EFFECTIVENESS OF RECURVE WALLS IN REDUCING WAVE OVERTOPPING ON SEAWALLS AND BREAKWATERS

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Designers of vertical seawalls and breakwaters have often included some form of seaward overhang (*recurve / parapet / wave return wall / bullnose*) as part of the structure with the design motivation of reducing wave overtopping by deflecting back seaward uprushing water. Despite a lengthy track record in the field and relevance to current design issues, very little generic guidance is available for their incorporation into seawall / breakwater design. This paper reports a study whose aim is the formulation of generic guidance for recurve structure design. Particular attention is given to high freeboard and / or wave breaking conditions under which the recurve / parapet gives very large reductions (recurve *k*-factor < 0.05). The paper presents tentative guidance in the form of a decision chart. Finally, overtopping and loading results from a case study into a wall of particularly complex geometry are presented and compared with earlier studies. Forces on the vertical wall are found to be highly impulsive in nature and approximately double the magnitude of those expected on a simple wall, with additional forces of a similar magnitude measured on the underside of the parapet.

1. Introduction

For well over a century, designers of seawalls and breakwaters have often included some form of seaward overhang as part of the structure. This design feature is referred to variously as a *recurve / parapet / wave return wall / bullnose.* While arguably there are some distinctions to be made between these, they all share the design motivation of reducing wave overtopping by deflecting back seaward uprushing water (Figure 1). This design feature (for simplicity hereafter referred to as a *recurve* if it is curved, otherwise *parapet*) has many

attractions, not least at a time when there is evidence of increased storm activity in many parts of the world placing increased pressure on the performance of existing coastal defence structures. For reasons of visual amenity, simply enhancing the performance of a wall against overtopping by increasing the crest level may not always be a satisfactory option − recurves offer an alternative.

With such a lengthy track record in the field and relevance to current design issues, it is surprising that very few systematic studies have been carried out and even less generic guidance offered for their incorporation into seawall / breakwater design.
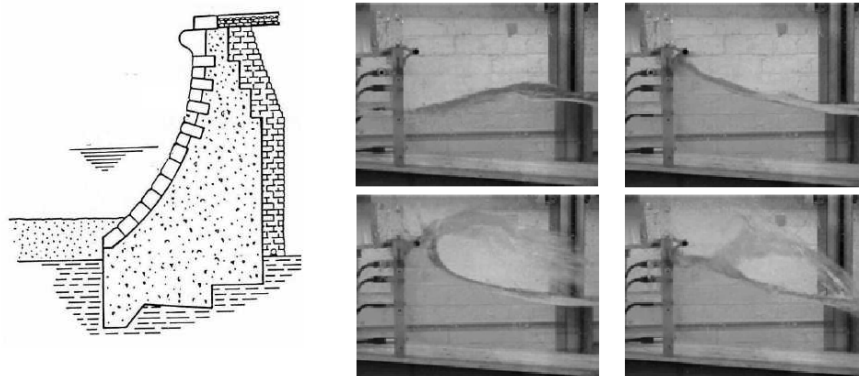

Figure 1. Left, a seawall with recurve. Right, a model recurve in the laboratory at Edinburgh.

This paper updates reporting of an on-going UK / German / Dutch collaborative study whose aim is the formulation of generic guidance for recurve / parapet structure design. It begins with a review of previous studies and a detailed reprise of initial project findings. Particular attention is then paid to modelling conditions (generally high freeboard and / or wave breaking) under which the recurve / parapet gives very large reductions (by greater than a factor of 20; *ie* recurve *k*-factor < 0.05). Finally, overtopping and loading results from a case study into a wall of particularly complex geometry are presented and compared with earlier studies.

