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Hydraulic stability of reshaping berm breakwaters using the wave momentum flux parameter

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ABSTRACT

An empirical new berm recession formula is derived based on the assumption that the maximum wave force causing armor movement and berm recession is proportional to the maximum wave momentum flux near the structure toe. This concept introduces a more physics-based first principles approach to estimate the berm recession. Recession seems well predicted by the new formula for reshaping berm breakwaters. The results from this formula show a better estimation than earlier formulae used for estimating the berm recession.

1. Introduction

Breakwaters are the structures constructed to provide protection to the port and harbor facility from dynamic forces of the ocean waves. The berm breakwater concept is basically rather old, but was not used very much until it was "reinvented" in the early 1980s, when a slope protection for an airfield runway extending into the sea in the Alutian Islands, Alaska was designed (Rauw, 1987). Berm breakwaters are rubble mound structures initially constructed with a large porous berm above or at still water level at the seaward side. During wave attack, the berm breakwater will typically reshape into an S-shaped profile. Fig. 1 shows the typical initial and reshaped profiles of the cross section and deformation parameters of a berm breakwater.

A berm breakwater is usually designed to make optimum use of the available quarry material and relatively simple construction equipment. The stone gradations will typically be rather wide to get almost 100% utilization of the quarry material (Sigurdarson et al., 2000). Another advantage of berm breakwaters, compared to the traditional rubble mound breakwaters, is that they require a smaller armor stone mass for a given slope.

Hydraulic stability of the berm breakwater has historically been based on empirical equations from experimental data with no physical relation between armor stone movement and wave forces. A representative free body diagram for incipient motion of an armor stone is shown in Fig. 2. In this figure the wave force (F_W) is decomposed into structure normal (F_N) and parallel (F_P) forces. The magnitude and direction of the wave force are varied over the wave cycle. Stone movement is caused by the fluid force due to the incident wave, and movement is resisted by the normal component of buoyant self weight, interlocking between stones, as well as friction between neighboring stones. As it can be seen from Fig. 2, the stimulus incident wave force has been shown during wave run-down, because in this time the parallel component of the gravity force is in the same direction as the parallel wave force component and both of them act as stimulus forces.

There are some commonly used parameters in relation to the stability of rubble mound breakwaters. The most commonly used dimensionless parameter is the stability parameter H_o, which gives a relation between the armor layer and the impact of the incoming wave height.

$$H_o = \frac{H_s}{\Delta D_{n,50}} \tag{1}$$

where, H_s = significant wave height, Δ = relative buoyant density $\left(\Delta = \frac{\rho_a}{\rho_w} - 1\right)$, ρ_a = density of stone, ρ_w = density of water, D_{n50} = median stone diameter $\left(D_{n50} = \left(\frac{M_{50}}{\rho_a}\right)^{1/3}\right)$ and M_{50} = median stone mass. Due to the importance of wave period in the stability of reshaping breakwaters, Van der Meer (1988) introduced the wave period stability number H_oT_o to take into account the effect of wave period to the stability number:

$$H_oT_o = \frac{H_s}{\Delta D_{n,50}} \sqrt{\frac{g}{D_{n50}}} T_z \tag{2}$$

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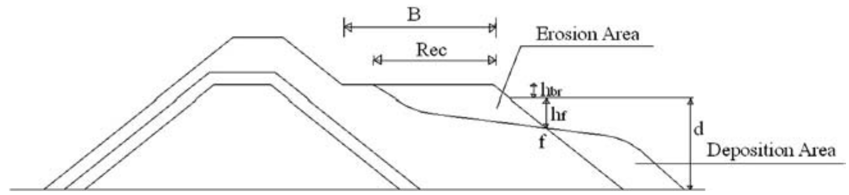

Fig. 1. Definition of cross sectional and deformation parameters of a berm breakwater.

where T_z = mean zero up-crossing period and g is the acceleration of gravity.

Moghim et al. (2011) presented a dimensionless parameter $H_o\sqrt{T_o}$ to consider the combined effects of wave height and wave period on the reshaping berm breakwaters. In this parameter the orders of wave height and wave period efficiency on reshaped profile are not the same.

$$H_o\sqrt{T_o} = \frac{H_s}{\Delta D_{n50}}\left(\sqrt{\frac{g}{D_{n50}}}T_z\right)^{1/2}. \quad (3)$$

Recession of the berm (Rec) is the most important parameter that has been considered as a critical factor for berm breakwaters. Failure of a berm breakwater is typically defined as $Rec > B$, where B is the berm width (PIANC, 2003). Several researchers have given some methods and formulae to estimate the recession of the berm, e.g., Van der Meer (1988, 1990, 1992), Hall and Kao (1991), Norton and Holmes (1992), Van Gent (1995, 1996), Tørum (1998), Tørum et al. (2003, 2012), Sigurdarson et al. (2008), Lykke Andersen and Burcharth (2009) and Moghim et al. (2011). Some of these works are based on experimental models and some of them are based on numerical models. Hall and Kao (1991), Tørum et al. (2003, 2012), Sigurdarson et al. (2008), Lykke Andersen and Burcharth (2009) and Moghim et al. (2011) have suggested formulae to calculate the recession with no physical relation between armor stone movement and wave forces. Van der Meer (1988), Norton and Holmes (1992) and Van Gent (1995) have developed computer programs to calculate the recession and the stability of the structure.

