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SENSITIVITY ANALYSIS OF EXISTING EXPONENTIAL EMPIRICAL FORMULAS FOR PORE PRESSURE DISTRIBUTION INSIDE BREAKWATER CORE USING NUMERICAL MODELING

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EXTENDED ABSTRACT

Il seguente elaborato è il frutto della tesi di laurea magistrale realizzata presso il Dipartimento di Ingegneria dell'Innovazione dell'Università del Salento finalizzata a studiare il fenomeno di interazione dell'onda con la diga frangiflutti a scogliera di Zeebrugge (Belgio), per mezzo di un sofisticato software di modellazione numerica. Nonostante si abbia una notevole conoscenza sui processi naturali che coinvolgono queste strutture, attualmente non è ancora ben chiaro il fenomeno di attenuazione della pressione porosa nel nucleo di una diga frangiflutti a scogliera, che condiziona la trasmissione dell'onda e il danno inflitto su tali opere. Questo elaborato sperimentale prova a fornire un valido aiuto per studiare il fenomeno dello smorzamento della pressione porosa nel nucleo delle dighe a scogliera per mezzo di una convalidazione di un modello numerico all'avanguardia per trovare la sensibilità delle formule esistenti rispetto ai parametri dell'onda. È stato effettuato uno studio sperimentale su scala reale con l'aiuto di un software di modellazione numerica (RANS/VOF implementato nel programma di modellazione numerica FLOW-3D).

In questo studio, viene rappresentata la simulazione numerica inerente il processo di interazione onda-struttura. Su questo sfondo vengono condotti gli esperimenti tridimensionali effettuati dal programma studiando in particolare, il fenomeno dell'attenuazione della pressione dei pori nel nucleo della diga a scogliera e valutando le grandezze che entrano in gioco e che potrebbero essere considerate in fase di progettazione. L'obiettivo è quello di confrontare la soluzione numerica offerta da Flow-3D con le soluzioni analitiche calcolate rispettivamente mediante la nuova formula Tomasicchio & Kurdistani (2020) e la formula di Biesel (1950). La fase di taratura del modello è stata conseguita basandosi sui dati sperimentali ottenuti da Schlütter *et alii* (1996). Dopo aver effettuato una serie di tentativi variando i Drag Coefficient, i valori sono stati ottenuti in modo tale che il modello numerico fosse in grado di riprodurre fedelmente il fenomeno.

Analizzando i dati di 27 esperimenti, emerge che la soluzione analitica calcolata per mezzo della formula Tomasicchio & Kurdistani (2020) approssima molto bene la soluzione numerica sovrapponendosi a quest'ultima addirittura per alcuni tratti, in diverse simulazioni. Mentre la formula di Biesel (1950), invece, dimostra di essere molto lontana dalla soluzione numerica. Ciò può essere dovuto al fatto che in questa formula esistono due parametri, D e a_δ, i quali assumono valori fissati, mentre nella formula Tomasicchio & Kurdistani (2020), è stata eliminata la dipendenza della $P(x)$ da questi due costanti esplicitando tutte le grandezze in gioco. Ne consegue che la formula di Biesel (1950) è molto sensibile al periodo dell'onda. Pertanto la formula Tomasicchio & Kurdistani (2020) consente una rapida nonchè corretta valutazione della pressione porosa all'interno del nucleo di una diga frangiflutti a scogliera, senza ricorrere a svariate ore di elaborazione dati (in questo studio, tra calibrazione ed esperimenti numerici, sono state spese più di 150 ore di calcolo computazionale).

Infine per completare il lavoro di ricerca, si studia il comportamento dell'attenuazione della pressione porosa all'interno del nucleo, da parte di Flow-3D, al variare dell'altezza del'onda, del periodo dell'onda e della profondità dell'acqua. All'inizio 9 esperimenti sono stati svolti per tre altezze delle onde e tre periodi delle onde. Questi 9 esperimenti realizzano chiaramente la sensibilità della formula Biesel (1950) al periodo dell'onda mentre la formula di Tomasicchio & Kurdistani (2020) sempre segue i dati sperimentali e non è sensibile al periodo dell'onda. Questi 9 esperimenti sono stati ripetuti per altre due profondità dell'acqua confermando nessuna sensibilità delle formule rispetto alla profondità dell'acqua. Calcolando l'errore radice quadratico medio (Erms) si osserva che la formula Tomasicchio & Kurdistani (2020) con i valori minimi Erms, a differenza di Biesel (1950), segue con molta più precisione i risultati sperimentali.

