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PARASODE: a program for the probabilistic design and assessment of sea defences

T. S. Hedges[1] & M. T. Reis[2]
[1] *Department of Civil Engineering, University of Liverpool, UK.*
[2] *Harbours and Beaches Division, Hydraulics Department, National Laboratory of Civil Engineering (LNEC), Portugal.*

Abstract

Risk analysis provides a useful framework for the design of sea defences. However, coastal engineers have been slow in developing design methods based upon risk analysis. Whilst knowledge of coastal structures is insufficient to permit a full assessment of their safety, it remains possible to assess their safety against specific types of failure (i.e. to consider only single failure modes).

The paper starts with a brief summary of single failure mode probabilistic methods and introduces a computer program known as PARASODE, which uses the Level II First Order Reliability Method (FORM). PARASODE (the Probabilistic Assessment of Risks Associated with Seawall Overtopping and Dune Erosion) concentrates on the failure modes of random wave overtopping of simple embankment seawalls and of erosion to dunes. However, much of PARASODE can readily be adapted to other types of failure. The paper concludes with a case study involving the appraisal of a typical seawall with regard to wave overtopping during storms.

Single failure mode probability analysis

Theoretical expressions or empirical formulae may be used to define a failure function or limit state function, Z. The value of Z depends on the N random variables, $X_i, i = 1,...,N$ of the problem (e.g. water level, wave conditions, structure dimensions and material properties). Consequently, the probability of failure, P_f, during a specified reference period, can be expressed as:

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$$P_f = P(Z \le 0) = \int_{Z \le 0} \ldots \int f_{X_1,\ldots,X_N} dX_1 \ldots dX_N \qquad (1)$$

Here, $f_{X_1,\ldots,X_N}$ is the joint probability density function of the random variables $X_1,\ldots,X_N$.

Eqn (1) forms the mathematical basis of probabilistic analysis. Unfortunately, except for some special cases, the multiple integrations cannot be performed analytically. Usually, they must be approximated in some way. This is the aim of the various probabilistic methods.

Probabilistic methods are often classified according to the types of calculations performed and of the approximations made. Three levels are commonly distinguished. Listed in order of decreasing accuracy and complexity, they are as follows:

- Level III: full distribution approach. This method provides an 'exact' probabilistic analysis for whole structural systems, or structural elements, using full joint probability density functions including the correlations amongst the variables.
- Level II: semi-probabilistic approach. Approximation methods are applied in which the generally correlated and non-Normal variables are transformed into uncorrelated and Normal variables. Reliability indices are used as measures of the structure reliability.
- Level I: limit state approach. This level comprises calculations based on characteristic values and partial load and resistance factors. The factors represent, for example, the ratio of load at failure to a permissible working load. This ratio creates a desired margin between the characteristic values of resistance and working load.

The main practical advantage of the Level II First Order Reliability Method (FORM) over a Level III approach is that the computational effort is independent of the probability level. It also provides a rational basis for evaluating partial safety factors. Furthermore, it affords an automatic procedure for determining the sensitivity of the computed failure probability to each of the basic design variables. This last characteristic allows the designer to focus attention on the parameters of greatest significance and shows where effort to reduce uncertainty should be concentrated.

PARASODE

PARASODE (the Probabilistic Assessment of Risks Associated with Seawall Overtopping and Dune Erosion) has been developed for assessing the safety of sea defences. It operates in two ways (see Figure 1):

- the 'analysis mode' in which the failure probability is calculated for a given value of the design parameter, e.g. the crest level of a seawall;
- the 'design mode' in which the value of a specific design parameter is calculated for a target probability of failure.

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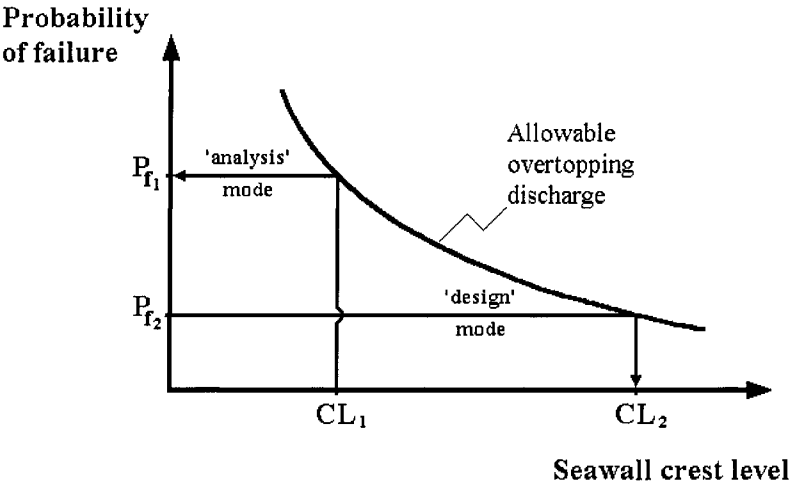


Figure 1: PARASODE's modes of operation (illustrated for wave overtopping of a seawall).