2. Previous studies

Systematic hydraulic model studies of wave overtopping date back to the 1970s (*eg* Goda, 1971 & 1975). Most work focussed upon simple sloping structures (*eg* Owen, 1980), later extended / modified to rubble mound structures and to steep and vertical walls (*eg* Franco *et al*, 1994 & 1995; van der Meer & Janssen, 1995; van der Meer *et al* 1998). For vertical walls, early studies were carried out under wave / structure combinations which gave few or no breaking waves at the wall. In the mid-90s it was realised that a transition to breaking or *impulsive*

conditions at a wall caused a significant change in overtopping performance not predicted by existing methods. Recent investigations (*eg* Allsop *et al*, 1995; Bruce *et al*, 2001; Pearson *et al*, 2002; Napp *et al*, 2004) have focussed on these impulsive conditions and verified / expanded guidance on the subject. Current guidance includes the UK *Environment Agency Overtopping Manual* (Besley, 1999) and even more recently in The Netherlands, the *TAW Manual* (van der Meer, 2002).

Early studies of structures with some form of recurve include the work of Owen & Steele (1991) and Juhl (1992). These studies offer overtopping reduction factors but are not generic in nature.

In Japan, a detailed research programme has investigated a *non wave overtopping seawall* (also known as a *flaring shaped seawall, FSS*). This type of structure has a large radius curve starting well below still water level whose radius changes with elevation. Results of regular wave tests and numerical simulations are given in Kamikubo *et al* (2000), with new irregular wave data being presented elsewhere at this conference (Yamashiro *et al*, 2004). The investigators demonstrated a reduction in required crest level of up to *c.* 30%.

Cornett *et al* (1999) describe an extensive and systematic investigation of the influence of parapets on overtopping. The test programme included "chamfered" walls where the parapet was angled landward rather than overhanging seaward. For conventional seaward leaning parapets, reduction factors of ten or more are reported even for parapets inclined at angles as little as 30^0. Helpful summary charts are presented with comparisons to standard formulae, but it is admitted that the overtopping response was found to be "highly variable" resulting quite some unresolved scatter.

Kortenhaus *et al* (2001) report on a series of tests in which overtopping and wave loading are measured for vertical walls with and without parapet. They found that the parapet is effective in reducing overtopping only under conditions where the relative crest freeboard $R_c/H_s > 1.5$. Wave loading on the structure was found to be significantly increased by the presence of the parapet for lower freeboards, $R_c/H_s < 1.2$, with factors of 2.0 and 1.7 being quoted for impulsive and non-impulsive waves respectively. This study, together with work in the UK under the *Violent Overtopping by Waves at Seawalls (VOWS)* project formed the starting point for the current investigation. First results were reported at the *Coastal Structures '03* conference (Kortenhaus *et al*, 2003). These are summarised in the next section.

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3. Review of tentative generic method (Kortenhaus *et al*, 2003)

Analysis was carried out of overtopping measurements from a number of datasets which included a wide range of recurve / parapet types, plain and composite walls and impulsive and non-impulsive conditions at small and large scale. It was seen that some "with recurve" data fell as much as three orders of magnitude below the discharges measured (or expected) for the plain structure. The effectiveness of the recurve / parapet in reducing overtopping was quantified by the *k-factor* defined as

$$k \equiv \frac{q_{\text{with\_recurve}}}{q_{\text{without\_recurve}}}$$

Plotting k against relative freeboard R_c/H_s for each structure / recurve combination (example in Figure 2) suggested a three-regime predictor going from "little or no effect" to "very large reduction" regimes via a transition regime. The first regime extends to $R_c/H_s = R_0^*$, with the transition to the third regime occurring at $R_c/H_s = m^*$. Equations for k, R_0^* and m^* are as follows.
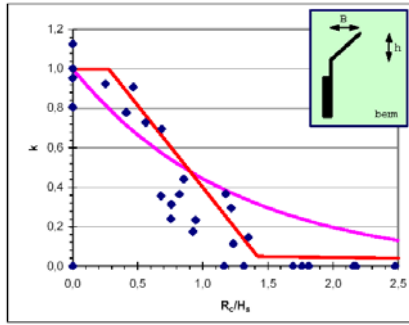

Figure 2. Recurve k-factor *vs* relative crest freeboard (from Kortenhaus *et al*, 2003). The curve shows an earlier predictor (from Kortenhaus *et al*, 2001).
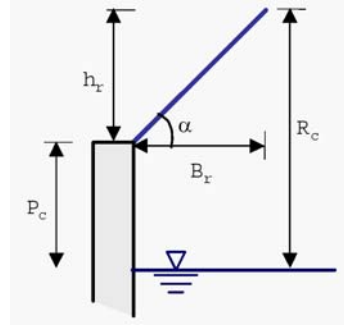
Figure 3. Parameter definition sketch.

