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Breaking wave loads at vertical seawalls and breakwaters

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ABSTRACT

This paper presents recent advances in knowledge on wave loads, based on experimental work carried out in the CIEM/LIM large flume at Barcelona within the framework of the *VOWS* (Violent Overtopping by Waves at Seawalls) project. Both quasi-static and impact wave forces from the new data set have been compared with predictions by empirical and analytical methods. The scatter in impact forces has been found to be large over the whole range of measurements, with no existing method giving especially good predictions. Based on general considerations, a simple and intuitive set of prediction formulae has been introduced for quasi-static and impact forces, and overturning moments, giving good agreement with the new measurements. New prediction formulae have been compared with previous measurements from physical model tests at small and large scale, giving satisfactory results over a relatively wide range of test conditions. The time variation of wave impacts is discussed, together with pressure distribution up the wall, which shows that within experimental limitations the measured pressures are within existing limits of previous study.

1. Introduction

It has long been recognised that wave loads on vertical seawalls and breakwaters (including steeply-battered and composite walls) may vary between slowly-acting, 'pulsating' loads, and more intense but shorter lasting 'impact' (or 'impulsive') loads. Loads from non-breaking (pulsating) waves can be predicted with reasonable confidence by empirical formulae, but wave impact loads have always been troublesome to designers, as impact loads can be 10–50 times greater in magnitude than pulsating loads, see Kirkgoz (1982) Allsop et al. (1996c) or McKenna (1997). Very short-duration loads may, however, not persist for long enough to cause any noticeable movement or damage, so wave impact loads are not always explicitly or appropriately treated in design or analysis. Improved awareness in recent years of the occurrence and effects of wave impact loads, including failures (Oumeraci, 1994; Franco, 1994), has focused the attention on the need to include dynamic responses to wave impact loads in the analysis of loadings (see, *e.g.* Oumeraci et al., 2001; Allsop, 2000). Recent experimental work has therefore focused more strongly on recording and analysing violent wave impacts.

This paper reports measurements of impulsive wave loads on a steeply-battered (10:1) wall from tests in the large wave flume at Barcelona under the *Violent Overtopping by Waves at Seawalls (VOWS)* project. From those loads, a set of simple formulae is derived for prediction of wave loads on vertical and near-vertical walls with steep foreshores, subject to breaking waves.

A short literature review is summarised in Section 2, including historical contributions from the beginning of the 20th Century. The new experiments are described in Section 3 and measurements compared with methods in literature (Section 4). Based on the analysis of relative importance of the main parameters (Section 5), a new set of formulae is introduced for both impact (Section 6) and quasi-static (Section 7) loads and compared with the new set of measurements. Based on the Mitsuyasu (1966) "compression model law", a semi-empirical scaling method is applied to impact pressures at different scales (Section 8) then predictions of impact forces by the new formulae are compared with measurements from physical model tests under the *PROVERBS* research project at both small and large scale.

Empirical expressions for the distribution of positive (shoreward) quasi-static pressures up the wall are also presented in Section 9. Pressure and force impulses recorded during physical model tests are compared with prediction by pressure impulse theory, and a semi-empirical relation is given for the estimation of impact rise times corresponding to a given impact magnitude (Section 10). Finally,

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conclusions and an assessment of the next challenges are given in Section 11.

2. Literature review

Much research has been carried out on wave forces on seawalls since Stevenson (1874) and Gaillard (1904) conducted the first observational studies at the end of the 19th century. Despite efforts by researchers worldwide, assessment of wave loads to be used in design of breakwaters or seawalls subject to breaking wave attack is still an open issue, mainly due to the highly stochastic nature of wave impact forces. Under the European PROVERBS project, Oumeraci et al. (2001) have summarised work on wave loads and suggested method for quasi-static and impulsive loads. Cuomo (2005) reviewed prediction methods for wave-induced forces on coastal structures, including caisson breakwaters and seawalls. A brief summary is given of selected works by previous researchers.

Based on field measurements, Hiroi (1920) suggested the following tentative prediction formula for the average wave pressure (P) from breaking waves:

$$P = 1.5 \cdot \rho \cdot g \cdot H_{\mathrm{D}} \tag{1}$$

where ρ is the water density, g is the acceleration due to gravity and H_{D} is the design wave height. The methodology assumes that the pressure given by Eq. (1) acts uniformly over the full height of an upright section, or to an elevation of 1.25 times the wave height above the still water level (SWL), whichever is less.

Sainflou (1928) derived a Lagrangian analytical solution for non-linear standing (i.e. non-breaking) water waves induced pressure on a vertical wall. Whilst still useful for pulsating wave loads, Sainflou's method does not give impulsive loads.

Work by Bagnold (1939) laid foundations for much subsequent research on wave impacts on coastal structures. Impact pressures were observed to vary greatly even for fixed nominal conditions, but the pressure impulse (defined as the integral of pressure over time) was far more repeatable. Bagnold noted the importance of entrained air, observing that pressures were greatest when the amount of air trapped by the wave as it met the wall was least, but not zero.