The program uses the Level II First Order Reliability Method (FORM). It incorporates routines for transforming the correlated variables to a set of non-correlated variables and for mapping non-Normal distributions to equivalent Normal distributions. There are ten continuous, pre-defined, statistical distributions programmed in PARASODE. Each distribution may be truncated either on the left or on the right side (which is important, for example, if the available water depth limits wave conditions at the seawall, as will often be the case). The user can also add his or her own distributions to PARASODE. This facility is of particular help when the distribution of a variable, X, is the result of measurements or other data (such as predicted tide levels, see later) which are not easily fitted by a pre-defined distribution.

Allowable overtopping discharges

Seawalls are rarely, if ever, designed for zero overtopping during extreme storms. A balance must be struck between satisfying the structural and functional requirements of the project, avoiding unnecessary expense, and having undesirable impacts on the surrounding environment.

Figure 2 shows recommended limiting values of the mean overtopping discharge to ensure the safety of vehicles and people in the immediate vicinity of a seawall, and to prevent damage to buildings in its lee and to the seawall itself. The main point to note from the figure is that the range of critical discharges runs from as little as $10^{-6}m^3s^{-1}$ to about $10^{-1}m^3s^{-1}$ per metre length of seawall. The significance of these limiting values will become apparent in the case study described later.

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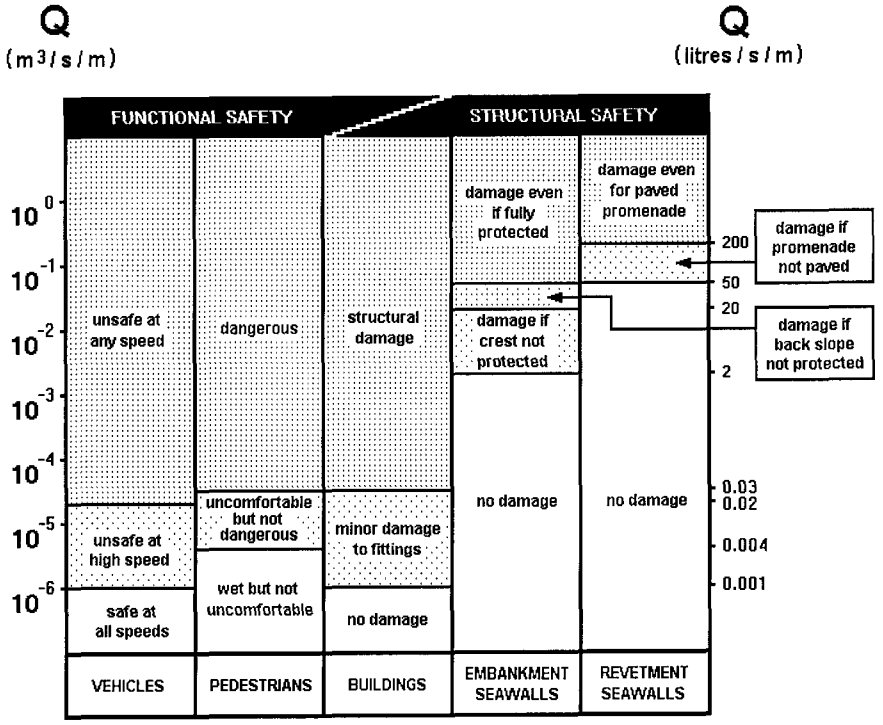


Figure 2: Critical mean overtopping discharges (modified after [1]).

Application of PARASODE to wave overtopping of seawalls

The failure mode of wave overtopping is implemented in PARASODE using the H&R model [2]. The basic variables in this model are listed in Table 1.

Table 1: Basic variables in H&R overtopping model.

Basic variables:	
Crest level of seawall	CL
Seawall slope roughness	r
Seawall slope	$\tan\alpha_s$
Still-water-level	SWL
Significant wave height	H_S
Peak wave period	T_p
Model parameters	A, B and e_B

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Note that PARASODE allows the still-water-level (SWL) to be specified either as a variable in its own right or as the sum of two variables: (i) tide level (denoted Tide), and (ii) surge (denoted Surge). Parameter r, describing the roughness of the seawall front slope, is the ratio of the run-up on a rough slope to that on the corresponding smooth slope. Values range typically from about 0.5 to 1.0 [1]. It is readily incorporated in the overtopping model despite the fact that the H&R model was originally developed for embankments with smooth front slopes.