ABSTRACT

A series of numerical experiments were carried out to perform a sensitivity analysis for existing exponential empirical formulas for pore pressure distribution inside the breakwater core. The Forchheimer equation was solved using a CFD modeling (Flow-3D) along with the official license from the Flow Science, Inc. Pore pressure field observations of Zeebrugge breakwater core were used to calibrate the numerical model. Results of sensitivity analysis represented the wave period as an effective parameter on wave-induced pore pressure inside the rubble mound breakwater core and a sensitive parameter for empirical formulas while other wave parameters like wave height and water depth did not stimulate the formulas sensitivity.

Keywords: *pore pressure, breakwater, Forchheimer, Zeebrugge, Flow-3D, wavelength, wave height, wave period, RANS, CFD* .

INTRODUCTION

Empirical equations generally have been used to determine the wave-induced pore pressure height distribution inside the core of the rubble mound breakwaters. The most repeated and applied equation is the Biesel (1950) formula that is referenced in many experimental and numerical contributions. Bürger *et alii* (1988) highlighted the necessity of an empirical equation for the pore pressure distribution within the breakwater as a function of the water depth and the wave characteristics. Oumeraci & Partenscky (1990) showed the complexity of the phenomena because of wave breaking and air entrainment, virtual mass effects, non-linearity and unsteadiness of the flow together with the uncertainties in the hydraulic properties of the different breakwater layers. Wibbeler & Oumeraci (1992) developed a Finite Element Model to simulate the wave-induced flow in a multilayered rubble mound breakwater solving the Forccheimer equation; they also confirmed that the reasons for some disagreements between numerical and experimental results are due to the air entrainment, unsteadiness of the flow and high turbulence within the first layers of the rubble mound breakwater.

Burcharth & Andersen (1995) considering the effect of the porosity, using dimensional analysis and the Navier-Stokes equations presented one-dimensional porous flow equations for both steady and unsteady flows. Whitaker (1996) presented the volume averaged form of the Navier-Stokes equations to derive Darcy's law with the Forchheimer correction for homogeneous porous media. Troch *et alii* (1996) comparing "Zeebrugge" rubble mound breakwater prototype measurements with laboratory results showed that wave run-down agrees well with laboratory data and the prototype wave run-up can be about 50% higher than the wave run-up on armoured slopes of scale models. Schlütter *et alii* (1996) by means of "Zeebrugge" rubble mound breakwater field measurements, experimentally showed that in the physical models scale effects can influence the results.

Brunone & Tomasicchio (1995) showed that evaluation of the accuracy of numerical solutions is more valuable due to the more frequent use of 1D numerical models in design of rubble-mound coastal structures. Brunone & Tomasicchio (1996) indicated that for the case of a rough permeable steep slope, it can be noted that wave kinematics is not correctly described by wave theories which are expected to apply considering only the values of relative water depth and relative wave height. Brunone & Tomasicchio (1997) showed the influence of the filter and the armour layer conducting an experimental study on the relevant characteristics of the flow field induced by a regular wave acting on a uniform steep slope. Kobayashi *et alii* (2000) measured free surface elevations and horizontal velocities of non-breaking regular waves on a 1:2 rough permeable slope to examine the cross-shore variations of the incident and reflected waves on the steep slope; they found that the incident wave energy flux was approximately constant along the 1:2 slope, whereas the data and linear theory were not accurate enough to detect the cross-shore variation of the relative small wave reflection coefficient.

Burcharth *et alii* (1998) studied the influence of core permeability on Accropode armour layer stability. Burcharth *et alii* (1999) depicted that the main problem related to the scaling of core materials in models is that hydraulic gradient and pore velocity are varying in space and time; this makes it impossible to arrive at a fully correct scaling and calculation of the characteristic of pore velocity can be done only using numerical simulations.

Muttray & Oumeraci (2005) studied theoretically and experimentally the wave damping in a rubble mound breakwater core for linear, quadratic and polynomial damping functions. They showed that determining the wave damping inside the breakwater core using the linear damping model results in exponential pore pressure height attenuation.

