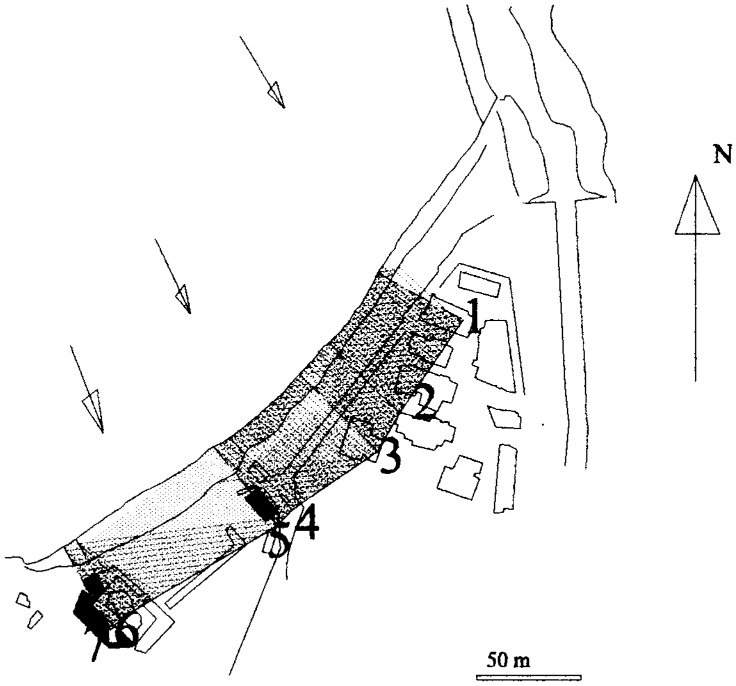


Figure 5c. Agropoli average flow 0.001 m^3/m, H_s = 4 m.

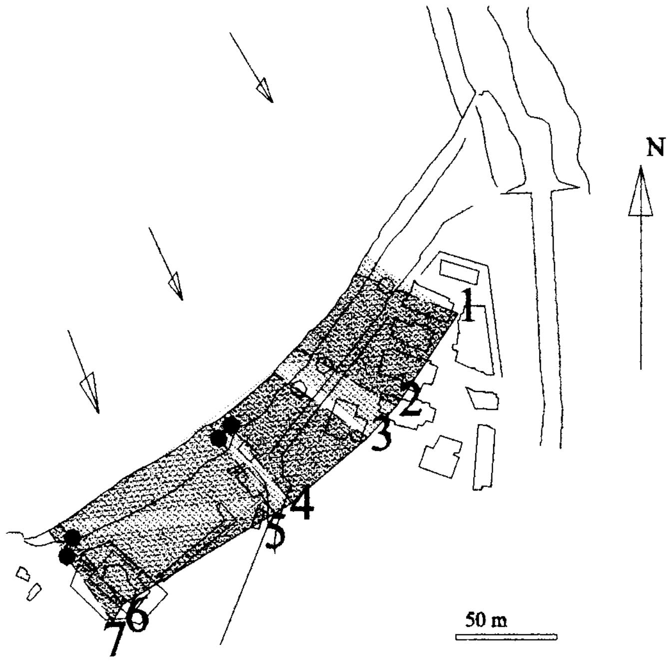


Figure 5d. Agropoli average flow 0.001 m^3/m, H_s = 6 m.

were shown to be remarkably similar from the point of view of the extreme wave probability.

Step (c), i.e., wave transformation and shoaling, should be carried out at an intermediate level ("provincial" for Italy). The first draft of the Salerno Civil Protection Plan used classical ray tracing procedures to calculate the shoaling effect up to an intermediate depth.

Run up and overtopping evaluation (step d) requires some nonspecialised work and a good historical knowledge of the area including the coastline variations deriving from erosion and beach nourishing and the occurrence of past wave-related damage. Therefore, it can be more easily carried out locally rather than centrally and should be left to the smallest local authorities ("Comuni"), with technical support from higher level organisations in order to carry out the numerical procedures.

Another very important aspect is the evaluation of the risk related to coastal structures and work: it is only natural that the evaluation of damage which might be caused by extreme waves should be left to the designer of the structure or – where this is impossible – to the public body or company operating and maintaining it, just as the constructors or the operators of dams are requested to carry out detailed calculations on the effects of a dam failure.

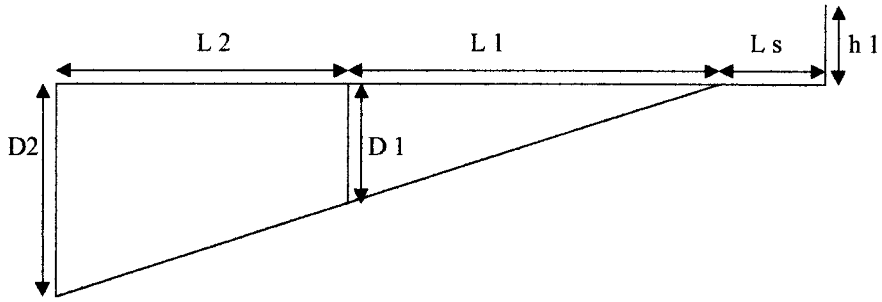
Within the work described in this paper, close co-operation has been envisaged between local and provincial authorities. About 400 potentially critical shoreline cross-sections have been identified from the available maps and sent, together with data tables to the Comuni, which should carry out detailed surveys along the coast and accurate work on large scale maps. Information is requested about the beach profiles and sand grain size distribution as well as about the presence of buildings or infrastructure within reach of the wave action.

A typical data collection diagram is shown in Figure 6: D1 and D2 refer to the first and second depth datum available (from maps or – occasionally – field data), while L1 and L2 are the respective distances from the shoreline (tide oscillations are negligible); h1 is the elevation of the first obstacle and LS its shoreward distance from the shoreline. The beach slope needed for the empirical formulas is obtained by interpolation, while shallow water waves model need a more accurate depth profile description that cannot be handled with standard data collection forms.

Once the data are gathered, they should be sent to the provincial centre, where run up calculations can be carried out and maps such as the ones shown can be produced and supplied to the Civil Protection and Planning authorities.

Given the changing nature of the coastline and the low quality of the original data, any Civil Protection Plan has to be verified and tested on the field; it has indeed been suggested (Versace *et al.*, 1995) that Civil Protection plans should be updated at least every three years.

In order to improve the reliability of the predictions, not only has the quality of the models to be improved, but an adequate network of instruments has to be set up in order to reconstruct the effects of significant storms by continuously



N.° Sezione	D 1 (m)	D 2 (m)	L 1 (m)	L 2 (m)	L s (m)	H 1 (m)	Località
001	9	21	200	400	50	50	Positano
005	69	100	100	250	10	60	Praiano
009	10	20	240	440	19	20	Pontecagnano
035	7	17	200	400	25	0	Foce Sele

Figure 6. Data collection diagram for run up calculation.

monitoring the physical parameters such as the state of the sea and the run-up in critical locations.

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