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Wave disturbance behind low-crested structures: Diffraction and overtopping effects

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ABSTRACT

In recent years the hydraulic performance of low-crested structures has been widely studied both theoretically and through experimental analyses, but only a few studies have been focused on the combined diffraction-overtopping effects on wave transmission and induced wave currents.

In this paper hydraulic model tests conducted at the 3D wave basin of Delft University of Technology (Cáceres et al., 2008) were used to obtain and discuss two simple methods for predicting the wave height at the lee of a single detached breakwater of finite length and the related current regime. For the first time diffraction effects are expressly accounted for. The agreement with experimental data is encouraging.

The main objective of the paper is to aid engineers in the first stage of the design process, when using a mathematical model could be unnecessarily excessive.

1. Introduction

Detached low-crested structures (hereafter LCS), either surface-piercing or underwater, are now becoming popular in countries where they have not traditionally been employed as a coastal defence. This is mainly due to their low impact on the landscape, which makes them suitable for protecting beaches of high naturalistic and economic value. Moreover, the low freeboard allows frequent overtopping, which guarantees proper water exchange between the open sea and the protected area. This is very important at locations where the tidal range is low, like most Mediterranean coasts.

However, constructing LCS significantly changes the nearshore circulation, since the breakwaters act as a filter for incident waves and as a partial barrier for the associated current field pattern (Cáceres et al., 2005). The hydrodynamics induced by the structure is driven by a number of phenomena related to wave–structure interaction, which include transmission through the structure (permeability effect), wave overtopping and diffraction around the ends of the breakwater (Fig. 1). However, lowering the wave height behind the barrier induces an alongshore misbalance of wave thrust that drives a shore-parallel current towards the shadow zone, which could cause a cusp or a tombolo to form. Conversely, as the overtopping water must return offshore due to conservation of mass, a longshore current is generated that extends from the protected area to the structure heads, which may increase the erosion rate after the barrier has been placed (Dean et al., 1997). This hydrodynamic complexity makes the shoreline response hard to predict, which is probably the main reason why LCS are sometimes not used.

This high degree of uncertainty has stimulated a huge amount of research work over the last years, aimed at providing engineers with both higher generation numerical models (Johnson et al., 2005; Penchev and Shukrieva, in press) and simple equations that aid the preliminary design of structures.

Most of this work was conducted within the EU project DELOS (Burcharth et al., 2007), which brought together a large number of scientists and engineers to develop guidelines for environmentally sustainable LCS systems.

The transmission coefficient, K_t, has been likely the most researched variable. It represents the ratio between the wave height generated leeward of the barrier by overtopping and filtration and the incoming wave height. Moreover, for linear waves it also equals the root square of the ratio between the corresponding wave energies. K_t has been thoroughly researched because it represents a major variable in the shoreline response to structure placement (Hanson and Kraus, 1991). The latest results on this topic seem to be very encouraging and include a variety of design tools, such as empirical formulae (van der Meer et al., 2005), neural networks (Panizzo and Briganti, 2007), and physically based equations (Wamsley and Ahrens, 2003; Buccino and Calabrese, 2007; Goda, and Ahrens, in press).

In addition to K_t, there is now information on other relevant 2D phenomena such as reflection (Zanuttigh and van der Meer, 2006),

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Nomenclature

B [m] Breakwater crest width
E [N/m] Wave energy
F [m] Feeding channel
g [m/s^2] Gravity acceleration
$h_{(s)}$ [m] Still water depth. The suffix “s” stands for “at the toe of the barrier”
$h_b^{(u),(D)}$ [m] Incipient breaking depth. The apexes “u” and “D” stand for undisturbed and disturbed waves
$\bar{h}$ [m] Mean water depth across the feeder channel
$H_E = H_{rms}$ [m] Energetically equivalent wave height
$H_{m_0(i),(d),(t)}$ [m] Spectral significant wave height. The suffixes “i”, “d” and “t” stand for incident, transmitted and diffracted wave height
K_D [−] Diffraction coefficient, H_d/H_i
$K_{D,t}$ [−] Global transmission coefficient, $K_{D,t} = \sqrt{K_D^2 + K_{t,BC}^2}$
$K_{t\ (BC)}$ [−] Transmission coefficient, Ht/Hi. The suffix “BC” stands for Buccino and Calabrese's formula
L_{op} [m] Offshore peak wave length
L_s [m] Structure length
m_0 [m^2] Zero order moment of wave power spectrum
q [m^3/s] Water discharged into the rip channel
q_{ot} [m^2/s] Overtopping rate per unit of structure length
R [−] Correlation coefficient
R_c [m] Crest freeboard
s [−] Bottom slope
S_{JJ} [N/m] JJ component of the radiation stress tensor
s_{om} [−] Mean fictional wave steepness
T [s] Regular wave period
T_m [s] Mean wave period
T_p [s] Peak wave period
V_{R_i} [m/s] Rip velocity
V_{SPC} [m/s] Structure-parallel velocity
VAR Variance
w_{R_i} [m] Semi-width of the rip channel
x [m] Distance of a generic rip channel section from the shoreline
X_c [m] Distance of the structure from the shoreline
x_b^u [m] Distance between the beach and the breaker line of the undisturbed waves
Y [m] Net hydraulic head
γ_f [−] Friction coefficient
γ [−] Breaker index, H/h
$\bar{n}$ [m] Wave set-up
η_D [m] Diffracted wave profile
ϑ [rad] Phase angles of diffracted waves
μ [−] Discharge coefficient
ρ[kg/m^3] Water density