$$k = \begin{cases} 1.0 & \text{for } \dfrac{R_c}{H_s} \leq R_0^* \\[2ex] 1 - \dfrac{1}{m}\left(\dfrac{R_c}{H_s} - R_0^* \right) & \text{for } R_0^* < \dfrac{R_c}{H_s} \leq R_0^* + m^* \\[2ex] k_{23} - 0.01\left(\dfrac{R_c}{H_s} - R_0^* - m^* \right) & \text{for } \dfrac{R_c}{H_s} \geq R_0^* + m^* \end{cases} \qquad (1)$$

where k_{23} is the k-factor at which the lowest k regime begins[†] (set to 0.2[‡]) and

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[†] k_{23} was referred to as k_3 in Kortenhaus *et al* (2003).
[‡] The value of 0.2 is preferred to 0.05 used in Kortenhaus *et al* (2003).

$$R_0^* \equiv 0.25 \cdot \frac{h_r}{B_r} + 0.05 \frac{P_c}{R_c} \qquad\qquad (2)$$

$$m \equiv 1.1 \sqrt{\frac{h_r}{B_r}} + 0.2 \frac{P_c}{R_c} \qquad\qquad m^* \equiv m(1 - k_{23}) \qquad\qquad (3), (4)$$

Applying this model for k to the available dataset and plotting the dimensionless mean discharge *adjusted by the k-factor* against relative crest freeboard gave the graph in Figure 4. This k-factor approach gave a useful reduction in the scatter in the data, and showed that the adjusted data generally lay on the conservative side of van der Meer and Janssen (1995). However, there was quite some data which lay very much below the line, by up to a factor of 100. This is in line with the scatter observed in the lowest k regime ($R_c/H_s \geq R_0^* + m^*$). The study has since been extended to focus on this regime of largest reduction factors – the topic of the next section.
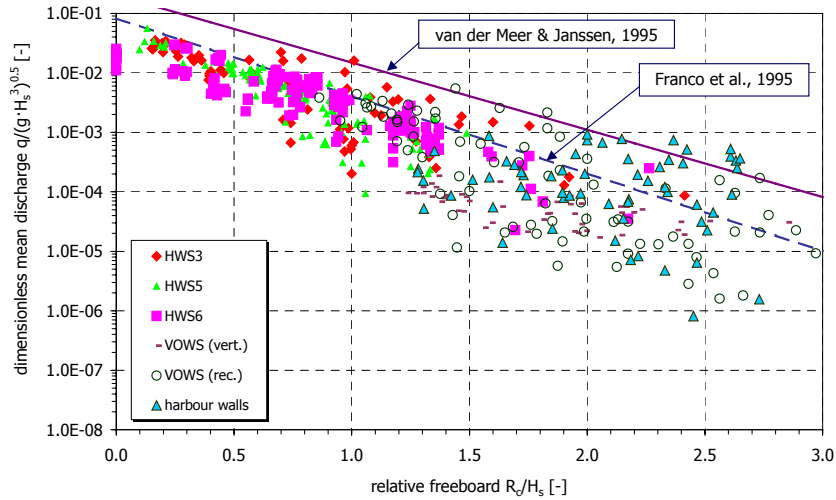

Figure 4. Non-dimensional mean overtopping discharge *vs* relative crest freeboard incorporating correction for reduction factor k (equation 1). From Kortenhaus *et al* (2003).

