STATISTICAL APPROACH OF DURATION OF EXTREME STORMS : CONSEQUENCES ON BREAKWATER DAMAGES

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Abstract

A statistical model of storm duration has been developped and successfully applied to wave records on various French sites. Distribution of storm durations at various significant wave-height levels are fitted to Weibull curves. Extrapolation of these distributions to rarer storm events is presented, and enables the estimation of return period of any storm as a function of the exceeded wave height and the duration of this exceedance.

These results on storm duration have been applied to breakwater design, with the help of laboratory tests displaying the influence of duration on breakwater damages.

1. INTRODUCTION

Actions of waves on natural shores or artificial structures are at first described by the height of incident waves. Observations of phenomena of littoral transport, or damages caused on breakwater also display the importance of duration of the action of this incident wave. This point of view of persistance of sea state is usually disregarded : analysis of waves records is most often carried out without taking interest in information about duration, however implicitly contained in the sampling, equally or irregularly time-spaced.

It is only in the 1970's that the first "mathematical persistance models" were developped, under the impulse of oil industry, for effective planning of offshore activities (HOUMB and VIK, 1975 ; GRAHAM, 1983).

In the same way, we developped a statistical method of analysis of the couple height/duration of storm from available waves record, successfully applied to various French sites, allowing to estimate distribution of storm duration for extreme events (TEISSON, 1984).

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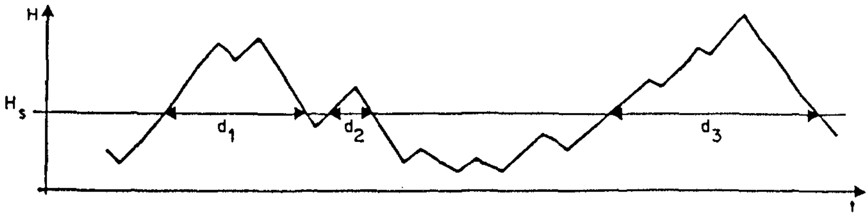

Fig.1: Definition of the duration of a storm at a selected wave height threshold from waves records