Troch (2001) numerically studied the pore pressure distribution inside rubble mound breakwaters. Vanneste & Troch (2010) and Cantelmo *et alii* (2010) are other experimental contributions with the objective of calibrating existing empirical equations; in particular, Cantelmo *et alii* (2010) tested a typical multi-layered rubble mound in a wave flume under regular and random wave conditions and validated semi-theoretical and numerical approaches describing wave damping in porous media. Vanneste & Troch (2012) developed an improved model to determine the wave-induced pore pressure distribution inside the core of the rubble mound breakwaters. Vanneste & Troch (2015) validated a bi-dimensional numerical model to simulate the large-scale physical model results of wave interaction with a rubble-mound breakwater using experimental measurements on a large-scale, multi-layered breakwater model.

Wolters *et alii* (2014) carried out a series of experiments on the wave damping process in rubble mound breakwaters in the Scheldt Flume of Deltares; they showed that, because of the flow regime variations, the analytical solution of the shallow-water equations within a porous media is not sufficient to resolve the damping phenomenon inside the breakwater core.

Guanche *et alii* (2015) by means of a hybrid modeling which is a combination of experimental, numerical and existing empirical formulations studied pore pressure height damping in rubble mound breakwaters. They showed that the most important differences between the semi empirical formulae and experimental results appear in the evaluation of the reference pressure and for the longest wave periods. Schiaffino *et alii* (2015) showed that low-crested breakwaters also influence a periodic salient formation whose evolution is tightly related not to the wave direction but to the wave height.

Losada *et alii* (2016) by means of Boussinesq approximations and solving the Navier-Stokes equations, showed the complexity of the influence of material grading, shape, or packing density on momentum damping for porous media flow.

Tomasicchio & Kurdistani (2020) using dimensional analysis and incomplete self-similarity (Barenblatt 1987) presented a new formula for wave pressure attenuation inside the breakwater core that in the proposed equation, the mean diameter of the core material has a main influence as a parameter while the previous empirical equations do not take it into account. Moreover, the new formula is independent of calibrating coefficients using observed data and there are no more coefficient values assumptions that are essentially needed for the Biesel (1950) formula.

The main purpose of the present study is to understand the effect of the wave period and wave height on wave-induced pore pressure inside the breakwater core. Therefore, a numerical model (Flow-3D) has been calibrated to estimate the pore pressure distribution inside the "Zeebrugge" rubble mound breakwater core; creating a virtual wave channel setup inside the Flow-3D model and conducting numerical experiments for different flow and wave parameters like approach water depth, maximum wave height, and wave period. Results have been compared with the results from Biesel (1950) formula and results from Tomasicchio & Kurdistani (2020) formula as a sensitivity analysis.

METHODOLOGY

Wave-induced pore pressure height

Darcy (1856) presented the relationship between the hydraulic gradient *I*, and the discharge velocity *U*, through porous media as $I = K\text{-}1\,U$ where *K* is the permeability coefficient (m/s) where more details about Darcy's law can be found in Cherubini *et alii* (2013). Forchheimer (1901), considering the term of turbulent flow, extended this expression as $I = a\,U + b\,|U|\,U$ where a and b are coefficients. According to Burcharth & Andersen (1995), taking into account the Navier-Stokes equation and Reynolds number, Forchheimer formula can be written in the following form:

$$I = \alpha\frac{(1-n)^2}{n^3}\frac{\upsilon}{g\,d_{50}^2}U + \beta\left(\frac{1-n}{n^3}\right)\frac{1}{g\,d_{50}}U|U| \tag{1}$$

where α and β are coefficients to be determined experimentally for different flow regimes (laminar or turbulent), see Burcharth & Andersen (1995), n is the porosity, d_{50} is the mean grain diameter of porous media and υ the kinematic fluid viscosity. More information about pore water pressure gradient can be found in Imaizumi & Miyamoto (2011). Biesel (1950) presented an equation in exponential form to determine the wave-induced pore pressure distribution inside a homogeneous porous core:

$$P_{(x)} = P_0\, e^{-\delta\frac{2\pi}{L'}x} \tag{2}$$

where $P(x)$ = wave-induced pore pressure height inside the breakwater core along the x-axis at the distance of y from free water surface; P_0 = wave-induced pore pressure at x = 0 (the interface between core and filter layer at the water surface) = $\rho g(H/2)$; H = incident wave height at the structure toe.; L = wavelength; D = seepage coefficient; $L' = (L\ D^{-0.5})$ is the wavelength inside the core; $\delta = (a_\delta\ n^{0.5}L^2)/bH$ is the wave damping coefficient in which n = porosity of the core, a_δ = coefficient related to the core material and b = width of the core at the depth of y from free water surface (Fig. 1).