4. High freeboard / low k cases

The basis for this part of the study is a dataset consisting of 85 tests carried out at small-scale supplemented by five tests carried out under closely comparable conditions at large scale (at UPC Barcelona, see Pearson *et al*, 2002). That the lowest k (largest reduction) regime of Kortenhaus *et al* (2003) performs generally conservatively but not particularly well for these tests is shown in Figure 5, where the measured k-factor is plotted against the value predicted.
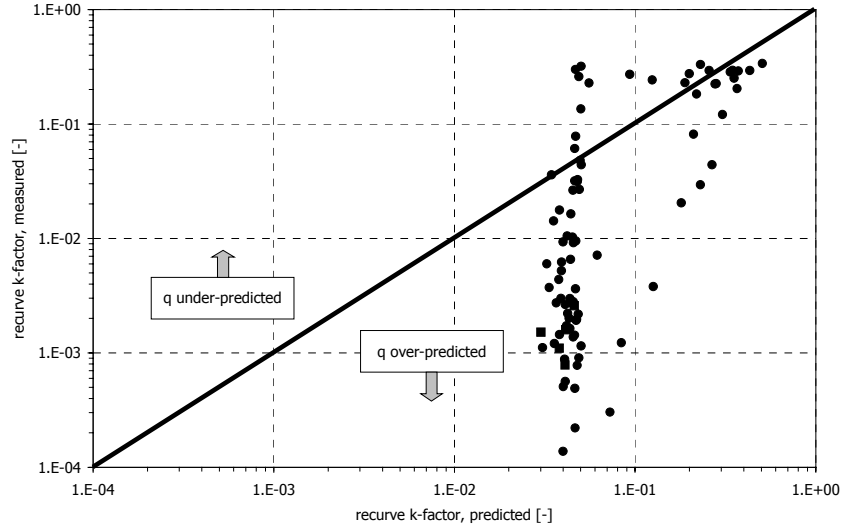
Figure 5. Measured *k*-factor *vs* predicted, VOWS data. Circles are small-scale data (85 tests); squares are large-scale data (five tests). Note logarithmic axes.

Exploration of the dependency of *k* upon key structural and wave parameters found some dependency upon both relative crest freeboard (*k* ↓ as R_c/H_s ↑ with quite some scatter) and upon the relative water depth at the base of the wall (*k* ↓ as h_s/H_s ↓ again with quite some scatter). The dependency upon relative freeboard is explained by the observation that the higher the relative freeboard, the more vertically upward any uprushing water travels, and the more effectively this is thrown entirely seaward by the recurve. The relative depth dependency seems to rest upon the fact that the incident waves are increasingly likely to be breaking (or even broken) at the wall as this parameter decreases. Again, such conditions favour vertically thrown uprush and improved recurve efficiency.

Combining these to give k as a function of $R_c/H_s \times H_s/h_s = R_c/h_s$ reduces scatter somewhat and reveals some organised behaviour. Plotting the ratio of measured to predicted k (Figure 6), it would appear that an approach similar to that taken for all cases (Section 3) should be taken, with the response falling into three regimes;

1. $R_c/h_s \leq 0.6$; *k* as per Kortenhaus *et al* (2003);
2. $0.6 < R_c/h_s \leq 1.1$; $k \rightarrow k \times 180 \exp(-8.5 \, R_c/h_s)$;
3. $R_c/h_s > 1.1$; $k \rightarrow k \times 0.02$.

The effectiveness of this adjustment to *k* can be gauged from Figure 7, which plots the ratio of the measured to new predicted *k*-factors against dimensionless discharge. The data is now scattered around the ideal (ratio = 1) line and all predictions fall within one order of magnitude of measurements.
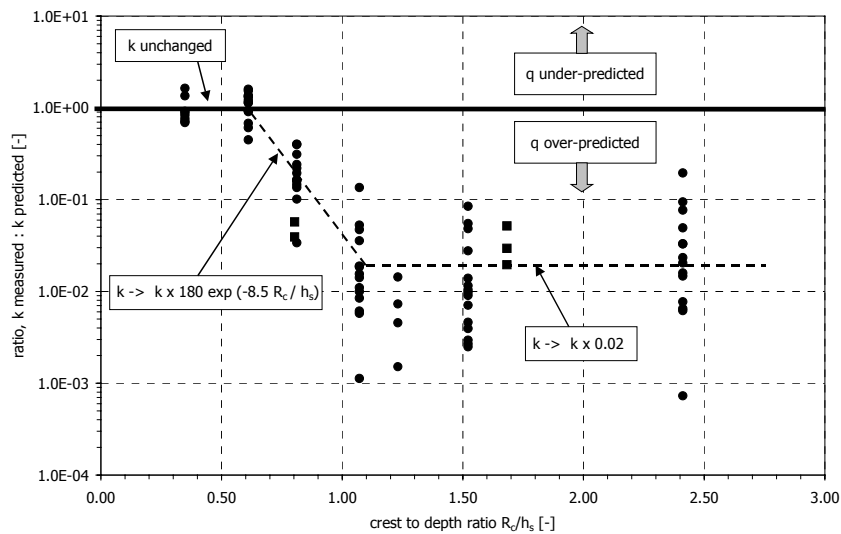