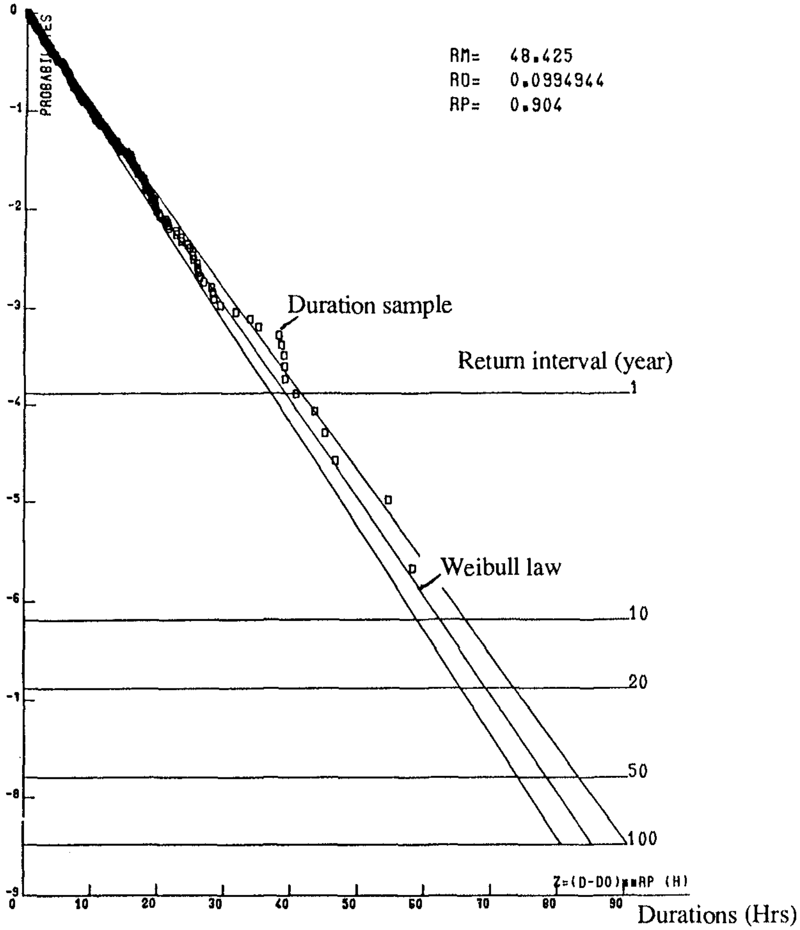

Fig.2: Statistical adjustement of durations for storms Hs > 1.50 m.

These results on storm duration have been applied to breakwater design, in order to judge their influence on the determination of the armour unit size. Previous tests conducted in laboratory enabled to check that storm duration clearly influence the damages : when using stability formulae, as Hudson type, the design wave height producing similar damages lies between $H_{1/10}$ and $H_{1/20}$.

These practical information, combined with the results of the statistical method lead to a more comprehensive use of waves records and a promising approach for breakwater design.

2. THE STATISTICAL METHOD

2.1. Return interval of storm including height and duration

When dealing only with wave height statistics, the definition of storm is reduced to storm peak. We tried to develop a statistical method saving more information and we immediately had to answer some puzzling questions : what is an occurence of a storm and its duration ? Following LAWSON and YOULL (1977), we defined the occurence of a storm when wave height passes, in an upward direction, a selected wave height level. The duration of the storm corresponds to the time exceedance of the wave height level, i.e., the duration of the uninterrupted sequence of significant wave height greater than the selected level (fig. 1). Therefore the same storm can be represented by various durations associated to different wave height levels.

For a selected wave height threshold, i.e. $H_{1/3} = 1.5$ m, the set of storm durations observed in the 5 years records was fitted to various distribution laws to estimate the 1 in a year, 1 in 10 years durations ; the best adjustement was obtained for Weibull laws (fig. 2) :

$$P(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

where P(t) is the probability that a storm duration exceeds t hours, above the selected wave height level of 1.5 m.

The same methodology was reproduced for higher wave height level H, i.e 2 m, 2.5 m, 3 m ..., leading to new values of P(t) at each level. Following the variations of α and β as a function of H enables to extrapolate α and β for extreme H. Thus, on Antifer harbour site :

$$\alpha(H) = 11.4 \ H^{-0.42}$$

$$\beta(H) = e^{\frac{H - 3.3}{5.4}}$$

Finally this method enables to estimate the distribution of storm duration for extreme events. Returns period R of any storm is thus known not only from the exceeded wave height, but also from the duration of this exceedance (fig.3) :

$$\frac{1}{R} = n(H) \times P(t) \quad (1)$$

where n(H) is the classical distribution of extreme wave height and P(t) is the conditional distribution of the duration, for a given threshold H in wave height. n(H) and P(t) are in general Weibull laws, adjusted by the renewal method developped previously at LNH.