The hydrodynamic interaction of waves with a reshaping rubble mound breakwater is complex, and steady progress has been made toward understanding wave/structure interactions. Some engineering aspects of reshaping rubble mound breakwater design are still not fully described by theory, e.g., berm breakwater stability. Engineers have established useful design guidance by augmenting theoretical reasoning with empirical coefficients determined from small-scale laboratory testing. The balance between theoretical and empirical contributions varies widely. The estimation of hydraulic stability of berm breakwater is almost entirely empirical (Moghim and Tørum, 2012).

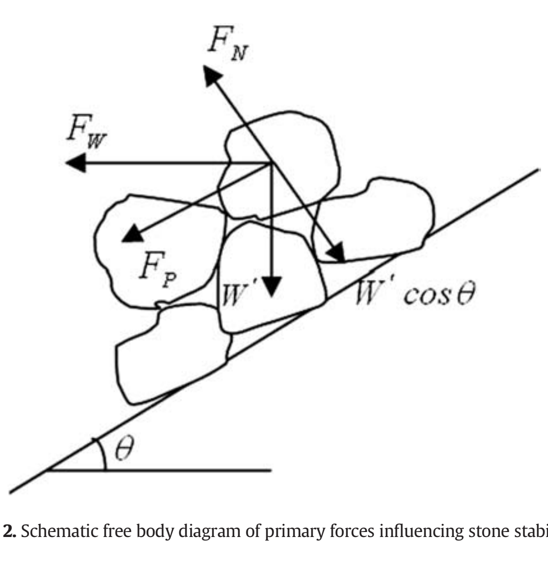

Fig. 2. Schematic free body diagram of primary forces influencing stone stability.

In this paper a simple physical argument is used to derive a new formula to calculate the berm recession in terms of a dimensionless wave parameter representing the maximum, depth-integrated momentum flux in a wave as it reaches the toe of the structure slope that was presented by Hughes, 2004a. The goal of the study was to provide an estimation technique that is at least as good as existing formulae, using a physical relation between armor stone movement and wave forces.

2. Previous work on berm recession

A number of formulae given for calculating the recession of a berm are cited here.

2.1. Hall and Kao formula

Hall and Kao (1991) investigated the influence of rounded stones and stone gradation on the reshaping of berm breakwaters. They proposed the following formula to calculate the recession of the berm:

$$\frac{\text{Rec}}{D_{50}} = \left(-10.4 + 0.51 H_o^{\,2.5}\right) + 7.52\left(\frac{D_{85}}{D_{15}}\right) - 1.07\left(\frac{D_{85}}{D_{15}}\right)^2 + 6.12 P_R \quad (4)$$

where D_{n85} is the nominal diameter of the stones for which 85% of the total sample mass is of lighter stones, D_{n15} is the nominal diameter of the stone for which 15% of the total sample mass is of lighter stones and P_R = fraction of rounded stones in the armor.

2.2. Tørum formula

Tørum et al. (2003) derived a formula for the recession on multilayer berm breakwaters, which Tørum (2007) modified to:

$$\frac{\text{Rec}}{D_{n50}} = 0.0000027(H_0T_0)^3 + 0.000009(H_0T_0)^2 + 0.11(H_0T_0) - \left(f_{Dn}\left(f_g\right) + f_d\left(\frac{d}{D_{n50}}\right)\right)\frac{H_oT_o}{120}. \quad (5)$$

The gradation factor function $f_{Dn}(f_g)$, f_g = stone gradation $\left(f_g = \frac{D_{n85}}{D_{n15}}\right)$, is given by:

$$f_{Dn}\left(f_g\right) = -9.9 f_g^{\,2} + 23.9 f_g - 10.5 \quad (6)$$

and the depth function $f_d\left(\frac{d}{D_{n50}}\right)$ is given by:

$$f_d\left(\frac{d}{D_{n50}}\right) = -0.16\left(\frac{d}{D_{n50}}\right) + 4.0 \quad (7)$$

where, d = water depth. This formula is valid for H_0T_0 > 20–30, $1.3 < f_g < 1.8$ and $12.5 < \frac{d}{D_{n50}} < 25$.