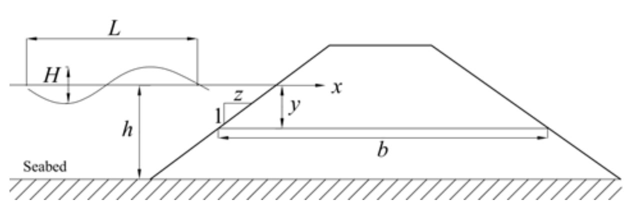

Fig. 1 - Sketch of wave-induced pore pressure main parameters.

Tomasicchio & Kurdistani (2020) by means of the dimensional analysis presented a new wave damping coefficient $\psi = (n^{0.5}\,x\ h)/b\ H$ in which there is no more necessity to assume appropriate values for seepage coefficient D and core material coefficient a_δ. Tomasicchio & Kurdistani (2020) considering ψ as the character of the self-similarity (Barenblatt 1987) presented a new formula for wave pressure attenuation inside the breakwater core as it follows:

$$\frac{P_{(x)}}{P_0} = e^{-e^{\left(0.5\frac{d_{50}}{h}\omega^{-1}\right)\psi}} \tag{3}$$

where ω = *(1/2π) tanh(2πh/L)* has been presented as a new non-dimensional wave parameter (see for more details on ω, Tomasicchio *et alii*, 2020).

Experimental setup

Numerical experiments have been conducted in a virtual channel 90 m long, 4 m wide and 15 m deep. Zeebrugge Breakwater is protected by two rows of rubble mound breakwaters armoured with 25 ton Antifer cubes. The porous core consists of materials with d_{50} = 0.262 m, G_s = 2.65, and porosity of n = 0.38. The under layer is made of 1 - 3 tons' rocks with a porosity of n = 0.38.

FLOW-3D MODEL

Calibration

Schlütter *et alii* (1996) observed data have been adapted to calibrate the numerical model. Several experiments have been conducted using different values of α and β for h = 4.62 m, H = 2.91 m and T = 7.9 s, and finally, α = 360 and β = 3.6 have been obtained. Figure 2 shows that all 5 measured data at y = 2.32

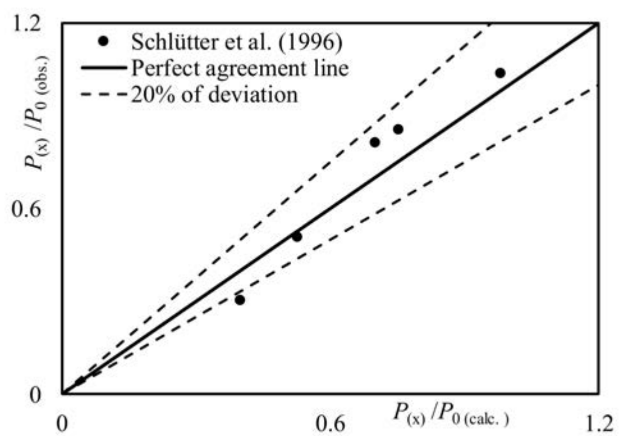

Fig. 2 - Adapted data from Schlütter et alii (1996) versus calculated results from Flow-3D.

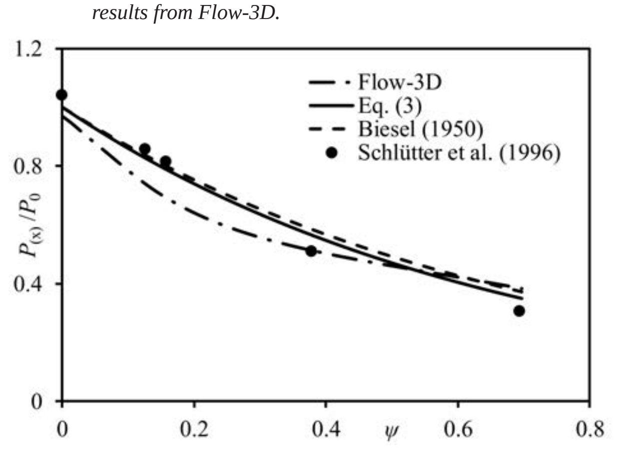

Fig. 3 - Comparing Schlütter et alii (1996) data with results from Flow-3D, Eq. (3) and Biesel (1950).

