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Wave transformation through flushing culverts operating at seawater level in coastal structures

V.K. Tsoukala [a,*], V. Katsardi [a,1], K.A. Belibassakis [b]

[a] Laboratory of Harbor Works, School of Civil Engineering, National Technical University of Athens, Zografos, Athens, Greece
[b] School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece

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ABSTRACT

The placement of flushing culverts in breakwaters is a simple way to counteract a decline in water quality in harbour basins. A series of 63 experiments, which were conducted in a physical model of a breakwater in a 2D wave flume, are used to investigate the effect of the wave properties as well as the geometrical characteristics of the flushing culvert placed on breakwaters, in the temporal water surface profiles, the harmonic generation and the transmission coefficient. It is shown (i) that the harmonic generation downwave of the structure is more intense when wave nonlinearity increases; (ii) the harmonic generation and the transmission coefficient is mostly affected by the culvert's dimensions, especially the culvert's width as it is associated with the energy transmitted to the lee side of the structure and with diffraction. A 2D coupled-mode system (CMS) model is applied for the numerical simulation of waves propagating through flushing culverts at seawater level that are never perfectly filled with water. Good comparisons with the experimental results for linear and weakly non-linear waves and wider culverts are shown; proving the usefulness of the CMS model in calculating the effectiveness of a flushing culvert in an every-day basis of harbour function.

1. Introduction

In harbour design water quality within a basin must be considered being particularly important for health and environmental purposes, especially in warmer climates where biological processes are accelerated. Successful control of water quality is usually dependent upon periodic exchange of the harbour basin water with the sea water of the open sea (Dunham and Finn, 2002; U. S. Army Corps of Engineers, 2002). A common and economic method to improve the water quality in harbour basins is the construction of flushing culverts (hereafter referred as FCs) at characteristic sites of external harbour structures, which enhance water circulation through the amplification of the velocity field inside the basin and consequently contribute to the reduction of the renewal times and water quality improvement (see e.g. Stamou et al., 2004). They are mainly constructed in protective structures, i.e., breakwaters (Papaioannou et al., 1999; Tsoukala et al., 2006). Underwater placement of culverts is standard internationally, where tidal hydrodynamics is the main mechanism for enhanced flushing. However, in regions, as the Mediterranean, where the ranges of the tides are low, it is preferred to construct the culverts with their longitudinal axis at sea water level (Tsoukala and Moutzouris, 2009).

The evolution of a surface water wave that propagates up a breakwater slope and through an FC at the seawater level (Fig. 1) is an interesting yet very complex physical phenomenon. In the vertical plane, it involves very sudden and large changes in the water depth leading to severe wave transformations including energy dissipation through friction as the wave propagates on the breakwater slope as well as inside the FC, wave reflection in both sides of the FC, wave shoaling, possible wave breaking and thus possible wave induced flow, wave diffraction at the exit of the FC due to the sudden change in water depth, harmonic generation as the surface wave passes through the FC, and additional complex phenomena when the wave's maximum crest elevation hits the top border of the FC. On the other hand, in the transverse direction, when the surface wave meets the FC, it is forced to propagate through a finite width as opposed to the open sea. This leads to less proportion of wave energy being transferred in the lee side of the breakwater, to more energy dissipation inside the FC and to wave diffraction at the exit on re-entering deep water; the magnitude of all the above being proportional to the culvert's width. This paper focuses on the effective design of FCs in breakwaters constructed in low tide areas. The FC design has to be associated with the everyday function of the harbour and hence

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* Corresponding author. Tel.: +30 2107722372.
E-mail addresses: v.tsoukala@hydro.civil.ntua.gr (V.K. Tsoukala), vkatsardi@civ.uth.gr (V. Katsardi), kbel@fluid.mech.ntua.gr (K.A. Belibassakis).

[1] Now in Civil Engineering Department, University of Thessaly, Volos, Greece.

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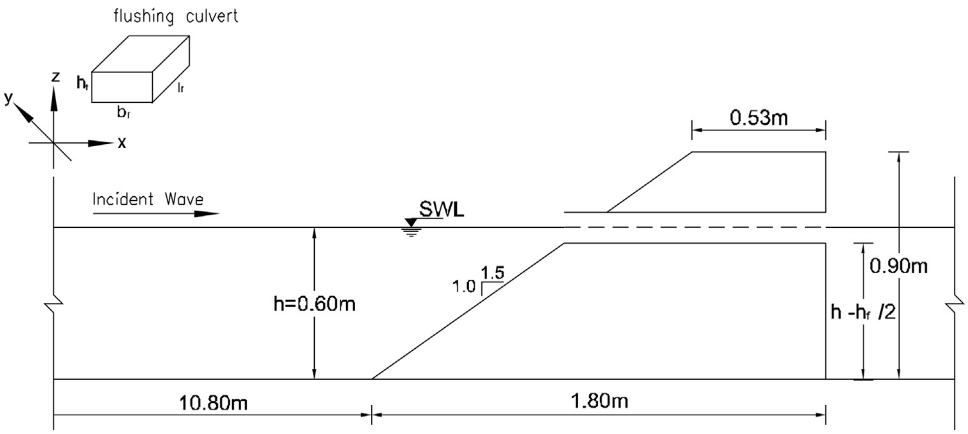

Fig. 1. Sketch of the breakwater's side and 3D detail of the flushing culvert showing basic notation.

naturally with waves of small amplitude and not with the low probability of occurrence of large waves incident to the breakwater. In effect, the waves considered in this study do not interact with the top border of the FC, providing no additional effects due to relevant reflections.