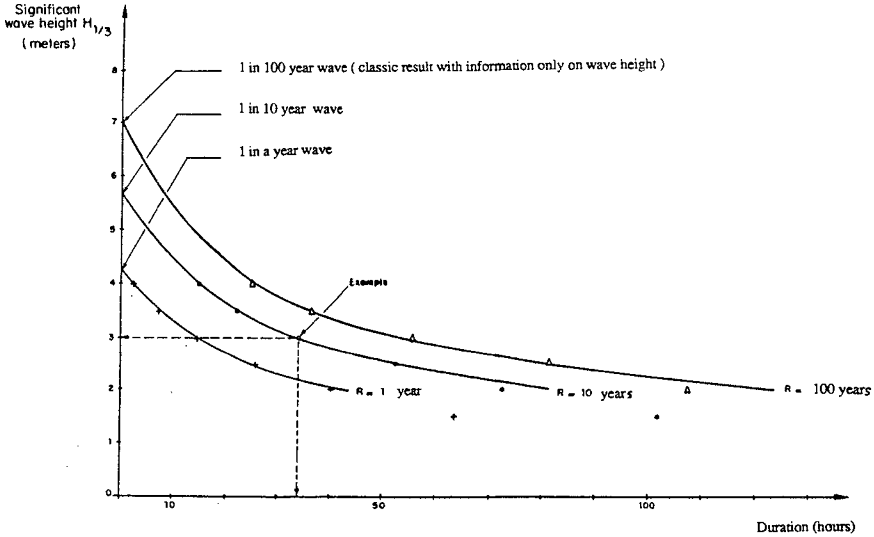

Fig.3: 1 a year, 1 in 10 years, 1 in 100 years storms defined from height and duration parameters
Ex: A storm with a wave height exceeding 3 m. during 34 hours is a 1 in 10 year storm

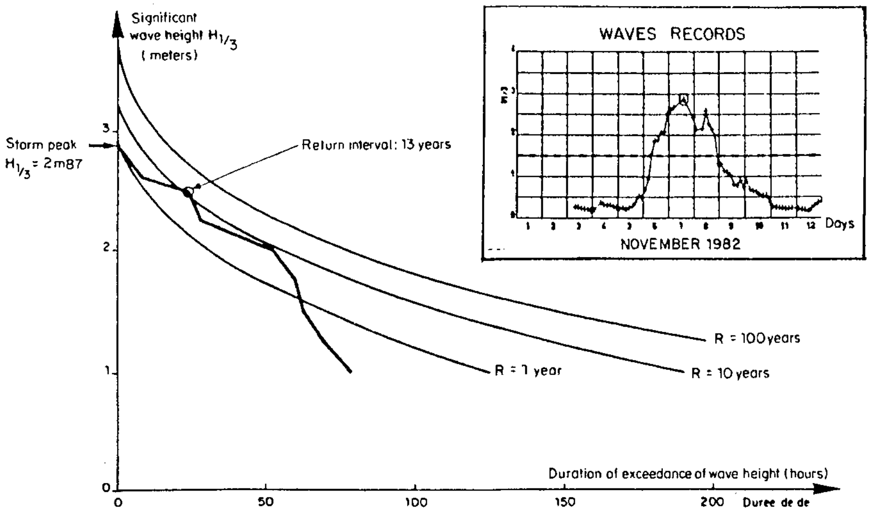

Fig.4: Return interval for the storm of november, 7, 1982 (Marseille site)

2.2. Severity of a storm

As seen above, a storm is a complex event, which cannot be reduced to the maximum wave height reached, or even a duration in hours above a single wave height threshold. In our method, a storm cannot be represented by a single event, and therefore its return interval is not unique. Nevertheless, it is possible to calculate the return interval for various wave height thresholds within the storm from (1), and the greatest return interval will symbolize the "severity" of the storm, and will be selected as the return interval of the storm. This return interval can be visualized by plotting, in the height-duration plan of fig. 3, the various couples wave height-duration of exceedance of any observed storm.

On fig. 4, the storm of november, 7, 1982 in Marseille is plotted in thick line with this value of duration at each level. With classical analysis carried out only on wave height, this storm would be a 1 in a year storm, according to its peak height. Information on duration shows that this storm, at lower height level was a more severe storm, with a return period of 13 years.

3. INFLUENCE OF STORM DURATION ON BREAKWATER DAMAGES

Results on storm duration have been applied to breakwater design, in order to judge their influence on the determination on the armour unit size. Previous tests conducted in a flume (LEPETIT and FEUILLET, 1979) enabled to evaluate the damages as a function of the duration of the action of random waves represented by significant wave height $H_{1/3}$ /(fig. 5):

$$D = a\,H_{1/3}^{b}\,t^{c} \qquad (2)$$

D : Cumulative damage at instant t, expressed in number of displaced blocks of the armour ; a, b, c, constants depending on type of blocks (for rubblemound beakwater a = 0.706, b = 3.9, c = 0.37).