Minikin (1963) developed a prediction method for the estimation of local wave impact pressures caused by waves breaking directly onto a vertical breakwater or seawall. Minikin's formula for wave impact forces on vertical walls is written:

$$F_{\mathrm{h,imp}} = \frac{101}{3} \cdot \frac{\rho \cdot g \cdot H_{\mathrm{D}}^{2} \cdot d}{L_{\mathrm{D}} \cdot D} \cdot (d + D) \tag{2}$$

where L_{D} is the design wave length, D is the water depth at distance L_{D} from the structure, d is the water depth at the toe of the structure. More recent studies (Allsop et al., 1996c) demonstrated Minikin's formula as above to be qualitatively incorrect, since $F_{\mathrm{h,imp}}$ in Eq. (2) decreases with increasing incident wave length L. as well as dimensionally inconsistent.

Goda (1974) developed new formulae for wave loads on vertical breakwaters based on a broad set of laboratory data and theoretical considerations (Goda, 1967). Further work by Tanimoto et al. (1976), Takahashi et al. (1993) and Takahashi and Hosoyamada (1994) extended the original method by Goda accounting for the effect of a berm, sloping top, wave breaking and incident wave angle. The prediction method by Goda (2000) represents the benchmark in the evolution of physically-rational approaches to the assessment of wave loads at walls.

Blackmore and Hewson (1984) carried out full scale measurements of wave impacts on a seawall in the South of West England using modern measuring and recording equipment. Comparison of new data sets with previous experiments and prediction formulae proved that impact pressures in the field are generally lower than those measured during laboratory tests, mainly due to the high percentage of air entrained. Based on their observations, Blackmore and Hewson developed the following prediction formula for average pressures under broken waves:

$$P = \lambda \cdot \rho \cdot c_{\mathrm{sw}}^{2} \cdot T \tag{3}$$

where the aeration factor λ has dimension of [s^{-1}] and accounts for the percentage of air entrainment, T is the wave period and c_{sw} is the shallow water wave celerity. British Standard code of practice for marine structures (BS 6349) suggests evaluating wave impact pressures on seawalls by means of Eq. (3) using $\lambda = 0.3\ \mathrm{s}^{-1}$ and $\lambda = 0.5\ \mathrm{s}^{-1}$ respectively for rough/rocky foreshores or regular beaches.

Kirkgoz (1982, 1983, 1990, 1991, 1992, 1995) performed two-dimensional experiments using regular waves forced to break in front of a vertical wall by means of an approaching beach of variable slope. Kirkgoz distinguished among early breaking, late breaking and perfect breaking and highlighted the relative importance of deep water wave steepness and beach slope on the maximum peak pressure and its position up the wall. Impact pressures and forces were found to vary significantly for small changes in water depth at the wall and to reduce drastically when an air pocket was entrapped between the wave front and the structure.

Within *PROVERBS* physical model tests at large- and small scale were run respectively in the Large Wave Flume (GWK) of Hannover, Germany and in the Deep Wave Flume (DWF) at HR Wallingford (HRW), Wallingford, UK. Analysis of large-scale tests led to results presented in Kortenhaus et al. (1994) and Klammer et al. (1996), respectively in terms of horizontal wave impact and up-lift loading. The smaller-scale HR Wallingford tests are described in depth in Allsop et al. (1996a,b,c). The analysis of wave pressures and forces suggested the development of a new prediction method for wave impact forces on vertical breakwaters (Allsop et al., 1996a; Allsop and Vicinanza, 1996). The method is recommended in Oumeraci et al. (2001) for preliminary design and the British Standards (BS6349-1, 2000) and is expressed by:

$$F_{\mathrm{h,imp}} = 15 \cdot \rho \cdot g \cdot d^{2} \cdot (H_{\mathrm{si}} / d)^{3.134} \tag{4}$$

where H_{si} is the (design) significant wave height at the toe of the wall and d the water depth.

The advances in knowledge and prediction of wave loadings within *PROVERBS* led to a new procedure to assess wave impact loads on vertical breakwaters or seawalls. The new methodology is the first to quantitatively account for uncertainties and variability in the loading process and therefore represented a step forward towards the development of a more rational and reliable design tool. Moving from the identification of the main geometric and wave parameters, the method proceeds through 12 steps to evaluate wave forces (landward, up-lift and seaward), together with the corresponding impact rise time and pressure distribution up the wall. The new design methods are described in details in Allsop et al. (1999) and Oumeraci et al. (2001). In the methodology it was shown that the maximum horizontal impact force could be given by,

$$F_{\mathrm{h,imp}} = F_{\mathrm{h,imp}}^{*} \cdot \rho \cdot g \cdot H_{\mathrm{b}}^{2} \tag{5}$$

where H_{b} is the wave height at breaking (Oumeraci et al., 2001). The relative maximum wave force $F_{\mathrm{h;imp}}^{*}$ is assumed to obey a Generalised Extreme Value (GEV) distribution, given by:

$$F_{\mathrm{h,imp}}^{*} = \frac{\theta}{\xi} \cdot (1 - \xi \cdot \ln P_{\%}) + \mu \tag{6}$$

where: $P_{\%}$ is the probability of non-exceedance of impact forces (suggested value for P is 90%) and θ, ξ and μ are the scale, shape and location parameters of the GEV pdf, given as a function of the bed slopes.