The failure function may finally be written as follows.

$$Z = Q - A.\sqrt{g.(C.H_S)^3}.\left[1 - \frac{CL - SWL}{r.C.H_S}\right]^{e_B.B} \quad \text{for} \quad 0 \le \left[\frac{CL - SWL}{r.C.H_S}\right] < 1$$
$$Z = Q \quad \text{for} \quad \left[\frac{CL - SWL}{r.C.H_S}\right] \ge 1 \qquad (2)$$

Q is the allowable wave overtopping discharge specified in the FORM calculation, whilst C denotes the ratio of the maximum run-up on a smooth front slope to the significant height of the incident waves ($C = R_{max} / H_S$). C depends upon the characteristics of the slope ($\tan\alpha_s$ and r) and of the incident waves (H_S and T_p). The height $CL - SWL$ is the seawall freeboard; $(CL - SWL)/r$ is the effective freeboard when the front slope is rough rather than smooth. Gravitational acceleration is denoted by g. The user also has to decide if the coefficient C is to be calculated using a 37% or 99% confidence level for the maximum run-up [2].

Case study

The case study is of a simple embankment seawall in Liverpool Bay in the south-eastern corner of the Irish Sea. Its assumed geometry is as follows:

- an impermeable front slope of 1:2 with a relatively smooth surface $(r \approx 0.95)$;
- a toe level of 0m OD (OD denotes Ordnance Datum);
- a crest level of between 8m OD and 16m OD.

The main statistical characteristics of the basic variables in the H&R model (other than the chosen design parameter, CL) are described next. It is necessary to define a mean value, μ, and the corresponding standard deviation, σ, of each basic random variable, and to postulate a type of distribution. Depending on the distribution type, other statistical values may also have to be provided (e.g. the lower limit of a Weibull distributed variable, or the lower and upper limits of a Beta distribution).

Salih [3] provides a scatter diagram describing the long-term distributions of wave heights and periods at the Mersey Bar in Liverpool Bay. The statistical

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parameters given in Table 2 are derived from his results. H_S denotes the significant wave height and T_p is the period corresponding to the peak of the wave spectrum (i.e. the period about which most of the wave energy is concentrated). A linear correlation coefficient between H_S and T_p of 0.6 has also been assumed [3].

Table 2: Parameters describing the Weibull distributions of H_S and T_p.

H_S (m)			T_p (s)		
μ	σ	Lower Limit	μ	σ	Lower Limit
1.2	0.7	0.45	6.4	1.15	4.2

Two types of performance have been evaluated during the case study [1, 4]:

- Performance under normal conditions in which the structure is assessed for all possible values of total water level (tide plus surge). This condition is relevant, for example, to the design of retention and drainage systems and for checking the safety of people and vehicles.
- Performance under extreme conditions in which survival of the structure is assessed during extreme water levels.

As noted earlier, PARASODE allows the water level to be specified either as a variable in its own right or as the sum of the tide and surge components. For performance under normal conditions, a user-defined distribution was established for the predicted tide levels at Liverpool (Figure 3); and a Gumbel distribution ($\mu = 0.019$m; $\sigma = 0.192$m) was fitted to represent the surge component. The tide and surge components were assumed independent, although tide-surge interaction may be important in very shallow water regions. For performance under extreme conditions, a user-defined distribution was established for extreme total water levels.

Overtopping of a seawall does not depend solely on the individual sea state or the individual water level, but on their combination. Even a very severe storm, leading to massive waves, may pass virtually unnoticed if water levels are low. In contrast, at very high water levels, even quite modest waves can cause problems. Hence, in the design of coastal structures, combinations of large waves and high water levels are of particular significance.

In the Liverpool Bay area of the Irish Sea, the tidal range is around 10m (Figure 3). This large tidal range masks the correlation between waves and surge: sea states and total water levels are not completely independent, but the correlation is very weak. No correlation has been assumed either between waves and total water level or between waves and surge in this study. Note that PARASODE allows the user to consider correlation between any two variables by providing a non-zero correlation coefficient between them. A value of zero for the correlation coefficient ensures independence between the two variables.