A design wave height H_D, producing similar damages in regular waves can be expressed as :

$$H_D = 1.18\,H_{1/3}\,t^{0.095}$$

On fig. 3, for a given return period, R = 10 years for instance, different values of height and durations as design conditions can be selected, leading to damages according to (2) :

1 in 10 year design condition	$H_{1/3}$	1,50m	2m	2,50m	3m	3,50m	4m	4,50m	5m	5,50m
	t (hours)	101,8	72,6	51,02	33,24	22,17	14,89	9,77	5,80	1,83
	H_D(m)	2,36	3,10	3,82	4,50	5,17	5,81	6,42	6,99	7,33

Table 1 : Influence of storm duration in stability formulae - "Equivalent design height H_D"

Duration clearly influence the damages : when using stability formulae, as Hudson type, the design wave height H_D producing similar damages lies between $H_{1/10}$ and $H_{1/20}$, compared with information only on wave height.

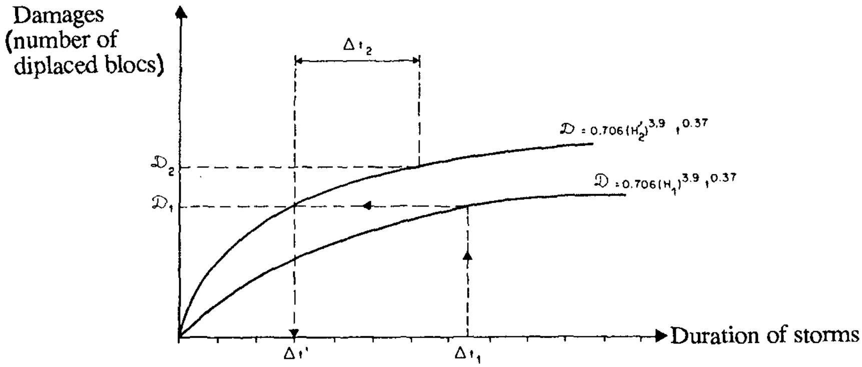

Fig.5: Evolution of damages as a function of duration of storms

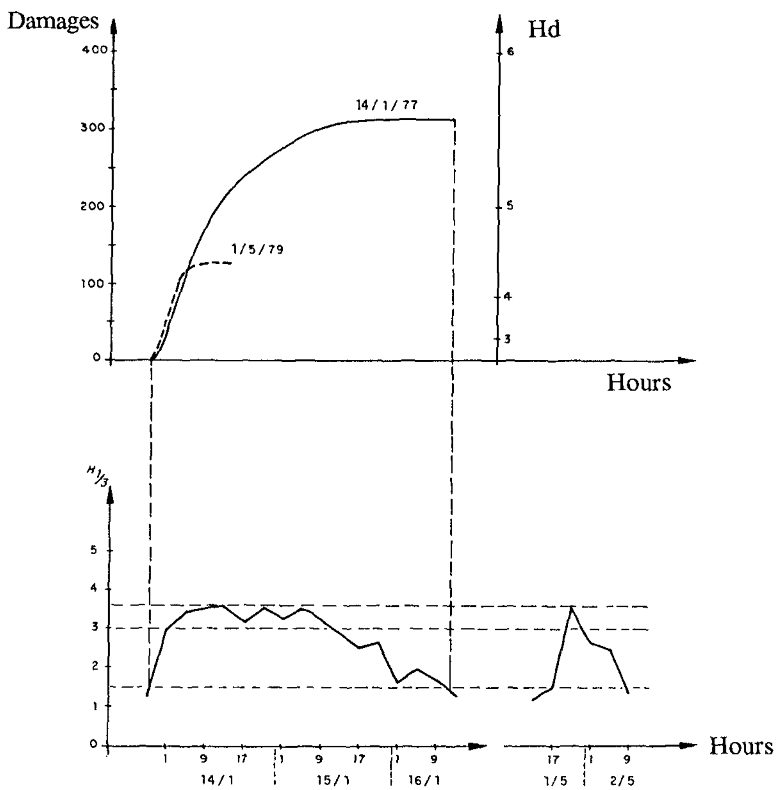

Fig.6: Damages and equivalent dimensional height for storms with same peak height but various durations

Recent developments relate to a better description of sea states, especially storm. The complete information of an occurence of a storm is tentatively saved : not only the peak height, as in classical long term statistic waves, neither duration at some reference waves level, as stated in the method above, but the complete cycle of waves height growing and then decreasing.

By an integrated theoretical approach from (2), we calculated damage all along the storms. Let us suppose that a storm can be described by a sequence of significant wave height H_i, i = 1, ..., n, the duration of each height being Δ ti, i = 1, ...n. The first wave height reaching the breakwater will produce damages according to (2) :

$$D_1 = 0.706\,(H_1)^{3.9}\,\Delta t^{0.37}$$