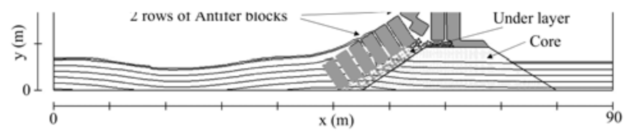

Fig. 4 - A stokes fifth order wave pressure counter lines inside the core and constant still water level in the other side of the breakwater during a test run.

m below the free water surface level adapted from Schlütter *et alii* (1996) in comparison with the results from the calibrated Flow-3D model are within 20% of deviation from the perfect agreement line.

Figure 3 compares adopted wave-induced pore pressure data from Schlütter *et alii* (1996) with the results from Flow-3D, the results from Tomasicchio & Kurdistani (2020) expression and results from Biesel (1950) formula. It shows that the results from Flow-3D are in good agreement with both Eq. (3) and Biesel (1950).

Figure 4 depicts the formation of a stokes fifth order wave generated by Flow-3D inside the 90 m channel at the maximum run-up moment in which h = 4.62 m, H = 2.91 m and T = 7.9 s. It shows pressure counter lines inside the core and a constant still water level on the other side of the breakwater during a test run.

Numerical experiments

27 numerical experiments have been conducted to find the sensitivity of both Biesel (1950) and Tomasicchio & Kurdistani (2020) formulas respect to various wave heights, wave periods and water depths. Water depths h = 4.62, 5 and 5.5 m, wave heights H = 2.41, 2.91 and 3.2 m and wave periods T = 3.6, 5 and 7.9 s have been examined and results have been discussed.

SENSITIVITY DISCUSSION

For each experiment, results have been extracted at y = 2.32 m below the free water surface level to be comparable with Schlütter *et alii* (1996) observations and Burcharth *et alii* (1999) calibration of Biesel (1950) formula. In the first instance, it has been tried to show the sensitivity of Biesel (1950) and Tomasicchio & Kurdistani (2020) formulas respect to the various wave periods and wave heights as it has been shown in Figs. 5(a-i). Figures 5(a-c) show the effect of decreasing the wave period on results from Biesel (1950) formula and Eq. (3) comparing with the results from Flow-3D. As it appears in Fig. 5a, the results from Biesel (1950) formula and Eq. (3) are overlapped close to the results from the numerical model for T = 7.9 s, h = 4.62 m, H = 2.41 m. Figure 5(b) depicts that in the case of decreasing the wave period to T = 5 s, the results from Eq. (3) remain close to the numerical model results but the results from Biesel (1950) are over-estimated. Figure 5(c) shows that with decreasing more the wave period to T = 3.6 s, still the results from Eq. (3) remain close to the numerical results and the results from Biesel (1950) are even more over-estimated. This shows clearly the sensitivity of Biesel (1950) formula to the wave period. This happened because of this reason that using Biesel (1950) formula needs to be calibrated by means of two empirical coefficients D and a_δ where Burcharth *et alii* (1999) chose $D = 1.4$ and $a_\delta = 0.0141$ to calibrate Biesel (1950) formula for $T = 7.9$ s, $h = 4.62$ m, $H = 2.91$ m. This means that for any wave condition, it is needed to calibrate the formula using experimental or filed observed data. To explain better this finding, the root means square error Erms (%) has been determined, defined as:

$$E_{rms} = 100\sqrt{\frac{\Sigma\left(\frac{P}{P_0}\left(formula\right) - \frac{P}{P_0}\left(\exp.\right)\right)^2}{\Sigma\frac{P}{P_0}\left(\exp.\right)^2}} \qquad (4)$$

where P/P_0 (formula) are the results from Eq. (3) or Biesel (1950) formula and $P/P_{0\ (\mathrm{exp.})}$ are the results from numerical experiments.

Figures 5(a-c) indicate the increasing of Erms for wave height $H = 2.41$ m and wave periods $T = 7.9$ s, $T = 5$ s, and $T = 3.6$ s respectively. Figures 5(d-f) and 5(g-i) show the same condition of figures 5(a-c) for wave heights $H = 2.91$ m and $H = 3.2$ m respectively showing that for other examined wave heights instead, there is no significant sensitivity of Biesel (1950) formula. In other words, looking at columns in Figs. 5(a-i) illustrates that values of Erms for Biesel (1950) formula are not ascending by increasing the wave height while a horizontal look shows that in any row, values of Erms for Biesel (1950) formula increase by decreasing the wave period and Biesel (1950) formula is highly sensitive to the wave period.