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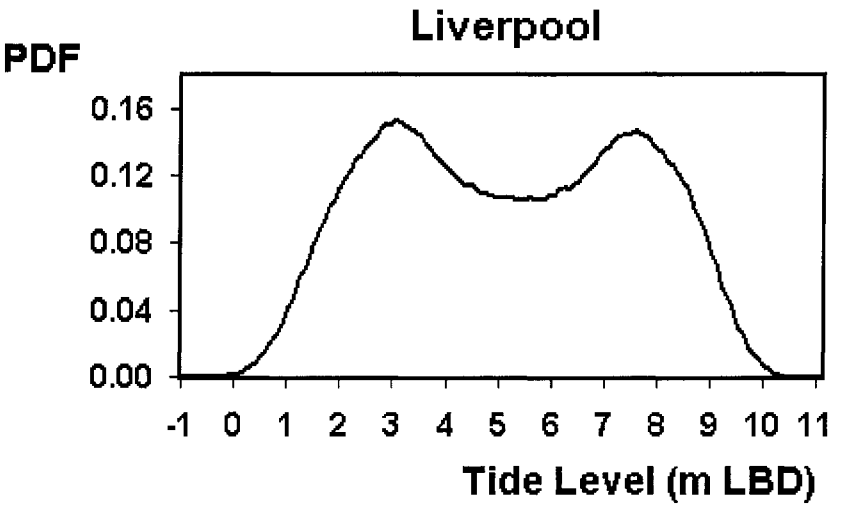


Figure 3: Probability density function of predicted tide levels at Liverpool (LBD = Liverpool Bay Datum; OD = Ordnance Datum; OD = LBD - 4.93m).

The angle at which a seawall front slope is constructed is rarely as specified in its design. Therefore, $\tan\alpha_s$ has been introduced as a random variable having a Normal distribution with a mean $\mu = 0.5$ and a standard deviation $\sigma = 0.05$. Obviously, the tailing off of the Normal distribution to infinity is not representative of the slope angle. However, the behaviour of the tails is not important where there is a small standard deviation associated with a high mean, as in this example.

The slope roughness, r, depends upon the type of cover layer [1]. As with the angle of the seawall slope, the roughness of the slope has been considered as a random variable. A Beta distribution has been chosen, with $\mu = 0.95$, $\sigma = 0.01$ and lower and upper limits of 0.9 and 1.0. Use of the Beta distribution addresses the fact that r can never be greater than unity and it has a specific range of values depending on the type of cover layer.

In the present case study, the values of the model parameters A, B and e_B have been selected in accordance with the recommendations of Reis [5]. The full results produced by PARASODE are also available in Reis [5]. However, only sample graphs are presented here. For example, Figure 4 illustrates the sensitivity of the probability of failure to the values of the H&R model basic variables for normal conditions. It is drawn for an allowable discharge of $0.001 m^3 s^{-1}$ per metre length of seawall and for a 37% confidence level in R_{max}. Figure 5, also for normal conditions, shows the probabilities of failure versus the crest level for various allowable discharges, this time for a 99% confidence level in R_{max}.

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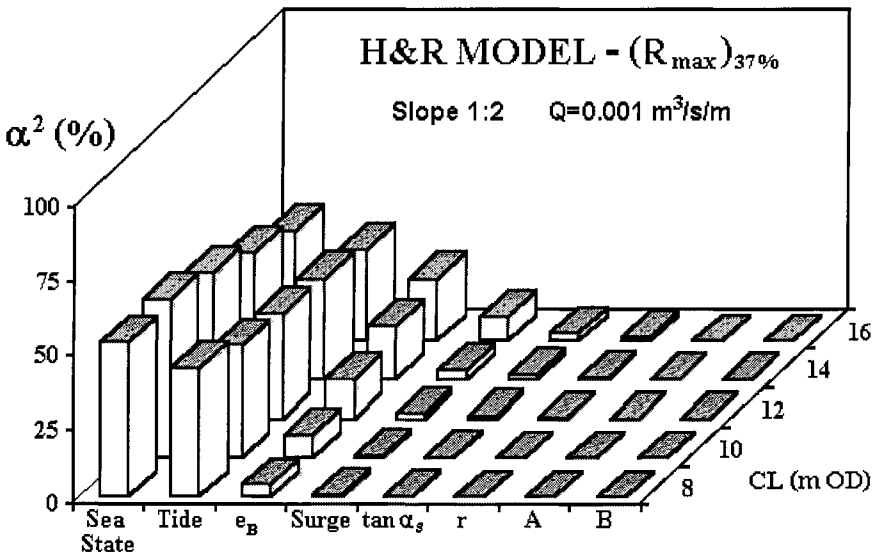


Figure 4: Sensitivity of the probability of failure to values of the H&R model basic variables at the design point for one allowable discharge.

