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IMPROVEMENTS TO THE CORE SCALING METHOD FOR RUBBLE-MOUND BREAKWATERS

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1. Introduction and problem statement

Geometric scaling of the underlayer and the core of a rubble-mound breakwater generally leads to an incorrect representation of the hydraulic resistance due to the effect of the fluid viscosity and surface tension. In order to maintain the similitude of the Froude scaling law in a physical model, a so-called 'distorted scaling method' is applied to determine the average diameter d_{50}^m of the granular material in the model. A widely used method (Burcharth et al., 1999) yields the requested diameter d_{50}^m, stating that

$$\bar{v}_f^p = \bar{v}_f^m \sqrt{\lambda_L} \qquad [1]$$

where $\overline{v_f}^p$ and $\overline{v_f}^m$ are characteristic filter velocities (averaged in time and space) in the core of the prototype and physical model, respectively and λ_L is the geometric scale factor. The characteristic filter velocities are computed with the Forchheimer equation, which relates the horizontal pressure gradient $I_x = -\partial P(x)/\rho g \partial x$ to the pore velocity v_f, which takes the form in a steady flow:

$$I_x = \alpha \frac{(1-n)^2}{n^3} \frac{\nu}{g d_{50}^2} v_f + \beta \frac{(1-n)}{n^3} \frac{1}{g d_{50}} v_f |v_f| \qquad [2]$$

where n is the porosity, ν the kinematic viscosity, g the gravitational constant and α and β the so-called shape coefficients, dependent on the grain shape and grading , but also on the flow regime, governed by the Reynolds number $Re = v_f d_{50}/\nu$. Since the flow regime depends on the requested grain diameter, unknown a priori, the scaling method is to be applied iteratively. In every step it is verified whether the choice of the shape coefficients α and β is in accordance with the specific flow regime, as it occurred during the experimental derivation of the shape coefficients.

Eq. [2] relates the hydraulic resistance characteristics of the grain material to the filter velocity and the pressure gradient. In the scaling method, the wave-induced pore pressure height in the breakwater core is obtained using an empirical calculation model, given by Burcharth et al. (1999). It has been found that this calculation model does not result in an accurate prediction under varying wave conditions (Vanneste and Troch, 2012). In order to overcome the shortcomings of the existing calculation model, a new model has been formulated. Its use in the scaling method is discussed hereafter and illustrated by means of an example case.

2. Discussion of the existing model for the distribution of pore pressure height

In the method of Burcharth et al. (1999), an exponential decay of pore pressure height is assumed:

$$P(x) = P_0 \exp(-\delta k' x) \qquad [3]$$

where P_0 is the reference pore pressure height at the interface between core and underlayer, δ a dimensionless damping coefficient and k' the internal wavenumber, related to the wavenumber k as $k' = k\sqrt{1.4}$. A practical approximation for the reference pressure $P_0/\rho g H_{m0}$ equal to 0.5 is taken, being constant along the interface between core and underlayer. The damping coefficient is obtained using an empirical formulation:

$$\delta = 0.014 \frac{\sqrt{n L_p^2}}{H_{m0} b} \qquad [4]$$

where H_{m0} is the incident significant wave height at the toe of the breakwater, L_p the peak wave length and b the width of the considered core section at a given depth below SWL. The validity of this practical model has been tested extensively against experimental pore pressure measurements both on a large and a small scale physical model (Vanneste and Troch, 2010; 2012). The constant value 0.5 for the reference pressures results to be an underestimation in cases of large wave run-up, where values of 1, up to almost 2 were measured. The spatial variation of the reference pressures along the interface is moreover not negligible. The results of the experimental tests show a weakly positive correlation between the damping coefficient and the incident wave height, opposite to the suggested inverse proportionality according to Eq. [4]. Additionally, it was found that the assumption of an exponential decay of pore pressure height does not match the measured decay in the experiments in the front zone of the breakwater core, under the core slope. An alternative approach is proposed to describe the attenuation of pore pressure height (Vanneste and Troch, 2012), taking into account the previous considerations. The new calculation model is capable of predicting the pore pressure distribution with higher accuracy than the existing model, in a broad range of wave conditions.

3. Application of the new calculation model in the core scaling method

The application of the modified scaling procedure is illustrated by means of the example case of the Zeebrugge breakwater core (scaled with $\lambda_L = 30$), included in the original paper by Burcharth et al. (1999). The same hydraulic resistance properties for the prototype material are used. The hydraulic resistance properties for the model core material were estimated from Burcharth and Christensen (1991), together with a hypothetical value for the core porosity of 0.4. Two different wave climates are employed. Results of the original and the modified scaling method are shown together in Table 1.

Table 1. Results of both scaling procedures.

method	Case	U^p $[m/s]$	d_{50}^m $[m]$	λ_L^c $[-]$
original	H_{m0}=2m ; T_p=7s	0.058	0.0149	17.6
	H_{m0}=4m ; T_p=12s	0.072	0.0141	21.5
new	H_{m0}=2m ; T_p=7s	0.061	0.0144	18.2
	H_{m0}=4m ; T_p=12s	0.095	0.0136	19.3

The new calculation model leads to higher pressure gradients in the front zone of the core, as shown in Figure 1. This is mainly due to the underestimation of the reference pressure in the original method. Consequently, higher filter velocities are obtained when the hydraulic resistance properties (n, α and β) of the core material remain constant. As a results, the application of Eq. [2] leads to a somewhat smaller grain diameter d_{50}^m , compensating for the increased pressure gradient.

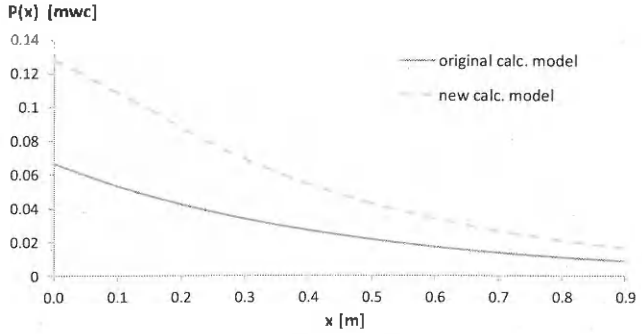

Figure 1. Evolution of pore pressure height $P(x)$ along a horizontal section at half the water depth, H_{m0}=4 m, T_p=12 s; obtained with the original (solid) and new calculation model (dashed).

4. Conclusion

It is noticed that the resulting geometric scales for the core material λ_L^c in Table 1 computed with both methods are comparable. Despite a more accurate prediction of the actual pore pressure height, the impact of the new calculation method is limited, since it is not the exact value of the pore pressure height, but the local gradient of the pore pressure height which has an impact on the calculation. However, the new calculation model contributes to making the core scaling method more reliable in varying wave conditions. A sensitivity analysis shows that the scaling method is most susceptible to the value of the porosity. The effect of a change in porosity is approximately a factor 10 times higher than a change of the shape coefficients. Thus, when applying the core scaling method in practice, an accurate value of the porosity is considered to be indispensable.

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