Figure 6. Ratio of *k* measured to *k* predicted by Kortenhaus *et al* (2003) plotted against crest to depth ratio. Lines show proposed three-regime adjustment.

It might be expected that scatter would be greatest for the very smallest discharges, and indeed this appears to be the case here (Figure 7). For non-dimensional mean discharges $q > 10^{-5}$, the scatter reduces to give agreement to with a factor of approximately two. The inherent scatter for the lowest discharges may mean that it is unlikely that *k*-factors of less than perhaps 0.05 could be safely realised in design, and certainly not without detailed physical model studies. The methodology is summarised in a decision chart (Figure 8).

5. Promenade wall case study

5.1. *Introduction*

This section reports results from a design study of an unusual seawall to defend against *very* long return period conditions. There are some important visual constraints on fixing the overtopping discharge by crest freeboard alone. Consideration instead is being given to a wall with parapet (Figure 9) whose crown deck will form a promenade. The purpose of the study was to determine a

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suitable parapet extension B_r to limit overtopping to an admissible level under extreme conditions.
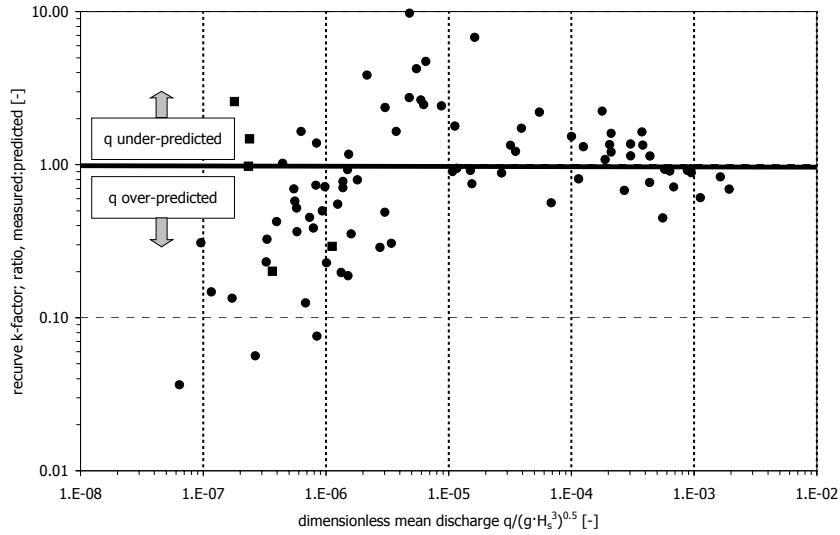

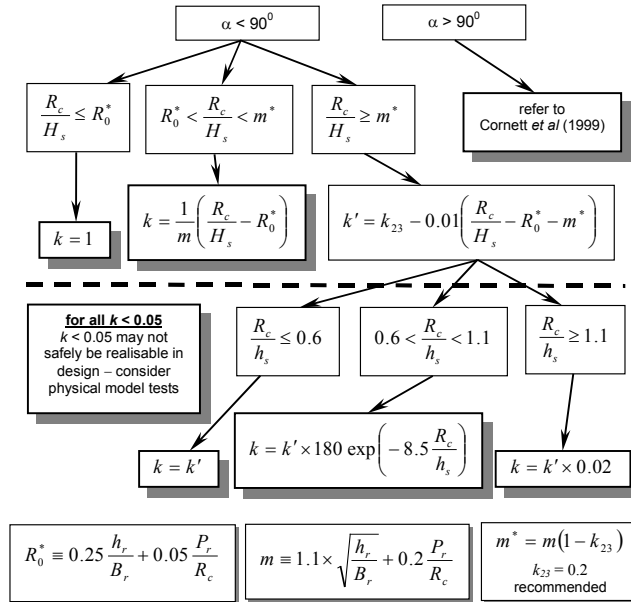Figure 7. Ratio, measured:predicted k-factor plotted against non-dimensional overtopping rate.