The next wave height H_2, lasting Δt_2, arrive on a breakwater which has already suffered from damages D1. We can calculate the equivalent duration $\Delta t'$ which would have produced similar damages with H_2 (fig. 5) :

$$\Delta t' = \Delta t_1 \left(\frac{H_1}{H_2}\right)^{\frac{3.9}{0.37}}$$

Therefore, it looks like if H_2 has played during $\Delta t' + \Delta t_2$, producing damages :

$$D_2 = 0.706\,H_2\,(\Delta t' + \Delta t_2)^{0.37}$$

Replacing $\Delta t'$, it comes :

$$D_2 = 0.706 \left|\Delta t_1\, H_1^{10.54} + \Delta t_2\, H_2^{10.54}\right|^{0.37}$$

Reproducing the reasoning step by step, one can write, if we assume that the wave is known in a continuous way :

$$D_{(t)} = 0.706 \left|\int_0^t H_{1/3}(\tau)^{10.54}\, d\tau\right|^{0.37}$$

To see the net influence of duration, this formula has been applied to two storms which appeared in the records, reaching nearly the same peak height of 3.5 m, but with very different durations (fig. 6), the first storm persisting 35 hours above 3 m, the second one only 3 hours. Damages are almost three times greater in the longer storm. Speaking in terms of equivalent design wave height, using HD = 1.29 $D_{1/3.9}$, we found :

H_D = 5.63 m   for the longest storm
H_D = 4.46 m   for the shortest one

Reminding that H_D plays at a power 3 in Hudson formula, for instance, the weight of the blocs of the armour layer would be in a factor of 2 between the two storms, if we have to design a breakwater for each of this storm condition. In this particular case, the duration of storm is as important as the reached wave height, for brekwater design.

Fig. 7 exhibits that for a quasi-symetric storm with respect to duration of growing and decreasing phase, 80 % of damages occur during growing height phase.
From another point of view, 80 % of the damages are concentrated near the peak ; this remark pleas for accurate recording of waves height, instead of time step of 4 hours as on fig. 7.