One possible measure concerning the effectiveness of a flushing culvert is the wave transmission coefficient, K_t, and it is used as one of the main non-dimensional parameters concerning the water quality within the harbour basin (Tsoukala and Moutzouris, 2009). It is defined as the ratio of the transmitted wave height through the FC to the incident wave height. It is correlated with the wave characteristics (wave height and wave period), the geometrical characteristics (height, h_f, width b_f and length l_f) of the FC and the water depth, h (see notation defined in Fig. 1).

Dimensional, parametric, and regression analysis has been used in order to define the wave transmission coefficient K_t (Tsoukala and Moutzouris, 2008) investigating a number of experimental results in a 3D wave basin (Tsoukala et al., 2006) as well as in a 2D wave flume (Tsoukala et al., 2010) involving regular incident waves that propagate normal to trapezoidal breakwaters with FCs. In the above studies it is clear that increased transmission coefficients are associated with large ratios of culvert height and width with respect to the wave height H (h_f/H and b_f/H respectively), related to the increased proportion of energy being transferred in the lee side of the openings, and small ratios of culvert length with respect to the wave height (l_f/H), related to small energy losses within the FC. In contrary, regular waves with increasing wave steepness (H/λ, with λ representing the wavelength) lead to smaller transmission coefficients, mainly due to wave breaking. Furthermore, several numerical methods have been examined in Stamou et al. (2004) and Michalopoulou et al. (2008) to simulate the wave transmission through FCs, based on the linear three-dimensional mass continuity and momentum equations where the field is divided in layers of constant width. This method is adequate for problems of constant flow such as wave-induced circulation and hence is not the most appropriate in describing the wave characteristics downstream of a flushing culvert. In the case of a wide FC with normal wave incidence, the system could be considered to be an extreme type of a submerged breakwater characterised by severely abrupt changes in water depth. The latter is because the ratio of the water depth in the FC to the water depth on the sea side h_s/h, with $h_s = h_f/2$ representing the depth over the breakwater crest (Fig. 1), is smaller than the usual relevant ratios in studies about submerged breakwaters. Moreover, wave propagation through FCs involve sudden changes in the available width of propagation, finding similarities in propagation through entrances in harbours and/or through series of breakwaters entailing wave diffraction.

In this connection, Dattatri et al. (1978) made a series of experimental measurements and found that the most important parameters affecting the transmission coefficient are the relative crest length (l_f/λ), where the longer crests are associated with smaller transmission coefficients, K_t, and the ratio of the water depth on the breakwater crest to the incident water depth (h_s/h), where larger ratios are associated with increased transmission, as it is naturally expected. On the topic of harmonic generation the interruption of the wave propagation process by a coastal structure, such as a submerged breakwater, produces flow perturbation, and consequently harmonic generation and energy transfers, which have important effects on the hydrodynamics at the lee side of the structure (Johnson et al., 1951; Mei and Black, 1969; Longuet-Higgins, 1977; Ohyama et al., 1995; Losada et al., 1997; Goda et al., 1999). When waves approach the breakwater containing the FC, part of the wave energy is reflected by the structure and this process is mainly linear regardless of the steepness of the wave field (Driscoll et al., 1992; Christou et al., 2008). Also, a part of the wave energy is dissipated (through friction and/or wave breaking). However, at the breakwater crest, which is the equivalent bottom of the culvert, harmonic generation with energy transfers to higher harmonics is observed and is transmitted to deeper water behind the breakwater as free waves. A second-order theory was developed by Massel (1983) where the second-order potential was linearly decomposed by using the wave steepness as the perturbation parameter. This theory has been extended by Belibassakis and Athanassoulis (2002) to treat weakly non-linear waves propagating over general bottom profiles, and is shown to accurately predict harmonic generation up to second order.

This paper is part of an ongoing research relating to wave propagation through flushing culverts. In effect, motivation for this study was given by the experimental results in a 3D wave basin (Tsoukala and Moutzouris, 2009) that involved physical models of existing harbours. Although the latter lead to very interesting results, the parameters associated with the problem were many and could not be easily isolated. Moreover, the experimental scale was relatively small leading to correspondingly small openings and questions have risen concerning the increased viscous effects in the culverts walls and whether these lead to underestimated transmission coefficients. Similar issues were pointed out in the experimental set-up presented in Lara et al. (2006). Therefore, standard Froude scaling has been applied to the experiments presented in this work, paying special attention to the minimum dimensions of the FC in order to avoid excessive dissipation effects (Figs. 1 and 2).