Figure 8. "Decision chart" summarising methodology for tentative guidance.

It can be seen from the cross-sections that this problem presents difficulties for application of the method described in Sections 3 and 4. Firstly, the recurve does not reach up to the crest of the structure, leaving a problem of what is h_r. The parapet section also begins at an unusually low relative elevation, P_c. It was decided that a physical model study should be carried out. Three cross-sections were tested with increasing parapet overhangs, B_r. Pressure measurements were made on the vertical wall and on the underside of the overhanging parapet.
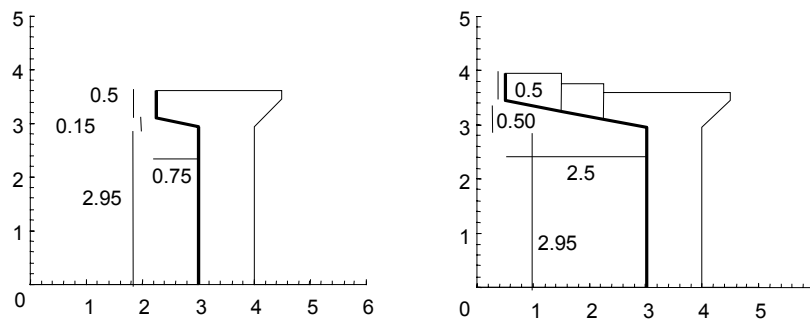

Figure 9. Left; the basic *"small recurve" structure*. Right; showing two added sections increasing parapet width B_r (*"medium recurve" and "large recurve"*). Dimensions in m at prototype scale.

5.2. *Overtopping observations and measurements*

Tests were carried out in the wave channel at the University of Edinburgh. The channel is 20m long by 0.4m wide with a working water depth of 0.7m. The channel is equipped with an absorbing flap-type wave paddle. Overtopping discharge was collected in a tank suspended from a load cell. Pressure measurements were taken using seven Druck PDCR 800 pressure transducers (natural frequency 28 kHz) sampled at 2 kHz. The test matrix included both uni- and bi-modal seas with nominal steepnesses around 0.04 and 0.02.

With a relatively small gap between still water level and the underside of the parapet, some particularly violent behaviour was observed, as incoming waves filled the gap under the parapet (Figure 10).

The overtopping results are shown in Figure 11. It is immediately striking that the mean discharge does not show as strong an influence from the parapet overhang B_r as the influence of steepness. Indeed, the overtopping response of these structures was seen to be very sensitive to wave period, with the shorter period waves generally more affected by the presence of the parapet than the longer waves. Observations show that these longer waves are more capable of filling the under-parapet gap and then overflowing this filled volume to overtop.

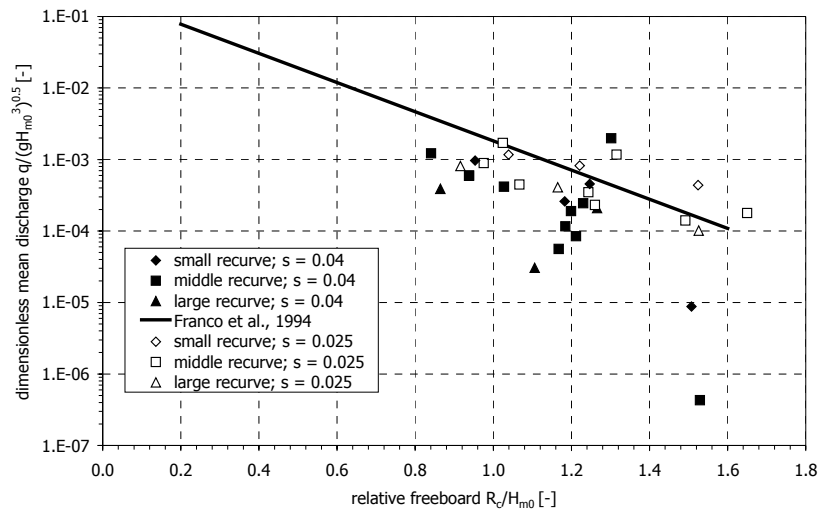Figure 10. Example of a wave being deflected seaward in the promenade wall study