Once again looking at Eq. (3) and Eq. (2), shows that new non-dimensional wave parameter ω has an important role to keep the results from Eq. (3) close to the results from the numerical model that actually are results from solving the Forchheimer equation (Eq. 1). Moreover, Eq. (3) consists of a new wave damping coefficient ψ that doesn't need to be calibrated and also d_{50} of the core material enters directly in the formula while using Biesel (1950) formula (Eq. 2) needs the calibration of coefficients D and α_δ for any wave period. All 9 experiments shown in Fig. 5 have been repeated for two other water depths $h = 5$ m and $h = 5.5$ m and results showed no significant sensitivity for both examined formulas respect to the water depth.

CONCLUSIONS

A sensitivity analysis was conducted for existing exponential empirical formulas for determining wave-induced pore pressure distribution inside the core of rubble mound breakwaters.

Forchheimer equation was solved using numerical modeling

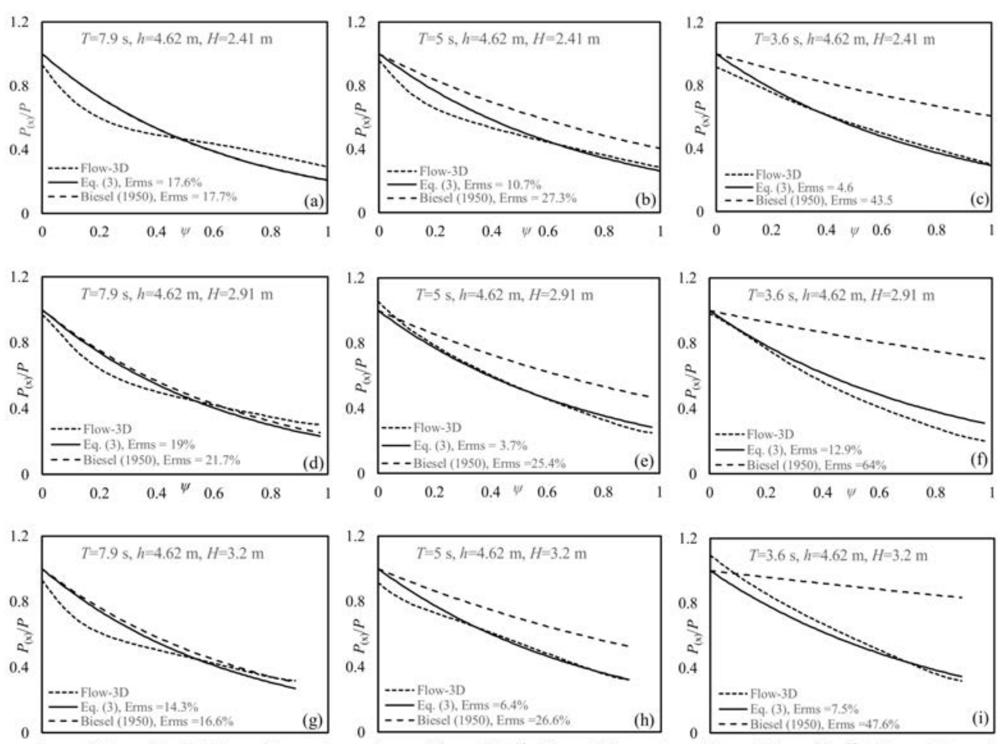

Fig. 5 - Comparison of results from Eq. (3) with Flow-3D and Biesel (1950) results, indicating the root mean square error values (Erms).

(Flow-3D) calibrated for Zeebrugge breakwater in Belgium.

The results from Biesel (1950) formula and the results from Tomasicchio & Kurdistani (2020) formula were examined numerically. Results showed high sensitivity to the wave period for Biesel (1950) formula while Tomasicchio & Kurdistani (2020) formula was not sensitive to the variation of the wave period.This is because of this reason that Tomasicchio and Kurdistani (2020) formula contains d_{50} of the core material as a parameter while the Biesel (1950) formula does not take into account the direct effect of d_{50}. Moreover, the new wave damping coefficient ψ makes Tomasicchio & Kurdistani (2020) formula independent of calibrating empirical coefficients that are essentially needed for the Biesel (1950) formula. Finally, new non-dimensional wave parameter ω controls well the effect of the wavelength and wave period in using TTomasicchio & Kurdistani (2020) formula, giving fewer sensitivities and more reliable results.

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