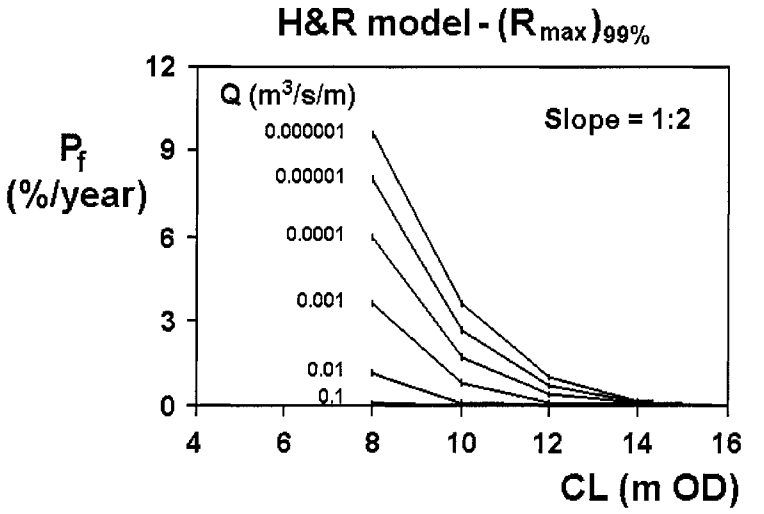


Figure 5: Probability of failure versus crest level for different values of the allowable discharge.

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For wave overtopping under normal conditions, the following points are noteworthy from the examples given here and from those provided by Reis [5]:

- The sensitivity parameters, $\alpha^2(\%)$, for the H&R model show that the main influence on the probability of failure is generally provided by the sea state, i.e. H_S and T_p. The tide also has a major contribution. For the biggest allowable discharges, the model parameter, e_B, occasionally plays the strongest role. The effect of the surge is much less important, and the angle of the seawall front slope and its roughness have only minor influences.
- As expected, the probability of failure, $P_f(\%/\text{year})$ increases as the crest level of the seawall decreases. Likewise, for the same value of the crest level, P_f increases as the allowable discharge decreases. Acceptable probabilities of failure for coastal structures are generally between 10^{-2} and 10^{-5} (i.e. 1 to 0.001% per year). Furthermore, to ensure structural safety, Q must be less than about $10^{-2}m^3s^{-1}$ per metre, whilst for functional safety Q must be less than about $10^{-5}m^3s^{-1}$ per metre (see Figure 2). Consequently, for the input conditions considered, a crest level greater than about 10m would be required to satisfy structural safety. A level of at least 12m would be required to satisfy functional safety. Note that the probability of failure over the lifetime of the structure may be determined quite simply from knowledge of the probability of failure in a year, if statistical independence of each year is assumed.

The results produced by PARASODE for wave overtopping under extreme conditions are not presented here but are discussed in detail by Reis [5].

Concluding remarks

The main objectives of this paper have been to introduce the ideas of risk analysis and their application in the design of seawalls. This final section provides some more general comments about the value of probabilistic calculations in assessing the safety of coastal defences.

- Probabilistic methods provide a useful framework for the design of coastal structures, accounting for the probability and consequences of failure as well as coping, to some degree, with variability and uncertainty. However, when assessing structural safety using probabilistic methods, it must be stressed that the process involves detailed knowledge about the individual structure. Confidence in the calculated value of the probability of failure must change with the amount and quality of the information used for its calculation.
- Much has been learned recently about the application of probabilistic methods in the assessment of coastal structures. However, at present, there is insufficient knowledge about coastal structures to enable a full assessment of their safety. But, instead of abandoning this approach, efforts are now being made to better identify the specific physical processes with which coastal engineers must deal, to better communicate their data requirements to meteorologists, oceanographers and other researchers, to subsequently collect

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the required data sets, and to establish appropriate models for the complete implementation of the methods.

- Assessment of the safety of coastal structures depends fundamentally on assessment of individual failure modes. All single failure mode probabilistic methods have their advantages and disadvantages. It is important to be aware of the characteristics of the various probabilistic methods, their applicability and their limitations, otherwise wrong conclusions can be drawn, incorrect decisions can be made and unsound action may be taken. If probabilistic methods are used with foresight and understanding, they are powerful and can provide reliable results. Comparison of design alternatives using these methods is a particularly promising way in which to apply them.

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