Figure 11. Graph of relative mean overtopping rate *vs* relative freeboard; all cross-sections. The only *s*=0.04 point lying above the line corresponds to a bi-modal sea for which the definition of steepness is less physically meaningful.

For completeness, a comparison of these measurements with the tentative generic method was made. Making the assumption that the parapet can be modelled as an average line from its base to the crest of the structure, overtopping was generally under-predicted by factors of up to ten. This reinforces the argument that this is a complex configuration with wave-structure interactions and resultant overtopping performance strongly affected by the parapet lying so close to still water level.

5.3. *Loadings on parapet*

It is clear from fundamental momentum considerations that a structure deflecting water through a greater angle must experience enhanced loadings, but how these are distributed (and thus the effect on overturning moments) is not well understood. Kortenhaus *et al* (2001) give horizontal load increase factors of 1.7 and 2.0 for non-impulsive and impulsive conditions respectively. The upward loads on the parapet are reported as being of a similar magnitude.

The results of the force measurements are summarised in Table 1, together with comparator forces from a Delft Hydraulics study. The forces have been non-dimensionalised in the conventional manner. The "upwards" force is the force acting normal to the underside of the parapet.

Table 1. Dimensionless forces measured on promenade wall, plain vertical wall comparison.

dimensionless force, $F / \rho g H_{m0}^{2}$	Horizontal [-]	Upwards, on parapet [-]
plain vertical wall (den Heijer, 1998)	9.3 – 11.4	
promenade wall, s*mall recurve*	17.2	16.3
promenade wall, *medium recurve*	20.5	21.1

Thus, for this parapet configuration structure, measured horizontal forces are higher than for a plain wall by factors $k_F \approx 2$, with further comparable (or even slightly larger) forces acting on the underside of the parapet. These factors are very much in line with those reported by Kortenhaus *et al* (2001).

Impulsive loads on a parapet are of some importance as the parapet structure is likely to have a higher natural frequency than the main part of the wall and thus may be able to "feel" and respond to the impulsive part of the loading to a greater extent. Observations of these tests suggested some highly impulsive loads, supported by very abrupt and loud slamming noises being heard repeatedly. Mean rise time measured at model scale was 2.0 ms ($\pm$ 1.1 ms), with mean total impact duration 7.2 ms ($\pm$ 2.7 ms).

6. Conclusions

Kortenhaus *et al* (2003) presented a generic method for the prediction of the reduction in overtopping due to recurves / parapets. Quite some scatter remained for the largest reductions (smallest *k*-factors). This paper has presented an extended method with focus on this regime. The method builds upon a dependency of recurve effectiveness upon the crest to depth ratio R_c / h_s. The combined prediction method is summarised in a "decision chart".

Results from a physical model study of a "promenade wall" with unusual parapet have been presented, illustrating the difficulty in applying a generic method to complex structures (in this case, one with parapet unusually close to

still water level). The model study showed that for this structure, overtopping reduction due to the parapet was more strongly influenced by wave period than by the parapet overhang, B_r.

Basic momentum considerations require that the presence of a recurve / parapet must increase the total load. Measurements of horizontal and upward loading on the "promenade wall" gave load horizontal increase factors (k_F) of around two as compared to loads on a simple vertical wall. Upward loads on the underside of the parapet were of a similar magnitude (indeed greater in some cases). These findings were in line with those of Kortenhaus *et al* (2001). Very short-duration impulsive (slamming) loads were measured as the gap under the parapet filled. Parapets may be particularly able to respond to (and be damaged by) such loads.

Acknowledgements

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