overtopping (Bruce et al., 2006) and piling up (Calabrese et al., 2008). After analyzing 2D phenomena, some authors have then focused on structure-induced circulation and determined very interesting simplified methods for calculating characteristic values of the nearshore flows, such as the rip current at gaps of a segmented array of barriers (Bellotti, 2004; Zanuttigh et al., 2008). Although these works are based on limited data, they are very interesting because they consider the 3D nature of the wave–structure interaction. However, it is surprising that wave diffraction has not yet been dealt with, as it is clear that a proper tool for predicting wave height behind the barrier must add diffraction effects to those of overtopping and filtration. It should also be noted that the variation in wave height due to diffraction also affects the forcing of the circulation system in the shadow region (Hanson and Kraus, 1991).

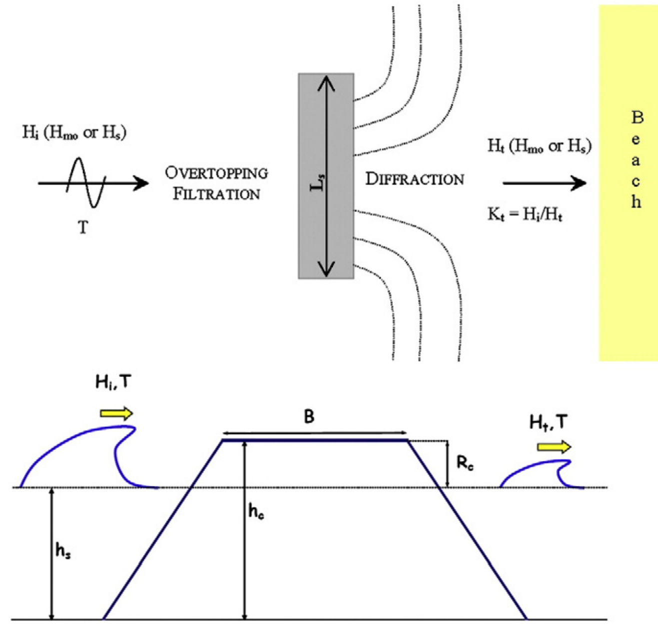

Fig. 1. Wave transformation around LCS and main geometric parameters.

In this paper, 3D random wave experiments have been employed to research the combined effects of diffraction and “2D transmission” (overtopping and filtration) on the generation of wave height leeward of a single breakwater of finite length. The tests were carried out at the wave basin of Delft University of Technology (DUT). To properly evaluate the contribution of diffraction, the breakwater models were constructed with an impermeable core to prevent filtration. This clearly limits the 2D transmission process to the overtopping contribution only.

The paper is organized as follows. After the experiments have been described, a method for predicting the global transmission coefficient that includes both the diffraction and overtopping effects is proposed. Once this tool has been determined, a simplified model for predicting the velocity of the primary currents in the shadow region is presented. The concluding sections discuss the results obtained and provide a flow scheme for practical applications.

2. Laboratory experiments

The physical experiments employed for the analyses presented below were conducted at the wave basin of the Fluid Mechanics Laboratory of Delft University of Technology. They are described in detail in Cáceres et al. (2008).

The wave tank was 15 m wide and 30 m long and was equipped with three piston-type wave generators located at the offshore end of the facility. The height of the wave board allowed a maximum water depth of 0.40 m. Opposite the wavemakers, a 1:20 concrete plane slope stretched across the entire width of the tank and acted as a dissipative beach (Fig. 2).

All the structures used in the experiments had an impermeable concrete core that prevented seepage, and were armoured with rock. Three different layouts with adjustments on the structure freeboard (R_c) were tested. The first one (Layout 1) had the crest at the SWL ($R_c = 0$), the second one (Layout 2) was designed with an emerged 3.5 cm freeboard, and the third one (Layout 3) had a 25 cm crest height to make overtopping impossible. The barrier was placed at a depth, h_s, of 29.2 cm for all the layouts (Fig. 2).

The test conditions were obtained by scaling down three sea states that are commonly found in the Mediterranean. The prototype for modelling the scale ratio was set to 20 in a Froude similitude.