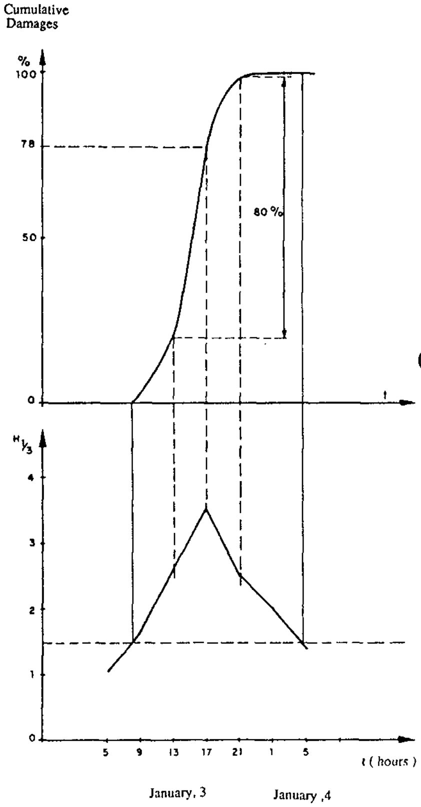

Fig.7: Storm of january, 3 1978

. Time evolution of cumulative damages

(in % of the damages at the end of the storm)

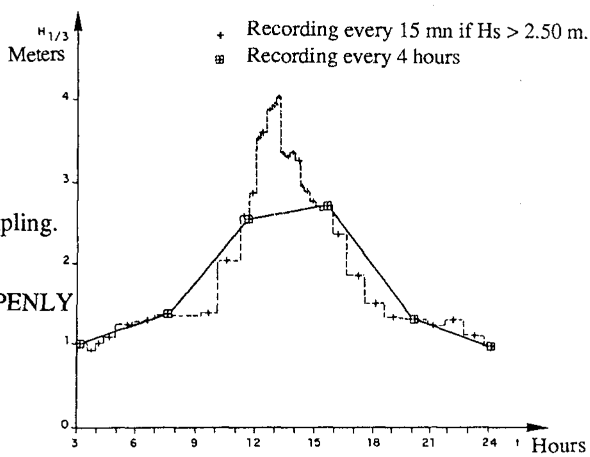

Fig.8: Influence of time sampling.

Storm of 22 March 1981 at PENLY

4. INFLUENCE OF TIME SAMPLING

Usually wave data acquisition is performed in the following manner : the significant wave height is calculated from records of length 20 minutes, every 4 hours. But what does happen in between ? In fact :

- the persistance of waves at the peak cannot be precised in the range 20 minutes - 4 hours,
- the true peak reached is unknown.

Now these missing information are of major importance. From (2) :

- a storm persisting 4 hours at a given level is 3 times more damageable than a storm of 15 minutes (influence of duration),
- for a given duration, a wave of 6 m is 2 times more damageable than a wave of 5 m (influence of true peak).

What does really happen is shown on fig. 8, on a site where classical records every 4 hours were available, together with another record every 15 minutes in case of storm.

When available, recording every 15 minutes leads to strong influence on design conditions, as a consequence of better description of sea state (TEISSON, 1986). On the same data base, 1 in 10 years extreme significant wave height can be increased by 25 % when changing the time step from 4 hours to 15 minutes.

5. PRACTICAL CONCLUSIONS AND FURTHER DEVELOPMENTS

The synthesis of the theoretical statistical developments and laboratory tests lead to some practical information on storm duration and breakwater damages :
- a storm persisting 4 hours at a wave height level is three times more damageable than a storm persisting only 15 minutes at the same level (influence of storm duration),
- to select $H_{1/3}$ as design wave height in Hudson formulae assumes that the associated storm will last for only 10 minutes : this choice could lead to an under estimation of breakwater design,
- to speak of 1 in 10 years wave estimate has no significance without referring to the time sampling of the records.

On going developments try to treat the waves records, and especially storms, with respect to their specific final aim : each storm is transformed into cumulative potential damages on rubblemound breakwater (see fig. 7). These damages are then expressed in an equivalent dimensional height, by an inverse transformation, which could be extrapolated to extreme event. This theoretical approach, which is now under verification in flume tests, could lead to complete new definitions of design conditions, closer and more adequate for breakwater layout.
All these researches, aiming at a better description of sea state including persistency, may help in a more precise evaluation of design conditions for coastal activities.

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